The variability of delays, as a measure of reliability and quality of service, should be integrated into tactical formulations. Additionals real-life preoccupations should also be considered in tactical models. Fleet size constraints, for example, are an important planning issue that is not currently included in tactical models. We think that the delay-penalty modeling approach is appropriate for this problem, but the issue should be further investigated.

Increased efficiency could be pursued for the various algorithms that compose the solution procedure. Parallelly, "exact" algorithms should be developed to allow a more rigorous evalutation and validation of the heuristic methods. Postoptimization procedures should also be developed and integrated to the planning system.

Finally, we want to emphasize that recent advances in operations research methods, computer science software and hardware, artificial intelligence and decision support systems open up new and exciting research possibilities for transportation science in general and rail tactical planning in particular. So, it is possible now to build comprehensive interactive-graphic planning systems that run on microcomputers and thus, to put impressively powerful computational and planning means within easy financial reach of practically every transportation related organization. Also, the combination of traditional optimization models and algorithms and expert system techniques or interactive optimization methods may yield very interesting results for the development and utilization of tactical planning models for freight rail transportation.

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DATA NEEDS FOR THE SCAN SYSTEM

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REPORT BN/NSF-87-3-1

FINAL REPORT FOR TASK 3 OF SECOND YEAR STATEMENT OF WORK

January 1988–(revised)

JAN '88 S/N 7/629417 AC

Contents

Chapter 1

INTRODUCTION

The *Schedule Analysis (SCAN)* System is a computer-based tool for the analysis and development of schedules for freight railroad operations. In the final report of Task 2, August 1987 the philosophy and structure of the SCAN system was presented. The purpose of the present report is to describe in detail the data needs for the SCAN system and to discuss the means by which SCAN can be linked to the existing databases at Burlington Northern in order to provide easy updating of the data needed by SCAN and/or the schedules in the D1260 file. Thus, this report documents the organization of the databases which "feed" the SCAN system, as well as considering the future data requirements and information systems necessary for the overall system development. Version 1.1 of SCAN provides a solid foundation with which to pursue many attractive research directions and to begin the task of analyzing and updating the schedules on the BN system. However, before such tasks are realized, SCAN must have ready acccess to a well-organized database. It is the goal of this report to present a framework for consideration at Burlington Northern which will provide such access on an on-going basis. Without such ready access to the data necessary to run SCAN, the impact of SCAN within the organization will be limited at best. Thus, data is the "bottleneck" which must be overcome if SCAN is to achieve its potential at BN.

SCAN's existing database represents the Northern Corridor of Burlington Northern Railroad. Throughout this report, it serves to illustrate file format, naming conventions, data derivation, and developmental considerations. Seven sources of information which are available at BN are identified below. When creating new data sets, it is important to perform calculations under the assumptions underlying the SCAN data structures. For example, time travel computations for a new train should have reference to the same time zone as existing trains. Thus, interpretation of these sources (or new sources introduced) should follow a set of *consistent, well-defined* procedures. The generation of SCAN's input data is presented in later sections.

Data Sources:

1. Track Data File - BN Operating Track Network File (See Appendix A)
2. Train Performance Simulation(TPS) Detailed Report (See Appendix B)
3. Train Idenification Classifications (See Appendix C)
4. *D1260.data* - The BN Schedule Table (See Appendix D)
5. BN Corridor Timetables (See Appendix E)
6. Train Briefs
7. TPS Train Mapping (See Appendix F)

The database consists of the six file organizations listed below which correspond to unique characterizations of information. Modifying the database (ie., adding, deleting, and updating information) is accomplished by changing existing files and creating new files. After one understands SCAN's file structures, database maintenance is fairly straightforward. This report is divided into sections which separately focus on each of the following file organizations' contents and their interrelationships. The issues surrounding future needs and software will be presented in the last section.

File Contents:

1. Corridor Master File
2. Reporting Station Master File
3. Track Files
4. Travel Times Files
5. Train Master File
6. Train Schedule Files

1.1 Database Format

SCAN's present database is contained in the same root directory as the SCAN program itself, on the distribution diskette.

Filenames consist of a descriptive name plus a three character extension with the exception of the Train Schedule Master File filename. Some filenames have a fixed length format. In this case, it is important to substitute an underscore, "_", in place of a blank character. For example, two existing filenames are *North_corr.mst* and *Eola__Sava.trk*. Internal file documentation share certain characteristics. First, comments can appear on any line following the last defined field in a given record. Record comments are preceeded with an asterisk, "*", in examples to emphasize this. However, this is not a requirement. Secondly, some files reserve the first four lines for internal comments, such as a short description or the date of file creation. Lastly, some files require the insertion of internal markers. These markers are not part of the railroad data, rather they are pre-defined character strings having special meaning to SCAN's execution. For example, the *end-of-file* marker "000 END" is interpreted to mean that the last station is encountered. File format specifications are described in later sections using these notations:

- CHAR STRING N - a character string of length N, left justified, blank characters are allowed
- PACKED CHAR STRING N - a packed character string of length N, left justified, blank characters are not allowed, used for filenames, example: *eola__sava.trk* is PACKED CHAR STRING 10
- INT N - an integer of length N, right justified
- REAL N.M - a real number of length N with M decimal places, right justified, example: 99.99 is a REAL 4.2 which is a five character field.
- @N - start field at column N

Chapter 2

CORRIDOR MASTER FILE

This file is the main input to the SCAN system. For every corridor in SCAN's database, this file contains its name (as it will appear in the Corridor menu), its Reporting Station Master File filename, and the pathname of its Train Master File. The Corridor Master File's filename is required to be *corridor.inp*.

File Name: PACKED CHAR STRING 12: "corridor.inp"

Record Format:

@1 CorridorName: CHAR STRING 20;

@1 CorridorMasterFileName: PACKED CHAR STRING 10 + ".mst";

@1 TrainSchedulePathName: CHAR STRING 32

Example: A listing of *corridor.inp* is between the dashed lines.

```
---------------------------------------------------------------------------
Northern Corridor             * 1st corridor -name
north_corr.mst                *   -reporting station master filename
cicer_seat_tr_filenms         *   -file containing all train schedule filenames
Dumm1 Corridor                * 2nd corridor (test data) ...
dumm1_corr.mst
dumm1_zzzz_tr_filenms
---------------------------------------------------------------------------
```

Chapter 3

REPORTING STATION MASTER FILE

Each new corridor has a Reporting Station Master File which lists the names of reporting stations in the corridor from East to West (or South to North) and the names of the Track Files for this corridor. Reporting stations are defined as the stations where *all* trains are scheduled. Each Track File contains information about one section of track between two adjacent reporting stations, called a *lane*. Reporting station numbers are found in the Track Data File. The Master File filename must be 14 characters long: 10 character name plus the extension ".mst". Its name is referenced in the Corridor Master File.

The first four lines of this file are not read by SCAN. They can contain a title or comments. Next, comes the east-most station in the corridor. It has to be a reporting station. Between records corresponding to adjacent reporting stations there must be a string giving the filename containing the data for this lane. The required extension for this file is ".trk" and the convention that is followed is the first five characters are the beginning of the east station name, followed by a "_", and the first four characters of the west station name. For example, the filename for the lane between Whitefish and Libby is *white_libb.trk*.

One problem in preparation of schedule data has been the idenification of the set of reporting stations. First, the compilation of this data has turned up inconsistencies with the reporting station numbers. Station number 502, which is a yard, is often a reporting station, yet not always. Moreover, there is the difference between the AMTRAK and freight train reporting stations. For example, trains 1007 and 1008 are not scheduled at station 1845 (New Hauser), whereas freight trains are scheduled there. SCAN logic, at least in its present version, requires all trains to be explicitly scheduled at all the reporting stations they are passing. Thus, it is necessary to manually add schedule times. We used linear interpolation to derive an approximation for the time the AMTRAK train passes by the reporting station.

After the west-most reporting station record, the next line must contain the string "0000000000.000" and the last line must contain the string "0 END". The number of reporting stations in a corridor can range from 2 to 100.

File Name Format: PACKED CHAR STRING 10 + ".mst"

Record Format:

@1 BNStationNo: INT 5;

@7 StationName CHAR STRING 9;

@1 LaneFileName: PACKED CHAR STRING 10 + ".trk"

Example: Northern Corridor Master File *north_corr.mst* is between the dashed lines.

```
"MASTER FILE" for the Northern Corridor. Contains all reporting stations from Ciero
              to Everette  going sequentially from East to West.
              (UPDATED 10/7/87 SFH)

    9 CICERO       * Cicero is the yard just west of Chicago
cicer_eola.trk     * track data name for first lane
   33 EOLA
eola__sava.trk
  143 SAVANNA
savan_lacr.trk
 0299 LACROSSE
lacro_st_c.trk
 0409 ST CROIX
st_cr_dayt.trk
  426 DAYTONS B
dayto_n_tw.trk
  441 NORTHTOWN
n_twn_coon.trk
  448 COON CREE
coon__stap.trk
  567 STAPLES
stapl_dilw.trk
  673 DILWORTH
dilwo_farg.trk
  679 FARGO
fargo_mino.trk
  911 MINOT          * (also refered to as GAVIN YARD in timetables)
minot_will.trk
 1036 WILLISTON
willi_glas.trk
 1192 GLASGOW
glasg_havr.trk
 1345 HAVRE
havre_shel.trk
 1451 SHELBY
shelb_whit.trk
 1601 WHITEFISH
white_libb.trk       * completed track data from here down
 1718 LIBBY
libby_troy.trk
 1736 TROY
troy__sand.trk
 1803 SANDPOINT
sandp_new_.trk
 1845 NEW HAUSE
new_h_spok.trk
 1866 SPOKANE
spoka_wena.trk
 2044 WENATCHEE
wenat_ever.trk
 2166 EVERETT
0000000000.000       * mark end of file
    0 END
```

Chapter 4

TRACK FILES

There is a Track File for each lane [1] of a corridor. The names of the Track Files must correspond to the names given in the Reporting Station Master File. A Track File filename is 14 characters long; the first five characters are the beginning of the east station name, the sixth character is a "_", followed by the first four characters of the west station name, plus the extension ".trk".

Track Files contain the reporting stations on both ends of the lane, as well as information about the points where trains can meet or pass, called *meet-points*, given in order from East to West (or South to North). Meet-points include sidings, yards, and beginnings/ends of multiple track sections.

The source data for the Track Files is the Track Data File. Appendix A contains a partial listing of the Track Data File. The following set of rules has been established to create meet-points:

- Treat all multiple track sections as double-track.
- Ignore sidings of length less than 1000 feet.
- Ignore sidings contained in double track sections; double track has precedence.
- Treat double track sections of length less than 3 miles as sidings.
- Yards, which tend to be reporting stations, have a default length of 10,000 feet. SCAN's logic assumes infinite capacity in reporting stations and that no queueing problems arise. Future versions of SCAN may relax this assumption.
- Sometimes there exists no station near (within .5 miles) the beginning/end of a double track section or siding. In this case, it is necessary to create a "dummy" meet-point in order to define the network topology. In the current database, these meet-points are generically assigned names the MEET-PT-A, MEET-PT-B, MEET-PT-C, ..., MEET-PT-N.
- In the current version of SCAN, the graphics routines require that siding length is greater than or equal to 1,100 feet. When it is necessary to create a meet-point, generally to establish the beginning or end of double track sections, assign its "siding" length a symbolic value of 1,100 feet. Version 2.0 will not require the assumption of nonzero siding length.
- When less than 0.1 miles exists between a double track section or a siding followed immediately before or after a double track section, treat this as a continuous case.

The first four lines of each Track File are reserved for comments. Next, comes the meet-points records, starting with the eastern reporting station. Each record contains (1) a serial number, starting with "1", (2) the meet-point type, either "S" for siding, "D" for start of double track, or "T" for the end of double track, (3) the meet-point name, and (4) the length in feet of the meet-point. Between fields corresponding to adjacent meet-points is the distance in miles between them. This value is used solely for SCAN's graphics, but should reflect the correct relative distances between meet-points.

[1] A lane is defined as the track between any two reporting stations; e.g., the Whitefish to Libby *lane*.

After the last meet-point record (which is also the reporting station at the West end), the next line must contain a zero, "0", the next line should contain the string "0 END", and the last line the name of the Travel Time File filename for this lane. This filename is 14 characters long; the name is by convention the same as the the Track File filename but must end with extension ".trv".

File Name Format: PACKED CHAR STRING 10 + ".trk"

Record Format:

©1 SerialNo: INT 2;

©4 Meet-PointType: PACKED CHAR STRING 1 ("S", "D", or "T");

©6 Meet-PointName: CHAR STRING 9;

©16 Length: INT 5;

©1 Distance: REAL 5.1

Travel Times Filename: ©1 FileName: PACKED CHAR STRING 10 + ".trv"

Example: Track File for Eola to Savanna lane, *eola__sava.trk*, is between the dashed lines.

```
SCAN track data for lane:
EOLA      - SAVANNA


 1 D EOLA       10000    *yard and beginning of double track section
   5.8
 2 T MEET-PT-A  1100     * siding assigned symbolic length for end of double track
   6.0
 3 S SUGAR GRO  6442
   5.8
 4 S BIG ROCK   8026
   4.3
 5 S HINCKLEY   3432
   3.5
 6 S MORED      6389
   4.0
 7 S WATERMAN   3379
   6.0
 8 S SHABBONA  11616
   2.7
 9 S LEE        2640
   6.2
10 S STEWARD    3749
   0.9
11 D STEWARD J  1100  * beginning of double track, symbolic length
   7.9
12 T FLAG CENT  1100  * end of double track, symbolic length
   6.8
13 S CHANA      7973
   5.7
14 S OREGON     4699
   9.0
15 S STRATFORD  8184
   8.0
16 S CARTER     7656
   7.5
17 S MILLEDGEV  7867
   6.0
18 S CHADWICK   7867
   8.6
19 S BURKE      7709
   4.9
20 S SAVANNA   10000   *  yard
 0
0 END
EOLA__SAVA.trv
```

Chapter 5

TRAVEL TIMES FILES

In order to run SCAN, there must exist a Travel Time File for each lane of a corridor. These travel times are calculated *outside of* the SCAN system by a Train Performance Simulator (TPS); historical travel times *cannot* be used due to the fact that they will always contain interaction effects between trains, and, thus, are not a true reflection of the running times of trains. Therefore, TPS runs must be made prior to using SCAN in order to ascertain the running times for each type of train [1]. The access to the TPS times is the biggest "bottleneck" in providing a smooth flow of data from BN databases to SCAN and will be discussed at length in the conclusion.

The name of the Travel Time File must correspond to the name given in the Track File. It is 14 characters long: the first five characters are the beginning of the east station name, the sixth character is a "_", followed by the first four characters of the west station name plus the extension ".trv".

Travel Time Files contain travel times in minutes [2] between every two adjacent meet-points in the lane, in each direction, for each of the TPS train types that are scheduled in the lane. The travel times are found in the detailed TPS Report which contains a list of trains scheduled in a given lane and the travel times every quarter mile. The reference for extracting these times is different for various meet-points. For sidings, use the beginning/end mile post of the siding when travel is in the east/west direction. For yards, the station mile post is used. For multiple track sections, the start/end of the multiple track mile post is used. Consequently, the meet-point distance is the distance from the start/end of double track in SCAN, not the near-by station which is used in the graphics for the display; i.e., one must be more precise with the meet-point distances for purposes of computing the TPS times than one needs to be for the graphics files..

The first four lines of this file are not read by SCAN, but are reserved for comments. Next, comes the literal uppercase string indicating the direction of travel, either "WESTBOUND" or "EASTBOUND". Westbound travel times must be the first encountered. For each direction and for each TPS train type which is scheduled in this lane, there is a heading record followed by the sequential listing of meet-point serial number and travel times between adjacent meet-points. These meet-points correspond exactly to those in the Track File. Please note, however, that the distances between meet-points found in the track files are used only for display purposes. The heading record contains the train type number, and the train type name. A listing of established train types is presented in Appendix C. Not all the TPS types need be included in all files. But, all the types that appear in the schedule for a given lane should be present in the sequential order of TPS type numbers and meet-point serial numbers.

After the last TPS type for the given direction, the next line on the file must begin with the integer zero, "0".

[1] Trains are classified into various categories depending on their relative TPS performance; see Appendix C.
[2] Time is rounded up to the nearest minute.

File Name Format: PACKED CHAR STRING 10 + ".trv"

Direction: @1 Dir: PACKED CHAR STRING 9, "WESTBOUND" or "EASTBOUND"

Train Heading Record Format:

@1 TPSTypeNo: INT 3;

@5 TPSTypeCode: CHAR STRING 8;

Travel Times Record:

@1 SerialNo: INT 2;

@3 TPSTravelTime: INT 4;

Example: Eola to Savanna lane's Track File, *eola__sava.trv*, is between the dashed lines.

```
 TPS train travel times in minutes on lane
EOLA      - SAVANNA


WESTBOUND
   3 DSTK
  1  11
  2   8
  3   6
  4   4
  5   4
  6   4
  7   8
  8   3
  9   7
 10   1
 11  10
 12   7
 13   7
 14  11
 15   9
 16   8
 17   6
 18   9
 19   6
   4 INTERMOD
  1  11
  2  10
  3   7
  4   5
  5   4
  6   5
  7   9
  8   4
  9   7
 10   1
 11  11
 12   8
 13   7
 14  13
```

15	11
16	8
17	7
18	10
19	6

5 PRIFRT

1	11
2	8
3	6
4	5
5	4
6	4
7	8
8	3
9	7
10	1
11	10
12	7
13	7
14	12
15	9
16	8
17	7
18	9
19	6

6 SECFRT

1	11
2	11
3	7
4	6
5	5
6	6
7	11
8	4
9	8
10	1
11	11
12	8
13	7
14	15
15	12
16	8
17	7
18	10
19	7

0

EASTBOUND

3 DSTK

1	11
2	6
3	6
4	6
5	3
6	5
7	6

8	5
9	9
10	2
11	10
12	7
13	9
14	10
15	10
16	9
17	6
18	11
19	18
4	INTERMOD
1	12
2	6
3	6
4	6
5	3
6	5
7	6
8	6
9	10
10	2
11	10
12	8
13	9
14	10
15	10
16	9
17	6
18	12
19	20
5	PRIFRT
1	12
2	6
3	6
4	6
5	3
6	5
7	6
8	5
9	10
10	2
11	10
12	8
13	9
14	10
15	10
16	10
17	6
18	12
19	19
6	SECFRT
1	13
2	6

3	6
4	6
5	3
6	5
7	6
8	6
9	12
10	2
11	11
12	10
13	10
14	10
15	11
16	11
17	7
18	14
19	22
0	

Chapter 6

TRAIN MASTER FILE

The Train Master File contains pathnames for all Train Schedule Files that are defined on a given corridor. Currently, there exist subdirectories for the Train Schedule Files, such as *cicero_seat_trsch.dir*. The Train Master File filename can be a string of any length up to 32 characters. However, the filename must correspond to the name given in the Corridor Master File.

As will be discussed in the conclusion, the creation of this file and the detailed schedules for each train is the second "bottleneck" after the TPS times due to the nonunique representation of the schedules vis a vis the given reporting stations and/or the TPS times. Thus, the creation of this file must be automated if SCAN is to be successfully employed at BN.

Each record in the file is a character string, up to 80 characters long, containing the pathname and filename of a Train Schedule File. Initial Train Schedule File filenames must end with the extension ".org", which stands for original, and can have a name up to 32 characters long. Currently, SCAN follows the convention that the filename is five characters; the first characters are idenical to the train idenification code and trailing blanks are substituted with underscores, "_". Note that trains will appear in the SCAN menus in the same order the corresponding filenames appear in this file. In addition, trains running in an Eastern/Western direction have even/odd numbers. The next section presents the train schedule files in detail.

File Name Format: CHAR STRING 32

Train Schedule Filename Record: @1 TrnSchPathname: CHAR STRING 80

Example: A listing of *cicer_seat_tr_filenms* is between the dashed lines.

```
Cicer_seat_trsch.dir/001__.org
Cicer_seat_trsch.dir/002__.org
Cicer_seat_trsch.dir/003__.org
Cicer_seat_trsch.dir/004__.org
Cicer_seat_trsch.dir/007__.org
Cicer_seat_trsch.dir/008__.org
Cicer_seat_trsch.dir/009__.org
Cicer_seat_trsch.dir/010__.org
Cicer_seat_trsch.dir/012__.org
Cicer_seat_trsch.dir/013__.org
Cicer_seat_trsch.dir/014__.org
Cicer_seat_trsch.dir/015__.org
Cicer_seat_trsch.dir/019__.org
Cicer_seat_trsch.dir/021__.org
Cicer_seat_trsch.dir/022__.org
Cicer_seat_trsch.dir/024__.org
Cicer_seat_trsch.dir/033__.org
Cicer_seat_trsch.dir/034__.org
Cicer_seat_trsch.dir/040__.org
Cicer_seat_trsch.dir/041__.org
Cicer_seat_trsch.dir/042__.org
Cicer_seat_trsch.dir/043__.org
Cicer_seat_trsch.dir/044__.org
Cicer_seat_trsch.dir/045__.org
Cicer_seat_trsch.dir/048__.org
Cicer_seat_trsch.dir/049__.org
Cicer_seat_trsch.dir/050__.org
Cicer_seat_trsch.dir/051__.org
Cicer_seat_trsch.dir/053__.org
Cicer_seat_trsch.dir/054__.org
Cicer_seat_trsch.dir/055__.org
Cicer_seat_trsch.dir/056__.org
Cicer_seat_trsch.dir/057__.org
Cicer_seat_trsch.dir/060__.org
Cicer_seat_trsch.dir/062__.org
Cicer_seat_trsch.dir/063__.org
Cicer_seat_trsch.dir/065__.org
Cicer_seat_trsch.dir/091__.org
Cicer_seat_trsch.dir/092__.org
Cicer_seat_trsch.dir/095__.org
Cicer_seat_trsch.dir/096__.org
Cicer_seat_trsch.dir/1005_.org
Cicer_seat_trsch.dir/1006_.org
Cicer_seat_trsch.dir/1007_.org
Cicer_seat_trsch.dir/1008_.org
Cicer_seat_trsch.dir/100__.org
Cicer_seat_trsch.dir/1011_.org
Cicer_seat_trsch.dir/1014_.org
Cicer_seat_trsch.dir/101__.org
Cicer_seat_trsch.dir/1027_.org
Cicer_seat_trsch.dir/1028_.org
Cicer_seat_trsch.dir/103__.org
Cicer_seat_trsch.dir/104__.org
Cicer_seat_trsch.dir/106__.org
```

Cicer_seat_trsch.dir/107__.org
Cicer_seat_trsch.dir/108__.org
Cicer_seat_trsch.dir/111__.org
Cicer_seat_trsch.dir/112__.org
Cicer_seat_trsch.dir/119__.org
Cicer_seat_trsch.dir/120__.org
Cicer_seat_trsch.dir/121__.org
Cicer_seat_trsch.dir/1346_.org
Cicer_seat_trsch.dir/1347_.org
Cicer_seat_trsch.dir/1348_.org
Cicer_seat_trsch.dir/143__.org
Cicer_seat_trsch.dir/144__.org
Cicer_seat_trsch.dir/151__.org
Cicer_seat_trsch.dir/160__.org
Cicer_seat_trsch.dir/161__.org
Cicer_seat_trsch.dir/162__.org
Cicer_seat_trsch.dir/1795_.org
Cicer_seat_trsch.dir/1796_.org
Cicer_seat_trsch.dir/1797_.org
Cicer_seat_trsch.dir/1798_.org
Cicer_seat_trsch.dir/195__.org
Cicer_seat_trsch.dir/196__.org
Cicer_seat_trsch.dir/203__.org
Cicer_seat_trsch.dir/204__.org
Cicer_seat_trsch.dir/206__.org
Cicer_seat_trsch.dir/208__.org
Cicer_seat_trsch.dir/209__.org
Cicer_seat_trsch.dir/211__.org
Cicer_seat_trsch.dir/212__.org
Cicer_seat_trsch.dir/218__.org
Cicer_seat_trsch.dir/228__.org
Cicer_seat_trsch.dir/231__.org
Cicer_seat_trsch.dir/232__.org
Cicer_seat_trsch.dir/241__.org
Cicer_seat_trsch.dir/242__.org
Cicer_seat_trsch.dir/284__.org
Cicer_seat_trsch.dir/402__.org
Cicer_seat_trsch.dir/403__.org
Cicer_seat_trsch.dir/600__.org
Cicer_seat_trsch.dir/601__.org
Cicer_seat_trsch.dir/602__.org
Cicer_seat_trsch.dir/603__.org
Cicer_seat_trsch.dir/627__.org
Cicer_seat_trsch.dir/631__.org
Cicer_seat_trsch.dir/632__.org
Cicer_seat_trsch.dir/633__.org
Cicer_seat_trsch.dir/634__.org
Cicer_seat_trsch.dir/663__.org
Cicer_seat_trsch.dir/664__.org
Cicer_seat_trsch.dir/666__.org
Cicer_seat_trsch.dir/671__.org
Cicer_seat_trsch.dir/672__.org
Cicer_seat_trsch.dir/681__.org
Cicer_seat_trsch.dir/682__.org
Cicer_seat_trsch.dir/691__.org

```
Cicer_seat_trsch.dir/692__.org
Cicer_seat_trsch.dir/693__.org
Cicer_seat_trsch.dir/694__.org
Cicer_seat_trsch.dir/699__.org
Cicer_seat_trsch.dir/807__.org
Cicer_seat_trsch.dir/809__.org
Cicer_seat_trsch.dir/810__.org
Cicer_seat_trsch.dir/835__.org
Cicer_seat_trsch.dir/836__.org
Cicer_seat_trsch.dir/837__.org
Cicer_seat_trsch.dir/838__.org
Cicer_seat_trsch.dir/883__.org
Cicer_seat_trsch.dir/884__.org
Cicer_seat_trsch.dir/897__.org
Cicer_seat_trsch.dir/898__.org
```

Chapter 7

TRAIN SCHEDULE FILES

Each train scheduled in a given corridor will have a Train Schedule File which contains scheduled arrival and departure times at the reporting stations defined in the Reporting Station Master File. This data is derived from the file *D1260.data* which contains scheduled running and station dwell times. Changes to train schedules are easy because there is one Train Schedule File per train. Initial Train Schedule File filenames must end with the extension ".org", which stands for original, and can have a name up to 32 characters long. Currently, SCAN follows the convention that the filename is five characters; the first characters are idenical to the train idenification code and trailing blanks are substituted with underscores, "_". Only Train Schedule filenames that appear in the Train Master File will be used by SCAN.

The train heading record consists of (1) Train Identification - the field TRNID in D1260 file, (2) TPS train type name (3) TPS type number (4) Maximum length of the train in feet, (5) BN Train type - the field THRULO in D1260 file and *all_trains.ids*, (6) the creation date - the field CREDTE in D1260 file, and (7) the effective date - the field EFFDTE in D1260 file. The assignment of TPS train types was performed manually and then the files were edited. Obviously, it would be highly desirable to have an input file which contained a mapping from train ids to train types. In addition, we have used the maximum train lengths from the Train Briefs to derive a very simplified mapping from TPS type to train length; see Appendix C for a table of the train classifications.

Following the train heading record, reporting station records appear in order of travel. Each record contains (1) the reporting station number - see the Reporting Station Master File, (2) exclude flag - "X", if on, blank otherwise, instructing SCAN to exclude this train from the corridor starting with this reporting station until the next reporting station which appears in the corridor *master* file, required only if the train is leaving corridor taking some other route and then returning to it, (3) direction of departure - either "E" for East or "W" for West, (4) number of days since the train departure - all trains have reference starting departure day zero, (5) scheduled arrival time at the meet-point - two digits for the military hour and two digits for the minutes, and (6) scheduled departure time from the meet-point - two digits for the military hour and two digits for the minutes. At present, all times must refer to *one time zone*. We have arbitrarily selected the Central time zone as our data's reference point. Appendix G contains the peusdocode for a mapping of reporting station number to time zone. In addition, some trains might not explicitly be scheduled at all reporting stations. That is, a train runs through the entire lane between two reporting stations, but is not scheduled at one or both of the reporting stations defining the lane. In this case, we used linear interpolation to calculate an approximate scheduled times. In the future, these times should be determined by some desired rules.

After the last reporting station time record, on the same line following the scheduled departure time, must be the literal string "END OF TRAIN". The last line of the file must begin with the integer zero, "0".

Consider the illustration following the file format specifications. Note, that station number 502 is *not* a reporting station (as defined in the Reporting Station Master File). But, it may be included in this file without effecting SCAN's execution - SCAN is solely concered with times at reporting stations. Also, it is not necessary to schedule a train on contiguous track lanes. For example, AMTRAK trains 1007 and 1008 appears east of reporting station number 679 (Fargo) and west of reporting station number 911 (Minot), but not on the lane defined by Fargo to Minot.

File Name Format: CHAR STRING 32, TrainID + ".org"

Train Heading Record:

@1 TrainID: CHAR STRING 5;

@6 TPSType: CHAR STRING 8;

@14 TPSTypeNo: INT 3;

@17 MaxTrainLen: INT 5;

@23 D1260TrainType: CHAR 1;

@25 CreationDate: PACKED CHAR STRING 6 (YYMMDD);

@32 EffectiveDate: PACKED CHAR STRING 6 (YYMMDD)

Reporting Station Time Record:

@1 StaNo: INT 5;

@7 EXclude: CHAR 1 (either "X" or " " (blank));

@7 Direction: CHAR 1 (either "E" or "W");

@8 NoDaysSinceDeparture: INT 2;

@11 ArrivalTime: PACKED CHAR STRING 4 (HHMM);

@16 DepartTime: PACKED CHAR STRING 4 (HHMM)

Example: Listings of *cicer_seat_trsch.dir/1007__.org* for the Amtrak train 1007 and *cicer_seat_trsch.dir/001__.org* for the intermodal BN train 001, both running at least partially over the Northern Corridor are given between the dashed lines. Data fields 6 and 7 in the reporting station time records are not used by SCAN - they are copied along with the schedule data from the *D1260.data* file.

```
--------------------------------------------------------------------------------
1007 AMTRAK    1 1000 C 861013 861013
99434 W 0 2305 2305  0005 T
  435 W 0 2310 2310  0000 0013
  441 W 0 2323 2323  0000 0020 * Added manually approx from TPS
  448 W 0 2343 2343  0000 0154
  567 W 1 0137 0140  0003 0133
  673 W 1 0313 0313  0000 0013 * Added manually from a timetable
  679XW 1 0326 0330  0004 0115 * no amtrak from 679 to 911
 5295 W 1 0445 0450  0005 0112 * this reporting station is not used in SCAN
 5383 W 1 0602 0605  0003 0215 * this reporting station is not used in SCAN
  911 W 1 0820 0835  0015 0200
 1036 W 1 1035 1040  0005 0219
 1192 W 1 1259 1301  0002 0229
 1345 W 1 1530 1545  0015 0285
 1451 W 1 1710 1710  0000 0245 # Added manually from a timetable
 1601 W 1 2115 2125  0010 0145
 1718 W 1 2310 2310  0000 0022 # Added manually from a timetable
 1736 W 1 2332 2332  0000 0133
 1803 W 2 0105 0105  0000 0065
 1845 W 2 0210 0210  0000 0025 # Added manually proportional to TPS time
 1866 W 2 0235 0300  0025 0316
 2044 W 2 0616 0620  0004 0310
 2166 W 2 0930 0930  0000 0035
 2182 W 2 1005 1005  0000 0110
 2200 E 2 1115 1115  END OF TRAIN 1007
0
--------------------------------------------------------------------------------

--------------------------------------------------------------------------------
001  INTERMOD  4 7000 D 861006 861006
    9 W 0 2330 2330  0045 C
   33 W 1 0015 0045  0030 0210
  143 W 1 0255 0255  0000 0325
  299 W 1 0620 0625  0005 0220
  409 W 1 0845 0845  0000 0045
  426 W 1 0930 0930  0000 0035
  441 W 1 1005 1130  0125 0025
  448 W 1 1155 1155  0000 0100
  502 W 1 1255 1255  0000 0120
  567 W 1 1415 1420  0005 0200
  673 W 1 1620 1625  0005 0010
  679 W 1 1635 1635  0000 0450
  911 W 1 2125 2130  0005 0245
 1036 W 2 0015 0015  0000 0255
 1192 W 2 0310 0315  0005 0250
 1345 W 2 0605 0715  0110 0250
 1451 W 2 1005 1005  0000 0420
 1601 W 2 1425 1430  0005 0155
 1718 W 2 1625 1625  0000 0045
 1736 W 2 1710 1710  0000 0120
```

```
 1803 W 2 1830 1830  0000 0125
 1845 W 2 1955 1955  0000 0045
 1866 W 2 2040 2140  0100 0035
12010 W 2 2215 2215  0000 0330
12143 W 3 0145 0150  0005 0230
12269 W 3 0420 0425  0005 0205
12365 W 3 0630 0630  0000 0040
12372 W 3 0710 0710  0000 0020
12373 E 3 0730 0730  END OF TRAIN 001
0
```

Chapter 8

PASCAL PROGRAMS FOR DATA PREPARATION

In order to speed up the preparation of the data base for the Northern Corridor several Pascal programs have been developed: three for the extraction of train schedules from D1260 file and their formatting, and one for the creation of track *.trk* and TPS travel time *.trv* files on the lane by lane basis, from 'raw' data files. Source code of those programs and some comments on their use are given in this chapter.

Please note that the programs were used just as the development tools and thus are far from being finished: many important input items have to be hard- coded, for example. Also, the whole data preparation process is far from automation. Formatted train schedule files require manual addition of missing reporting stations, setting of *Exclude* flags, checking of TPS train types, and so on, while extensive manual editing and manipulation of TPS report files and *optrknet.data* file is required before the data processing program can be applied. However, need for much of the manual work can be reduced by extending the provided programs.

8.1 Train Schedules Extracting and Formatting Programs

First task in creation of train schedule files to be used in SCAN is to extract scheduled trains (in this phase; unscheduled ones will be included as well in the later phases), that run over at least the part of the corridor under consideration, from the *D1260* schedule file. This is accomplished using *pull_trains.pas* or *pull_trains_stream.pas* program. Because of the limitations of Apollo workstations in handling file records longer than 256 characters, special file reading procedures have to be used to read *D1260* which has records almost 1500 characters long. Program *pull_trains.pas* is written in plain Pascal and it reads additional dummy character after every 256 characters read in order to correctly read each record of *D1260*. However, this program may fail under newer versions of Domain operating system (above 9.35), so more involved *pull_trains_stream.pas* program was created which uses the operating system stream I/O calls rather than standard Pascal *read* procedure in order to handle oversize record length.

Except extraction, none of these two programs does any processing of the D1260 data, so that they are written out unchanged, but in a more manageable format to the output file. Note that all the file names are hard-coded.

Listings of *pull_trains_.pas* and *pull_trains_stream.pas* are given below:

```
PROGRAM PullTrainsFromD1260;
TYPE
    Junk18Type = PACKED ARRAY[ 1..18 ] OF CHAR;
    TrainIDStrType = PACKED ARRAY[ 1..5 ] OF CHAR;
    TimeStrType = PACKED ARRAY[ 1..4 ] OF CHAR;
```

```
    Str8Type = PACKED ARRAY[ 1..8 ] OF CHAR;
    Str13Type = PACKED ARRAY[ 1..13 ] OF CHAR;

VAR c:    CHAR; incount, i,k,s,t, TrainNo,Maxs : INTEGER;
    TrainIn : BOOLEAN;
    StatNoArr : ARRAY[ 1..62 ] OF INTEGER32;
    junk15: PACKED ARRAY[ 1..15 ] OF CHAR;
    junk2: PACKED ARRAY[ 1..2 ] OF CHAR;
    junk16: PACKED ARRAY[ 1..16 ] OF CHAR;
    Junk18Arr: ARRAY[ 1..100 ] OF Junk18Type;
(*    StatNoList: ARRAY[ 1..100 ] OF StatNoStrType; *)
    SchedTrainsFile, SampleTrainsFile : TEXT;
    ch, DirCh, RegCde,TrTypeCh: CHAR;
    PerfType, RunTime, Day, ArrTime, DprTime, StaTime : INTEGER;
    TrainID : TrainIDStrType;
    TrTypeStr, StatName : Str8Type;DatesStr:Str13Type;
    StatNo, AbsArrTime, AbsDprTime : INTEGER32;
    ArrTimeStr, DprTimeStr, StaTimeStr,RunTimeStr, JunkTimeStr : TimeStrType;

(*-------------------------------------------------*)
FUNCTION InRange( Argument: INTEGER32 ): BOOLEAN;
    BEGIN
        IF (Argument >= 7) AND (Argument < 1601) (* Whitefish - Seattle *)
          THEN InRange := TRUE
          ELSE Inrange := FALSE;
    END; (* Function *)
(*-------------------------------------------------*)

BEGIN (* Main *)
  Open( SchedTrainsFile,'//leviticus/users/bn.dir/schedule.dat','OLD' );
  Reset( SchedTrainsFile );
  Open( SampleTrainsFile,'Cicer_whit_all_trns.form','UNKNOWN' );
  Rewrite( SampleTrainsFile );
  Writeln( SampleTrainsFile,' Cicero - Whitefish;' );
  TrainNo := 0;
  FOR t := 1 TO 448 DO   (* For every sched. train *)
   BEGIN
writeln('  in for loop');
    TrainIn := FALSE;

    FOR i := 1 TO 5 DO
    begin
      Read( SchedtrainsFile, TrainID[ i ] );
      write (TrainID[i])
    end;

writeln(' after first read                       in for loop');
    FOR i := 1 TO 15 DO
      Read( SchedtrainsFile, junk15[ i ] );
writeln(' after 2nd read                         in for loop');

(*    FOR i := 1 TO 5 DO       *)
      Read( SchedtrainsFile, StatNoArr[ 1 ] );
    Writeln( TrainId, StatNoArr[ 1 ]:6 );
    FOR i := 1 TO 16 DO
```

```
  Read( SchedtrainsFile, junk16[ i ] );
IF InRange( StatNoArr[ 1 ] ) THEN TrainIn := TRUE;
s := 1; incount := 41;
WHILE StatNoArr[ s ] > 0  DO
  BEGIN
    s := s + 1; Read( SchedtrainsFile, StatNoArr[ s ] );
    incount := Incount + 5;
    IF InRange( StatNoArr[ s ] ) THEN TrainIn := TRUE;
    FOR i := 1 TO 18 DO
      BEGIN
       Read( SchedtrainsFile, Junk18Arr[ s,i ] );
       incount := incount + 1;
       IF incount = 256 THEN
        BEGIN
         Read( SchedtrainsFile, ch );
         incount := 0;
        END; (* If *)
      END; (* For i=...*)

  END; (* While StatNoArr ... *)
Maxs := s - 1;
FOR k := s+1 TO 61 DO
  BEGIN
    Read( SchedtrainsFile, StatNoArr[ k ] );
    incount := Incount + 5;
    FOR i := 1 TO 18 DO
      BEGIN
       Read( SchedtrainsFile, Junk18Arr[ k,i ] );
       incount := incount + 1;
       IF incount = 256 THEN
        BEGIN
         Read( SchedtrainsFile, ch );
         incount := 0;
        END; (* If *)
      END; (* For i=...*)

  END; (* For k=... *)
Read( SchedtrainsFile, StatNoArr[ 62 ] );
FOR i := 1 TO 2 DO
  Read( SchedtrainsFile, junk2[ i ] );
Readln( SchedtrainsFile );

IF InRange( StatNoArr[ 62 ] ) THEN TrainIn := TRUE;
IF (TrainID < '001  ') OR (TrainID > '899  ')
  THEN TrainIn := FALSE;

IF TrainIn THEN
  BEGIN
    TrainNo := TrainNo + 1;
    Writeln( TrainNo:3,' ',TrainID, StatNoArr[ 1 ]:5,junk16 );

    Writeln( SampleTrainsFile, TrainID, junk15 );
    Writeln( SampleTrainsFile, StatNoArr[ 1 ]:5,junk16 );
    FOR s := 2  TO MaxS DO
    Writeln( SampleTrainsFile,  StatNoArr[ s ]:5,
```

```
                              Junk18Arr[ s ]  );
      Writeln( SampleTrainsFile, StatNoArr[ 62 ]:5, junk2,
                              ' END OF TRAIN ',TrainID   );
     END; (* If TrainIn *)

   END; (* For t=...*)
 Writeln( SampleTrainsFile,'END OF FILE' );
END (* Main *) .
----------------------------------------------------------------------

----------------------------------------------------------------------
PROGRAM PullTrainsFromD1260_Stream;

%include '/sys/ins/base.ins.pas';
%include '/sys/ins/error.ins.pas';
%include '/sys/ins/pgm.ins.pas';
%include '/sys/ins/streams.ins.pas';

const
    blen            =   1;
    LF              =  10;
    maxlen          = 256;
  Space = 32;
  Carriage_Return = 13;
  Line_Feed = 10;
  Tab = 7;


TYPE
    Maximum_Train_String = packed array [1..30] of char;
    Train_Header_String_Type = packed array[1..20] of char;


VAR
    SchedTrainsFile, SampleTrainsFile : TEXT;
    i : integer;
    Train_Header_String : Train_Header_String_Type;
    Line_Number : integer;
    j : integer;

    buf_ptr,
      return_ptr       : ^char;
    wrapper, tot     : integer;
    return_lgth        : integer32;
    buf_lgth           : linteger;
    statt              : status_$t;
    stream_id          : stream_$id_t;
    seek_key           : stream_$SK_t;
    f                  : text;


(*-------------------------------------------------*)
FUNCTION InRange( Argument: INTEGER32 ): BOOLEAN;
    BEGIN
```

```
        IF (Argument >= 7) AND (Argument < 1601) (* Cicero - Whitefish *)
          THEN InRange := TRUE
          ELSE Inrange := FALSE;
    END; (* Function *)
(*-------------------------------------------------*)


procedure error_check(statt : status_$t);
begin
    if statt.all<>status_$ok then begin error_$print(statt); pgm_$exit; end;
end;


function Get_Long_Integer : integer32;
const
  Maximum_Digits_per_Long_Integer = 64;
var
  Current_Long_Integer_Array : array[1..Maximum_Digits_per_Long_Integer] of char;
  Total_Digits_in_Long_Integer : integer;
  Finished_Collecting_Digits_for_Integer : boolean;
  Current_Long_Integer : integer32;
  Index : integer;
begin
  (*
   * Initialize integer digit array to spaces (chr 32).
   *)
  for Index := 1 to Maximum_Digits_per_Long_Integer do
    Current_Long_Integer_Array[Index] := chr(Space);
  (*
   * Initialize number of digits to zero.
   *)
  Total_Digits_in_Long_Integer := 0;
  (*
   * Get the first character of the digit string.
   *)
  stream_$get_rec(stream_id,
                  addr(buf_ptr),
                  blen,
                  return_ptr,
                  return_lgth,
                  seek_key,
                  statt);
  error_check(statt);  (* check status of last get char *)
  while (Return_Ptr^ = chr(Space))
     or (Return_Ptr^ = chr(Carriage_Return))
     or (Return_Ptr^ = chr(Line_Feed))
     or (Return_Ptr^ = chr(Tab)) do
    (*
     * Eliminate whitespace before the digits begin.
     * Should really use sets instead of the or statements
     * in the while loop above.
     *)
    begin
      stream_$get_rec(stream_id,
```

```
                    addr(buf_ptr),
                    blen,
                    return_ptr,
                    return_lgth,
                    seek_key,
                    statt);
   end;

  (*
   * We have something, should be a digit, so begin processing.
   *)
  for Index := 1 to 5 do
    (********
     * Temporary kludge.
     ********)
    begin
{
      if (ord(Return_Ptr^) >= ord('0')) and (ord(Return_Ptr^) <= ord('9'))
        then
          begin
            (*
             * Increment the total number of digits.
             *)
            Total_Digits_in_Long_Integer := Total_Digits_in_Long_Integer + 1;
            (*
             * Store the current digit in the string array.
             *)
            Current_Long_Integer_Array[Total_Digits_in_Long_Integer] := Return_Ptr^;
          end
        else
          begin
            (*
             * Current character is not a digit.  Just report the error to the
             * screen and ignore it, assuming it was line noise or extraneous
             * in some way.  Should really do something more clever here.
             *)
            writeln('Warning: non-digit encountered in file.');
          end;
}

            (*
             * Increment the total number of digits.
             *)
            Total_Digits_in_Long_Integer := Total_Digits_in_Long_Integer + 1;
            (*
             * Store the current digit in the string array.
             *)
            Current_Long_Integer_Array[Total_Digits_in_Long_Integer] := Return_Ptr^;


        (*
         * Get the next character from the input stream.
         *)
        stream_$get_rec(stream_id,
                        addr(buf_ptr),
```

```
                        blen,
                        return_ptr,
                        return_lgth,
                        seek_key,
                        statt);
    end;

  Current_Long_Integer := 0;
  for Index := Total_Digits_in_Long_Integer downto 1 do
    begin
      Current_Long_Integer := Current_Long_Integer +
                              (round((ord(Current_Long_Integer_Array[Index]) - ord('0'))
                              * (exp(ln(10) * (Total_Digits_in_Long_Integer - Index)))));
      writeln('Current digit is : ', Current_Long_Integer_Array[Index],
              ' and running total is ', Current_Long_Integer);
    end;

  writeln('Final integer was: ', Current_Long_Integer);
  Get_Long_Integer := Current_Long_Integer;
end;


procedure Return_String(Number_of_Characters_to_Read : integer);
var
  Current_String : Maximum_Train_String;
  Index : integer;
begin
  for Index := 1 to 30 do
    Current_String[Index] := ' ';
  for Index := 1 to Number_of_Characters_to_Read do
    begin
      Current_String[Index] := Return_Ptr^;
      (*
       *  Get the next character from the input stream.
       *)
      stream_$get_rec(stream_id,
                      addr(buf_ptr),
                      blen,
                      return_ptr,
                      return_lgth,
                      seek_key,
                      statt);
      error_check(statt);
    end;

   Index := 1;
   while ord(Current_String[Index]) <= ord('0') do
     begin
       Current_String[Index] := ' ';
       Index := Index + 1;
     end;

   if Current_String <> '                              ' then
     begin
```

```
      writeln(Current_String);
      writeln(SampleTrainsFile, Current_String);
    end;
end;


BEGIN (* Main *)

Line_Number := 0;
  stream_$open('//leviticus/users/bn.dir/schedule.dat', 37, stream_$read,
               stream_$unregulated, stream_id, statt);
  error_check(statt);

  Open( SampleTrainsFile,'Cicer_Whit_all_trns.form','UNKNOWN' );
  Rewrite( SampleTrainsFile );
  Writeln( SampleTrainsFile,' Cicero - Whitefish;' );
  for i := 1 to 20 do
    Train_Header_String[i] := ' ';
  REPEAT
    FOR I := 1 TO 20 DO
      BEGIN
        stream_$get_rec(stream_id, addr(buf_ptr), blen,
                        return_ptr, return_lgth,
                        seek_key, statt);
        error_check(statt);
        Train_Header_String[I] :=RETURN_PTR^;
      END;
    (* check if train is int scheduled tr. range: 0???? - 8???? *)
    if (ord(Train_Header_String[1]) >= ord('0')) and
       (ord(Train_Header_String[1]) <= ord('8')) then
      begin
Line_Number := Line_Number + 1;
writeln('Processing line: ', Line_Number);
writeln('Train header: ', Train_Header_String);
        writeln(SampleTrainsFile, Train_Header_String);
        Return_String(21);
        for j := 1 to 60 do
          Return_String(23);
        while Return_Ptr^ <> chr(LF) do
          begin
            stream_$get_rec(stream_id, addr(buf_ptr), blen,
                            return_ptr, return_lgth,
                            seek_key, statt);
            error_check(statt);
            if Return_Ptr^ <> chr(LF) then
              begin
                write(SampleTrainsFile, Return_Ptr^);
                write(Return_Ptr^);
              end;
          end;
        write(SampleTrainsFile, ' END OF TRAIN ');
        write(' END OF TRAIN ');
        for j := 1 to 5 do
          begin
```

```
            write(SampleTrainsFile, Train_Header_String[j]);
            write(Train_Header_String[j]);
          end;
        writeln(SampleTrainsFile);
        writeln;
      end (* if *)
    else
      begin
Line_Number := Line_Number + 1;
writeln('Processing line: ', Line_Number);
      repeat
        stream_$get_rec(stream_id, addr(buf_ptr), blen,
                        return_ptr, return_lgth,
                        seek_key, statt);
        error_check(statt);
      until Return_Ptr^ = chr(LF);
end;

  until (statt.all = stream_$end_of_file);

writeln('EOF');
  Writeln( SampleTrainsFile,'END OF FILE' );

  stream_$close (stream_id, statt);
  error_check(statt);

END.
```

Second step in the creation of train schedule files consists in processing the origin departure time and subsequent running and dwell times from D1260 to arrive at the absolute arrival and departure times at each reporting station, using the reference time zone. Also, train length and TPS type are assigned to each train at this stage, but those items have to be checked manually. Final output of the second step are schedule files, one for each train, in the format usable by SCAN. Note, however, that final checking of TPS type and train length data, as well as addition of missing reporting stations and setting of *Exclude* flags have to be done by manual editing of the schedule files.

Second step is accomplished by *proc_train_sched.pas*, which reads formatted *D1260* data file, produced by the *pull_trains.pas* program in the previous step. Input file name is hard-coded in the program, as well as the name of the train schedule directory, while schedule file names are assigned by the program.

Note that once the problem of reading the *D1260* file by the Apollo workstation is permanently solved, these two steps can be merged using just one schedule files creating program without the intermediary file. Also, the whole process can be automated to great extent by expanding the logic built into these programs.

Listing of *proc_train_sched.pas* is given below:

```
PROGRAM ProcessTrainSchedules;
(* Purpose: to read formatted schedule file, to determine scheduled arriv. & dprt.
   times at reporting stations, for a given train schedule,
   and to write that schedule to a file usable by SCAN,
   for each train in the formatted schedule file
*)
  CONST DirPathStrConst = '\scan.dir/cicer_seat_trsch.dir/' ;
        (* 23 to 52 = 30 chars *)
        FileNameExtConst ='.org';
  TYPE
```

```
   FileNameExtType = PACKED ARRAY[ 1..4 ] OF CHAR;
   TrainIDStrType = PACKED ARRAY[ 1..5 ] OF CHAR;
   TimeStrType = PACKED ARRAY[ 1..4 ] OF CHAR;
   Str8Type = PACKED ARRAY[ 1..8 ] OF CHAR;
   Str13Type = PACKED ARRAY[ 1..13 ] OF CHAR;
 VAR
   DirPathStr : PACKED ARRAY[ 1..31 ] OF CHAR;
   FileNameExt : PACKED ARRAY[ 1..4 ] OF CHAR;
   TrFileName : PACKED ARRAY[ 1..40 ] OF CHAR;
   ch, DirCh, RegCde,TrTypeCh: CHAR;
   PerfType, RunTime, Day, ArrTime, DprTime, StaTime,
   TZoneShift, Length, i,k,s,t               : INTEGER;
   TrainID : TrainIDStrType;
   TrTypeStr, StatName : Str8Type;
   DatesStr:Str13Type;
   StatNo, AbsArrTime, AbsDprTime : INTEGER32;
   ArrTimeStr, DprTimeStr, StaTimeStr,RunTimeStr, JunkTimeStr : TimeStrType;
   TrainSchedFile, ProcTrainSchedFile, TrIDFile : TEXT;
(****************************************************************************)

FUNCTION TimeValue( TStr: TimeStrType ): INTEGER;
(* Converts time char. string in format HHMM to time in minutes *)

VAR Ord0, Value : INTEGER;

  BEGIN
    Ord0 := Ord('0');
    TimeValue := ( (Ord( TStr[1] )- Ord0)* 10 + Ord( TStr[2] )- Ord0 )* 60
               + ( Ord( TStr[3] )- Ord0 )* 10 + Ord( TStr[4] )- Ord0 ;
  END; (* Function *)

(****************************************************************************)

  PROCEDURE TimeStr( Minutes: INTEGER; VAR TimeString4 : TimeStrType );
  (* Converts integer no. of minutes into 4 char. time string with format: *)
  (* HHMM                                                                  *)

   VAR  Ord0, i : INTEGER;
        time : ARRAY[ 1..4 ] OF INTEGER;

    BEGIN
      DirPathStr := DirPathStrConst;
      FileNameExt := FileNameExtConst;
      Ord0 := Ord('0');
      time[ 1 ] := Minutes DIV 600;              (* HOUR DECADE CIPHER *)
      time[ 2 ] := Minutes DIV 60 - 10* time[ 1 ]; (* HOUR CIPHER *)
      time[ 3 ] := ( Minutes MOD 60 )DIV 10;     (* MINUTES DECADE CIPHER *)
      time[ 4 ] := ( Minutes MOD 60 ) - 10* time[ 3 ];   (* MINUTES cipher *)
      FOR i := 1 TO 4 DO
        TimeString4[ i ] := Chr( time[ i ] + Ord0 );
(*
Write( Minutes,' ' );  FOR i := 1 TO 4 DO Write( Time[ i ],' ' );
Writeln( TimeString4 );
*)
    END; (* Procedure *)
```

```
    Order := 1000; (* One thou. - 4th decade position *)
    RealNo := 0;
    FOR c := 1 TO 7 DO Read( TrackFile, Str7[ c ] );
    FOR c := 1 TO 7 DO IF Str7[ c ] = ' ' THEN Str7[ c ] := '0';
    FOR c := 1 TO 7 DO IF Str7[ c ] <> '.' THEN
      BEGIN
        RealNo := RealNo + Order *( Ord( Str7[ c ] ) - Asci0 );
        Order := Order /10 ;
      END;
(*
Writeln( Str7 );
*)
  END; (* Procedure *)

(*................................................*)

  PROCEDURE ReadSTKRec( VAR TrackFile : TEXT;
                        VAR MeetPoint : MeetPointRecType );
  VAR c : INTEGER; ch : CHAR;

  BEGIN
   WITH MeetPoint DO
    BEGIN
      ReadReal_7_2_Str( TrackFile, BegMP );
      ReadReal_7_2_Str( TrackFile, EndMP );
      ReadReal_7_2_Str( TrackFile, Length );
Writeln( 'STK', BegMP:8:2, EndMP:8:2, Length:8:2 );
    END; (* With *)
   Readln( TrackFile );
  END; (* Procedure *)

(*................................................*)

  PROCEDURE ReadSTARec( VAR TrackFile : TEXT;
                        VAR CurrStaNo : INTEGER32;
                        VAR MeetPoint : MeetPointRecType);
  VAR c : INTEGER; ch : CHAR; junkMP : REAL;

  BEGIN
   WITH MeetPoint DO
    BEGIN
      ReadReal_7_2_Str( TrackFile, junkMP );
(*
Writeln( 'STA', JunkMP:7:2 );
*)
      ReadReal_7_2_Str( TrackFile, junkMP );
      ReadReal_7_2_Str( TrackFile, MP );
      Read( TrackFile, StaNo );
      ReadStr9( TrackFile, StaName );
      CurrStaNo := StaNo;
Writeln('STA', JunkMP:8:2, JunkMP:8:2,MP:8:2, StaNo:6, StaName:10 );
    END; (* With *)
   Readln( TrackFile );
  END; (* Procedure *)
```

```
(*..............................................*)

  PROCEDURE ReadYDJRec( VAR TrackFile : TEXT;
                        VAR YardJunction : YDJRecType );
  VAR c : INTEGER; ch : CHAR;  TrackNoStr : String5Type;

  BEGIN
   WITH YardJunction DO
    BEGIN
      ReadReal_7_2_Str( TrackFile, MP );
      ReadStr5( TrackFile, TrackNoStr );
      Read( TrackFile, AccessDirCh , ch, YardNo );
Writeln( 'YDJ', MP:8:2, TrackNoStr, AccessDirCh, ch, YardNo:6 );
    END; (* With *)
   Readln( TrackFile );
  END; (* Procedure *)

(*----------------------- Main -------------------------------------*)
BEGIN (* Main *)

(*---------------------------------------------------------------------*)
(* PClassNo- # of train performance classes,  PtypeStr- name of the performance class *)

   PClassNo := 6;        PTypeNo[ 0 ] := 1;  PTypeNo[ 1 ] := 1;  PTypeNo[ 7  ] := 7 ;
  PTypeNo[ 2 ] := 2;    PTypeNo[ 3 ] := 3;  PTypeNo[ 4 ] := 4;  PTypeNo[ 5 ] := 5;
  PTypeNo[ 6 ] := 6;

  PTypeStr[ 1 ] := 'AMTRAK  ';
  PTypeStr[ 2 ] := 'EXPEDITE';
  PTypeStr[ 3 ] := 'DSTK    ';
  PTypeStr[ 4 ] := 'INTERMOD';
  PTypeStr[ 5 ] := 'PRIFRT  ';
  PTypeStr[ 6 ] := 'SECFRT  ';
  PTypeStr[ 7 ] := 'REGFRT  ';
(*---------------------------------------------------------------------*)
writeln('*******enter main program ');

    TrackFileName :='tps.dir/         .trk' ;
  TravTimeFileName :='tps.dir/         .trv' ;

  FOR i := 1 TO MaxNoOfMeetPoints DO
    MeetPoint[ i ].Length := 0;


  OPEN( TrackDatFile, ConsTrackDataFileName,'OLD' );
  RESET( TrackDatFile );


  (* Read through track data file until the beginning stat. line *)
  REPEAT
    ReadRecID( TrackDatFile, RecIDScalar );
    CASE RecIDScalar OF
      YRD : Readln( TrackDatFile );
      LSN : Readln( TrackDatFile );
```

```
      TRK : Readln( TrackDatFile );
      STK : Readln( TrackDatFile );
      LSJ : Readln( TrackDatFile );
      YDJ : Readln( TrackDatFile );
      STA : ReadSTARec( TrackDatFile, CurrStaNo, MeetPoint[ 0 ] );
    END; (* Case *)
  UNTIL CurrStaNo = BegStaNo;

writeln('*****found first station going to work...');

  MeetPoint[ 1 ] :=  MeetPoint[ 0 ];
  MeetPoint[ 1 ].Length := BegStaLength;


  CurrMptNo := 1;
  REPEAT
    ReadRecID( TrackDatFile, RecIDScalar );

    CASE RecIDScalar OF
      YRD : Readln( TrackDatFile );
      LSN : Readln( TrackDatFile );
      TRK : Readln( TrackDatFile );
      STK :
        BEGIN
          CurrMptNo := CurrMptNo + 1;
          ReadSTKRec( TrackDatFile, MeetPoint[ CurrMptNo ] );
          ReadRecID( TrackDatFile, RecIDScalar );
          ReadSTARec( TrackDatFile, CurrStaNo, MeetPoint[ CurrMptNo ] );
        END; (* STK case *)
      LSJ : Readln( TrackDatFile );
      STA : ReadSTARec( TrackDatFile,CurrStaNo, MeetPoint[ 0 ] );
      YDJ :         Readln( TrackDatFile );
    END; (* Case *)

  UNTIL CurrStaNo = EndStaNo;

  IF MeetPoint[ 0 ].StaNo = EndStaNo
   THEN MeetPoint[ CurrMptNo ] :=  MeetPoint[ 0 ];

writeln(' ****** nuber of meetpoints = ', currmptno:2);
writeln( '******   last mp is ', meetpoint[currmptno].MP:7:2);

  FOR i := 1 TO CurrMptNo DO
    IF MeetPoint[ i ].Length = 0 THEN
     BEGIN
       MeetPoint[ i ].EndMP := MeetPoint[ i ].MP;
       MeetPoint[ i ].BegMP := MeetPoint[ i ].MP;
     END;


  CLOSE( TrackDatFile );

Writeln( 'after trackdata file is closed' );  (**************************************)
```

```
FOR c := 1 TO 5 DO
  IF MeetPoint[ 1 ].StaName[ c ] <> ' '
    THEN  TrackFileName[ c+8 ] := MeetPoint[ 1 ].StaName[ c ]
    ELSE  TrackFileName[ c+8 ] := '_';
TrackFileName[ 6+8 ] := '_';
FOR c := 1 TO 4 DO
  IF MeetPoint[ CurrMptNo ].StaName[ c ] <> ' '
    THEN  TrackFileName[ c+6+8 ] := MeetPoint[ CurrMptNo ].StaName[ c ]
    ELSE  TrackFileName[ c+6+8 ] := '_';



FOR c := 1+8 TO 10+8 DO
  TravTimeFileName[ c ] := TrackFileName[ c ] ;

Writeln( '************ TRACK FILE NAME IS ', TrackFileName );
Writeln( '************ TRAVEL TIME FILE NAME IS ', TravTimeFileName );


DirStr[ West ] := OutboundStr; DirStr[ East ] := InboundStr;

NoOfMeetPoints := CurrMptNo;;

Open( TPSRawFile, ConsTPSrawFileName,'OLD' );
Reset( TPSRawFile );
writeln('*****opening tpsrawFile ', constpsrawfilename);

If AMTRAKDATA = 'YES'
   THEN BEGIN
writeln(' *****opening tpsamtrawFile ', constpsamtrawfilename);
     Open( TPSAmtRawFile, ConsTPSAmtrawFileName,'UNKNOWN' );
     Reset( TPSAmtRawFile );
   END;

FOR trDir := West TO East DO
BEGIN
CASE trDir OF
West:
BEGIN

 REPEAT
   Readln( TPSRawFile );
   Read( TPSRawFile, ch );
   IF ch = '1' THEN FOR i := 1 TO 5 DO Readln( TPSRawFile );
   Read( TPSRawFile, MilePost );      (* here *)
 UNTIL ( ( MilePost-0.2 ) <= MeetPoint[ 1 ].EndMP) AND
         ( MeetPoint[ 1 ].EndMP <= ( MilePost+0.2 )   ) ;
 FOR  i := 9 TO 15 DO Read( TPSRawFile, ch );
 FOR  i := 16 TO 23 DO Read( TPSRawFile, Name8Str[ i - 15 ] );
 Read( TPSRawFile, junkint,CumSegLengthArr[ 1 ],
       junkint );

 (* Write( MilePost:7:2, Name8Str:9, CumSegLengthArr[ 1 ]:6:1 );  *)
 FOR k := 2 TO PClassNo DO
    Read( TPSRawFile, junkint, TPSRealTimeArr[ TrDir, k, 1 ] );
```

```
 FOR m := 2 TO NoOfMeetPoints DO
  BEGIN
    REPEAT
      Readln( TPSRawFile );
      Read( TPSRawFile, ch );
      IF ch = '1' THEN FOR i := 1 TO 5 DO Readln( TPSRawFile );
{writeln('****** mp # ', m:2, ' = ', MeetPoint[m].EndMP:7:2,
       '     current tps mp is ', milepost:7:2);}
      Read( TPSRawFile, MilePost );
    UNTIL ( ( MilePost-0.2 ) <= MeetPoint[ m ].EndMP) AND
          ( MeetPoint[ m ].EndMP <= ( MilePost+0.2 )   ) ;

    FOR  i := 9 TO 15 DO Read( TPSRawFile, ch );
    FOR  i := 16 TO 23 DO Read( TPSRawFile, Name8Str[ i - 15 ] );
    Read( TPSRawFile, junkint, CumSegLengthArr[ m ],
          junkint );

{Write( MilePost:7:2, Name8Str:9, CumSegLengthArr[ m ]:6:1 );}
    SegLengthArr[ m - 1 ] := CumSegLengthArr[ m ] - CumSegLengthArr[ m - 1 ];
    FOR k := 2 TO PClassNo DO
     BEGIN
      Read( TPSRawFile, junkint, TPSRealTimeArr[ TrDir, k, m ] );
{Write( TPSRealTimeArr[ TrDir, k, m ]:6:1 );}
      TPSTravelTimeArr[ TrDir, k, m-1 ] := Round ( TPSRealTimeArr[ TrDir,
         k, m ] - TPSRealTimeArr[ TrDir, k, m -1 ] + 0.19 );
     END; (* For k :=...*)
Writeln;
   END; (* For m=...*)

(* Read Amtrak TPS file: *)
IF AMTRAKDATA = 'YES'
  THEN BEGIN
  REPEAT
    Readln( TPSAmtRawFile );
    Read( TPSAmtRawFile, ch );
    IF ch = '1' THEN FOR i := 1 TO 5 DO Readln( TPSAmtRawFile );
    Read( TPSAmtRawFile, MilePost );
  UNTIL ( ( MilePost-0.2 ) <= MeetPoint[ 1 ].EndMP) AND
          ( MeetPoint[ 1 ].EndMP <= ( MilePost+0.2 )   ) ;
  FOR  i := 9 TO 15 DO Read( TPSAmtRawFile, ch );
  FOR  i := 16 TO 23 DO Read( TPSAmtRawFile, Name8Str[ i - 15 ] );
  Read( TPSAmtRawFile, junkint,CumSegLengthArr[ 1 ],
        junkint );

Write( MilePost:7:2, Name8Str:9, CumSegLengthArr[ 1 ]:6:1 );
  FOR k := 1 TO 1 DO
     Read( TPSAmtRawFile, junkint,
           TPSRealTimeArr[ TrDir, k, 1 ] );

FOR k := 1 TO 1 DO Write( TPSRealTimeArr[ TrDir, k, 1 ]:6:1 );
Writeln;

  FOR m := 2 TO NoOfMeetPoints DO
   BEGIN
```

```
Writeln;

  FOR m := NoOfMeetPoints - 1 DOWNTO 1 DO
   BEGIN

     REPEAT
       Readln( TPSRawFile );
       Read( TPSRawFile, ch );
       IF ch = '1' THEN FOR i := 1 TO 5 DO Readln( TPSRawFile );
       Read( TPSRawFile, MilePost );

writeln('eastbound mp = ', MilePost:7:2, '    ', MeetPOint[m].BegMP:7:2);

     UNTIL ( ( MilePost-0.2 ) <= MeetPoint[ m ].BegMP) AND
           ( MeetPoint[ m ].BegMP <= ( MilePost+0.2 )    ) ;
     FOR  i := 9 TO 15 DO Read( TPSRawFile, ch );
     FOR  i := 16 TO 23 DO Read( TPSRawFile,  DummyMeetPointName[ i - 15 ] );
     Read( TPSRawFile, junkint, DummySegLength, junkint );

Write( MilePost:7:2,  DummyMeetPointName:9, DummySegLength:6:1 );
     FOR k := 2 TO  PClassNo DO
      BEGIN
       Read( TPSRawFile, junkint, TPSRealTimeArr[ TrDir, k, m ] );
       Write( TPSRealTimeArr[ TrDir, k, m ]:6:1 );
       TPSTravelTimeArr[ TrDir, k, m ] := Round ( TPSRealTimeArr[ TrDir,
          k, m ] - TPSRealTimeArr[ TrDir, k, m + 1 ] + 0.39 );
      END; (* For k :=...*)
Writeln;
   END; (* For m=...*)

                         (* Read eastbound Amtrak TPS times *)
IF AMTRAKDATA = 'YES'
  THEN BEGIN
  REPEAT
    Readln( TPSAMTRawFile );
    Read( TPSAMTRawFile, ch );
  UNTIL ch ='E';
  Writeln( ch );

  REPEAT
    Readln( TPSAMTRawFile );
    Read( TPSAMTRawFile, ch );
    IF ch = '1' THEN FOR i := 1 TO 5 DO Readln( TPSAMTRawFile );
    Read( TPSAMTRawFile, MilePost );
  UNTIL ( ( MilePost-0.2 ) <= MeetPoint[ NoOfMeetpoints ].MP) AND
          ( MeetPoint[ NoOfMeetpoints ].MP <= ( MilePost+0.2 )    ) ;
  FOR  i := 9 TO 15 DO Read( TPSAMTRawFile, ch );
  FOR  i := 16 TO 23 DO Read( TPSAMTRawFile, DummyMeetPointName[ i - 15 ] );
  Read( TPSAMTRawFile, junkint, DummySegLength,
        junkint );

Write( MilePost:7:2,  DummyMeetPointName:9,  DummySegLength:6:1 );
  FOR k := 1 TO 1 DO
     Read( TPSAMTRawFile, junkint,
           TPSRealTimeArr[ TrDir, k, NoOfMeetPoints ] );
```

```
    BEGIN
      Writeln( TPSTimesFile, PTypeNo[ k ]:3, PTypeStr[ PTypeNo[ k ] ]:9 );
      FOR m := 1 TO NoOfMeetPoints - 1 DO
        Writeln( TPSTimesFile, m:2,' ', TPSTravelTimeArr[ TrDir, k, m ]:3 );
    END; (* For k=....*)
    IF PClassNo = 6
       THEN BEGIN
          Writeln( TPSTimesFile, PTypeNo[ 7 ]:3, PTypeStr[ PTypeNo[ 7 ] ]:9 );
          FOR m := 1 TO NoOfMeetPoints - 1 DO
             Writeln( TPSTimesFile, m:2,' ', TPSTravelTimeArr[ TrDir, 6, m ]:3 )
       END;
    Writeln( TPSTimesFile, 0:3 );
  END; (* For TrDir=...*)

  Close(TPSTimesFile );

Writeln( '******** before opening .trk file  **********' );

{
  OPEN( ScanTrackFile, TrackFileName );
  REWRITE( ScanTrackFile );
  Writeln( ScanTrackFile, ' SCAN track data for lane:' );
  Writeln( ScanTrackFile, MeetPoint[ 1 ].StaName,' - ',
                      MeetPoint[ CurrMptNo ].StaName );
  Writeln( ScanTrackFile );
  Writeln( ScanTrackFile );

  FOR m := 1 TO CurrMptNo - 1 DO WITH MeetPoint[ m ] DO
    BEGIN
     Writeln( ScanTrackFile, m:2,' S ',StaName,' ',Round( Length*5280 ):5 );
(*    Writeln( ScanTrackFile, ( MeetPoint[ m+1 ].MP - MP ):7:2  );      *)
    Writeln( ScanTrackFile,  SegLengthArr[ m ]:6:1 );
    END;
  WITH MeetPoint[ CurrMptNo ] DO
    Writeln( ScanTrackFile, CurrMptNo:2,' S ',StaName,' ',Round( Length*5280 ):5 );
  Writeln( ScanTrackFile, 0:2 );
  Writeln( ScanTrackFile, '0 END' );

  Writeln( ScanTrackFile, TravTimeFileName );
  Writeln( ScanTrackFile, TravTimeFileName );
  CLOSE( ScanTrackFile );

               }
END. (* MAIN *)
```

will require a much more powerful software engine than currently exists in SCAN. The users of SCAN must weigh the merits of this detail versus the increased computational and data requirements.

9.2 Train Schedules

The next major issue in the routine use of SCAN involves the creation of train schedules and the updating of these schedules in the D1260 file. As was stated in the original SCAN report, three phases of analysis are envisioned:

Phase I: the analysis of all scheduled traffic moving over a corridor,

Phase II: Phase I plus the addition of a sample (random or average?) of the unscheduled traffic,

Phase III: Phase II plus the addition of a sample (?) of maintenance work on the corridor.

In all three phases, database software is needed in order to extract ther schedules from the D1260 files or the historical files and to put these schedules into the SCAN format. Also, this software should provide the analyst with the capability to perform *scenario analysis* [3] in which new trains are introduced into the analysis. Given the complexity of the databases, this software should reside on the mainframe and simply feed the Apollo system. At this point, the exact form in which this sacenario analysis will be implemented is unclear due to the "fuzziness" of the user needs. This item should be seriously considered in the final version of SCAN.

Another missing aspect of the schedules involves updating of the D1260 file after a SCAN analysis is performed. The SCAN system currently provides no reports or updates to the schedules due to the fact that it is unclear how these updates should be performed. The SCAN software can easily be updated to provide ".new" schedule files as opposed to the ".org" files which create the schedules used in SCAN. The uploading of these changes to the D1260 file remains a major software task before SCAN is to be successfully employed.

9.3 Track Data

The third issue involves the automation of the track data. Currently, no data exists on yard capacities, the layout of the yards with respect to access (east or west) and availability of tracks for the meeting and passing of trains, and the location of cross-over points. The creation of the track data is in some sense a "one-time" affair except for the analysis of the addition or deletion of sidings, etc., but some automation of the track data is vital if SCAN is to be employed for the entire railroad. This automation is complicated by the nonunique naming of points on the railroad and the omission of certain data in the track file. However, this task can be automated to a great extent given a *good* computerized database of track layout.

9.4 Reliability Analysis

As described in the original SCAN report, the design of the SCAN system provides for the ability to analyze the reliability of a given set of schedules. This capability will be included in Version 2.0. In order to provide this capability, the distribution of the TPS times is necessary. That is, one must provide for each train type a probability distribution for the likelihood that the TPS times can be achieved [4]. Most likely, this distribution is not known obvectively, but subjectively. Version 2.0 of SCAN will provide the capability for the graphical input of these subjective distributions. A major work item involves the development of a library of these distributions in order to lessen the workload on the analyst. Version 2.0 will contain the software capability to collect and use the distributions, but BN must provide the library (i.e., database) capabilities.

9.5 Enhancements to the SCAN System

The major emphasis in the second year of work on the development of the SCAN system, as outlined in the second year statement of work, entails the following items:

1. The current version of the SCAN system only provides for the westbound overtaking of trains; Version 2.0 will provide the logic for the eastbound overtaking.

[3] per the suggestion of T. Krueger.

[4] The TPS times are calculated assuming 100% locomotive efficiency and thus, can be considered the "best" achievable times.

2. The ability to quickly decide which lanes contain the most trouble in order to focus the analyst's energies on the worst lanes in the corridor first. That is, to derive the probability of finding a feasible meet-pass plan if SCAN were run to completion. Operationally, one would choose a corridor and then ask for corridor feasibility. The result of this request would be a probability (0.0 — —1.0) for each lane that the schedules over this lane are feasible; these numbers will be displayed on the corridor graphics. The analyst can then select the worst lane and begin the process of schedule updating. During the updating process, the probabilities will vary on adjacent lanes and these probability changes will be shown.
3. The ability to find a set of "optimal" schedules given the data. At this time, the very notion of what constitutes "optimal" is unclear; this step is at the basic research stage. The outcome of this research is the capability of the analyst to request that SCAN find a set of feasible and optimal schedules for the corridor under investigation.
4. The consideration of time periods longer than one day. Currently, SCAN only considers one day's traffic over a lane. Technically, the software can handle multiple days but computational performance will degrade. Basic research focused on the issue of deriving methods which can handle multiple days *and* are computationally tractable is underway.
5. The ability to deal with data ambiguity. Currently, SCAN uses Boolean logic to decide whether or not a given set of schedules is feasible. However, the data is subject to error and thus, the conclusions may be too strong. We are currently investigating the use of *fuzzy logic* and *fuzzy inferrence* in order to relax the assumption of "perfect" data. Again, this relaxation will increase the computational complexity of the algorithm and some compromise must be reached between this complexity and the reality of the model.

9.6 Minor Problem Areas

In addition to the major issues listed above, several minor points must be addressed before SCAN can be fully operational at BN:

1. Currently, reporting stations are not standardized; i.e., some trains have scheduled times at a particular reporting station and some do not. Reporting stations should be standardized in order for SCAN to be effective.
2. Scheduled times are currently not given at junctions; i.e., junctions are rarely reporting stations. Given the fact that junctions form a major point at which conflicts occur and that they are often at the boundary of dispatchers' territories, these should be considered as reporting stations. This would enable the SCAN system to better schedule traffic and the real-time control models to better control traffic flow in the railroad.
3. Each reporting station should be given a timezone classification in the track database.
4. A method must be devised to handle local traffic [5]. This traffic is currently ignored in SCAN.
5. A better method for defining the train lengths must be devised. We have simply assumed a "maximum" length.

In summary, SCAN is operational at the present, but these future enhancements must be made before it is truly operational on an ongoing basis at Burlington Northern.

[5] defined as traffic which is scheduled strictly between two reporting stations and thus, will not have schedules

Appendix A

Track Data File

In order to create the Track Files and Reporting Station Master File, one must use various sources of information. One main source of information is the Operating Track Network File. However, one should be careful in using this file due to the discrepancies between it and the Timetables; e.g., one source may list a siding at a particular point and the other source will not list this point. For completeness, a partial listing of the BN Operating Track Network File, referred to as Track Data File in this report, is given below along with the June 16, 1987 memo from R.G. Patton which describes the format of this data:

```
YRD 80000006CICERO     10000    10
YRD 46300006CICERO HU 10000     20
YRD 80600033EOLA       8000     20
YRD 80700037AURORA     3000     20
YRD 82100083ROCHELLE   7000      2
YRD 82000098OREGON     2000      1
YRD 81000143SAVANNA    8000     10
YRD 81100296NLACROSSE  8000      5
YRD 54600426DAYTONS B 10000     15
YRD 21300439NORTHTOWN 10000     20
YRD 55300567STAPLES   10000      5
YRD 56000673DILWORTH   7000      7
YRD 46800911GAVIN YRD 10000     20
YRD 70001036WILLISTON 10000      3
YRD 70101345HAVRE     10000     10
YRD 65001601WHITEFISH 10000      5
YRD 65101866YARDLEY   10000     10
YRD 65201870SPOKANE    2000      2
YRD 65602045WENATCHEE 10000     20
YRD 60515005DELTA     10000      1
YRD 60402166EVERETT   10000      5
YRD 47002195INTERBAY  10000     20
LSN  71     .85  38.10
LSJ     .85ALL  00001D 9999    0.  00001CUDEP
TRK     .85  38.10  37.261     MAIN
TRK     .85  38.10  37.262     MAIN
TRK    1.68   8.01   6.203     MAIN
TRK    1.71   6.43   4.484     MAIN
STA    0.     0.     1.80      2CHICAGO H
STA    0.     0.     3.00      3CHICAGO E
STA    0.     0.     3.83      4CHICAGO W
```

```
STA   0.     0.      5.00    5CHICAGO V
STA   0.     0.      6.00    6CHICAGO H
YDJ   6.434    U  463
STA   0.     0.      7.02    7CICERO
STA   0.     0.      7.10    9CHICAGO
YDJ   7.501    U  800
TRK   8.01   8.03    .023     MAIN
TRK   8.02  38.10  30.093     MAIN
STA   0.     0.      8.54    8CLYDE
YDJ   8.751    D  800
YDJ   9.003    D  463
STA   0.     0.      9.62   10BERWYN
STA   0.     0.     11.06   11RIVERSIDE
 .     .      .       .          .
 .     .      .       .          .
 .     .      .       .          .
```

Overland Park, Kansas
June 16, 1987

To: Professor P.T. Harker
The Whorton School
University of Pennsylvania
Philadelphia, PA
19104-6366

From: R.G. Patton
Manager Operations Planning

Subject: Train Schedual Analyzer;
Tape of Burlington Northern Track Network,
between Chicago Ill. and Seattle Wa.
Note: Confidential and Proprietary Information of
Burlington Northern Railroad Co.

The file is a standard flat file with variable records identified with a three character record type code. They are sorted, for the most part, in the mile post order in which they occur on the track. A full description of each record is attached. Differences between actual location in the field and the way they are stored in the file is due to the data base conventions from which this data was collected.

Our data base systems for track information are based on a code we call a Line Segment (LS). The LS is defined as a unique route or yard or building or area that has its own description and is not repeated. We are only concerned with routes and yards here. Routes have dimension and are measured by Mile Posts (MP), and are always stored in the computer in order by low MP. Each LS has a record for the portion of the line required for this study. Main operating tracks, Side tracks, Stations, Line Segment Junction points, and others are identified and will be improved in future versions of the file.

The portions of our railroad this file contains are as follows;

Route name	LS	Begin MP	End MP
Chicago to Aurora	0071	0000.85	0038.10
Aurora	0001	0038.11	0038.45
Aurora to St Paul	0003	0038.45	0450.00
St Paul to Fargo	0025	0000.00	0251.10
Fargo to Casselton	0026	0000.00	0031.15
Casselton to Nolan	0024	0003.00	0024.30
Nolan to Surrey	0034	0040.00	0226.30
Surrey to Minot	0033	0196.20	0203.30
Minot to Havre	0035	0000.00	0434.00
Havre to Sandpoint	0036	0964.00	1403.50
Sandpoint to Spokane	0045	0002.91	0071.50
Spokane to SunSetJ	0046	0000.00	0001.10

SunSetJ to Everett	0037	1481.00	1785.00
Seattle to Everett	0050	0000.00	0032.10

Tracks, other physical objects, and locations that are components of the route are related to the LS and MP with their own unique identifiers. For convenience I have called these Line Segment Markers (LSM) as they are individual markers of some physical or important event in the route. There will be several types of LSM's which are described in the attachment with their attributes.

Main line track is the most important for this study and is identified as a TRK record. Track numbers are controlled by government reporting and historical coding such as S for single main line, 1,2,3,4 for multiple mains and numbering from north to south. The beginning, end and length are also given.

Sometimes the track codes are confusing and require additional information to distinguish them such as yards or industry areas. Then a track number is supplemented with a track type that defines the main purpose of that track and frees the track number to be coded with almost anything. For our study the siding have a variety of track numbers but always have a track type 5. Future enhancements to this file will use this to define cross overs, rail road crossings, etc.

Yard LS are another problem due to their nebulus territory. Our data bases store the yards with its own Line Segment number but they have no length or dimension. Each yard required for this study is identified in the file. In order to supply the connections between route LS's and the yards I have put a record in the file called a Yard Junction that describes the point that joins a route to a yard. They are in mile post sequence with the other Marker records that describe the components and locations along an LS. The other locations that are important to the movement of trains or reporting are also recorded in the file.

The records do have a sequence that requires some explaination. Yard Segments that are used in this study are all given at the top of the file. They are referenced by the Line Segment Markers that will put them in their proper sequence for terminal operations. Track Line Segments are then listed in the order they occur for the trains. LS 71 from Chicago to Aurora Ill., connects to LS 1 at Aurora, connects to LS 3 at Aurora, etc. The Marker records that follow each Line Segment are then given in mile post order.

If you have trouble with the file and require any explaination feel free to call me at 913-661-4202.

R.G. Patton

R.G. Patton
Mananger Operations Planning

cc: P.L. Westine
G.T. Trafton

June 16, 1987
Record Description for Operating Track Network

Record Key = YRD	B 1	"YRD"	Yard Line Segment Record
LSNUM	B 4	I 4	Line / Yard Segment Number
LS.YRD.STA.NUM	B 8	T 5	Yard Station Number, Compass
LS.YRD.STA.NAME.9	B 15	T 9	Yard Station Name
LS.YRD.LENGTH	B 25	I 6	Yard Length
LS.YRD.CAPACITY	B 32	I 6	Capacity, Max. Number of Trains

Record Key = LSN	B 1	"LSN"	Line Segment Record
LSNUM	B 4	I 4	Line / Yard Segment Number
LS.BEG.MP	B 8	F7,2	Line Begin Mile Post
LS.END.MP	B 15	F7,2	Line End Mile Post

Record Key = TRK	B 1,	"TRK"	Line Segment Marker, Main Operating Track Range
LSM.TRK.BEG.MP	B 4,	F7,2	Track Begin Mile Post
LSM.TRK.END.MP	B 11,	F7,2	Track End Mile Post
LSM.TRK.LENGTH	B 18,	F7,2	Track Length
LSM.TRK.NUM	B 25	T 5	Track Number
LSM.TRK.FLAG	B 30	T 5	Track Flag "MAIN " = Main Line or Main Operating Track

Record Key = STK	B 1,	"STK"	Line Segment Marker, Side Tracks, Sidings and other tracks
LSM.STK.BEG.MP	B 4,	F7,2	Side Track Begin Mile Post
LSM.STK.END.MP	B 11,	F7,2	Side Track End Mile Post
LSM.STK.LENGTH	B 18,	F7,2	Track Length
LSM.STK.NUM	B 25	T 5	Track Number
LSM.STK.TYPE	B 30	T 5	Track Type "5" = Siding

Record Key = LSJ	B 1,	"LSJ"	Line Segment Marker, Line Segment Junction, connection from one line segment to another.
LSM.LSJ.MP	B 4,	F7,2	Line Segment Junction Mile Post
LSM.LSJ.TRK.NUM "ALL", track number "S__"	B 11,	T 5	Line Segment Junction Track Number, if "all" is shown then all track on this line segment connect to the next line at the specified milepost, or else a single track number is specified.
LSM.LSJ.STA.NUM	B 16,	T 5	Line Segment Junction Station Number
LSM.LSJ.ACCESS.DIR	B 21	T 2	Line Segment Junction Access Direction, indicates the direction a train is travelling to have access to this connection, U = UP the milepost numbers, D = Down the milepost range.
LSM.LSJ.CONN.LS.NUM	B 23	I 4	Line Segment Junction Connecting Line Segment Number
LSM.LSJ.CONN.MP	B 27	F7,2	Line Segment Junction Connecting Mile Post
LSM.LSJ.CONN.STA.NUM	B 34	T 5	Line Segment Junction Connecting Station Number
LSM.LSJ.CONN.TYPE	B 39	T 5	Line Segment Junction Connection Type, BNML = BN Main Line BNBL = BN Branch Line other = other symbols are used interchange Rail Roads
Record Key = STA	B 1,	"STA"	Line Segment Marker, Station Number and Descriptions
* LSM.STA.BEG.MP	B 4,	F7,2	* Future use, Station Begin Mile Post
* LSM.STA.END.MP	B 11,	F7,2	* Future use, Station End Mile Post
LSM.STA.ACT.MP	B 18,	F7,2	Station Actual Mile Post
LSM.STA.NUM	B 25	T 5	Station Number
LSM.STA.NAME.9	B 30	T 9	Station Name, 9 character Compass standard
Record Key = YDJ	B 1,	"YDJ"	Yard Junctions, A point on a line that allows entry from a given track to a Yard Line Segment or given yard
LSM.YDJ.MP	B 4,	F7,2	Yard Junctions Mile Post
LSM.YDJ.TRK.NUM	B 11	T 5	Yard Junctions Track Number
LSM.YDJ.ACCESS.DIR	B 16	T 2	Yard Junctions Access Direction, indicates the direction a train is travelling to have access to this connection, U = UP the milepost numbers, D = Down the milepost range.
LSM.YDJ.YARD.LS.NUM	B 19	I 4	Yard Junctions Yard Line Segment Number

Appendix B

Train Performance Simulation Report

As stated in the body of the report, TPS times between each meet-point in the track file must be provided for each train class. However, the TPS runs, as shown below, generate times between all mileposts. Therefore, a translation between mileposts and points in the track data must occur before this data can be used in SCAN. The majority of this translation can be automated. However, there are discrepancies in the naming conventions of points between the track files and the TPS files which forces a substantial amount of manual work in the creation of the train travel time files for SCAN. Below is a partial listing of the detailed TPS report. Note that the figures for AMTRAK trains are contained in different files. In the future it would be advantageous to store *all* trains TPS times for each corridor in one condensed file by major track location rather than by milepost due to the sheer size of the TPS files.

MILEPOST NUMBER	MILEPOST NAME	COMPENSATED ELEVATION	TOTAL DISTANCE	SPEED LIMIT	TRAIN 1 "EXPEDITE" SPEED	TRAIN 1 "EXPEDITE" TIME	TRAIN 2 "DSTK" SPEED	TRAIN 2 "DSTK" TIME	TRAIN 3 "INTERMOD" SPEED	TRAIN 3 "INTERMOD" TIME	TRAIN 4 "PRIFRT" SPEED	TRAIN 4 "PRIFRT" TIME	TRAIN 5 "SECFRT" SPEED	TRAIN 5 "SECFRT" TIME
8.20	CICERO Y	28	0.0	40	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
8.45		34	0.25	40	24	1.0	22	1.2	24	1.1	18	1.4	18	1.4
8.51	CLYDE	37	0.31	40	26	1.2	23	1.3	25	1.2	20	1.6	20	1.6
8.70		35	0.50	40	30	1.6	27	1.8	29	1.6	23	2.1	23	2.1
8.95		30	0.75	40	37	2.0	30	2.3	33	2.1	26	2.8	26	2.8
9.08	LA VERGN	30	0.88	40	39	2.2	32	2.6	35	2.3	27	3.1	27	3.1
9.19	EL CHG	31	0.99	40	40	2.4	33	2.8	37	2.5	28	3.3	28	3.3
9.20		31	1.00	40	40	2.4	33	2.8	37	2.5	28	3.3	28	3.3
9.45		32	1.25	40	40	2.8	35	3.2	40	2.9	31	3.8	31	3.8
9.56	SPEED	32	1.36	45	40	3.0	36	3.4	40	3.1	32	4.0	32	4.0
9.61	BERWYN	32	1.41	45	40	3.0	36	3.5	40	3.2	32	4.1	32	4.1
9.70		32	1.50	45	40	3.2	37	3.7	40	3.3	33	4.3	33	4.3
9.95		34	1.75	45	42	3.5	39	4.0	40	3.7	34	4.7	34	4.7
10.20		35	2.00	45	44	3.9	40	4.4	40	4.0	35	5.2	35	5.2
10.45		37	2.25	45	45	4.2	40	4.8	41	4.4	36	5.6	36	5.6
10.70		38	2.50	45	45	4.5	40	5.2	42	4.8	37	6.0	37	6.0
10.95		38	2.75	45	45	4.9	41	5.5	44	5.1	38	6.4	38	6.4
11.20		42	3.00	45	45	5.2	42	5.9	45	5.5	38	6.8	38	6.8
11.45		49	3.25	45	45	5.5	42	6.3	45	5.8	38	7.2	38	7.2
11.70		44	3.50	45	45	5.9	42	6.6	45	6.1	38	7.6	38	7.6
11.95		42	3.75	45	45	6.2	43	7.0	45	6.5	39	8.0	39	8.0
12.20		43	4.00	45	45	6.5	44	7.3	45	6.8	40	8.4	40	8.4
12.45		45	4.25	45	45	6.9	44	7.7	45	7.1	41	8.7	41	8.7
12.70		47	4.50	45	45	7.2	45	8.0	45	7.5	42	9.1	42	9.1
12.95		53	4.75	45	45	7.5	45	8.3	45	7.8	42	9.4	42	9.4
13.08	CONG PAR	56	4.88	45	45	7.7	45	8.5	45	8.0	42	9.6	42	9.6
13.20		58	5.00	45	45	7.9	45	8.7	45	8.1	41	9.8	41	9.8
13.45		62	5.25	45	45	8.2	44	9.0	45	8.5	41	10.2	41	10.2
13.70		65	5.50	45	45	8.5	44	9.3	45	8.8	40	10.5	40	10.5
13.81	LA GRANG	65	5.61	45	45	8.7	44	9.5	45	8.9	40	10.7	40	10.7
13.95		66	5.75	45	45	8.9	44	9.7	45	9.1	39	10.9	39	10.9
14.20		67	6.00	45	45	9.2	44	10.0	45	9.5	39	11.3	39	11.3
14.45		73	6.25	45	45	9.5	44	10.4	45	9.8	40	11.7	40	11.7
14.70		79	6.50	45	45	9.9	44	10.7	45	10.1	39	12.1	39	12.1
14.95		84	6.75	45	45	10.2	43	11.1	45	10.5	39	12.5	39	12.5
15.20		89	7.00	45	45	10.5	43	11.4	45	10.8	38	12.8	38	12.8
15.45		90	7.25	45	45	10.9	42	11.8	45	11.1	37	13.2	37	13.2
15.70		87	7.50	45	45	11.2	42	12.1	45	11.5	37	13.7	37	13.7
15.95		87	7.75	45	45	11.5	43	12.5	45	11.8	38	14.1	38	14.1
16.20		93	8.00	45	45	11.9	43	12.8	45	12.1	39	14.5	39	14.5
16.45		100	8.25	45	45	12.2	44	13.2	45	12.5	39	14.8	39	14.8
16.70		107	8.50	45	45	12.5	43	13.5	45	12.8	38	15.2	38	15.2
16.90	HINSDALE	111	8.70	45	45	12.8	43	13.8	45	13.1	37	15.5	37	15.5
16.95		112	8.75	45	45	12.9	43	13.9	44	13.1	37	15.6	37	15.6
17.20		117	9.00	45	45	13.2	42	14.2	44	13.5	36	16.0	36	16.0
17.45		125	9.25	45	45	13.5	41	14.6	44	13.8	35	16.5	35	16.5
17.70		132	9.50	45	45	13.9	40	15.0	44	14.2	34	16.9	34	16.9
17.95		139	9.75	45	45	14.2	39	15.3	43	14.5	32	17.3	32	17.3
18.20		146	10.00	45	45	14.5	38	15.7	43	14.8	31	17.8	31	17.8
18.45		152	10.25	45	45	14.9	37	16.1	43	15.2	30	18.3	30	18.3

18.70		155	10.50	45	45	15.2	36	16.5	42	15.5	29	18.8	29	18.8
18.95		161	10.75	45	45	15.5	36	16.9	43	15.9	29	19.3	29	19.3
19.20		168	11.00	45	45	15.9	36	17.4	43	16.3	29	19.9	29	19.9
19.45		169	11.25	45	45	16.2	36	17.8	43	16.6	29	20.4	29	20.4
19.70		165	11.50	45	45	16.5	36	18.2	44	16.9	29	20.9	29	20.9
19.95		161	11.75	45	45	16.9	38	18.6	45	17.3	31	21.4	31	21.4
20.20		157	12.00	45	45	17.2	39	19.0	45	17.6	34	21.9	34	21.9
20.45		153	12.25	45	45	17.5	42	19.4	45	17.9	37	22.3	37	22.3
20.70		149	12.50	45	45	17.9	44	19.7	45	18.3	39	22.7	39	22.7
20.95		144	12.75	45	45	18.2	45	20.0	45	18.6	42	23.1	42	23.1
21.18	DOWNR GR	140	12.98	45	45	18.5	45	20.4	45	18.9	44	23.4	44	23.4
21.20		140	13.00	45	45	18.5	45	20.4	45	18.9	44	23.4	44	23.4
21.45		137	13.25	45	45	18.9	45	20.7	45	19.3	45	23.7	45	23.7
21.63	SPEED	134	13.43	50	45	19.1	45	21.0	45	19.5	45	24.0	45	24.0
21.70		133	13.50	50	45	19.2	45	21.0	45	19.6	45	24.1	45	24.1
21.95		131	13.75	50	46	19.5	45	21.4	45	19.9	45	24.4	45	24.4
22.20		130	14.00	50	49	19.9	45	21.7	45	20.3	45	24.7	45	24.7
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Appendix C

TPS Train Classifications

Below is a listing the the classification of trains by TPS type. Please note that the current database contains only BN train codes 1 through 7. The remainder of this list is provided to illustrate the overall classification scheme. Also, the origonal memo from BN which was used to create this list is included.

BN CODE	BN TRAIN CLASS	TPS TRAIN TYPE NUMBER	TPS TRAIN TYPE NAME	-----MAX TRAIN LENGTH (FEET)----- WESTBOUND	EASTBOUND
	-	1	AMTRAK	1000	1000
1	EXPEDITER	2	EXPEDITE	3240	3240
2	DOUBLE STACK	3	DSTK	7000	6500
3	INTERMODAL	4	INTERMOD	7000	6500
4	PRIORITY FREIGHT	5	PRIFRT	7000	6500
5	2NDARY FREIGHT	6	SECFRT	7000	6500
6	REGIONAL FREIGHT	7	REGNFRT	7000	6500
7	LOCAL FREIGHT	8	LOCALFRT	7000	6500
8		9	COALLOAD		
9		10	COALMTY		
10		11	GRNS4L		
11		12	GRN108L		
12		13	GRAINLDS		
13		14	GRN80E		
14		15	GRN115E		

PROPRIETARY AND CONFIDENTIAL INFORMATION OF THE BURLINGTON NORTHERN RAILROAD COMPANY

TRAIN CLASS CODES

	CODE	TRAIN CLASS
1	EXPEDITE	EXPEDITER
2	DSTK	DOUBLE STACK
3	INTERMOD	INTERMODAL
4	PRIFRT	PRIORITY FREIGHT
5	SECFRT	SECONDARY FREIGHT
6	REGNFRT *	REGIONAL FREIGHT
7	LOCALFRT *	LOCAL FREIGHT
8	COALLOAD	UNIT COAL TRAIN-LOADS
9	COALMTY	UNIT COAL TRAIN-EMPTIES
10	GRN54L	UNIT GRAIN TRAIN-54 LOADS
11	GRN108L	UNIT GRAIN TRAIN-108 LOADS
12	GRAINLDS	UNIT GRAIN TRAIN-52 LOADS (Spokane-Seattle segment only)
13	GRN80E	UNIT GRAIN TRAIN-80 EMPTIES
14	GRN115E	UNIT GRAIN TRAIN-115 EMPTIES
15		

* Travel continuity not preserved between segment runs.

PROPRIETARY AND CONFIDENTIAL INFORMATION OF THE BURLINGTON NORTHERN RAILROAD COMPANY

SEGMENT/TRAIN CLASS LISTING

SEGMENT	DIR	TRAIN CLASSES RUNNING OVER SEGMENT
CICERO-NORTHTOWN WB	W	EXPEDITE, DSTK, INTERMOD, PRIFRT, SECFRT
CICERO-NORTHTOWN EB	E	EXPEDITE, DSTK, INTERMOD, PRIFRT, SECFRT
NORTHTOWN-HAVRE	W	DSTK, INTERMOD, PRIFRT, SECFRT
NORTHTOWN-HAVRE	E	DSTK, INTERMOD, PRIFRT, SECFRT
HAVRE-INTERBAY	W	DSTK, INTERMOD, PRIFRT, SECFRT
HAVRE-INTERBAY	E	DSTK, INTERMOD, PRIFRT, SECFRT
HAVRE-PORTLAND	W	INTERMOD, PRIFRT, SECFRT
HAVRE-PORTLAND	E	INTERMOD, PRIFRT, SECFRT
CICEROY-STCROIXT	W	REGNFRT, LOCALFRT
CICEROY-STCROIXT	E	REGNFRT, LOCALFRT
ST.CROT-WILLIST	W	REGNFRT, LOCALFRT
ST.CROT-WILLIST	E	REGNFRT, LOCALFRT
WILLISTON-HAVRE	W	REGNFRT, LOCALFRT, GRN54L, GRN108L
WILLISTON-HAVRE	E	REGNFRT, LOCALFRT, GRN80E, GRN115E
HAVRE-SPOKANE	W	REGNFRT, LOCALFRT, GRN54L, GRN108L
HAVRE-SPOKANE	E	REGNFRT, LOCALFRT, GRN80E, GRN115E
SPOKANE-SEATTLE	W	REGNFRT, LOCALFRT, GRAINLDS
SPOKANE-SEATTLE	E	REGNFRT, LOCALFRT, GRN80E, GRN115E
SPOKANE-PORTLAND-CH	W	REGNFRT, LOCALFRT, GRN54L, GRN108L
SPOKANE-PORTLAND-CH	E	REGNFRT, LOCALFRT, GRN80E, GRN115E
CASSELTON-NOLAN	W	GRN54L, GRN108L
CASSELTON-NOLAN	E	GRN80E, GRN115E
NOLAN-NEWROCKFOR	W	GRN54L, GRN108L
NOLAN-NEWROCKFOR	E	GRN80E, GRN115E
NEWROCKFOR-MINOT	W	GRN54L, GRN108L
NEWROCKFOR-MINOT	E	GRN80E, GRN115E
MINOT-WILLISTON	W	GRN54L, GRN108L
MINOT-WILLISTON	E	GRN80E, GRN115E
CASSELTON-SURLNJ	W	COALMTY
CASSELTON-SURLNJ	E	COALLOAD
DILWORT-CASSELTON	W	COALMTY
DILWORT-CASSELTON	E	COALLOAD
STAPLES-DILWORTH	W	COALMTY
STAPLES-DILWORTH	E	COALLOAD

Appendix D

The D1260 Schedule File

The D1260 file, known as *schedule.dat* in Wharton's directory, is the main file for generating all of the schedule files for the trains running over the corridor. Thus, one must first go through this file to ascertain whether or not a train travels over the corridor of interest and if so, then generate the schedule file for that train. Note that this step can be automated to a large extent, although some discrepancies such as no scheduled time at a reporting station, etc. can occur which require manual resolution. The following pages contain the description of the D1260 database from T.H. Krueger, April 1, 1987.

For Thomas H Krueger:OPER:BNRR

WHARTON – PG1

Created 1 – Apr – 87 15:56:36

Printed 1 – Apr – 87 15:56:33

1 Sheet(s), 1 Copy.

Xerox Print Service 10.0 on OPER – PS15

```
(  MMAND ===>                                                          SCROLL ===> P
                 PAGE 1 OF 6 PAGES OF SPECIFICATIONS :

 @1 TRNID $5. @6 THRULO $1. @7 CREDTE $6. @14 EFFDTE $6. @21 LOC1 Z5.
 @26 DIR1 $1. @27 ORGTYP 1. @28 DEPART1 $4. @32 NRUNT1 $4. @36 SRUNT1 $4.
 @40 REGCDE $1.
 @42 LOC2 Z5. @47 DIR2 $1. @48 STSTA2 $4. @52 NTSTA2 $4. @56 NRUNT2 $4.
 @60 SRUNT2 $4.
 @65 LOC3 Z5. @70 DIR3 $1. @71 STSTA3 $4. @75 NTSTA3 $4. @79 NRUNT3 $4.
 @83 SRUNT3 $4.
 @88 LOC4 Z5. @93 DIR4 $1. @94 STSTA4 $4. @98 NTSTA4 $4. @102 NRUNT4 $4.
 @106 SRUNT4 $4.
 @111 LOC5 Z5. @116 DIR5 $1. @117 STSTA5 $4. @121 NTSTA5 $4.
 @125 NRUNT5 $4. @129 SRUNT5 $4.
 @134 LOC6 Z5. @139 DIR6 $1. @140 STSTA6 $4. @144 NTSTA6 $4.
 @148 NRUNT6 $4. @152 SRUNT6 $4.
 @157 LOC7 Z5. @162 DIR7 $1. @163 STSTA7 $4. @167 NTSTA7 $4.
 @171 NRUNT7 $4. @175 SRUNT7 $4.
 @180 LOC8 Z5. @185 DIR8 $1. @186 STSTA8 $4. @190 NTSTA8 $4.
 @194 NRUNT8 $4. @198 SRUNT8 $4.
 @203 LOC9 Z5. @208 DIR9 $1. @209 STSTA9 $4. @213 NTSTA9 $4.
 @217 NRUNT9 $4. @221 SRUNT9 $4.
 @226 LOC10 Z5. @231 DIR10 $1. @232 STSTA10 $4. @236 NTSTA10 $4.
```

ABOVE STARTS INPUT FILE SPEC FOR DATA PASSED TO TAPE FROM D1260 TRAIN SCHEDULE DATA. TAPE WAS BLOCKED AT 1600 BPI AND CONTAINS ONLY TRAIN SCHEDULE DATA. APPROXIMATELY FIVE HUNDRED (500) RECORDS.

EXPLANATION OF VARIABLES AND FORMATS:

TRNID = Train Number, 5 bytes, $(dollar sign)indicates character forma

THRULO = Train Type, 1 byte, character.

CREDTE = Creation date, 6 bytes character (format yymmdd = 870101).

EFFDTE = Effective date, 6 bytes character (format yymmdd = 870101).

LOC1 = Origin station, 5 bytes numeric, zero filled.

(See bottom of page 2 for continuation of variable labels and formats).

```
@240 NRUNT10 $4. @244 SRUNT10 $4.
@249 LOC11 Z5. @254 DIR11 $1. @255 STSTA11 $4. @259 NTSTA11 $4.
@263 NRUNT11 $4. @267 SRUNT11 $4.
@272 LOC12 Z5. @277 DIR12 $1. @278 STSTA12 $4. @282 NTSTA12 $4.
@286 NRUNT12 $4. @290 SRUNT12 $4.
@295 LOC13 Z5. @300 DIR13 $1. @301 STSTA13 $4. @305 NTSTA13 $4.
@309 NRUNT13 $4. @313 SRUNT13 $4.
@318 LOC14 Z5. @323 DIR14 $1. @324 STSTA14 $4. @328 NTSTA14 $4.
@332 NRUNT14 $4. @336 SRUNT14 $4.
@341 LOC15 Z5. @346 DIR15 $1. @347 STSTA15 $4. @351 NTSTA15 $4.
@355 NRUNT15 $4. @359 SRUNT15 $4.
@364 LOC16 Z5. @369 DIR16 $1. @370 STSTA16 $4. @374 NTSTA16 $4.
@378 NRUNT16 $4. @382 SRUNT16 $4.
@387 LOC17 Z5. @392 DIR17 $1. @393 STSTA17 $4. @397 NTSTA17 $4.
@401 NRUNT17 $4. @405 SRUNT17 $4.
@410 LOC18 Z5. @415 DIR18 $1. @416 STSTA18 $4. @420 NTSTA18 $4.
@424 NRUNT18 $4. @428 SRUNT18 $4.
@433 LOC19 Z5. @438 DIR19 $1. @439 STSTA19 $4. @443 NTSTA19 $4.
@447 NRUNT19 $4. @451 SRUNT19 $4.
@456 LOC20 Z5. @461 DIR20 $1. @462 STSTA20 $4. @466 NTSTA20 $4.
@470 NRUNT20 $4. @474 SRUNT20 $4.
@479 LOC21 Z5. @484 DIR21 $1. @485 STSTA21 $4. @489 NTSTA21 $4.
```

CONTINUATION OF VARIABLE LABELS AND FORMATS

DIR1 = DEPARTS DIRECTION, 1 BYTE, CHARACTER.

ORGTYP = ORIGIN STATION TYPE, 1 BYTE NUMERIC (1=MINOR AREA 2=MAJOR ARE
3=TYE YARD).

DEPART1 = ORIGIN DEPARTURE, 4 BYTES CHARACTER, (HHMM FORMAT).

REGCDE = ORIGIN STATION REGION CODE, 1 BYTE CHARACTER.

NRUNT1 = NORMAL RUN TIME ORIGIN TO NEXT STATION, 4 BYTES CHARACTER,
(HHMM FORMAT = EXAMPLE 0244 = 2 HOURS 44 MINUTES).

SRUNT1 = SCHEDULED RUN TIME ORIGIN TO NEXT STATION FORMAT SAME AS NRU

(see bottom of page 3 for continuation).

```
COMMAND ===>
                PAGE 3 OF 6 PAGES:

   @493 NRUNT21 $4. @497 SRUNT21 $4.
   @502 LOC22 Z5. @507 DIR22 $1. @508 STSTA22 $4. @512 NTSTA22 $4.
   @516 NRUNT22 $4. @520 SRUNT22 $4.
   @525 LOC23 Z5. @530 DIR23 $1. @531 STSTA23 $4. @535 NTSTA23 $4.
   @539 NRUNT23 $4. @543 SRUNT23 $4.
   @548 LOC24 Z5. @553 DIR24 $1. @554 STSTA24 $4. @558 NTSTA24 $4.
   @562 NRUNT24 $4. @566 SRUNT24 $4.
   @571 LOC25 Z5. @576 DIR25 $1. @577 STSTA25 $4. @581 NTSTA25 $4.
   @585 NRUNT25 $4. @589 SRUNT25 $4.
   @594 LOC26 Z5. @599 DIR26 $1. @600 STSTA26 $4. @604 NTSTA26 $4.
   @608 NRUNT26 $4. @612 SRUNT26 $4.
   @617 LOC27 Z5. @622 DIR27 $1. @623 STSTA27 $4. @627 NTSTA27 $4.
   @631 NRUNT27 $4. @635 SRUNT27 $4.
   @640 LOC28 Z5. @645 DIR28 $1. @646 STSTA28 $4. @650 NTSTA28 $4.
   @654 NRUNT28 $4. @658 SRUNT28 $4.
   @663 LOC29 Z5. @668 DIR29 $1. @669 STSTA29 $4. @673 NTSTA29 $4.
   @677 NRUNT29 $4. @681 SRUNT29 $4.
   @686 LOC30 Z5. @691 DIR30 $1. @692 STSTA30 $4. @696 NTSTA30 $4.
   @700 NRUNT30 $4. @704 SRUNT30 $4.
   @709 LOC31 Z5. @714 DIR31 $1. @715 STSTA31 $4. @719 NTSTA31 $4.
   @723 NRUNT31 $4. @727 SRUNT31 $4.
   @732 LOC32 Z5. @737 DIR32 $1. @738 STSTA32 $4. @742 NTSTA32 $4.
```

CONTINUATION OF VARIABLE LABELS AND FORMATS FROM PAGE 2

LOC2 THRU LOC61 = INTERMEDIATE STATIONS, 5 BYTES NUMERIC, ZERO FILLED.
DIR2 THRU DIR61 = INTERMEDIATE DEPART DIRECTION, 1 BYTE CHARACTER.
STSTA2 THRU STSTA61 = INTERMEDIATE SCHEDULED TIME IN STATION, 4 BYTES CHARACTER, HHMM FORMAT.
NTSTA2 THRU NTSTA61 = INTERMEDIATE NORMAL TIME IN STATION, 4 BYTES CHARACTER, HHMM FORMAT (EXAMPLE 0113 = 1 HOUR 13 MINUTES).

LOC62 = DESTINATION STATION, 5 BYTES NUMERIC, ZERO FILLED.
DIR62 = ARRIVES DESTINATION DIRECTION, 1 BYTE CHARACTER.
DSTTYP = DESTINATION STATION TYPE, 1 BYTE NUMERIC (1=MINOR 2=MAJOR 3=TYE YARD).

END OF SPECIFICATIONS.

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      PAGE 4 OF 6 PAGES:

@746 NRUNT32 $4. @750 SRUNT32 $4.
@755 LOC33 Z5. @760 DIR33 $1. @761 STSTA33 $4. @765 NTSTA33 $4.
@769 NRUNT33 $4. @773 SRUNT33 $4.
@778 LOC34 Z5. @783 DIR34 $1. @784 STSTA34 $4. @788 NTSTA34 $4.
@792 NRUNT34 $4. @796 SRUNT34 $4.
@801 LOC35 Z5. @806 DIR35 $1. @807 STSTA35 $4. @811 NTSTA35 $4.
@815 NRUNT35 $4. @819 SRUNT35 $4.
@824 LOC36 Z5. @829 DIR36 $1. @830 STSTA36 $4. @834 NTSTA36 $4.
@838 NRUNT36 $4. @842 SRUNT36 $4.
@847 LOC37 Z5. @852 DIR37 $1. @853 STSTA37 $4. @857 NTSTA37 $4.
@861 NRUNT37 $4. @865 SRUNT37 $4.
@870 LOC38 Z5. @875 DIR38 $1. @876 STSTA38 $4. @880 NTSTA38 $4.
@884 NRUNT38 $4. @888 SRUNT38 $4.
@893 LOC39 Z5. @898 DIR39 $1. @899 STSTA39 $4. @903 NTSTA39 $4.
@907 NRUNT39 $4. @911 SRUNT39 $4.
@916 LOC40 Z5. @921 DIR40 $1. @922 STSTA40 $4. @926 NTSTA40 $4.
@930 NRUNT40 $4. @934 SRUNT40 $4.
@939 LOC41 Z5. @944 DIR41 $1. @945 STSTA41 $4. @949 NTSTA41 $4.
@953 NRUNT41 $4. @957 SRUNT41 $4.
@962 LOC42 Z5. @967 DIR42 $1. @968 STSTA42 $4. @972 NTSTA42 $4.
@976 NRUNT42 $4. @980 SRUNT42 $4.
@985 LOC43 Z5. @990 DIR43 $1. @991 STSTA43 $4. @995 NTSTA43 $4.
```

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PAGE 5 OF 6 PAGES:

```
@999 NRUNT43 $4. @1003 SRUNT43 $4.
@1008 LOC44 Z5. @1013 DIR44 $1. @1014 STSTA44 $4. @1018 NTSTA44 $4.
@1022 NRUNT44 $4. @1026 SRUNT44 $4.
@1031 LOC45 Z5. @1036 DIR45 $1. @1037 STSTA45 $4. @1041 NTSTA45 $4.
@1045 NRUNT45 $4. @1049 SRUNT45 $4.
@1054 LOC46 Z5. @1059 DIR46 $1. @1060 STSTA46 $4. @1064 NTSTA46 $4.
@1068 NRUNT46 $4. @1072 SRUNT46 $4.
@1077 LOC47 Z5. @1082 DIR47 $1. @1083 STSTA47 $4. @1087 NTSTA47 $4.
@1091 NRUNT47 $4. @1095 SRUNT47 $4.
@1100 LOC48 Z5. @1105 DIR48 $1. @1106 STSTA48 $4. @1110 NTSTA48 $4.
@1114 NRUNT48 $4. @1118 SRUNT48 $4.
@1123 LOC49 Z5. @1128 DIR49 $1. @1129 STSTA49 $4. @1133 NTSTA49 $4.
@1137 NRUNT49 $4. @1141 SRUNT49 $4.
@1146 LOC50 Z5. @1151 DIR50 $1. @1152 STSTA50 $4. @1156 NTSTA50 $4.
@1160 NRUNT50 $4. @1164 SRUNT50 $4.
@1169 LOC51 Z5. @1174 DIR51 $1. @1175 STSTA51 $4. @1179 NTSTA51 $4.
@1183 NRUNT51 $4. @1187 SRUNT51 $4.
@1192 LOC52 Z5. @1197 DIR52 $1. @1198 STSTA52 $4. @1202 NTSTA52 $4.
@1206 NRUNT52 $4. @1210 SRUNT52 $4.
@1215 LOC53 Z5. @1220 DIR53 $1. @1221 STSTA53 $4. @1225 NTSTA53 $4.
@1229 NRUNT53 $4. @1233 SRUNT53 $4.
@1238 LOC54 Z5. @1243 DIR54 $1. @1244 STSTA54 $4. @1248 NTSTA54 $4.
```

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)MMAND ===>                                                      SCROLL ===> P

        PAGE 6 OF 6 PAGES OF SPECIFICATIONS:

   @1252 NRUNT54 $4. @1256 SRUNT54 $4.
   @1261 LOC55 Z5. @1266 DIR55 $1. @1267 STSTA55 $4. @1271 NTSTA55 $4.
   @1275 NRUNT55 $4. @1279 SRUNT55 $4.
   @1284 LOC56 Z5. @1289 DIR56 $1. @1290 STSTA56 $4. @1294 NTSTA56 $4.
   @1298 NRUNT56 $4. @1302 SRUNT56 $4.
   @1307 LOC57 Z5. @1312 DIR57 $1. @1313 STSTA57 $4. @1317 NTSTA57 $4.
   @1321 NRUNT57 $4. @1325 SRUNT57 $4.
   @1330 LOC58 Z5. @1335 DIR58 $1. @1336 STSTA58 $4. @1340 NTSTA58 $4.
   @1344 NRUNT58 $4. @1348 SRUNT58 $4.
   @1353 LOC59 Z5. @1358 DIR59 $1. @1359 STSTA59 $4. @1363 NTSTA59 $4.
   @1367 NRUNT59 $4. @1371 SRUNT59 $4.
   @1376 LOC60 Z5. @1381 DIR60 $1. @1382 STSTA60 $4. @1386 NTSTA60 $4.
   @1390 NRUNT60 $4. @1394 SRUNT60 $4.
   @1399 LOC61 Z5. @1404 DIR61 $1. @1405 STSTA61 $4. @1409 NTSTA61 $4.
   @1413 NRUNT61 $4. @1417 SRUNT61 $4.
   @1422 LOC62 Z5. @1427 DIR62 $1. @1428 DSTTYP 1.
   ;
END;
```

Appendix E

BN Corridor Timetables

As stated in the discussion of the Track Data File, the timetables are vital in providing a check on the validity of data from the Operating Track Network File. However, the timetables are not computerized and thus, are very difficult to use in any type of automated system. If the timetables are provided in a computerized form in the near future, they may be very effective in checking the information in the Operating Track Network File. For completeness, the timetables used to construct the current Northern Corridor database are included.

WESTWARD Length of Siding in Feet	Station Numbers	Line Segment	Mile Post Location		1st Subdiv MAIN LINE STATIONS (Office Calls)	Rule 6(A)	Distance From Chicago EASTWARD
	00001		0.0		GB CHICAGO UN. STA. BKR — 0.8 —		0.0
			0.8	2MT	ROOSEVELT ROAD — 0.6 —	APB	0.8
	00002		1.4		UNION AVE. I — 0.3 —		1.4
			1.7	4MT	HALSTED STREET — 1.7 —		1.7
	00004		3.7		WESTERN AVE. — 3.5 —		3.4
	00007		7.0		HY CICERO BKRT — 1.6 —		6.9
	00008		8.5		CLYDE — 0.5 —		8.5
	00009		9.0		LA VERONE — 0.5 —		9.0
	00010		9.6		BERWYN — 0.5 —		9.5
			10.0		HARLEM AVENUE — 1.0 —		10.0
	00011		11.0		RIVERSIDE — 0.7 —		11.0
			11.7		HOLLYWOOD — 0.5 —		11.7
	00012		12.3		BROOKFIELD — 0.8 —		12.2
	00013		13.0		CONGRESS PARK — 0.7 —		13.0
	00014	71	13.7		LA GRANGE — 0.4 —		13.7
			14.1		STONE AVENUE — 1.3 —		14.1
	00015		15.4		WESTERN SPGS. — 0.9 —	CTC	15.4
	00016		16.3		HIGHLANDS — 0.5 —		16.3
	00017		16.8	3MT	HINSDALE — 0.9 —		16.8
			17.8		WEST HINSDALE — 0.5 —		17.7
	00018		18.2		CLARENDON HILLS — 1.2 —		18.2
	00019		19.4		WESTMONT — 0.9 —		19.4
	00020		20.3		FAIRVIEW AVE. — 0.8 —		20.3
	00021		21.1		DOWNERS GROVE — 1.5 —		21.1
	00023		22.6		BELMONT — 1.8 —		22.6
	00024		24.4		LISLE — 4.0 —		24.4
	00028		28.4		NAPERVILLE — 5.0 —		28.4
	00033		33.4		OA EOLA BKRT — 1.9 —		33.4
	00035		35.3		WEST EOLA — 2.4 —		35.3
	00037		38.1		RO AURORA BI To West Chicago— JKR 12.1		37.7

SCHEDULES FOR REGULAR SUBURBAN PASSENGER TRAINS ARE SHOWN IN BURLINGTON NORTHERN'S SUBURBAN SERVICE PASSENGER TIMETABLE OPERATING AS FIRST CLASS TRAINS, AND TIMES SHOWN THEREIN WILL INDICATE A REGULAR STOP. CONTINENTAL TIME WILL NOT BE AUTHORIZED IN SUBURBAN TIMETABLE. EMPLOYEES WHOSE DUTIES ARE IN ANY WAY AFFECTED BY SUBURBAN TRAINS MUST HAVE A COPY OF THE CURRENT SUBURBAN TIMETABLE IN THEIR POSSESSION WHILE ON DUTY.

BN Radio Channel No. 1 and No. 2 in service on this Subdivision.

See inside of back cover for routes, times and station stops for NRPC trains.

1. Speed Restrictions—

Zone—Between	Maximum Speeds Permitted Passenger	Freight
Chicago and Aurora	65 MPH.	50 MPH.
Aurora and West Chicago		20 MPH.
Loaded ore trains		35 MPH.
Except as indicated below:		

	Main 1 P	Main 1 F	Main 2 P	Main 2 F	Main 3 P	Main 3 F	Main 4 P	Main 4 F
MP 0.8 - MP 1.4	25	10	25	10				
MP 1.4 - MP 2.2							10	10
MP 1.4 - MP 1.7	35	15	35	15				
MP 1.7 - MP 2.1	45	15	45	15	35	15		
MP 2.2 - MP 6.3							40	35
MP 2.1 - MP 5.7	60	25	60	25	60	25		
MP 5.7 - MP 7.2	60	40	60	40	60	40		
MP 6.3 - MP 6.8							25	15
MP 7.2 - MP 9.6		40		40		40		
MP 9.6 - MP 21.6		45		45		45		
MP 21.6 - MP 35.1		50		50		50		
MP 35.1 - MP 37.5		35		35		35		
MP 36.5 - MP 37.0	45							
MP 37.1 - MP 37.3	50							
MP 37.3 - MP 38.0	35	25	35	25	35	25		
MP 38.0 - MP 38.1	50	25	50	25	50	25		

	Passenger	Freight
West Eola to Eola on running track MP 33.3 to MP 35.3	10 MPH.	10 MPH.
Union Avenue interlocking (MP 1.4) crossovers:		
Main 1 to 2 westward; Main 2 to 1 eastward, east of Union Avenue	25 MPH.	20 MPH.
Main 1 to 2 westward; Main 2 to 1 eastward, Union Avenue	25 MPH.	20 MPH.
Main 2 to 3 westward, and Main 3 to 2 eastward	12 MPH.	12 MPH.
Track No. 5 between Union Avenue and Amtrak connection and on north and south legs of south wye	10 MPH.	10 MPH.
Track No. 5 north wye Union Avenue	5 MPH.	5 MPH.
Kedzie Avenue MP 4.8 crossovers:		
Main 3 to 4 westward; Main 4 to 3 eastward	25 MPH.	25 MPH.
MP 6.3 - MP 8.9 crossovers:		
Main 1 to 2; Main 2 to 1; Main 2 to 3; Main 3 to 2	35 MPH.	35 MPH.
Main 3 to 4	25 MPH.	25 MPH.
MP 9.2 crossovers:		
Main 1 to 2 eastward; Main 2 to 1 westward; Main 2 to 3 eastward; Main 3 to 2 westward	30 MPH.	30 MPH.
Congress Park; Highlands; West Hinsdale; Fairview Avenue; Downers Grove; Lisle and Naperville: All crossovers	35 MPH.	35 MPH.
Eola and West Eola: All crossovers	30 MPH.	30 MPH.
Aurora interlocking crossovers	25 MPH.	25 MPH.
Loaded ore cars MP 35.1 - MP 37.5		25 MPH.

2. Bridge, Engine and Heavy Car Restrictions—

Maximum height of any on-rail equipment or shipments to be handled between Cicero yard and 16th and Canal Bridge, Chicago, must not exceed the following measurements from top of rail at the locations and on the tracks designated:

16th and Canal Bridge MP 1.4

Main 1 and 2 .... 16 feet, 6 inches high
South leg of south wye .... 19 feet, 6 inches high
North leg of south wye .... 17 feet, 4 inches high

CTA overcrossing MP 2.95

Main 1 ....19 feet 5 inches high
Main 2 ....18 feet 11 inches high
Main 3 ....20 feet 11 inches high
Main 4 ....20 feet 8 inches high

CTA overcrossing MP 4.6

Main 1 ....19 feet 6 inches high
Main 2 ....19 feet 1 inch high
Main 3 ....19 feet 3 inches high
Main 4 ....19 feet 3 inches high

[redacted]

MP 115.0 and MP 115.8	75 MPH.	50 MPH.
MP 116.8 and MP 117.2	70 MPH.	50 MPH.
MP 130.9 and MP 131.9	55 MPH.	50 MPH.
MP 80.4—Through crossovers between main tracks at east end of advance track	30 MPH.	30 MPH.
MP 82.1—Through crossover between Main 2 and advance track	30 MPH.	30 MPH.
Buda—Through crossovers between main tracks	35 MPH.	30 MPH.
MP 157.7 and MP 161.7 Main 3.....	45 MPH.	30 MPH.
MP 161.7 and MP 163.0 Main 3.....	10 MPH.	10 MPH.
MP 161.7 and MP 163.6 Main 1 westward, Main 2 eastward	30 MPH.	30 MPH.
MP 161.7 and MP 162.6 Main 1 eastward	10 MPH.	10 MPH.
MP 162.0 and MP 162.5 Main 2 westward	10 MPH.	10 MPH.
MP 163.6 and MP 164.0	75 MPH.	50 MPH.
MP 163.0 and MP 167.0 Quincy Main	59 MPH.	50 MPH.
MP 164.86 bridge between Waterman and West Waterman	10 MPH.	10 MPH.
Bishop—Through turnout Main 3 to Main 2	35 MPH.	30 MPH.
Galesburg Terminal—All tracks other than main tracks	Restricted Speed	
Waterman and Graham	35 MPH.	35 MPH.
Graham cut-off; eastward track between MP 165.2 and MP 164.7	10 MPH.	10 MPH.
Turnouts at following locations:		
MP 165.5 end of two main tracks	35 MPH.	35 MPH.
Graham	35 MPH.	35 MPH.
Bristol, Somonauk, Earlville, Zearing, Kewanee, Galva, Wataga: Through all crossovers between main tracks	35 MPH.	35 MPH.

2. **Bridge, Engine and Heavy Car Restrictions—**

Locomotives in Groups G, H and I not permitted on the following tracks:

Sandwich.........New Idea Plant
Foundry track—300 feet beyond clearance point

3. **Train Register Exceptions—None.**

4. **Clearance Provisions and Exceptions Rule 82(A)—**

Track bulletins are authorized this Subdivision.

Galesburg—Rule 405 applies.

5. **Rule 99—When flagging is required, distance will be 1.5 miles.**

6. **Kewanee—After stopping at Kewanee Passenger Station, east-ward passenger trains on either track must not exceed 5 MPH until locomotive or car occupies Tremont Street.**

7. **Galesburg—Hump Repeater Signals Galesburg Terminal in the following locations:**

MP 167.9—Between Quincy Main and the Hump Lead
MP 167.2—On overhead bridge between Waterman and West Waterman

Aspects displayed by these two signals will be identical to those displayed by the Hump Signal located at the Hump Crest. A green aspect will indicate hump fast, to allow trains to be brought up to humping position at normal yard speed. A yellow aspect will indicate hump slow, to advise hump engines to reduce to humping speed. A red aspect will be displayed to indicate hump stop, advising hump engines on the Hump Lead to stop, and communicate with the Yard-master via radio.

These special signal aspects govern humping operations only, and are not a part of automatic block, CTC, or interlocking systems. Verbal authority from Yardmaster or Engine Foreman will supersede the indication of these Repeater Signals.

8. **Galva—Trains and engines have crossing gates down at Chester Street, after passing Hwy. Circuit which is located approximately 900 ft. east of N.E. 6th Ave.**

9. **The following Track Side Warning Detectors protect bridges, tunnels or other structures—**

Montgomery—Eastward MP 43.9 main 1 and 2.

Other Track Side Warning Detector Locations—

MP 56.9—Main 1 and 2.
MP 87.3—Main 1 and 2.
MP 113.0—Main 1 and 2.
MP 142.6—Main 1 and 2.

WESTWARD ↓ — 3rd Subdiv MAIN LINE — EASTWARD ↑

Length of Siding in Feet	Station Numbers	Line Segment	Mile Post Location		Office Calls	STATIONS	Rule 6(A)		Distance From Aurora
4,016	00037	3	38.1		RO	AURORA	BIJKX	CTC	0.0
						6.8			
5,823	00045		44.7			SUGAR GROVE			6.8
						5.5			
7,196	00050		50.2			BIG ROCK			12.3
						4.8			
	00055		55.1			HINCKLEY			17.1
						3.2			
	00058		58.0			MORED			20.3
						3.9			
2,990	00062		62.1			WATERMAN			24.2
						5.0			
11,016	00067		67.1			SHABBONA			29.2
						10.2			
	00077		77.3			STEWARD			39.4
						5.9			
W4,485	00083		83.2	2MT	RC	ROCHELLE	ABKX		45.3
						3.1			
	00086		86.3			FLAG CENTER To Rockford 23.8	T		48.4
						6.0			
7,365	00092		92.4			CHANA			54.4
						6.0			
4,198	00098		98.4		ON	OREGON To Mt. Morris 6.8	BK		60.4
						8.5			
7,539	00107		107.4			STRATFORD			68.9
						8.4			
7,055	00114		116.0			CARTER			77.3
						6.7			
7,242	00122		122.5			MILLEDGEVILLE			84.0
						6.9			
7,293	00129		129.4			CHADWICK			90.9
						9.0			
7,158	00138		138.5			BURKE			99.9
						4.3			
			142.3			PLUM RIVER	JX		104.2
						0.9			
	00143		143.7	2MT DT	JO	SAVANNA	AX	ABS Rule 251	105.1

BN Radio Channel No. 1 and No. 2 in service on this Subdivision.

Train Dispatcher Calls—Hinckley (Victor)-32, Stratford (Polo)-30, Rochelle-3

1. **Speed Restrictions— Zone—Between** | **Maximum Speeds Permitt Freig**

Zone—Between	Freig
Loaded ore trains..	35 M
MP 38.44 and MP 40.0	40 M
MP 64.9 and MP 65.0	40 M
MP 77.3 and MP 77.8	40 M
MP 81.4 and MP 83.7	45 M
MP 83.7 and MP 83.9	45 M
MP 83.9 and MP 84.4	45 M
MP 95.8 and MP 102.3	45 M
Jct. switch, South River Street, Aurora	25 M
Industrial track from controlled siding Aurora........	10 M
MP 77.9: Through turnout two main tracks...........	35 M
Flag Center: Through turnout two main tracks.......	40 M
MP 142.3: Through crossovers (Plum River)	30 M

4th Subdiv MAIN LINE STATIONS

WESTWARD ↓ / EASTWARD ↑

Length of Siding in Feet	Station Numbers	Line Segment	Mile Post Location		Office Calls	Stations	Rule 6(A)		Distance From Savanna
	00143		143.7		JO	SAVANNA	AX		0.0
						10.1			
	00153	3	153.8	DT		PROVING GROUND	X	ABS Rule 251	10.1
						3.1			
	00156		156.9			ROBINSON SPUR	X		13.2
						14.6			
C5,670	00170		171.6	2MT		GALENA	X		27.8
						0.8		CTC	
	00171		172.3			PORTAGE	J		28.6
						12.5			

BETWEEN PORTAGE AND EAST DUBUQUE OPERATE ON CCP TRACKAGE.

4th Subdiv, Cont. MAIN LINE STATIONS

WESTWARD ↓ / EASTWARD ↑

Length of Siding in Feet	Station Numbers	Line Segment	Mile Post Location		Office Calls	Stations	Rule 6(A)		Distance From Savanna
			184.9		CB	EAST CABIN	JIKXY		41.1
						0.2			
C6,435	00184		185.0			EAST DUBUQUE	IXY		41.3
						28.0			
	00212		213.0			CASSVILLE	X		69.3
						9.8			
	00222		222.8			GLEN HAVEN	X	ABS Rule 251	79.1
				DT		5.6			
	00227		228.4			BAGLEY	X		84.7
						3.6			
	00231		232.0			WYALUSING			88.3
						3.6			
	00235		235.6			PORTS			91.9
						1.4			
	00236		237.0			CRAWFORD	M	CTC	93.3
				2MT		2.7			
E3,760 W5,380	00239		239.7		CD	PRAIRIE DU CHIEN	Y		96.0
						14.0			
	00254		254.4			LYNXVILLE	X		110.0
						8.5			
	00261		262.2			FERRYVILLE	X(2)		118.5
						7.7			
	00269		270.1	DT		DE SOTO	X	ABS Rule 251	126.2
						10.8			
	00280		280.7			GENOA	X		137.0
						13.8			
	00294		294.7			HERRINGTON			150.8
						1.6			
	00295		296.3	2MT		GRAF		CTC	152.4
						3.6			
			299.9			GRAND CROSSING	IY		156.0
						0.2			
	00299		300.2		CX	NORTH LA CROSSE	BJKRTY		156.2
						1.8			
				2MT				CTC	
	00301		303.1			SULLIVAN	Y	ABS Rule 251	158.0
		3		DT		15.7			
	00315		317.4			TREMPEALEAU	X		173.7
						7.0			
10,145	00324		325.7			EAST WINONA	J		180.7
						2.5		CTC	
	00326		328.2			WINONA JCT.			183.2
						7.0			
	00332		333.9			FOUNTAIN CITY	X		190.2
						7.9			
	00341		343.1	DT	RA	COCHRANE	X	ABS Rule 251	198.1
						8.2			
	00349		351.3			ALMA	X(2)		206.3
						8.7			
	00356		358.7			NELSON	X		215.0
						2.1			
	00360		362.1			TREVINO		CTC	217.1
				2MT		0.8			
	00361		362.9			MEARS			217.9
						3.2			
	00364		366.2			PEPIN	X		221.1
						12.6			
	00377		378.7			MAIDEN ROCK	X		233.7
						7.6			
	00384		386.3			BAY CITY	X(2)		241.3
				DT		4.7			
C5,821	00389		391.0			HAGER		ABS Rule 251	246.0
						6.6			
	00394		396.3			DIAMOND BLUFF	X		252.6
						10.0			
	00405		407.6			PRESCOTT			262.6
				2MT					
						0.2			
	00407		407.8			BURNS		CTC	262.8
				2MT		2.7			
	00409		410.5		OM	ST. CROIX TOWER	J		265.5

BN Radio Channel No. 1 and No. 2 in service on this Subdivision.

Train Dispatcher Calls—Savanna (Mt. Carroll)-41, Cassville (Balltown)-42, Prairie Du Chien (Pikes Peak)-43, Desoto (Lansing)-44, No. LaCrosse (Onalaska)-45, Nelson (Wabasha)-46, Bay City (Red Wing)-47.

1st Subdiv MAIN LINE

WESTWARD ↓ / EASTWARD ↑

Soo Line Mile Post Location	Station Numbers	Line Segment	Mile Post Location		Office Calls	STATIONS	Rule 6(A)		Distance From St. Croix
392.1	00409	3	410.5			ST. CROIX	JX		0.0
						11.9			
402.5	00420		422.2			NEWPORT	X(2)		11.9
						2.9			
405.0						DUNN			14.8
						1.6			
406.5	00424		426.7			OAKLAND	X(2)		16.4
						0.8			
407.4			427.5	2MT		ST. PAUL YARD			17.2
						0.5			
407.9	00426		428.3			DAYTONS BLUFF			17.7
						0.9			
408.8			429.1			HOFFMAN AVENUE	X(2)		18.6
						0.6			
409.4			429.7			DIVISION STREET	JX	CTC	19.2
						0.6			
			430.0						
	00429	25	0.0	2MT		7th STREET	JX		19.8
						1.5			
	51202		1.3			MISSISSIPPI ST.	X(2)		21.3
						0.6			
	51204		2.3			SOO LINE JCT.	JY		21.9
						4.4			
	51209		6.7	DT		UNION	XY	ABS	26.3
						1.5			
	51210		8.3			PARK JCT.	AXY		27.8
						1.5			
	51211		9.8			EAST MPLS	JTXY		29.3
						2.1			
			11.7	2MT		UNIVERSITY	JX(2)		31.4
						0.8			
	00439		12.5			38th AVE.	JX		32.2
						1.4			
	00441		13.9			NORTHTOWN	BJKRTX		33.6
						1.8			
	00442		15.5			INTERSTATE	X(2)	CTC	35.4
						5.7			
	00448		21.1	2MT	CN	COON CREEK	JX(2)		41.1
						5.7			

1st Subdiv, Cont. MAIN LINE

WESTWARD ↓ / EASTWARD ↑

Length of Siding in Feet	Station Numbers	Line Segment	Mile Post Location		Office Calls	STATIONS	Rule 6(A)		Distance From St. Croix
	00453	25	26.8			ANOKA	X		46.8
						11.8			
	00463		38.6	DT		ELK RIVER	X	TWC ABS	58.6
						8.4			
	00475		47.0			BIG LAKE			67.0
						10.5			
9,150	00482		57.5			BECKER		CTC	77.5
						5.2			
	00490		62.7	2MT		CLEAR LAKE			82.7
						11.3			
	00502		73.9			ST. CLOUD JCT.	JTX(2)Y		94.0
						4.4			
E7,207	00506		78.4			SARTELL	XY		98.4
						9.9			
	00516		88.7	DT		RICE	X	TWC ABS	108.3
						6.6			
	00523		95.2			ROYALTON	X		114.9
						8.1			
	00531		103.3			GREGORY			123.0
						2.8			
10,725	00533		106.0			LITTLE FALLS	T		125.8
						4.4			
11,618	00538		110.8			DARLING			130.2
						5.8			
11,813	00544		116.5			RANDALL		CTC	136.0
						11.0			
11,878	00555		127.8			LINCOLN			147.0
						6.2			
	00561		134.0			PHILBROOK			153.2
						6.3			
			140.0	2MT					
	00567		148.0		SO	STAPLES	BJKR TX(2)Y		159.5
						11.0			
	00578		159.0			VERNDALE	X		170.5
						6.7			
E6,870	00585		165.6			WADENA	X		177.2
						12.9			
	00598		178.5			NEW YORK MILLS	X		190.1
						10.8			
	00608		189.3			PERHAM	X		200.9
						11.1			
	00619		200.4			FRAZEE	X		212.0
						9.7			
W6,135	00629		210.1			DETROIT LAKES	AX		221.7
						3.0			
	00632		213.1	DT		RICHARDS SPUR	X		224.7
						9.7			
	00642		222.8			LAKE PARK	X	TWC ABS	234.4
						7.9			
	00650		230.5			MANITOBA JCT.	TX		242.3
						3.7			
	00653		234.4			HAWLEY	X		246.0
						7.3			
	00661		242.4			WITHEROW	X		253.3
						7.3			
	00668		248.8			GLYNDON	JX		260.6
						5.3			
		26	0.0						
	00673		3.2		DH	DILWORTH	BKRTX(2)Y		265.9

BN Radio Channel No. 1 in service for road crews.
BN Radio Channel No. 2 in service for St. Cloud and Daytons Bluff area.
BN Radio Channel No. 3 in service for Minneapolis area.
BN Radio Channel No. 4 in service for Northtown area.

Train Dispatcher Calls—Elk River-26, St. Cloud-27, Staples-28, Perham-29, Hawley-30.

See inside of back cover for routes, times and station stops for NRPC trains.

1. Speed Restrictions— Zone—Between	Maximum Speeds Permitte Passenger	Freigh:
St. Croix and Dilworth................	75 MPH.	
St. Croix and Coon Creek—Loaded unit trains exceeding 100 tons O/B		35 MPH
MP 410.2—MP 410.5—Between East and West St. Croix..................	25 MPH.	25 MPH

[redacted]

WESTWARD Length of Siding in Feet	Station Numbers	Line Segment	Mile Post Location	Track	Office Calls	1st Subdiv MAIN LINE STATIONS	Rule 6(A)	Method of Operation	Distance From Dilworth EASTWARD
	00673	26	3.2	DT	DH	DILWORTH	BIKRTX(2)Y	TWC ABS	0.0
						2.4			
	00675		5.6			MOORHEAD JCT	LJX(2)Y		2.4
						3.0			
	00679		8.6			FARGO	JX(2)Y		5.4
						4.3			
	00683		12.9			WEST FARGO	LJX(2)Y		9.7
						3.0			
W4,290	00686		15.9			FIFE	Y		12.7
						4.3			
	00690		20.2			MAPLETON			17.0
						7.6			
	00698		28.4			CASSELTON	JX(2)Y		24.6
				2MT		3.2		CTC	
			31.2			SURREY JCT. SWITCH	JX		27.8
				DT		7.8		TWC ABS	
			38.8			MAGNOLIA			35.6
						5.0			
	03279		43.8			BUFFALO			40.6
						5.9			
	03285		49.7			TOWER CITY			46.5
						2.7			
6,239	03288		52.4			KOLDOK			49.2
						7.9			
6,794	03296		60.4			PEAK			57.1
						5.2			
	03301		65.5			VALLEY CITY			62.3
						4.4			
S6,330 N6,371	03306		70.0			BEREA	Y		66.7
						6.1			
7,940	03312		76.1			SANBORN	JT		72.8
						5.3			
6,470	03317		81.4			ECKELSON			78.1
						7.7			
6,302	03325		89.1			SPIRITWOOD	Y		85.8
						5.6			
	03331		94.7			BLOOM	Y		91.4
						6.0			
			99.2	DT					
		38	92.2						
	03336		93.7		JY	JAMESTOWN	BJKRTX(2)Y		97.4
						6.0			
	03342		99.7			ELDRIDGE	Y		103.4
						9.3			
7,243	03352		109.0			WINDSOR			112.8
						3.8			
3,635	03356		112.8			CLEVELAND			116.6
						8.7			
7,336	03364		121.5			MEDINA			125.3
						12.9			
11,585	03377		134.5			LADOGA			138.2
						8.7			
6,235	03386		143.2			DAWSON			146.9
						7.8			
7,396	03394		151.0			STEELE			154.7
						10.7			
8,451	03404		161.9			DRISCOLL			165.4
						7.8			
6,197	03412		169.6			STERLING			173.2
						6.6			
4,531	03419		176.2			McKENZIE	JT		179.8
						5.5			
6,313	03424		181.6			BURLEIGH			185.3
						7.8			
6,571	03432		189.5			PIERCE			193.1
						5.0			
7,932	03437		194.5			BISMARCK	AY		198.1

BN Radio Channel No. 1 in service on this Subdivision.

BN Radio Channel No. 2 in service between MP 0.0 and MP 16.4.

Train Dispatcher Calls—Magnolia-35, Peak-36, Spiritwood-37, Jamestown-38, Cleveland-39, Tappen-40, Sterling-41, Pierce-42.

Between MP 0.0 and Dilworth MP 3.2, employees are under the jurisdiction of Dakota Division superintendent.

See inside of back cover for routes, times and station stops for NRPC trains.

1. Speed Restrictions—

Zone—Between	Maximum Speeds Permitted
Against the current of traffic on double track	49 MPH.
Freight trains over 100 Tons/OB between MP 9.1 and MP 38.8—Westward main track	40 MPH.
MP 3.0 and MP 9.1, both tracks	35 MPH.
MP 27.0 and MP 28.0, both tracks	40 MPH.
MP 64.4 and MP 65.4, Valley City bridge	45 MPH.
MP 97.6 east of Jamestown and MP 96.0 west of Jamestown, both tracks	30 MPH.
Moorhead—All trains and yard engines stopping on main track between Fourth Street and Fourteenth Street crossing from point where stop is made until engine passes either Fourth Street or Fourteenth Street to permit proper operation of crossing signal and gates	10 MPH.
Valley City Shoe Fly MP 67.3 to MP 67.5	5 MPH.
Jamestown—Over spring switch on westward track at west end of yard	30 MPH.
Soo crossing MP 192.4	35 MPH.
Bismarck—Over street crossings, 3rd to 26th Streets, including engine or leading end of all trains	35 MPH.
Through No. 20 turnouts at following locations:	35 MPH.

West Fargo ......Connecting track switch, MP 12.8.
West Fargo .... Controlled crossover, MP 13.0.
Between Casselton and Surrey Jct. Switch through turnouts located 1575 feet west of MP 28.0 and 335 feet west of MP 31.0

Casselton—Through No. 20 turnout (Third Subdiv.)	30 MPH.
Through No. 20 turnouts at following locations	35 MPH.

Magnolia ... Through turnout end of double track.
Koldok .... East and west siding switches.
Peak .... East siding switch.
Eckelson .... West siding switch.
Bloom .... Through turnout end double track.
Eldridge ....Through turnout end double track.
Windsor .... East and west siding switches.
Medina .... East and west siding switches.
Ladoga .... East siding switch.
Steele .... East and west siding switches.
Driscoll .... East and west siding switches.
Sterling .... East siding switch.
Burleigh .... West siding switch.
Pierce .... East and west siding switches.

Head end speed restrictions for west bound freight trains:	Up to 100 tons/OB	Over 100 tons/OB
Signal 26.5 between Mapleton and Casselton	50 MPH.	
Signal 190.7 between Pierce and Bismarck	55 MPH.	
Head end speed restrictions for eastbound freight trains:		
Signal 17.6 between Mapleton and Fife	55 MPH.	
Eastward Home Signal on Eastward track at MP 28.1 between Surrey Jct. Switch and Casselton	55 MPH.	

If the designated signal displays a green aspect, the freight train may resume normal speed after head end passes signal.

Item 1A. All Subdivisions, applies on both tracks between MP 0.0 and MP 16.0, between MP 93.0 and MP 96.0 and between MP 97.0 and MP 99.0, east of Jamestown.

2. Bridge, Engine and Heavy Car Restrictions—

Valley City—Locomotives in Groups G, H and I must not use freight lead.

Berea—International Multifoods and Peavey tracks locomotives in Groups G, H and I must not be used in multiple.

Jamestown—Locomotives in Groups G, H and I must not use yard tracks 7 through 14 or the wye.

Spiritwood—At Ladish Malt Plant, locomotives not permitted on scale or inside building at east end of trackage.

3. Train Register Exceptions—

1st Subdiv MAIN LINE

WESTWARD ↓ / EASTWARD ↑

Length of Siding in Feet	Station Numbers	Line Segment	Mile Post Location	Office Calls	STATIONS	Rule 6(A)		Distance From Williston
	01036		121.1	WT	WILLISTON CST	BKRT		
20,215				WT	WILLISTON			0.0
					12.0			
15,021	01049		133.2		TRENTON			12.0
					13.9			
12,267	01063		147.2		SNOWDEN	JT		25.9
					12.0			
8,552	01075		159.2		BAINVILLE	J		37.9
					14.3			
8,437	01089		173.5	CU	CULBERTSON			52.2
					5.5			
8,430	01095		179.1		BLAIR			57.7
					13.7			
12,990	01108		192.8		BROCKTON			71.4
					14.0			
8,422	01122		206.8		POPLAR			85.4
					15.4			
8,424	01138		222.1		MACON			100.8
					5.8			
14,025	01144		227.3	WO	WOLF POINT			106.6
					11.3			
8,422	01155		239.2		OSWEGO			117.9
					12.4			
8,495	01167	35	251.8		KINTYRE			130.3
					11.4			
8,431	01179		263.2		NASHUA			141.7
					14.5			
11,700	01192		277.5	GS	GLASGOW	BKR	CTC	156.2
					11.8			
8,431	01205		289.4		TAMPICO			168.0
					14.1			
13,183	01219		303.5		HINSDALE			182.1
					12.7			
10,169	01232		316.2		SACO			194.8
					13.7			
8,000	01245		330.7		BOWDOIN			208.5
					13.3			
8,418	01259		343.3	MF	MALTA			221.8
					9.6			
10,389	01268		352.8		WAGNER			231.4
					7.9			
7,264	01276		360.7		DODSON			239.3
					15.3			
8,456	01291		376.0		SAVOY			254.6
					11.8			
7,463	01303		387.8	HM	HARLEM			266.4
					11.8			
10,302	01315		399.6		ZURICH			278.2
					9.3			
7,525	01324		405.8	CK	CHINOOK			287.5
					8.1			
10,109	01332		416.7		LOHMAN			295.6
					13.6			
	01345		430.4	HA	HAVRE	BKRTX(2)		309.2

BN Radio Channel No. 1 in service on this Subdivision.

Dispatcher Radio call-in code 81 or 82 in service on this Subdivision.

See inside of back cover for routes, times and station stops for NRPC trains.

1. **Speed Restrictions—**

Zone—Between	Maximum Speeds Permitted Passenger	Freight
Williston and Havre	79 MPH.	

The following head end restrictions are in effect:	Over 100 Tons/OB
Head end of westward trains:	
Signal 430.1	30 MPH.
Signal 431.0	30 MPH.
Signal 431.82	30 MPH.
Signal 433.1	40 MPH.
Head end of Eastward Trains	
Signal 433.4	40 MPH.

Trains or engines through No. 20 turnouts at following locations: .... 35 MPH.

Trenton	Macon	Glasgow	Malta
Snowden	Wolf Point	Tampico	Dodson
Bainville	Oswego	Hinsdale	Harlem
Brockton	Kintyre	Saco	Lohman
Poplar	Nashua	Bowdoin	

West siding switch at Williston.
West siding switch at Blair.
East siding switch at Savoy and Culbertson.

Trains leaving sidings on a proceed signal indication may increase speed to 35 MPH. after engine has passed signal at the following locations:

Harlem	Bowdoin	Hinsdale	Kintyre
Dodson	Saco	Nashua	Oswego

Wolf Point (Westward trains or engines at west signal only)
Brockton
Blair (Westward trains or engines at west signal only)

2. **Bridge, Engine and Heavy Car Restrictions—**None.

3. **Train Register Exceptions—**

Glasgow—NRPC trains need not register.
Williston—Through freight trains need not register.

4. **Clearance Provisions and Exceptions, Rule 82(A)—**

Dakota Division clearance and train orders will govern between Williston and Bainville.

Dakota Division clearance received at Havre will apply at Bainville.

Montana Division freight trains which do not change crews at Williston and passenger carrying trains will obtain their Montana Division clearance at Soo Tower which will apply at Bainville.

Dakota Division clearance received at Soo Tower will clear the train at Williston.

Incoming engineers and conductors on passenger crews at Williston must deliver all train orders, clearances and messages personally to relieving engineers and conductors.

Montana Division freight trains originating at Williston will obtain their Montana Division clearance at Williston which will apply at Bainville.

Unless otherwise provided all trains arriving at Glasgow must deliver all clearances, train orders and messages to relieving conductor, engineer or both.

Glasgow—If a connecting crew is not rested, conductor and engineer will turn their clearances, orders and messages over to an operator who will be on call under these conditions. These orders will then be delivered by the operator to the outgoing train and engine crew when called.

5. **Rule 99—**When flagging is required, flagging distance is 2.0 miles.

6. **Test Mile Locations—**

Trenton— MP 139.4 and 140.4
Nashua— MP 259.0 and 260.0
Glasgow— MP 269.6 and 270.6
Glasgow— MP 283.1 and 284.1
Chinook— MP 411.6 and 412.6

7. **Rule 350(B)—**

Following switches are not equipped with electric locks:

Lakeside
Culbertson—Safflower Spur
Sproie
Bowdoin

8. Account electronic scales, do not exceed 5 MPH over scales on industry track at Macon and Oswego.

9. **Havre**—Westward trains must not pass signals at Havre East MP 427.4 and eastward trains must not pass signals at Havre West MP 432.0 without permission of Havre Yardmaster.

10. **Track Bulletins**—Authorized on this subdivision.

11. **The Following Track Side Warning Detectors Protect Bridges, Tunnels or Other Structures—**

Culbertson—	MP 175.5	Hinsdale—	MP 307.5
Blair—	MP 182.1	Saco—	MP 313.2
Poplar—	MP 203.7	Malta—	MP 340.9
Poplar—	MP 210.8	Malta—	MP 346.1
Glasgow—	MP 282.2		

Other Track Side Warning Detector Locations—

Trenton—	MP 142.8	Vandalia—	MP 293.0
Culbertson—	MP 166.1	Saco—	MP 323.0
Sprole—	MP 202.5	Malta—	MP 347.0
Wolf Point—	MP 234.2	Dodson—	MP 364.0
Kintyre—	MP 248.0	Harlem—	MP 383.5
Nashua—	MP 269.0	Chinook—	MP 404.0

WESTWARD ↓ — 2nd Subdiv MAIN LINE — EASTWARD ↑

Length of Siding in Feet	Station Numbers	Line Segment	Mile Post Location		Office Calls	STATIONS	Rule 6(A)		Distance From Havre
	01345	35	430.4	2MT	HA	HAVRE	BKRTX(2)		0.0
						4.0			
			434.0						
	01350		964.0			PACIFIC JCT.			4.0
						5.7			
8,431	01356		970.9			BURNHAM			9.7
						9.6			
8,574	01365		980.1			KREMLIN			19.3
						10.1			
8,577	01375		990.7			GILDFORD			29.4
						5.9			
	01381		996.8			HINGHAM			35.3
						6.0			
8,579	01387		1002.7		RU	RUDYARD			41.3
						6.2			
	01394		1009.0			INVERNESS			47.5
						3.8			
	01397		1012.8			JOPLIN			51.3
						3.0			
7,221	01400		1015.8			BUELOW			54.3
						7.1			
8,552	01407		1022.9		CH	CHESTER			61.4
						13.1			
8,585	01420		1035.6			LOTHAIR			74.5
						12.0			
8,556	01432		1047.6			DEVON			86.5
						8.6			
9,062	01441		1056.3			DUNKIRK			95.1
						9.5			
	01451		1065.4		SL	SHELBY	BJKRTX		104.6
						2.7			
			1068.4	2MT		TETON	X(2)		107.3
						10.3			
	01464		1078.7			ETHRIDGE			117.6
						11.2			
	01475		1090.1		CT	CUT BANK	BKRX		128.8
						16.4			
	01491	36	1106.5	2MT		PIEGAN	X(2)	CTC	145.2
						9.7			
	01501		1116.2			BLACKFOOT	T		154.9
						7.3			
12,183	01508		1123.9		SG	BROWNING			162.2
						7.9			
	01517		1131.8			SPOTTED ROBE			170.1
				2MT		4.3			
			1136.1			GRIZZLEY			174.4
						2.0			
4,631	01522		1138.1		MD	GLACIER PARK			176.4
						5.3			
9,536	01525		1144.0			BISON			181.7
						6.3			
	01534		1149.8			SUMMIT			188.0
						2.4			
			1152.2			MARIAS	TX(2)		190.4
						4.6			
	01540		1157.6	2MT		BLACKTAIL	X		195.0
						7.3			
	01548		1165.2			JAVA EAST			202.3
						0.9			
			1166.1			JAVA WEST			203.2
						4.1			
	01552		1170.2	2MT		ESSEX	TX(2)		207.3
						3.0			
	01558		1173.2			PINNACLE			210.3
						4.3			
			1177.6			PAOLA			214.6
						7.5			
	01568		1185.2	2MT		RED EAGLE	TX		222.1
						2.9			
			1188.0			NYACK			225.0
						7.7			
10,232	01578		1196.1		BE	BELTON			232.7
						7.9			
11,157	01586		1204.9			CORAM			240.6
						4.4			
	01590		1208.3			CONKELLEY			245.0

BN Radio Channel No. 1 in service on this Subdivision.
Dispatcher Radio call-in code 91 or 92 in service on this Subdivision.
See inside of back cover for routes, times and station stops for NRPC trains

St. Regis—MP 193.2 Heron—MP 76.6
Kootenai—MP 111.8

8. **Track Bulletins**—Authorized on this subdivision.

9. **TWC**—In effect between CTC Frenchtown and MP 218.0.

10. Train location lineup will be issued by the train dispatcher in accordance with Rule 35 of the Rules of the MW for track occupancy not protected by track warrant authority.

– HAVRE - INTERBAY (SEATTLE) SUMMARIES
BEGIN AT LINE 16382, FOR TRAIN 1
– 16699, FOR TRAIN 2
317
– 17650 - TRAIN 1, WESTB.
[illegible]
17731 - TRAINS 4-4 SUMMARY [illegible] BEGINS WESTB.
19733 - SANDPOINT - [illegible]
20056 - SPOKANE - [illegible]
21559 - INTERBAY
EASTBOUND
TRAINS 1-4
22961 - INTERBAY
24429 - SPOKANE

WESTWARD Length of Siding in Feet	Station Numbers	Line Segment	Mile Post Location		6th Subdiv MAIN LINE STATIONS (Office Calls / Rule 6(A))		Distance From Conkelley EASTWARD
	01590		1208.3		CONKELLEY		0.0
					2.9		
W4,015	01593		1211.6	DT	CF COLUMBIA FALLS TX(2)Y To Kalispell 14.4	ABS Rule 251	2.9
					7.6		
	01601		1219.2		WF WHITEFISH BKRTX(2)Y		10.5
					5.4		
7,060	01607		1224.6		VISTA		15.9
					6.4		
9,329	01613		1231.1		LUPFER		22.3
					11.2		
9,711	01624		1243.3		RADNOR		33.5
					7.1		
	01631		1249.3		STRYKER JT		40.6
					3.4		
9,722	01636		1252.8		BRIMSTONE		44.0
					10.7		
9,763	01646		1263.5		TWIN MEADOWS		54.7
					9.6		
9,760	01656		1273.2		ROCK CREEK		64.3
					9.0		
9,730	01665		1282.2		WOLF PRAIRIE		73.3
					7.9		
10,344	01672		1290.0		TAMARACK		81.2
					7.9		
9,769	01683		1298.0		FISHER RIVER		89.1
					8.9		
10,799	01692	36	1306.9		RIVERVIEW		98.0
					7.0		
9,568	01710		1312.2		RIPLEY		105.0
					7.2		
10,510	01718		1319.6		CK LIBBY BK		112.2
					11.0		
8,641	01729		1331.3		KOOTENAI FALLS		123.2
					7.2		
14,286	01736		1337.9		UX TROY BRT		130.4
14,286	01736		1337.9		UX TROY BRT		130.4
					6.7		
6,982	01742		1343.3		YAKT		137.1
					6.6		
9,552	01749		1350.3		LEONIA	CTC	143.9
					13.5		
8,394	01763		1364.3		CROSSPORT		157.4
					4.3		
9,742	01767		1368.4		BONNERS FERRY		161.7
					11.4		
9,577	01778		1379.8		NAPLES		173.1
					7.4		
9,912	01786		1387.4		ELMIRA		180.5
					6.7		
7,439	01793		1394.1		COLBURN		187.2
					7.2		
10,363	01803		1401.3		BOYER JM		194.4
					2.0		
			1403.3		SANDPOINT JCT.		
	01798		2.9		To Kootenai 1.5 J		196.4
					0.1		
	01803		3.0		SA SANDPOINT BR		196.5
					7.2		
	01810		10.1	2MT	ALGOMA		203.7
					6.7		
10,828	01817		17.6		COCOLALLA		210.4
					12.6		
13,247	01830		31.5		ATHOL		223.0
					7.3		
10,600	01837		37.7		RAMSEY		230.3
					5.7		
9,156	01843	45	45.5		RATHDRUM		236.0
					1.4		
	01845		47.0		HAUSER		237.4
					5.6		
	01850		51.5		HAUSER JCT. J		243.0
					5.8		
10,095	01855		57.9		OTIS ORCHARDS		248.8
					5.9		
	01861		63.3		IRVIN		254.7
				2MT	3.3		
	01865		66.6		PARKWATER XY		258.0
					1.5		
	01866		68.1		YARDLEY BKRTXY		259.5
					1.6		
			69.7	DT	CG UP TOWER LJXY	ABS Rule 251	261.1
					1.9		
			71.5				
	01870	46	0.0		SF SPOKANE BKRXY		263.0
					1.0		
	01877		1.1		SUNSET JCT. JX(2)		264.0
					0.8		
	01878	37	1481.6		LATAH JCT.	CTC	264.8

WESTWARD ↑ | EASTWARD ↓

Length of Siding in Feet	Station Numbers	Line Segment	Mile Post Location		1st Subdiv MAIN LINE STATIONS (Office Calls / Rule 6(A))		Distance from Latah Jct.
	01878	37	1481.6		LATAN JCT. J		0.0
					7.8		
7,442	01883		1489.8		LYONS	CTC	7.8
					9.5		
6,930	01893		1499.3		ESPANOLA		17.3
					12.2		
7,532	01905		1510.8		EDWALL		29.5
					9.1		
	01914		1520.2		BLUESTEM		38.6
					7.5		
	01922		1527.7	DT	HARRINGTON X	ABS Rule 251	46.1
					15.1		
	01937		1542.9		LAMONA		61.2
					10.2		
9,232	01947		1553.2		ODESSA		71.4
					12.5		
9,552	01959		1565.6		GIBSON		83.9
					10.4		
8,794	01970		1577.0		WILSON CREEK		94.3
					13.1		
10,794	01983		1588.8		ADRIAN		107.4
					10.0		
	01993		1599.3		EPHRATA	CTC	117.4
					5.1		
10,360	01998		1603.4		NAYLOR		122.5
					11.2		
10,536	02009		1615.5		QUINCY		133.7
					10.8		
7,856	02020		1628.3		TRINIDAD		144.5
					9.3		
8,154	02030		1635.0		COLUMBIA RIVER		153.8
					5.6		
	02035		1640.1		ROCK ISLAND		159.4
					3.3		
5,000	02038		1643.3		MALAGA		162.7
					6.9		
	02044		1650.2		WC WENATCHEE BJKRY	ABS	169.6

BN Radio Channel No. 1 in service on this Subdivision.

Train Dispatcher Calls—Edwall-20, Harrington-21, Odessa-24, Wilson Creek-25, Ephrata-26, Wenatchee East-27

See inside of back cover for routes, times and station stops for NRPC trains.

1. **Speed Restrictions—**

Zone—Between	Maximum Speeds Permitted Passenger	Freight
Latah Jct. and Wenatchee	79 MPH.	
Lamona and Bluestem against current of traffic	49 MPH.	40 MPH.
Latah Jct., turnout to Portland Fifth Subdivision............................	35 MPH.	35 MPH.
Trains or engines through turnouts and on sidings at following locations: Edwall, Odessa, Gibson, Wilson Creek, Adrian, Columbia River, Malaga, Espanola; End of double track Lamona and Bluestem. Wenatchee #1 crossover MP 1646.7	35 MPH.	35 MPH.
Trains or engines through turnouts and on sidings at following locations: Lyons, Naylor, Quincy, Trinidad........	30 MPH.	30 MPH.
Wenatchee—MP 1652.7 and MP 1650 on W.O. main yard track	Up to 100 Tons O/B	25 MPH. Over 100 Tons O/B
Wenatchee and Appleyard Engines of eastward freight trains passing signal 1649.4................		30 MPH.
Engines of westward freight trains passing signal: 1601.1	55 MPH.	50 MPH.
Trinidad Absolute Signal 46W MP 1627.0....................................		40 MPH.
Trinidad and Columbia River: 1629.9....................................		40 MPH.
1631.7....................................		45 MPH.
Malaga Absolute Signal 42W at MP 1643.7....................................		45 MPH.
Appleyard Absolute Signal 41W at MP 1646.7....................................	40 MPH.	30 MPH.

2. **Bridge, Engine and Heavy Car Restrictions**—None.

3. **Train Register Exceptions**—None.

4. **Clearance Provisions and Exceptions Rule 82(A)**—

   Track warrant received at Spokane or Yardley applies at Latah Jct.

   Westward trains departing Spokane or Yardley enroute Lamona, and Eastward trains departing Wenatchee enroute Lamona, will secure a second track warrant which applies at Lamona.

5. **Rule 99**—When flagging is required, distance will be 2.5 miles, except between Bluestem and Lamona when operating against the current of traffic the distance will be 1.5 miles.

6. **Between Lamona and Bluestem**—

   Territory between Spokane (Latah Jct.) and Lamona is under jurisdiction of Boyer West train dispatcher, Seattle.

   Territory between Lamona and Wenatchee is under the jurisdiction of Seattle East train dispatcher, Seattle.

   Between Bluestem and Lamona, trains may proceed without train order or numbered clearance authority over either track in either direction when an aspect to proceed is displayed by signal governing movement at either Bluestem or Lamona. Crossover movements must not be made unless authorized by the train dispatcher.

   Between Bluestem and Lamona, train location lineups will not be issued to maintenance forces. Main track permission must be secured from Boyer West train dispatcher, Seattle, before maintenance forces or on-track equipment may occupy either main track within these limits. Main track permission will be obtained in the following form:

   "(Name of employee in charge of M/W track car or on-track equipment) may use (track or tracks) between _____ and _____ (or at _____) _____M until _____M"

   When requesting main track permission, give your name, location or hi-rail vehicle number if applicable and specify track or tracks to be used. When main track permission is granted, the instructions must be repeated to the train dispatcher, who will make a record of it in Track and Time book, along with name of person repeating the instructions. Before issuing main track permission, Boyer West train dispatcher must communicate with the Seattle East train dispatcher and insure there are no conflicting train or engine movements within the limits to be granted and ascertain that the Seattle East train dispatcher has blocked controlling signal governing eastward movements on the track or tracks affected at Lamona at STOP. Boyer West train dispatcher will then block controlling signal governing westward movements on the track or tracks affected at Bluestem at STOP.

   When main track permission has been granted, the train dispatcher must not authorize train or engine movements into the same territory until the employee granted main track permission has reported clear.

   Maintenance forces or on-track equipment must be clear of the track or work completed and switches restored to normal position before expiration of the time specified, and the train dispatcher so advised. If additional time is required, authority must be secured from train dispatcher before the previously authorized time expires.

7. **Ephrata**—On industry track, stop and verify that crossing signals are working properly at Division Street and Southeast Boulevard before proceeding over crossings.

8. **Crossovers on Double Track not otherwise shown—**
Trailing Point—
MP 1534.8 Mohler
MP 1536.7 Downs

9. **Wenatchee**—Engine whistle must not be sounded except to prevent an accident not otherwise avoidable.

10. **Handling 80-Feet or Longer Cars—**
Between Quincy and Wenatchee—
Trains of greater than 5700 trailing tons must handle empty cars, 80 feet and longer, in the rear 5700 tons.
Trains of greater than 8800 trailing tons must handle loaded cars, 80 feet and longer, in the rear 8800 tons except 80 feet and longer cars in excess of 100 gross tons will have no restriction on location in train.

11. **Westward freight trains will not use in excess of a fourth throttle setting west of Sunset Jct. until all units are on the Latah Creek bridge, observing posted speed restrictions.**

12. **Track Bulletins**—Authorized on this Subdivision.

13. **The following Track Side Warning Detectors protect bridges, tunnels or other structures—**

Trinidad— MP 1622.3	Trinidad— MP 1625.6
Trinidad— MP 1623.9	Voltage— MP 1638.1

Other Track Side Warning Detector Locations—

Fairchild— MP 1495.9	Stratford— MP 1580.2
Bluestem— MP 1524.6	Naylor— MP 1607.9
Odessa— MP 1555.8	Columbia River— MP 1633.6

WESTWARD

2nd Subdiv MAIN LINE STATIONS

Length of Siding in Feet	Station Numbers	Line Segment	Mile Post Location		Office Calls	Stations	Rule 6(A)		Distance From Wenatchee
	02044		1650.2		WC	WENATCHEE	BKRTY	ABS	0.0
						2.7			
			1652.9		OL	OLDS JCT.	JY		2.7
						8.3			
6,049	02056		1661.2		OM	CASHMERE			11.0
						11.0			
7,905	02067		1672.2		CH	LEAVENWORTH			22.0
						13.5			
10,978	02081		1686.9		WI	WINTON			35.5
						6.6			
6,729	02087		1692.4		CK	MERRITT	T		42.1
						7.0			
12,323	02094		1698.5		BR	BERNE			49.1
						9.0			
			1708.5						
9,259	02103		1719.5		SN	SCENIC			58.1
						12.8			
8,949	02116		1732.3		KY	SKYKOMISH	T		70.9
						7.6			
10,099	02124	37	1739.5		BA	BARING			78.5
						14.5			
10,244	02139		1755.7		GB	GOLD BAR			93.0
						12.9			
11,988	02152		1768.6		RO	MONROE			105.9
						6.6			
	02159		1775.2		SE	SNOHOMISH JCT. EAST	JT		112.5
						1.0			
	02159		1776.2		SH	SNOHOMISH JCT. WEST	JT	CTC	113.5
						5.0			
	02164		1781.2		W	LOWELL			118.5
						1.5			
12,517	02165		1782.7		PJ	PA JCT.	J		120.0
						0.5			
			1783.2		PA	PACIFIC AVE.			120.5
						0.9			
	02166		1783.9		JN	EVERETT			121.4
						0.8			
			1784.7						
	02169		32.1		EJ	EVERETT JCT.	JX		122.2
						3.8			
	02172		28.3	2MT	MU	MUKILTEO	X		126.0
						0.5			
			27.8			MP 28			126.5
						1.7			
			27.1			MP 27			128.2
				2MT		8.4			
			17.8			MP 18			136.6
						0.2			
	02182		17.6		DR	EDMONDS			136.8
						1.7			
		50	15.9			MP 16			138.5
				2MT		8.2			
			7.9			MP 8.0	Y		146.7
						0.8			
			7.1			MP 7	Y		147.3
						0.7			
	02193		6.4	2MT	BD	BALLARD	IY		148.0
						0.2			
			6.2		DB	DRAWBRIDGE 4	IY		148.2
						1.1			
			5.1		RD	23rd STREET	IY	APB	149.3
						0.3			
	02195		4.9		RB	INTERBAY (Balmer Yard)	BIKRTY		149.6
						1.1			
			3.3		GS	GARFIELD STREET	IY		150.7
						2.1			
			1.4	2MT	J	NORTH PORTAL	IXY		152.8
						1.4			
	02200		0.0		CF	SEATTLE (King St. Station)	BIKRTX(2)Y		154.2

EASTWARD

BN Radio Channel No. 1 in service on this Subdivision.
Train Dispatcher Calls—Wenatchee-28, Cashmere-29, Merritt-30, Cascade Tunnel-57, Skykomish-31, Monroe-32, Everett-34, Mukilteo-35, Richmond Beach-36

See inside of back cover for routes, times and station stops for NRPC trains.

Appendix F

TPS Train Mapping

In order to run SCAN, one must associate with each train I.D. a TPS train type in order to compute the travel times for this train. This mapping from train I.D. to TPS type is currently not automated. In what follows, the mapping provided by G. Trafton which was used in the development of the current database is listed.

ALL TIP TRAINS FROM D-260 FILE

WE NEED MAPPING TO TPS TYPES.

all_trains.ids 06/29/87 11:07:41 Page 1

1	AT126	L870330	870330	L
2	AT127	T870330	870330	
3	AT260	L870304	870304	L
4	AT261	T870310	870310	
5	AT262	L870130	870130	L
6	AT263	T870202	870202	
7	AT290	L870312	870312	L
8	AT291	T870312	870312	
9	BB006	L870130	870130	L
10	BB007	T870202	870202	
11	BB018	L860911	860911	L
12	BB019	T870312	870312	
13	BT414	P870130	870130	L
14	BT415	U870202	870202	
15	BU138	L870312	870312	L
16	BU139	T870312	870312	
17	CC006	L870318	870318	L
18	CC007	T870318	870318	
19	CC018	L860822	860822	L
20	CC019	T870320	870320	
21	CC060	L860818	860818	L
22	CC061	T870202	870202	
23	CC090	L860818	860818	L
24	CC091	T870320	870320	
25	CC126	L860902	860902	L
26	CC127	T860902	860902	
27	CC180	I870130	870130	L
28	CC181	I870202	870202	
29	DDE00	L870320	870320	L
30	DDE01	T870320	870320	
31	DDP00	L870320	870320	L
32	DDP01	T870320	870320	
33	DD036	L870316	870316	L
34	DD037	T870316	870316	
35	DD042	L870316	870316	L
36	DD043	T870316	870316	
37	DD072	L870316	870316	L
38	DD073	T870316	870316	
39	DD126	L870217	870217	L
40	DD127	T870217	870217	
41	DD142	L870316	870316	L
42	DD143	T870316	870316	
43	DD226	L870217	870217	L
44	DD227	T870328	870328	
45	DP278	L870312	870312	L
46	DP279	T870320	870320	
47	DWM	A851011	851012	
48	FC000	L870202	870202	L
49	FC001	T851010	851010	
50	GA1	X861211	861211	
51	GA2	X870202	870202	
52	GA3	X861211	861211	
53	GA5	X870202	870202	
54	GB1	X861211	861211	
55	GB2	X861211	861211	
56	GB3	X861211	861211	
57	GB5	X870206	870206	

L = LOADED COAL TRAIN = COALLOAD
Blank = EMPTY COAL TRAIN = COALMTY

USE "GRN108L" unless route is Spokane - Seattle, in which case use 'GRAINLDS'.

2

58	GC1	X861211	861211
59	GC2	X870206	870206
60	GC3	X861211	861211
61	GC5	X870206	870206
62	GC8	X870317	870317
63	GC9	X861104	861104
64	GD1	X870127	870127
65	GD2	X870206	870206
66	GD3	X861211	861211
67	GD5	X870206	870206
68	GD6	X870206	870206
69	GE1	X870206	870206
70	GE3	X861211	861211
71	GE8	X870206	870206
72	GF1	X870206	870206
73	GF3	X861211	861211
74	GG1	X870313	870313
75	GG2	X870313	870313
76	GG3	X870313	870313
77	GG5	X870313	870313
78	GM1	X861211	861211
79	GM2	X861211	861211
80	GM3	X861211	861211
81	GM5	X861211	861211
82	GO1	X870206	870206
83	GO2	X870206	870206
84	GO3	X870206	870206
85	GO5	X870206	870206
86	GR1	X870123	870123
87	GR2	X870123	870123
88	GR3	X870123	870123
89	GR5	X870206	870206
90	GS0	X870206	870206
91	GS2	X861211	861211
92	GS3	X861211	861211
93	GS5	X861211	861211
94	G0S	Y870206	870206
95	G1A	Y870206	870206
96	G1B	Y870206	870206
97	G1C	Y870206	870206
98	G1D	Y870206	870206
99	G1E	Y870206	870206
100	G1F	Y870206	870206
101	G1G	Y870313	870313
102	G1M	Y861212	861212
103	G1O	Y870211	870211
104	G1R	Y861212	861212
105	G2A	Y870211	870211
106	G2B	Y870211	870211
107	G2C	Y870211	870211
108	G2D	Y870211	870211
109	G2G	Y870313	870313
110	G2M	Y861212	861212
111	G2O	Y870211	870211
112	G2R	Y861212	861212
113	G2S	Y861212	861212
114	G3A	Y861212	861212

USE "GRN108L" unless route is Spokane - Seattle, in which case use "GRAINLDS".

USE "GRN115E"

3

115	G3B	Y861212	861212	
116	G3C	Y870211	870211	
117	G3D	Y861212	861212	
118	G3E	Y870211	870211	
119	G3F	Y861212	861212	
120	G3G	Y870313	870313	
121	G3M	Y861212	861212	
122	G3O	Y870211	870211	
123	G3R	Y861212	861212	
124	G3S	Y870211	870211	
125	G5A	Y870211	870211	
126	G5B	Y870211	870211	
127	G5C	Y870211	870211	
128	G5D	Y870211	870211	
129	G5G	Y870313	870313	
130	G5M	Y861212	861212	
131	G5O	Y870211	870211	
132	G5R	Y870211	870211	
133	G5S	Y870211	870211	
134	G6D	Y870211	870211	
135	G9D	Y861212	861212	
136	HT400	P870320	870320	L
137	HT401	U870320	870320	
138	LL018	L870217	870217	L
139	LL019	T870217	870217	
140	M60	S860523	860601	L
141	M61	W860523	860601	
142	NA018	L870217	870217	L
143	NA019	T870226	870226	
144	NCS00	L870320	870320	L
145	NCS01	T870320	870320	
146	NC000	L870320	870320	L
147	NC001	T870320	870320	
148	NN126	L870217	870217	L
149	NN127	T870320	870320	
150	NN226	L870313	870313	L
151	NN227	L870313	870313	
152	NN280	L870217	870217	L
153	NN281	T870320	870320	
154	NN326	L870313	870313	L
155	NN327	T870313	870313	
156	NT400	P870320	870320	L
157	NT401	U870326	870326	
158	OG300	S870320	870320	L
159	OG301	W870320	870320	
160	PPE00	L870320	870320	L
161	PPE01	T870320	870320	
162	PPP00	L870320	870320	L
163	PPP01	T870320	870320	
164	PP036	L870316	870316	L
165	PP037	T870316	870316	
166	PP042	L870316	870316	L
167	PP043	T870316	870316	
168	PP072	L870316	870316	L
169	PP073	T870316	870316	
170	PP142	L870313	870313	L
171	PP143	T870313	870313	

USE "GRN115E"

L = LOADED COAL TRAIN = COALLOAD
Blank = EMPTY COAL TRAIN = COALMTY

```
172 QQ018 L870313 870313 L
173 QQ019 T870313 870313
174 RC006 L870318 870318 L
175 RC007 T870318 870318
176 RC018 L870217 870217 L
177 RC019 T870226 870226
178 RC126 L870330 870330 L
179 RC127 T870330 870330
180 RC260 L870226 870226 L
181 RC261 T870320 870320
182 RC262 L861226 861226 L
183 RC263 T870320 870320
184 RC290 L870316 870316 L
185 RC291 T870316 870316
186 RC292 L870316 870316 L
187 RC293 T870316 870316
188 RN400 P870320 870320 L
189 RN401 U870320 870320
190 TT018 L870217 870217 L
191 TT019 T870226 870226
192 TT126 L870330 870330 L
193 TT127 T870330 870330
194 UP101 V850112 850112
195 UP200 Q870320 870320
196 UP202 Q860307 860307
197 UP204 Q870320 870320
198 UP206 Q860730 860730
199 UP208 Q850112 850112
200 UP210 Q860729 860729
201 UP300 Q870320 870320
202 UP301 V870320 870320
203 UP302 Q870320 870320
204 UP304 Q870320 870320
205 UP306 Q870320 870320
206 UP308 Q870320 870320
207 UP310 Q850913 850913
208 UP312 Q870320 870320
209 VV018 L870217 870217 L
210 VV019 T870226 870226
211 WW006 L870318 870318 L
212 WW007 T870318 870318
213 WW018 L860822 860822 L
214 WW019 T870226 870226
215 WW060 L860818 860818 L
216 WW061 T860818 860818
217 WW090 L870316 870316 L
218 WW091 T870316 870316
219 WW126 L860902 860902 L
220 WW127 T860902 860902
221 X01   I870226 870226
222 X02   I870108 870108
223 X03   I870226 870226
224 X04   I870108 870108
225 X05   I870217 870217
226 X06   I870217 870217
227 X11   I870226 870226
228 X12   I861007 861007
```

L = LOADED COAL TRAIN = COALLOAD
Blank: EMPTY COAL TRAIN = COALMTY

Delete

L = LOADED COAL TRAIN = COALLOAD
Blank: EMPTY COAL TRAIN = COALMTY

REGNFRT

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229	X13	I870226	870226	
230	X14	I870226	870226	
231	X17	I870320	870320	
232	X18	I870320	870320	
233	X26	I870227	870227	
234	X27	I870227	870227	
235	X30	I860729	860729	
236	X31	I870227	870227	
237	X32	I860625	860625	
238	X33	I861007	861007	
239	X34	I870227	870227	
240	X35	I870227	870227	
241	X50	I861104	861104	
242	X51	I861104	861104	
243	X58	I861010	861010	
244	X59	I870227	870227	
245	X75	I860625	860625	
246	X76	I870227	870227	
247	X77	I860911	860911	
248	X78	I870227	870227	
249	YYE00	L870320	870320	L
250	YYE01	T870227	870227	
251	YYP00	L870320	870320	L
252	YYP01	T870320	870320	
253	YY036	L870316	870316	L
254	YY037	T870316	870316	
255	YY042	L870316	870316	L
256	YY043	T870316	870316	
257	YY072	L870316	870316	L
258	YY073	T870316	870317	
259	YY126	L870227	870227	L
260	YY127	T870217	870217	
261	YY142	L870316	870316	L
262	YY143	T870326	870326	
263	YY226	L870217	870217	L
264	YY227	T870328	870328	
265	ZC000	L861118	861118	L
266	ZC001	T861118	861118	
267	ZJC00	L861030	861030	L
268	ZJC01	T870227	870227	
269	ZMP00	L870313	870313	L
270	ZMP01	T870313	870313	
271	ZNP00	L870313	870313	L
272	ZNP01	T870313	870313	
273	ZN000	L870313	870313	L
274	ZN001	T870313	870313	
275	ZS000	L850112	850112	L
276	ZS001	T870320	870320	
277	ZW000	L860729	860729	L
278	ZW001	T860729	860729	
279	001	O861006	861006	
280	002	O861013	861013	
281	003	O870227	870227	
282	004	O870119	870119	
283	007	O870227	870227	
284	008	O870227	870227	
285	009	O870227	870227	

REGNFRT

L = Loaded Coal train = COALLOAD

Blank = Empty Coal train = COALMTY

INTERMODAL

DSTK

6

286	010	O870227	870227	DSTK
287	012	O870325	870325	
288	013	O861013	861013	
289	014	O870213	870213	INTERM
290	015	O870313	870313	
291	019	J870209	870209	PRIFRT
292	021	O870217	870217	
293	022	O870227	870227	
294	024	O870227	870227	INTERM
295	033	O870226	870226	
296	034	O870323	870323	
297	040	M870227	870227	
298	041	M870227	870227	
299	042	M870227	870227	
300	043	M870227	870227	
301	044	M870318	870318	EXPEDITE
302	045	M870318	870318	
303	048	M870227	870227	
304	049	M870306	870306	
305	050	M870331	870331	
306	051	M870325	870329	
307	053	J870122	870122	
308	054	J870203	870203	PRIFRT
309	055	O870227	870227	
310	056	O870213	870213	EXPEDITE
311	057	M870112	870112	
312	060	J870227	870227	
313	062	J870205	870205	
314	063	O861104	861104	
315	065	J861104	861104	INTERMODAL
316	091	O870218	870218	
317	092	O870227	870227	
318	095	M870313	870313	EXPEDITE
319	096	M870313	870313	
320	100	A870113	870113	PRIFRT
321	1005	C861104	861104	
322	1006	C861104	861104	
323	1007	C861013	861013	AMTRAK
324	1008	C861014	861026	
325	101	A870204	870204	PRIFRT
326	1011	C850403	850428	
327	1014	C850403	850428	
328	1027	C860416	860427	AMTRAK
329	1028	C861013	861013	
330	103	A870220	870220	
331	104	A870306	870306	
332	106	A870227	870227	
333	107	A870121	870121	
334	108	A870313	870313	
335	111	A870219	870219	
336	112	A861028	861028	PRIFRT
337	119	A870203	870203	
338	120	A870227	870227	
339	121	A870217	870217	
340	1346	C850814	850815	
341	1347	C850814	850815	AMTRAK
342	1348	C850814	850815	

7

343	143	A870320	870320	
344	144	A870320	870320	
345	151	A870313	870313	
346	160	A870320	870320	PRI FRT
347	161	A870213	870213	
348	162	A870325	870325	
349	1795	C861014	861026	
350	1796	C850403	850428	
351	1797	C850403	850428	AMTRAK
352	1798	C861014	861026	
353	195	A870213	870213	PRI FRT
354	196	A870213	870213	
355	203	Z870108	870108	
356	204	Z870227	870227	
357	206	Z861006	861006	
358	208	Z870209	870209	
359	209	Z870106	870106	
360	211	Z861226	861226	
361	212	Z860730	860730	
362	218	Z860930	860930	
363	228	Z861016	861016	SEC FRT
364	231	Z870217	870217	
365	232	Z870210	870210	
366	241	Z870320	870320	
367	242	Z870320	870320	
368	284	Z870106	870106	
369	402	Z861028	861028	
370	403	Z870106	870106	
371	600	Z860524	860601	
372	601	Z860524	860601	
373	602	Z870106	870106	
374	603	Z870106	870106	
375	627	Z860624	860624	
376	631	Z870227	870227	
377	632	Z870219	870219	
378	633	Z870219	870219	
379	634	Z870219	870219	
380	663	Z870227	870227	REGN FRT
381	664	Z870227	870227	
382	666	Z870227	870227	
383	671	Z860307	860307	
384	672	Z860307	860307	
385	681	Z870227	870227	
386	682	Z861126	861126	
387	691	Z870227	870227	
388	692	Z861126	861126	
389	693	Z861126	861126	
390	694	Z851205	851205	
391	699	Z860524	860601	
392	807	Z870313	870313	
393	809	Z860522	860522	
394	810	Z860522	860522	
395	835	Z860310	860310	
396	836	Z870309	870309	
397	837	Z860212	860212	
398	838	Z860624	860624	
399	883	Z870210	870210	

(8)

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400 884   Z870113 870113
401 897   Z860730 860730
402 898   Z860730 860730
403 900   I850112 850112
404 901   I860815 860815
405 906   I850112 850112
406 907   I850112 850112
407 908   I860524 860601
408 909   I860524 860601
409 910   I870227 870227
410 911   I870227 870227
411 912   I860623 860623
412 913   I860623 860623
413 914   I860730 860730
414 915   I860729 860729
415 916   I860730 860730
416 917   I860730 860730
417 918   I860717 860717
418 919   I860524 860601
419 924   I860729 860729
420 925   I860729 860729
421 926   I850112 850112
422 927   I850112 850112
423 928   I860911 860911
424 929   I870302 870302
425 936   I850112 850112
426 937   I850112 850112
427 938   I850905 850905
428 939   I870302 870302
429 952   I850112 850112
430 953   I850911 850911
431 954   I870320 870320
432 955   I870320 870320
433 956   I870302 870302
434 957   I850112 850112
435 976   I860524 860601
436 979   I860524 860601
437 980   I860524 860601
438 982   I870302 870302
439 983   I870302 870302
440 986   I850112 850112
441 988   I850112 850112
442 990   I860729 860729
443 991   I860623 860623
444 992   I860623 860623
445 993   I850905 850905
446 994   I850905 850905
447 995   I850112 850112
448 996   I850112 850112
END OF FILE
```

REGNFRT

Appendix G

Time Zone Calculations for Northern Corridor

In order to create a uniform interpretation of the schedules, each station on the railroad must be located vis a vis its time zone. Below is the pseudo-code which is used to generate the time-zone information for each reporting station used in SCAN:

```
IF 1736   <  station number  <  16166
   THEN   time_zone = pacific
   ELSE IF 1036   <  station number  <  1735
      THEN   time_zone = mountain
      ELSE IF 30136  <  station number  <  34007
         THEN   time_zone = mountain
         ELSE   time_zone = central
```

The Use of ATCS in Scheduling and Operating Railroads: Models, Algorithms and Applications

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Harker

Abstract

This paper present an overview of a series of models and algorithms which have been developed for use with ATCS technology on railroads to improve the reliability and costs in operations. After describing the conceptual framework a hiriarchy of control models, examples are used to illustrate the use of the various models at each level of this hierarchy.

MAY '89

5/10 7/629417

AD

1 Introduction

The railroad industry in the United States is currently undergoing a major restructuring in terms of both its technology and management practices. Prior to the deregulation of the industry in 1980 through the Stagger's and Motor Carrier Acts, railroads were dominated by their operating departments; i.e., they were focused mainly on cost reductions at the expense of good marketing techniques (see Keeler (7) for a comprehensive review of the state of the rail industry prior to deregulation). Such a situation of low cost-low quality (as measured by reliability of arrivals, loss and damage of freight, etc.) was very profitable when the U.S. economy was dominated by bulk commodity production. However, the movement toward the production of high-valued goods and the implementation of more efficient (e.g., just-in-time) inventory policies created a demand for highly reliable and flexible freight transportation services. As a result, railroads today are reinvesting in technology and restructuring their management practices in order to respond to the market's demand for better transport service.

Recent technological developments in advanced train control systems (ATCS) and high-speed computers have provided railroads with a unique opportunity to automate many functions in rail operations and thus, to restructure their management systems. The Burlington Northern (BN) Railroad is precisely in this situation. The BN is one of the largest railroads in the United States with approximately 25,000 miles of track covering the north-western and central portions of the country. The BN is considered to be a very "progressive" railroad by most in the industry due to its development of many innovative technologies and management practices. For example, the BN has the highest revenue per employee at corporate headquarters (9), indeed making it a "lean and mean" operation.

The BN, however, has the same data problem facing all major railroads. Of the 25,000 miles of track, one-third is "dark territory" in the sense that whenever a train enters this portion of the rail network, the dispatcher knows its position only through voice communication with the train crew. In addition, signal blocks on a railroad like the BN can be long (30 miles) and when a train enters such a block, all other trains are prohibited from using this portion of track. Obviously, such a system does not make maximum use of the available track capacity. Furthermore, congestion at yards (terminals) which is caused by too many trains arriving within a short time period is a direct result of poor planning of traffic throughout the rail network and leads to sometimes dramatic under-utilization of yard capacity.

In order to overcome the difficulties mentioned above, the BN, in conjunction with Rockwell International, is in the process of developing the *A*dvanced *R*ailroad *E*lectronics *S*ystem (ARES). As described by Welty (14), ARES uses the NAVSTAR Global Positioning System which is being developed by the U.S. Air Force to provide locational information (plus or minus 50 feet) for each train or maintenance of way vehicle on the system at any point in time (750-2,500 trains). In addition to this location information, ARES includes the EMS locomotive system which provides automated procedures for train handling and energy conservation and the ROCS dispatching system which uses the location information from each train to help the dispatchers do a better job of operating the rail lines. Of course, any fully-implemented ATCS system will provide a similar wealth of information.

Thus, an ATCS like ARES provides a wealth of data heretofore not available to railroad management. However, this "wealth" can be more like a "flood" if the proper models and associated algorithms are not available to use this information effectively. The purpose of this paper is to provide an overview of an on-going research project at the University of Pennsylvania which is attempting to develop such models and algorithms. The next section will give an overview of the series of problems being studied, and Sections 3 and 4 will provide details on two of these models. Section 5 will give a summary of the progress to date as well as an overview of future research.

2 The Chase for Models

In order effectively utilize the information generated by an ATCS, a series of models and computational procedures are necessary:

Schedule Policy Evaluation

⇕

Tactical Scheduling of Trains

⇕

Real-Time Scheduling

-trains

-locomotives

-crews

-cars

⇕

Computer-Aided Dispatching

⇕

Optimal Train Control

In what follows, we will briefly discuss each level of this model hierarchy.

The first question one must ask when implementing an ATCS is whether or not a railroad should run scheduled operations. At first glance, this seems to be a rather odd question, particularly if one is accustomed to European or Japanese railroads. However, substantial cost savings can be achieved if one runs a "tonnage" operation; i.e., trains depart from a yard when sufficient traffic has accumulated. Of course, reliability as measured by the variance of travel time will suffer under such a system as compared with a scheduled operation. In either case, the question of which policy to follow in the scheduling of trains should be made at the long-term planning level by incorporating the tradeoffs of crew and equipment costs, service quality, and the ability to effectively route empty cars and locomotives. The ability to address this long-term question requires the development of detailed simulation and analytical models which incorporate a total view of rail operations, not simply a model which focuses on the movements of loaded trains between two points.

Once an overall schedule policy has been decided, one must implement this policy on a weekly or monthly basis. This *tactical* scheduling of trains differs from the above *strategic* question in that all trains at the tactical level will have schedules. Thus, for those trains which must be scheduled (passenger, intermodal, etc.), the tactical scheduling procedure will create a set of feasible schedules; i.e., a set of schedules which are logically consistent in the sense that an operating plan exists which can achieve the times stated in the schedules with high probability given the delays encountered by each train as a result of random occurences (wind, breakdowns, etc.) and interference with other trains. For trains which run on a tonnage basis, scheduled *slots* would exist. That is, trains would not be permitted to depart at random but rather, must depart within a stated time window if they are to be operated on a given day. Thus, a tactical scheduling system must also have the capability to create such slots and check that they are feasible when considered alone and when combined with the other scheduled traffic.

Given the tactical schedules, the purpose of the real-time models is to develop operating plans which will achieve the stated schedules as best as possible given that events have occured (breakdowns, crew shortages, etc.) which disrupt the plan of operations on which the tactical schedules are based. For trains, one wishes to develop a plan of arrival and departure times at each major yard or, more generally, at each point where the planning of the train operations changes (i.e., a boundary of the dispatchers' territories). For crews, locomotives and cars, one attempts to plan their movements in order to guarantee that sufficient resources are available at each yard in order to achieve the tactical schedule plan.

After defining the arrival and departure times of the trains at the boundaries of the dispatchers' territories (i.e., a planning line), the computer-aided dispatching system attempts to schedule the meets and passes along a rail line along with planned arrival and departure times at intermediate points (sidings, beginnings and ends of double track, etc.) in order to assure compliance with the times passed from the train scheduling model. Several approaches have been proposed for this function (12), but all tend to ignore the fact that significant fuel savings can be achieved by *pacing* trains; i.e., have the trains travel at less than maximum velocity in order to save fuel. In addition, the planning of meets and passes along with a planned pacing of trains will tend to increase the probability of arriving at the destination on-time since one is able to speed-up if disturbances do occur; planning at maximum velocity does not provide this flexibility.

Finally, the dispatching system provides each train with a specific goal in terms of the time and velocity at which it should reach each point on its path. The engineer and the on-board computer system must then calculate a velocity profile (a combination of throttle and dynamic/air brake settings) which will achieve this goal in a safe and fuel efficient manner. Again, the train must solve a pacing problem which is now much more complex due to the nature of train forces and handling techniques.

The above discussion has described the flow of information down the model hierarchy. Of course, the reverse flow is also very important. The train must constantly inform the dispatching model of its location and performance, the dispatching system must inform the network control model of the status of planning lines, and the performance of the network control system (the interline planner) must be monitored in order to assess the long-term viability of various schedule policies.

At present, the research program underway at the University of Pennsylvania is attempting to address all of the issues described above. In what follows, two topics will be discussed: the computer-aided dispatching system and interline planning model, and a new decision-support system for tactical scheduling. Due to length requirements, all of the details of these models cannot be discussed in this paper. However, reference is made to the relevant technical reports which are available from the author.

3 Tactical Schedule Validation and Creation

Given the overall policy concerning the frequency of train departures, the tactical scheduling problem is to create schedules for all trains which are logically consistent in the sense that there exist operating plans which can achieve these schedules with high reliability. As described by Assad (1), many simulation and optimization models exist for the analysis of rail operations. However, no model exists which can answer the simple question: is a given set of schedules feasible under the best operating conditions in the sense that there exists a plan of operation which can achieve the scheduled times? If not, what are minimal changes one can make to the schedules in order to make them feasible? If they are feasible under the best circumstances, what is the reliability of achieving these scheduled times when adverse conditions exist? Note that one could develop a large-scale optimization model which would attempt to find optimal schedules given well-defined cost or profit criteria (see, for example, Crainic *et al.* (3)). However, the definition of such an objective function is extremely difficult given the tradeoffs of marketing concerns, costs, crew and equipment utilization, etc. Thus, the approach taken in the *S*chedule *An*alysis (SCAN) system (6) is to provide a decision-support tool which answers the logical questions of whether or not schedules are feasible, and leaves the marketing/cost-tradeoffs to the analyst. As designed, SCAN is meant to support weekly or bi-monthly updates to the stated schedules.

SCAN is an interactive decision-support system which contains three modules: a database system for the updating of track and train data as well as train schedules, an algorithm for checking whether or not a given set of schedules is feasible, and a Monte-Carlo simulation technique for the calculation of the reliability of a given set of schedules. The feasibility algorithm takes as input the train schedules, track topology, and the free (unobstructed) meetpoint-to-meetpoint running times for each train which are calculated by one of many train performance simulators (TEM,TPS, etc.). Given this data, the feasibility algorithm searches for a meet-pass plan which can achieve this given set of schedules. If no plan can be found, the schedules are labeled infeasible and the algorithm presents the plan which would require the minimal change to the schedules in order to become feasible. The details of this integer-programming-based algorithm can be found in (6). If the analyst desires help in changing the schedules to achieve feasibility, SCAN contains a set of heuristics to attain this goal. However, the analyst is encouraged to make these changes manually due to the complex tradeoffs mentioned previously.

[Insert Figure 1]

Once the schedules have been modified so that they are feasible in the best case, the analyst may wish to know how often feasibility would be maintained under more adverse conditions (adverse weather conditions, breakdowns, etc.). SCAN answers this question through a simulation technique in which probability distributions of the free-running times for the trains are used as input to a Monte-Carlo model. The result of this simulation is the percentage of time one can expect adherence to the schedules under variable operating conditions.

In order to illustrate the working of the SCAN system, consider the example given in Figure 1; this picture shows the track topology on the vertical axis, the time of day on the horizontal axis, and the schedules for each train as straight lines connecting the departure and arrival times. Looking quickly at this set of schedules, one would be tempted to conclude that they are feasible given the spacing of the schedule lines. However, the analysis of these schedules with SCAN first uncovers the problem that some trains are scheduled to operate faster than is physically possible (i.e., in time lower than the free-running time). Once these problems are resolved, SCAN begins to uncover more subtle problems. For example, Figure 2 shows that no plan exists which could have Train 3 and Train 34 both arrive on schedule; in the best case, Train 34 would be late by ten minutes. Thus, one must change the schedule of Train 3, Train 34 or both in order to become feasible. After many such changes, one achieves a feasible schedule as indicated by the feasible meet-pass plan in Figure 3. Once theses feasible schedules are found, a simulation analysis finds that the schedules are not very reliable in the sense that the schedules were feasible in only 8% of the cases in which random delays to the trains were introduced. Thus, more time must be added to certain train schedules in order to increase this reliability. The details of several other examples which illustrate the various features of SCAN can be found in (6).

[Insert Figure 2]

SCAN is currently being used to re-schedule a major U.S. railroad as well as to analyze various capital improvements and/or maintenance policies. The ability to achieve a given set of schedules is obviously influenced by the track topology. One should consider carefully the impact of changes in track lay-out on the performance of the train movements; with SCAN, this relationship can be made explicit and seems to be a major use of such a system. For example, consider the situation depicted in Figure 4 which is a portion of double-tracked railroad with two small pieces of single track. In analyzing this situation with SCAN, the problem which is uncovered is not necessarily that single track exists but rather, that the speed limits on the portion of single track between MTPNT_2 and MTPNT_3 continually create infeasibilities in the schedules (note the shallow slope of the lines in Figure 4 on this portion of the track). Thus, one way to resolve this problem is to upgrade the single track to allow higher speed limits and not to go to the expense of adding an additional track at this point.

[Insert Figure 3]

[Insert Figure 4]

4 Real-Time Control of Train Movements

Once the tactical schedules have been set for the day, the purpose of the real-time scheduling system is to attempt to achieve the times stated in the schedules with a high degree of certainty. In practice, events (breakdowns, accidents, etc.) will occur which may inhibit the system from attaining the scheduled goals. Thus, the real-time models attempt to minimize the deviations from these goals while at the same time operating the trains in a safe and fuel efficient manner. In this section, two such models will be described along with the results of preliminary empirical studies.

4.1 Network Control of Train Movements: Interline Planning

The interline planning model attempts to minimize the deviations of arrival/departure times at various points on the rail network for each train from the times stated in the tactical schedules. As described by Harker and Kraay (5), this problem can be formulated as a large-scale mathematical program. This model takes the following general form:

minimize Disruptions to Schedule + Block Switching Delays
+ Costs for Work Rule Violations

subject to:

Crew change constraints
Physical constraints of the trains
Arrival time $\geq$ Departure time + free-running time + delays
Logical constraints

The disruptions to schedule can be any metric of the time of arrival/departure at a point (the variables) and of the stated times in the schedule (the data from a SCAN-like system). In particular, these metrics may be weighted since for a given point, it may not be crucial that a particular train arrive on-time but for another train, its on-time arrival is vital. The cost of block switching delays refers to the fact that cars will most likely have to switch trains at least once in their journey from origin to final destination. Blocks of cars are often scheduled to travel on one train and then switch to another train at a pre-defined yard. Thus, a precedence relationship is defined for the arrivals of trains at a particular yard by these block swapping conditions. Of course, if a block of cars misses a particular out-bound train, it can travel on another departing train but with a possible increase in the total travel time for the cars. The cost of the block swapping reflects this increased cost due to cars missing their planned connection at a yard. Finally, train crews are required by law to work no more than a prespecified number of hours. If the crews reach this limit, various penalties are assessed; these penalties define the last term of the objective function.

The first set of constraints simply state that crews must be changed at prespecified points on the network. The physical constraints of the train assure that each train departs after it arrives from a particular point, that sufficient time is given to the train if it must perform work at a given point (picking up and setting out cars, maintenance, etc.), and other such conditions. The third set of constraints states that the total running time of a train (arrival at point $i+1$ minus the departure from point i) must be greater than or equal to the free running time of the train plus any interference delays caused by the meeting and passing of other trains on the system. Finally, the logical constraints ensure that if two trains are scheduled to meet or overtake on a specified portion of the network, then this activity will in fact occur at the stated point.

The interference delays used in the third set of constraints merit discussion. There exists a large literature dealing with the delays encountered by trains operating on single- or double-track railways. However, these models all assume that trains depart randomly according to a uniform or Poisson distribution. In reality, the trains which are considered within the planning horizon of the interline planning model will depart at or near the planned departure time. That is, the departures are not purely random but rather, occur with some error around the stated departure time. To correct for this inaccuracy in the literature, Chen and Harker (2) have developed a model of delay for scheduled traffic which is formulated as a system of nonlinear equations. Using the successive approximation algorithm, Chen and Harker show how the mean and variance of travel times and hence, the reliability of on-time arrival, can be efficiently calculated.

The model just described is formulated in Harker and Kraay (5) as a mathematical program with a nonlinear objective function, nonlinear constraints due to the delay functions, and integer variables arising from the logical constraints. Research is currently underway to develop algorithms for this problem which are suitable for parallel-computing environments. A preliminary discussion of this research can be found in (5).

4.2 Computer-Aided Dispatching: The Pacing Problem

Once the interline planning model computes the time windows (targets) for the arrival and departures of each train in the network, the goal of a computer-aided dispatching system is to derive a meet-pass plan for the operation of a given planning line (the portion of the rail network between two specified points which comprises a dispatcher's region of authority). There have been many attempts at developing such a system (12,13). All of these methods try to minimize some measure of cost while assuring that the line is operated safely. Typically, this cost consists of fuel consumption and the cost of arriving early or late at the ends of the planning line. The algorithms are typically simple branch-and-bound methods which implicitly enumerate all feasible plans.

Two problems exist with the current state-of-the-art in computer-aided dispatching. First, by treating the arrival times as a cost rather than as a hard constraint, the models provide the dispatchers with a great deal of freedom to efficiently operate their line. Such freedom typically evolves into a system in which trains are given absolute priorities and some trains are made very late at the expense of others. Furthermore, the dispatchers are often too busy to consider the impacts of late/early arrivals on the performance of the rail network outside their regions of authority. However, it may often be the case that one would like to delay a high priority train in order to expedite the arrival of a late train even if the latter train has a low priority; priorities are therefore endogeneous rather than specified a priori. Also, the minimization of cost along a single planning line many lead to very sub-optimal operating plan for the entire network unless the impacts outside the planning region are taken into consideration.

The second problem with the current state-of-the-art involves the *hurry-up and wait philosophy* on which most rail system operate. Consider, for example, Train 007 in Figure 3. At MTPNT_3, this train arrives one and one-half hours earlier than necessary in order to meet the two northbound trains. Since fuel consumption rises as the square of velocity according to the Davis formulae (10), it is far better to pace this train to MTPNT_3 so that it will travel at a lower speed from STATION_Q to this point. Thus, one can simply slow down a train to arrive on-time at a planned meet. Can one do even better? Consider Trains 103 and 100 on the right-hand side of Figure 3. Note that Train 103 arrives approximately one hour early at MTPNT_2 for its meet with Train 100. Train 100, on the other hand, arrives one and a half hours early at its destination, STATION_Q. Why not simply slow down both trains? If this were done, Train 100 would not make its meet with Train 007 at MTPNT_7, Train 103 would be late for its meets at MTPNT_10 and MTPNT_11, and so forth. The problem with changing the times of Trains 100 and 103 is that we have a priori decided the locations of the meets rather than making this decision simultaneously with the times of arrivals at each meetpoint (and hence, the planned velocity of each train).

The *pacing model*, as defined by Kraay, Harker and Chen (8), is a mathematical program which attempts to *simultaneously* find the meet-pass plan (where trains meet or pass) and velocity profiles for each train (their arrival times at each meet-pass point) which minimizes the cost of operating a rail line subject to the scheduled time windows while at the same time obeying the various operating policies of the railroad. In addition to conserving fuel, this notion of pacing may increase the reliability of train operations. If one plans in such a way that all trains travel at maximum velocity, then any disruptions can propogate throughout the line, delaying many other trains. By pacing, late trains may have excess power which will permit them to travel faster than planned in order to achieve the stated arrival times if disruptions do occur.

The pacing model selects the locations for each meet and overtake as well as the time of arrival of each train at each intermediate point in the planning line so as to:

minimize Cost of Fuel + Operating Penalties

subject to:

Meeting the scheduled time windows at the ends of the planning line

Physical constraints of the trains

Speed restrictions

Logical constraints

The objective function of this model is nonlinear due to the fuel consumption term and the various forms which the operating penalties can exhibit. The time windows simply state that each train should not be permitted to leave the origin yard before the time defined by the interline planner, and should not arrive early or late to the destination yard. The physical constraints portray the physical capabilities of the train vis-á-vis acceleration and deceleration, and the speed restrictions ensure the safe operation of each train. The logical constraints are used to ensure that siding capacities are not exceeded, headways between following trains are maintained, various priority rules are observed, and that any other "reasonable" conditions such as following trains being permitted to pass one another at most once (i.e., no *leapfrogging*) are observed. Thus, the pacing model is a large-scale, mixed integer, nonlinear program which must be solved in real-time and with a range of solutions, not just one. This latter condition is essential if the model is to be used effectively since dispatchers may often reject the optimal solution in favor of some other, less optimal solution due to circumstances which the pacing model did not consider.

In Kraay *et al.* (8), several alternative algorithms were considered. The best solution procedure is a rounding heuristic in which a velocity profile for each train is computed for each train by not considering the interaction with any other trains. This problem becomes a much smaller nonlinear program which has a very special structure. Once these "unconstrained" velocity profiles (and hence, arrival times for each train at each point) have been computed, one then moves any conflicts which occur at infeasible points (e.g., a meet in the middle of single track) to the nearest siding while at the same time obeying all of the necessary logical constraints. This rounding procedure can be accomplished through a modification of the SCAN feasibility algorithm described in the previous section. Once a feasible meet-pass plan has been found via this rounding procedure (the places where trains are scheduled to interact), a nonlinear program with additional constraints is solved in order to compute the times of arrival. This last step is necessary due to the interactions between all trains as described above in the case of Trains 100 and 103; i.e., the algorithm must attempt to adjust all the times simultaneously in order to avoid infeasibilities. In certain cases, this simple rounding procedure can be proven to produce the optimal solution. In other cases, the experimental work reported in (8) shows that this heuristic is quite good.

Preliminary empirical evidence suggests that significant fuel and delay costs can be achieved through the use of this model. In the analysis of current practice, dispatchers tend to become overburdened when many trains are placed under their control. In such cases, they tend to follow the very simple practice of dealing first with the highest priority trains, and then progressively moving toward those trains with low priority. The pacing model, by treating all of these decisions simultaneously, often yields significant cost savings. The details of this empirical work will be reported in a subsequent paper. Finally, this notion of pacing extends to many other areas of transportation. For example, the scheduling of barge and ship traffic in a canal (11) fits very well into this paradigm; these topics will also be explored in the future.

4.3 Optimal Control of Train Movements

The pacing model provides the train with the time which it must reach the next point on its path as well as the velocity at which it should pass this point. The goal of the on-board computer system is to help the engineer achieve this time and velocity constraint in a safe and fuel efficient manner. This problem has been formulated by Harker and Chen (4) as a nonlinear optimal control problem. In fact, both a deterministic model and a stochastic model which takes into account the random nature of train performance due to engine problems, wind and other weather conditions, etc. have been formulated and analyzed. Research is now underway to develop fast and effective solution procedures for these models.

5 Summary and Future Research

The hierarchy of models presented in this paper has one goal in mind: to smooth the flow of traffic in rail networks by effectively using the wealth of information available from an ARES-like positioning system. In order to achieve this goal, a simple principle applies: *keep it simple!* Major policy tradeoffs are made at the top, the SCAN system attempts to implement these policies through the development of tactical schedules, and the real-time control systems develop operating plans which achieve these goals while optimizing performance. Note that this flow of authority is quite different than what one typically sees in railroad control system in the U.S.; in such systems, it is typically cost which is the driving force. In the schema presented in this paper, the marketing/customer concerns drive the schedules and thus, the entire operating philosophy. Simplicity is achieved by clearly stated goals: dispatchers are to obey time windows, engineers the arrival times given by the dispatcher, etc.

The research which is currently underway at the University of Pennsylvania involves the fleshing out of this hierarchy through the development of the necessary models and algorithms. In addition, various cost/benefit studies are being pursued in order to ascertain the ability of such a system to improve the reliability and costs associated with freight railroading. In addition, extensions of these concepts to other modes of transportation and, in general, manufacturing processes are currently being explored.

Acknowledgements

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Captions for Figures

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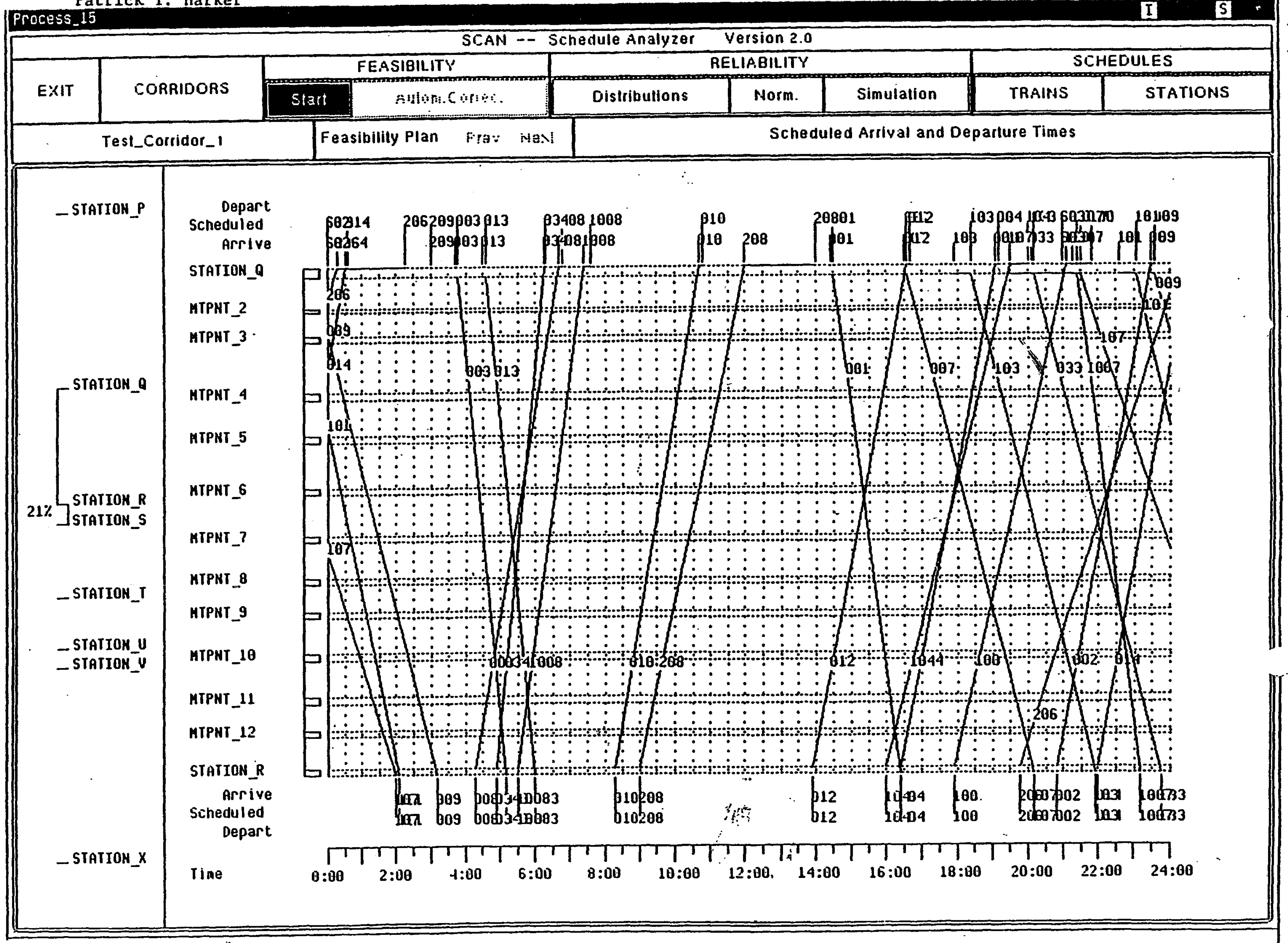
Fig. 1



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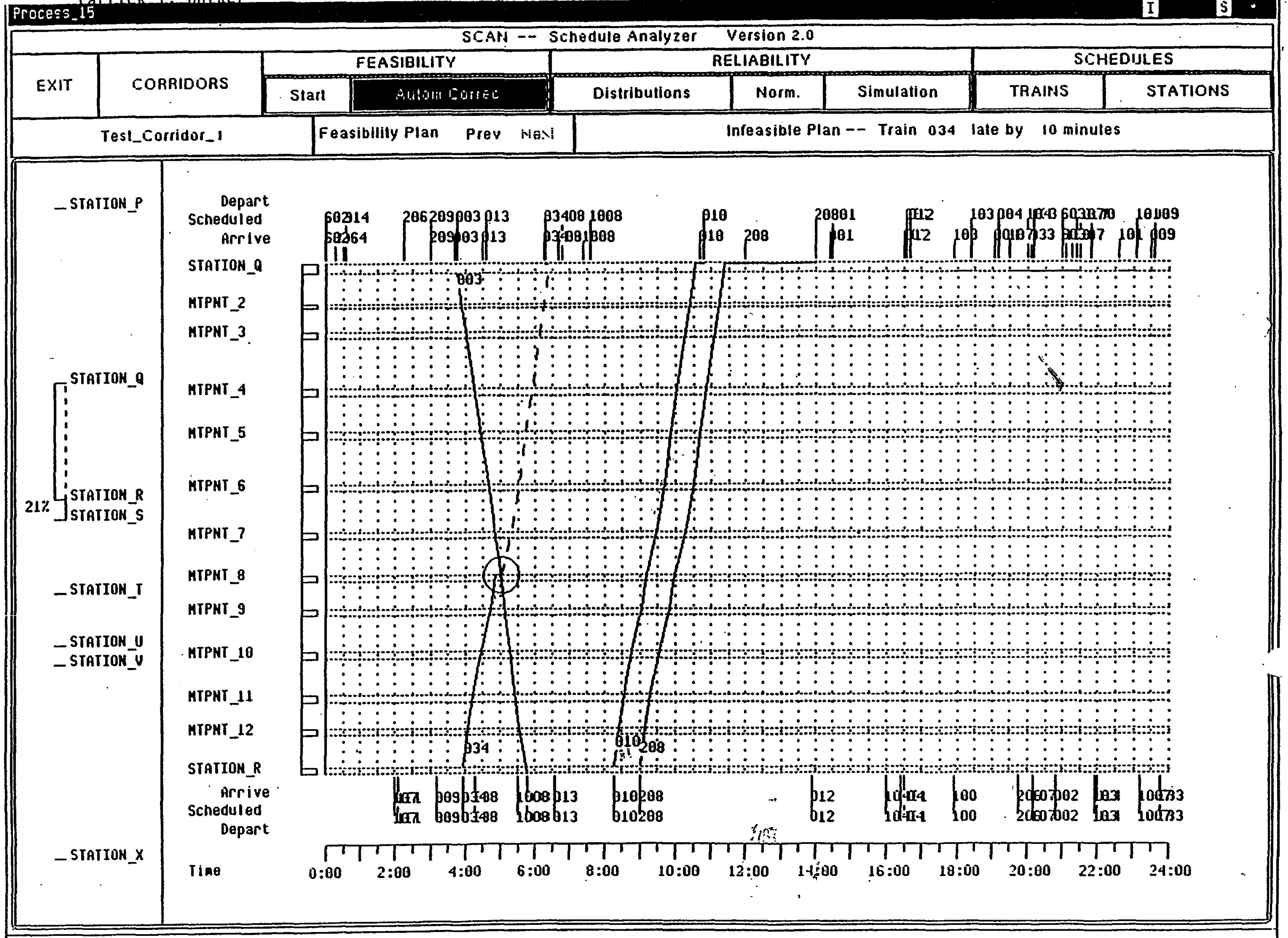

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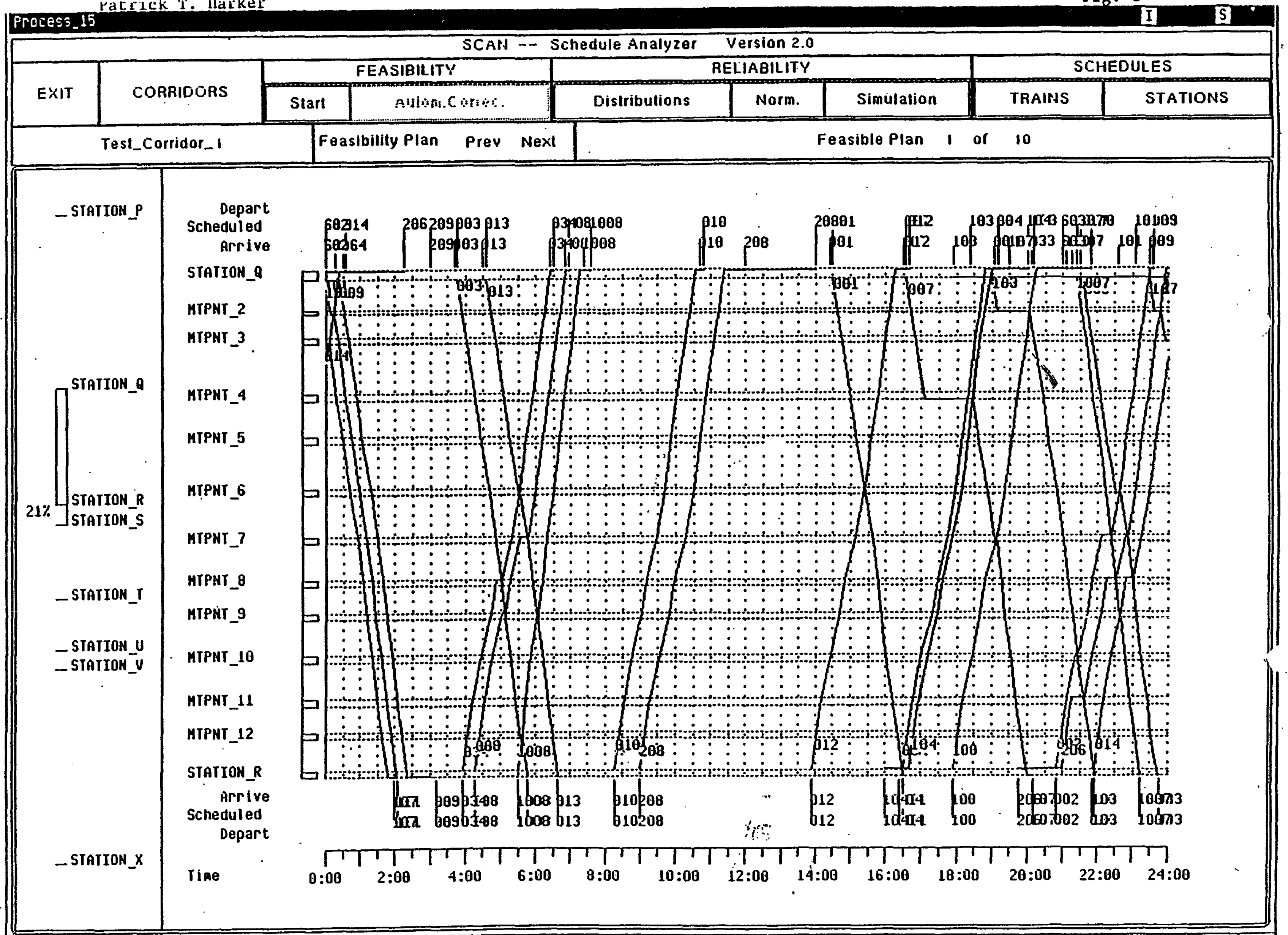
Fig. 3



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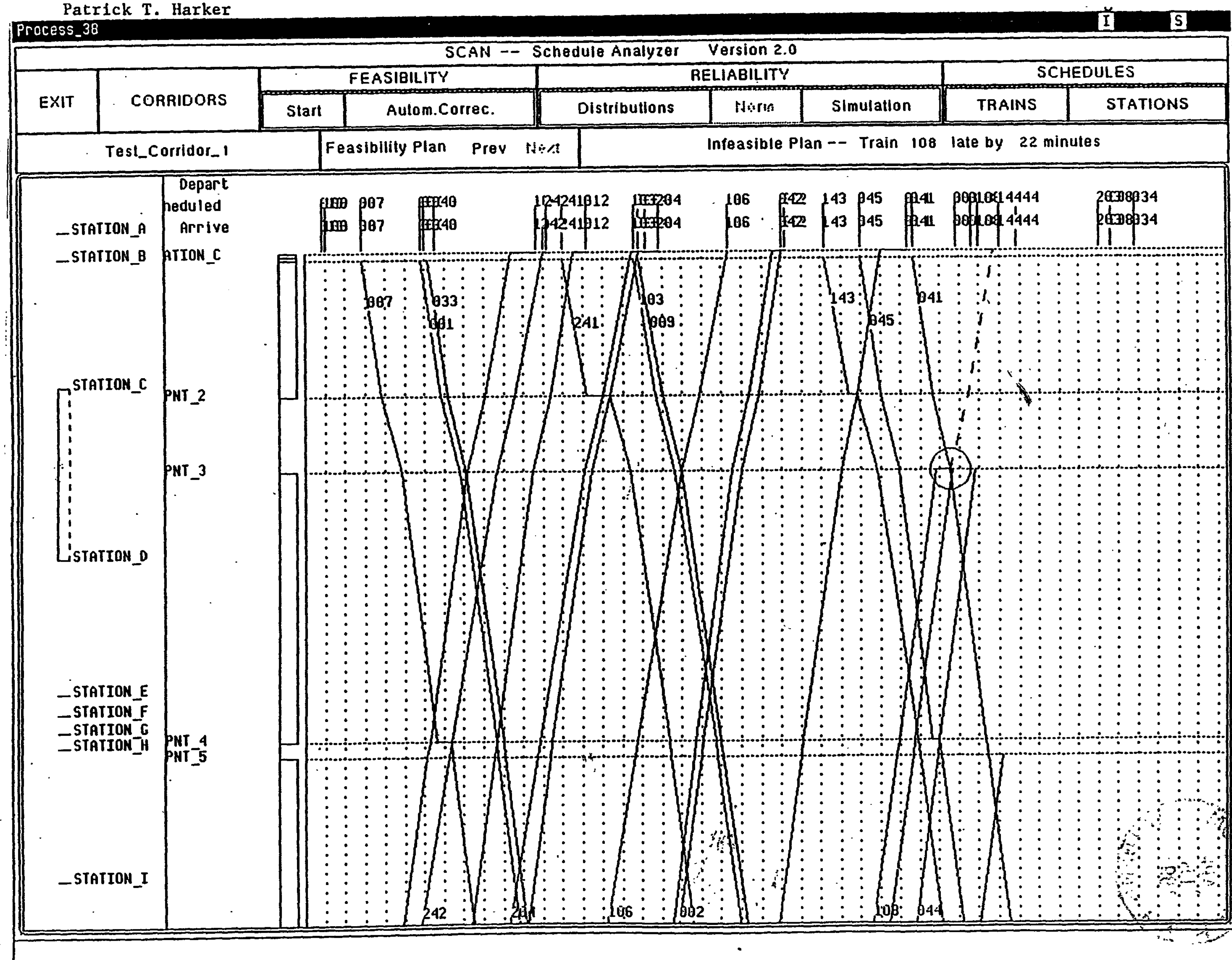

Computer Aided Train Dispatching: Decision Support Through Optimization

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Sauder

A mini-computer based information system with on-line optimal route planning capability was developed to assist dispatchers on the complex northern portion of Southern Railway's Alabama Division. The routing plan is revised automatically as conditions change. Since implementation in September 1980, train delay has been more than 15 percent lower, reflecting annual savings of $316,000.
The dispatching support system is now being expanded to all other Southern Railway operating divisions with $3,000,000 annual savings expected from reduced train delay.

Southern Railway Company operating throughout the southeastern United states is one of the nation's largest railroads. For years it has been a leader in profitability in the industry. In 1981 Southern's after tax profits totalled $212 million from revenues of $1.87 billion.

In June 1982, Southern Railway and the Norfolk and Western Railway merged to form the Norfolk Southern Corporation. The combined system provides efficient single system service throughout the South, East, and Midwest. The Norfolk Southern Corporation is now the nation's fifth largest and most profitable railway system. Had it existed in 1981, it would have produced revenue of $3.59 billion and realized profits of $500 million. Even in the 1982 recession year, after tax profits, on a pro forma basis, amounted to $411 million.

Southern Railway and the Norfolk and Western operate as autonomous organizations whose activities are coordinated at

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the holding company level. Each railroad is divided into two operating regions, and each region, headed by a general manager, contains five operating divisions.

Daily operations are controlled at the division headquarters level. Although movement of trains between divisions is coordinated through a centralized operations control center, the responsibility for the safe and efficient movement of trains over the division lies principally in the division dispatching office. Directly accountable to the division superintendent, the dispatching office is headed by an assistant superintendent, the "Super Chief"; reporting to him is a chief dispatcher and a staff of train dispatchers.

Dispatching trains is complex and demanding. In a typical eight hour shift, a train dispatcher will control the movement of 20 to 30 trains over territories spanning three to six hundred miles. In most cases, these trains operate over single tracks and opposing trains must meet at strategically placed passing sidings. The dispatcher arranges these "meets" with safety the paramount consideration. He also must safely coordinate movements of roadway maintenance gangs, signal maintenance crews, industrial switch engines, and motor car inspection crews.

The dispatcher is also in constant contact with yard personnel at freight terminals who report essential information regarding trains that will move over the division. Once trains reach their destinations, they report operating and delay statistics for the dispatcher to record. Federal law requires that the dispatcher maintain this "train sheet." Finally, the train dispatcher interacts and coordinates with other dispatchers, as well as with the chief dispatcher, giving and taking information about the operation of his territory.

Southern Railway's Alabama Division (Figure 1) is a complex operating division. Headquartered at Birmingham, Alabama, its most heavily travelled routes extend from Atlanta through Birmingham to Sheffield, Alabama, near Memphis. It interfaces with other operating divisions at each of these locations. Other major routes extend from Birmingham south to Mobile and from Birmingham southeast to Columbus, Georgia. Altogether, mainline trackage exceeds 800 miles and 80 to 90 trains operate daily. The division employs more than 1,200 persons, mostly in train and engine service.

Two train dispatchers are on duty around the clock at the Birmingham headquarters. One controls the high density Birmingham-Sheffield corridor (the North Alabama District) and the line south to Mobile. The other controls the Birmingham-Atlanta route (the East End District) and the line into southwest Georgia.

Both the North Alabama and the East End Districts operate under Centralized Traffic Control (CTC). This provides a failsafe system of signals and switches in the field controlled centrally by the dispatcher who monitors all field activity on an electronic display board. The other lines on the division have no signal control. In these "dark" territories, train movement is controlled solely by the dispatcher issuing stringent orders to train crews.

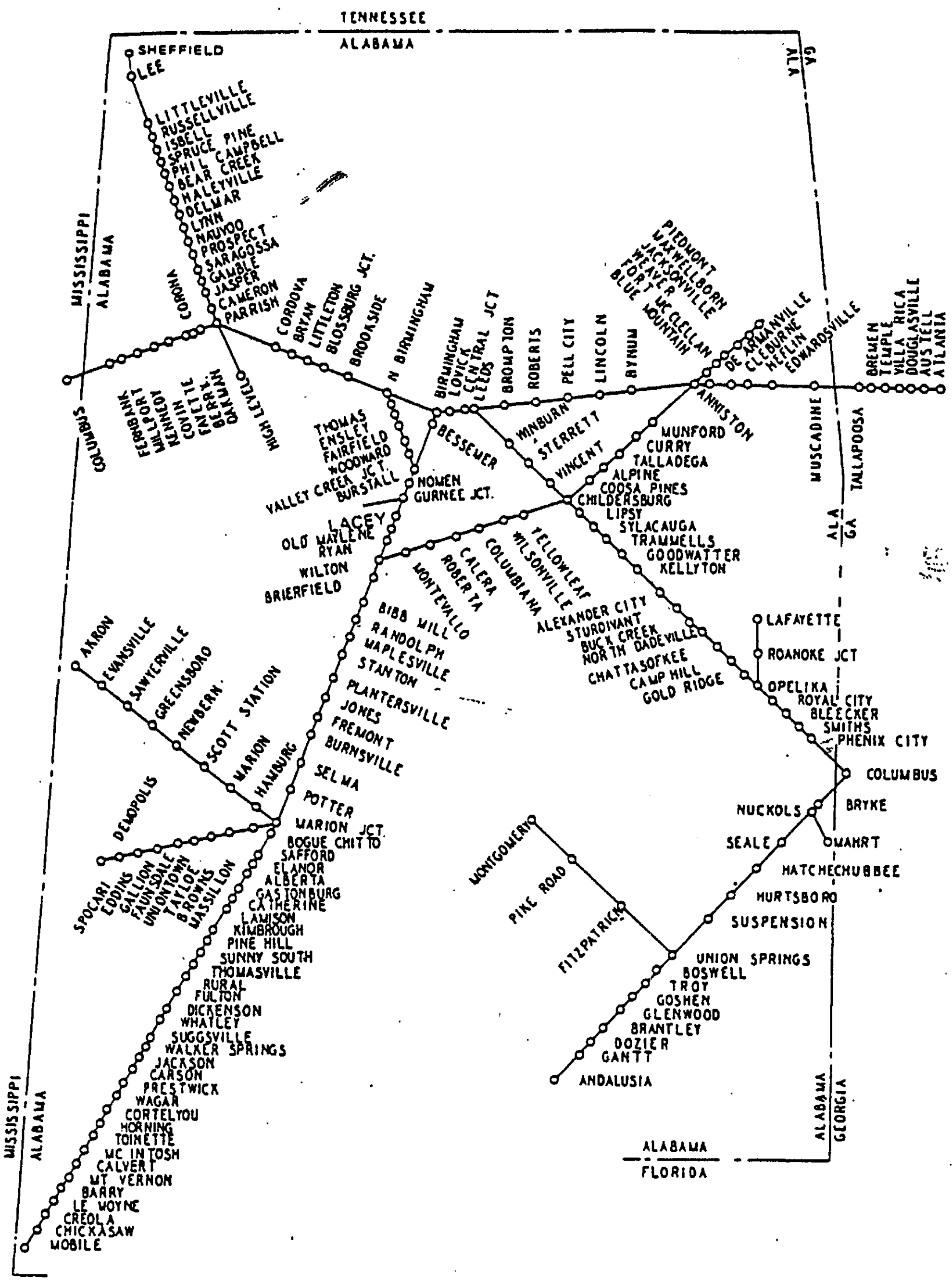

Figure 1. Southern Railway's Alabama Division.

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Until the mid-1970s, the operation of the Alabama Division was not overly complex; in fact, there was no centralized traffic control whatsoever. Then in 1974 with the opening of a large freight yard facility at Sheffield, merchandise traffic levels began to grow steadily, making the North Alabama District a major gateway to and from the Midwest. A coal loading facility near Sheffield was opened in 1977, further congesting the line. Unit trains (trains with up to seven locomotives and 96 loaded coal cars) began operating to key power plants in Georgia and Alabama. These trains operate on 40 hour "cycles," that is, moving loaded to their destination, unloading, and returning empty over the reverse route for reloading. Up to four such trains operate concurrently.

Management foresaw the need for centralized traffic control to assist dispatchers and began installation in 1976.

The research and development project to provide computer assistance for the dispatcher was in progress independently during this same period. As the CTC installation neared completion and as the R&D project began to show promise, it became clear that the Alabama Division was a logical location for determining how computer aided dispatching could further improve performance.

Development of the Support System

Southern Railway's operations research staff (which is now the Norfolk Southern Corporation's OR staff) has existed since the mid-1960s. Originally oriented toward computer model development, the operations research group by the early 1970s had become a corporate consulting staff providing *applications* support using tested analytical techniques, on one hand, and supporting *research and development* on the other.

The development staff began to investigate computer aid for the train dispatcher in 1975. Information systems for yard and terminal operations were already in place at many locations on the railroad. Extensions to this system requiring chief dispatchers to report realtime status of key trains were already envisioned. No other division-level systems were then being contemplated.

Concurrently, several signal manufacturers started selling turn-key systems to support CTC operations, providing features such as automatic "OS"-ing (On Station reporting of the time a train passed a key location). Some systems permitted automated record keeping. One system even incorporated a rudimentary planning capability, tracing the routes of two opposing trains to determine when they would meet.

Operations research personnel reviewed a number of these systems and rejected them as being too inflexible. They saw the potential for automating the vast amount of division level information being manually recorded and for integrating this with other information systems. With extensive experience using simulation models to analyze line changes, they also foresaw the real possibility of on-line predictive planning aids for the dispatcher. They proposed that a computerized physical simulator be developed to explore these possibilities. Southern's top management computer usage committee approved the R&D project in late 1976.

The mini-computer based simulator, built and thoroughly tested over a three-year period, emulated a centralized-traffic-control-office environment and permitted designers and dispatchers alike to play and replay real-life scenarios, refining features that could eventually be installed in a division office. The simulator contained a bank of four color CRT's. Two displayed the track layout of the territory being studied. A simulation model was written to emulate movement of trains over the territory and it displayed movement of trains on the two track-layout CRT's based on route decisions interactively keyed by the "dispatcher."

A third CRT served as a work sheet for updating automated train-data files. A specially designed function keyboard permitted screen formats to be displayed which allowed dispatchers to update train sheets, reports of delay, locomotive failures, weather conditions, and many other records, all of which were then kept manually at division offices. The computerized system did not change what was being recorded; it merely changed the manner in

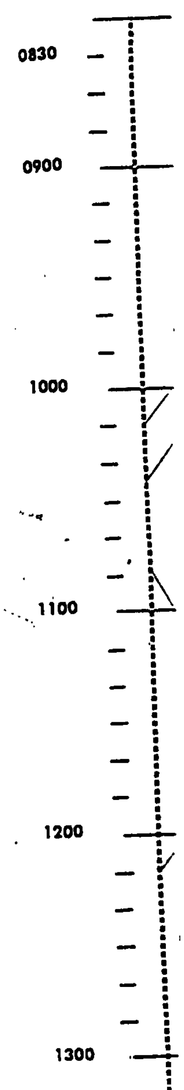
The Norfolk Southern is now the nation's fifth largest and most profitable railway system.

which data was being recorded. A fourth CRT was reserved for displaying how trains should be routed — a capability which was being developed at the same time.

The potential for an on-line planning algorithm lay in considering all feasible future train meets throughout the territory and advising the dispatcher of that combination which would minimize total train delay. This "meet/pass plan," as it was labeled, had to account for all realistic operating conditions: travel times between sidings based on power and tonnage, speed limits, speed restrictions, train length compared with siding length, the ability of a train to start once stopped in a siding, train adherence to schedule, special cargo requiring special handling, work locations, and so forth. It also had to respond to dynamically changing conditions and display its latest recommended plan of action to the dispatcher in a manner he could readily comprehend.

The time-distance graph shown in Figure 2 is a standard method for displaying train meeting points and associated delay. Even in this simplified example involving five sidings and four eastbound and five westbound trains, there are thousands of meet combinations that could occur. The meet-pass plan was designed to reevaluate the combination at any time conditions changed and to display this new plan starting at the current time (8:30 am in the Figure 2 example) and projecting six to eight hours into the future.

Also incorporated was the ability for the dispatcher to override the plan by stating specific meet locations, by taking track out of service and by forcing trains in one direction to be stopped in sidings prior to the arrival of an opposing train. This permitted dispatcher experience and judgment to be reflected in the plan. It



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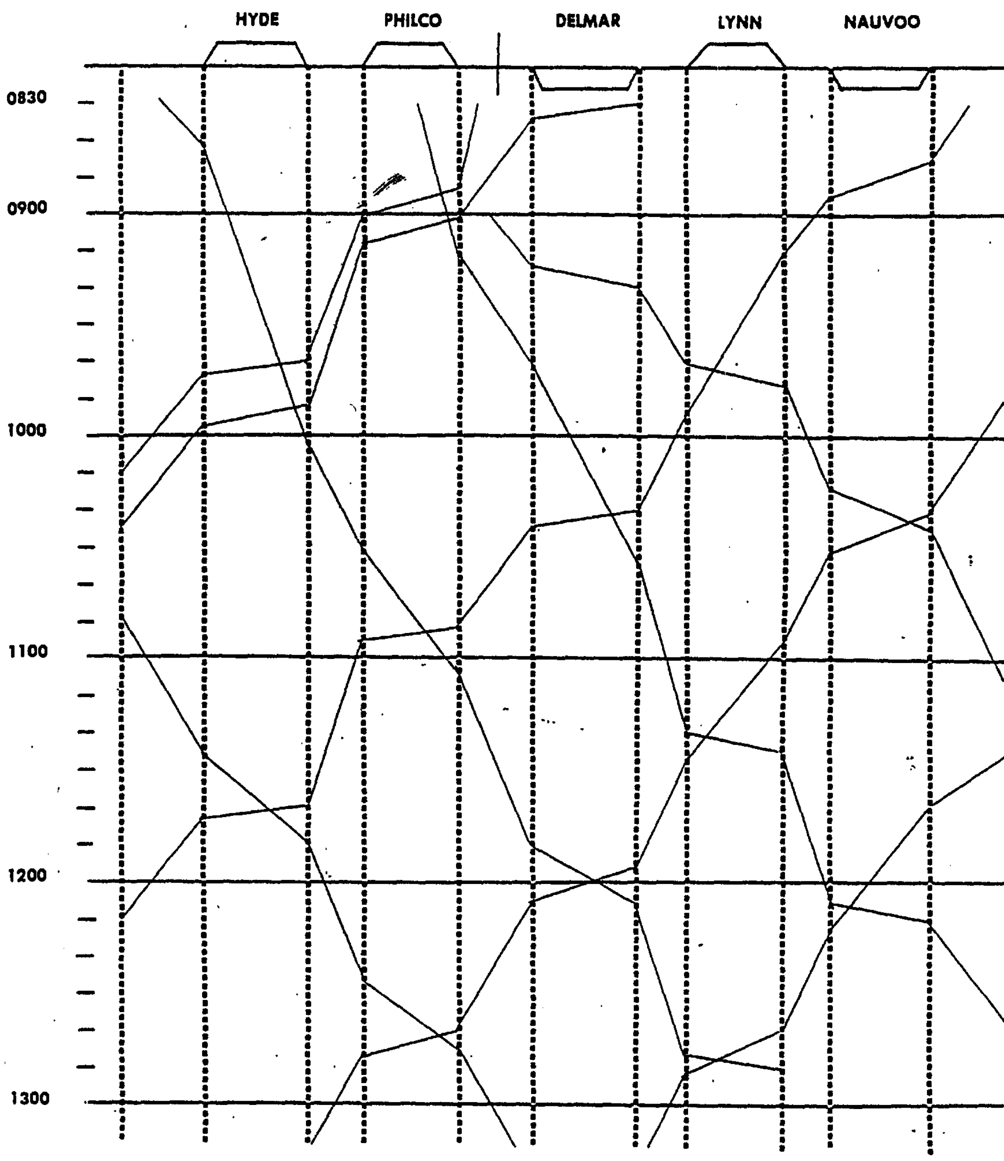

Figure 2. A time distance graph displaying train movement through a five siding network in a four and one-half hour time frame. Four eastbound trains move diagonally from left to right meeting five westbound trains where the lines intersect.

also formed the basis for a "what if" planning capability!

The first attempt to model the process evaluated feasible train routes with a decomposition approach incorporating a shortest path algorithm and a linear programming formulation. Although optimal solutions were obtainable, more often than not, convergence time was excessive and suboptimal solutions resulted. This method was subsequently replaced with a branch-and-bound technique enumerating all feasible meet locations and this approach did insure optimal results in a highly responsive fashion. (This model is further described in a technical appendix.)

The meet/pass plan was integrated into the simulator, and its use for on-line tactical planning was evaluated in detail. Possibly its most significant use was predicting the impact of the system operating in a real environment. During a periodic review of the project's status, the computer

> Until the mid-1970s, the operation of the Alabama Division was not overly complex; in fact, there was no centralized traffic control whatsoever.

usage committee directed the operations research group to evaluate the potential of the system on the North Alabama District.

Operation was simulated both with and without computer-aided planning, and the impact on resulting train delay was measured. Train sheets for the North Alabama line were reviewed, and a typically heavy, yet normal, day of operation was selected. Train-meet delay for the first eight-hour shift on that day had amounted to 457 minutes. An Alabama Division dispatcher operated that same shift of operation in the simulator. The session began with train locations shown and information available concerning oncoming trains. The dispatcher worked the entire shift with no planning assistance, and the delay recorded at the conclusion of the session amounted to 455 minutes — a two minute difference.

The dispatcher then replayed the shift, this time following meets recommended by the plan. The resulting delay, 300 minutes, reflected a reduction of 34 percent. Reductions in other scenarios subsequently simulated ranged from 22 to 38 percent. When the OR group presented these findings, the committee, perceiving that if even half of these benefits could be realized they would create a significant performance impact, immediately approved the project. The North Alabama pilot project was underway.

Implementation and Its Impact

Interfacing the mini-computers and the CTC system was the only significant task involved in converting from a simulated to an on-line environment. CRT's were added to the North Alabama dispatcher's work-station to complement the CTC display board: two "work" CRT's were installed to provide flexibility and backup, and a third CRT was installed solely for meet/pass plan display.

Installation and parallel testing of the North Alabama system began in January 1980. On September 15, 1980, the system was placed in production and the dispatchers' manual train sheets were removed. Six weeks later, instructions were issued to dispatchers to utilize the computer-generated plan.

Earlier in 1980, groundwork had been laid for installing a second, independent system to support the East End Alabama Division dispatcher. In the meantime, Data General Corporation, the minicomputer system manufacturer, announced an advanced operating system that would permit a *single* minicomputer,

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with additional internal memory, to support a large number of users and work stations simultaneously. The desirability of such a single system that could support two or more dispatchers and any others needing access to the system was evident.

Conversion of the system started in mid-1981, with East End operations added to the dispatching system in March 1982. A final system supporting all territories on the Alabama Division became a reality in September. What had begun as a system to support a single train dispatcher had now evolved into one supporting all division operations.

Auditing operating performance as the system gained acceptance and comparing it with prior performance experience was a vital step in measuring the impact of computer-aided dispatching. The improvement predicted in the simulator experiment now had to be verified. For two full years since implementation, performance statistics have been compiled daily reflecting the total numbers of trains operating, train meets, and the total delay caused by these meets. Reviewing manual train sheets for a full year of operation starting in September, 1979, provided similar data for pre-implementation comparison.

Forty weeks of operations in each of these periods were then selected for a comparison study (a choice made necessary to compensate for a ten-week coal strike in 1981). Corresponding weeks were used for the year before implementation (the base period) and the year after. In the second year of operation, the first 40 contiguous weeks, beginning September 15, 1981 were used, thereby eliminating from consideration a period when business took a sharp downturn during the latter half of 1982.

Comparing the first year of implementation with the previous year, traffic increased nearly nine percent, yet delay per train operated and delay per meet were both down more than twelve percent.

Stringent guidelines were developed for analyzing delay reports to insure consistent measurement across periods:
(1) Only delay within the limits controlled by the dispatcher was included.
(2) Only delay that the dispatcher's planning would influence was considered.
(3) Days reflecting highly abnormal operation, such as during a derailment, were excluded and replaced with an average for the same day in the four previous weeks. The operating statistics for the three measured periods are summarized in Table 1.

Comparing the first year of implementation with the previous year, traffic increased nearly nine percent, yet delay per train operated and delay per meet were down more than twelve percent. Traffic in the second year of operation returned to pre-implementation levels. The average number of trains operating weekly is nearly identical in the two periods yet delay is more than 25 percent less in the 1981-1982 period.

Of the two measures, delay/train and delay/meet, the latter is more meaningful because division personnel have some control in scheduling trains to avoid meets but have little control over the numbers of trains operating. This ability to plan and control meets is evident in the figures for the second year of operation when delay per meet was reduced 18.8 percent. Overall, combining the 80 weeks of measured operation since computer-aided dispatching was placed on line, delay per meet has improved 15.5 percent. In addition, as Figure 3 shows, the operation is more consistent. In the year prior to implementation delay per meet ranged from 31.0 to 44.4 minutes. In the first year after implementation, it ranged from 26.6 to 40.2 and in the second, from 26.2 to 33.7 minutes.

Optimal planning together with information availability has improved performance significantly, and the resulting operation is a more consistent one. Several of the reasons are:

(1) *A cleaner, neater, more professional operation*. Information is mechanically and electronically recorded, replacing hand-scrawled and often altered massive documents.

(2) *A readily accessible information base*. Information recorded by the dispatcher is readily available and functional in inquiry form to all division personnel. Train information can also be transferred from one dispatcher's territory to another, reducing manual recording.

(3) *An optimal plan clearly reflecting management policy*. The meet/pass plan considers management directives regarding key priorities for dispatching trains. The continually updated nature of the plan ensures compliance with this policy under dynamic conditions.

(4) *An equitable attitude toward dispatcher responsibility and action*. As should be expected, dispatchers are severely criticized

	PERIOD A Year Prior to Implementation	PERIOD B First Year Since Implementation	PERIOD C Second Year Since Implementation
Average Weekly Meet Delay (Minutes)	8893	8290 (−6.8%)	6645 (−25.3%)
Trains Operated (Weekly)	147.4	156.9 (+8.5%)	147.7 (+0.2%)
Train Meets (Weekly)	245.9	262.1 (+6.6%)	226.3 (−8.0%)
Meets Per Train Operated	1.67	1.67	1.53
Delay Per Train (Minutes)	60.3	52.8 (−12.4%)	45.0 (−25.4%)
Delay Per Meet (Minutes)	36.2	31.6 (−12.7%)	29.4 (−18.8%)

Table 1. North Alabama district operating statistics for the three-year period starting September 15, 1979.

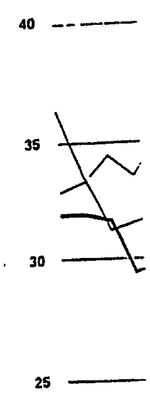

Figure 3. M

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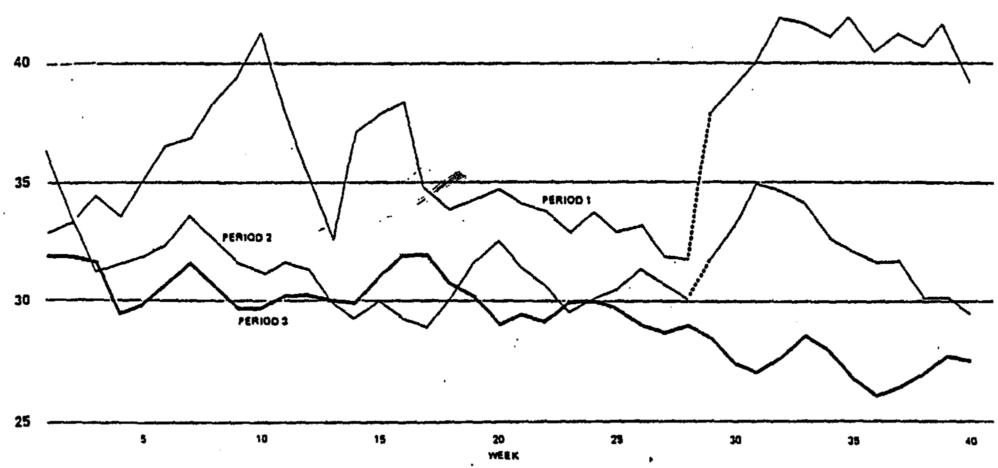


Figure 3. Minutes of delay per meet, a three-week moving average.

for delays caused by poor planning or inattention, for example if a high-priority train is delayed because a low-priority opposing train blocks its movement. A common dispatching solution had been to clear the low-priority train into a siding far in advance to minimize the possibility of delaying the hot train. Computer aided dispatching has virtually eliminated this waste. Dispatchers are encouraged to use the plan and are not hauled on the carpet if they follow it even should delay occur.

In addition to freeing the dispatcher from complex, diversionary, time-consuming calculations and risks, this computerized system has ancillary benefits. For instance, train crews now make their runs in consistently less time, giving them more time at home and substantially improving morale. By the same token, locomotive fuel and equipment requirements are cut, thereby effecting a measurable reduction in mechanical cost.

Reduction in train delay translates directly to cost savings. One hour of train operation equates to more than $240 using a formula which considers fuel consumption, crew costs, locomotive availability and utilization, freight car ownership costs, revenue producing potential, and a variety of other factors. The more than 15 percent reduction in delay experienced in the 80 measured weeks of performance directly reflects savings of $316,000 in each of the first two years of operation.

What are the anticipated division wide savings now that the system does in fact support all operating districts on the division? It is reasonable to expect similar percentage savings on the East End CTC line between Altanta and Birmingham. On the non-CTC portion of the division, some lesser improvement will occur from better planning and train scheduling. On this basis, future savings for the Alabama Division, when traffic returns to pre-1982 levels, are estimated at $675,000 annually. In addition, a proposed new passing siding on the North Alabama line, at a cost of $1,500,000, has been postponed indefinitely as a direct result of the greater dispatching efficiency.

Another monetary saving which cannot be easily quantified is additional track time for various types of maintenance crews. The dispatcher can now more quickly and efficiently allocate working time, because he can adjust the locations of train delays to accommodate these crews. Using the meet/pass plan's "what-if" capability, he can determine the best times to allocate, maximizing on-track working time yet minimizing train delay.

Beyond the Basic System

On the same basis that expected division wide savings were estimated for the Alabama Division, implementation of the computer-aided dispatching system on all Southern Railway divisions will produce cost savings of $3,000,000 annually in train delay reduction alone.

On September 27, 1982, a memo sent to the Executive Vice President Administration, Norfolk Southern, from the President of the Southern Railway read in part:

> . . . I am very much interested in extending this system to other divisions. I feel the results on the Alabama Division have been even better than we anticipated, and I believe we should move now to the north end of the Georgia Division between Chattanooga and Atlanta . . .

Computer hardware to support the Georgia Division operation was delivered in the last week of December. Starting in early January, operations research analysts, working with Georgia Division personnel, "defined" the division, using interactive file definition programs. On January 27, the Georgia Division support system was put on-line to begin dispatcher training and no computer program changes were required to transfer the existing Alabama Division support system to the Georgia Division.

Training continued through February, and on March 18 manual train sheets for the north end of the Georgia Division, Atlanta to Chattanooga, were removed. The total conversion effort required less than six operations-research man weeks, and less than three Georgia Division man weeks, including system support and training.

As should be expected, dispatchers are severely criticized for delays caused by poor planning or inattention . . .

Systems for three additional Southern Railway divisions are budgeted for the remainder of 1983. In January of 1983, the President of Southern Railway convened a task force representing transportation, engineering, operations research, and data processing to produce an implementation plan that considers real installation costs matched against previously derived benefits. At the present time, it is expected that total installation cost at each division, except for one that requires new building facilities, will be less than $300,000.

The system described to this point is in operation and results have been demonstrated. The need for some new features became evident in working with the implemented system and they will be implemented soon.

First is formal planning assistance for the chief dispatcher. Improved efficiency in his duties has already been achieved through the information processing capabilities of the system. The meet/pass plans now used by the train dispatchers are tactical plans that consider trains now on the territory and trains whose arrival is imminent. In a new approach, appropriately dubbed "SUPERPLAN," the individual meet/pass plans for each dispatching territory will provide input to a division-wide planning process and allow the chief dispatcher to adjust train schedules and work assignments to avoid unnecessary train meets and traffic congestion.

A second innovation provides information transfer among division offices. This step ties together each of the divisions through Southern Railway's central computer complex in Atlanta. This feature, first of all, eases the chief dispatcher's clerical effort in reporting key train movements. More important, it provides the basis for "SUPERPLAN-II" — optimal planning among divisions. The ultimate capability, now a potential reality, is vastly improved planning among divisions, at the general manager level and at the system control and coordination level. What was once a blue-sky dream of optimizing system-wide operation is now within reach because the basic building block, the division-level computer-aided dispatching system, works!

Conclusion

Today the working computer-aided dispatching system continues to demonstrate significant dollar impact. Direction to expand the application to other territories testifies to the faith management has in the future benefits of the system. From a management scientist's viewpoint, the dispatching system is a marriage of information processing and management science. It is a distributed system and a decision support system. Proven management science optimization techniques form the basis of the system which around the clock provides dispatchers and managers alike the real time key to improving productivity and expanding profitability.

Acknowledgement

The work described in this paper is a product of Southern Railway's operations research staff working together with Alabama Division personnel. We want to express our sincere gratitude to all involved in this effort, and in particular to: Kenneth W. Gohring (Development Manager), Herbert R. Jones and Roger N. McBrayer (Senior Operations Research Analysts), Paul C. Wright and Gudrun A. Klauss (Operations Research Analysts), Thomas D. Pace (Assistant Superintendent), W. Kenneth Bice (Chief Dispatcher), O. D. Prestridge, Susan Price, W. K. Smith, H. D. Stapler (Alabama Division Train Dispatchers), and John T. Braithwaite (Clerk-Operator).

Edward B. Burwell, President, Southern Railway Company commented: "The project has had a significant impact on the North Alabama district. Almost every day, when I would review trouble spots on the railroad, it would be at the top of the list — excessive delays, crews relieved for being on duty too long, and so forth. Then within a matter of weeks after this dispatching system was put in place, those problems went away. I didn't need to see statistics to prove it. The change in performance was obvious."

TECHNICAL APPENDIX: Meet/Pass Planning Algorithm

The planning algorithm is a complete enumeration technique which investigates all possible meet solutions to find the least "costly." Any definition of cost as a function of train delay could readily be incorporated.

The cost function that was implemented segregates delay for every train i, into two categories.

1) w_i = delay (beyond minimum origin to destination travel time, m_i) that would permit train i to reach its destination within a predefined scheduled run time (s_i).

2) y_i = delay that exceeds s_i.

Thus in any individual solution if we let:
$D_i = w_i + y_i$ = total delay for train i
$TT_i = m_i + D_i$ = train i's projected travel time between origin and destination,
then assuming $s_i \geq 0$, $m_i \geq 0$
we can express the two types of delay as:
$w_i = \max\ [0, \min\ [D_i, s_i - m_i]]$
$y_i = \max\ [0, \min\ [D_i, m_i + D_i - s_i]]$.
To promote adherence to schedule, the cost function multiplies y_i by train i's priority (p_i). A loaded unit coal train, for instance, maintains a priority of 10 while a local train serving industry has a priority of 1. The cost function also discounts the cost for those trains which have not yet arrived on the system. We define a discount factor

$$(T - a_i)/T$$

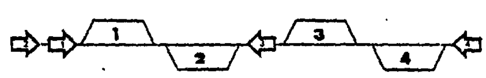
where T = the algorithm's predefined planning horizon (six hours in this instance) and
a_i = interval of time between the current time and train i's projected arrival time on the territory.

(Note: a_i = 0 for trains already on the system.)
Thus, assuming there are N trains in the problem, the total cost (C) for an individual solution can be calculated as follows:

$$C = \sum_{i=1}^{N} [w_i + (y_i \cdot p_i)]\ [(T - a_i)/T].$$

The function is repeatedly applied to all possible solutions. Obviously, if we consider all feasible solutions we will identify the optimal, or least cost, solution.

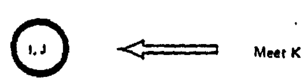
The enumeration of all possible solutions is accomplished as follows: First, all potential conflicts (i.e., meets and passes) are identified and the locations (sidings) where those conflicts might be resolved are identified. Referring to the inverted tree structure, each conflict, K, might be thought of as a level where the nodes on that level are all the potential locations, I, for resolving that conflict. The bottom level represents all possible solutions and their associated costs. In enumerating this tree, the routine considers two restrictions. A solution first must allow all trains to reach their destinations within an extended horizon (20 hours) and, second, must cost less than all previously enumerated solutions.
Assume a network involving four sidings and four trains, two eastbound, two westbound.



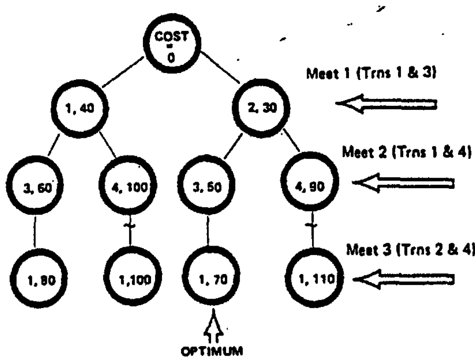
Further assume, for simplicity, the following potential meets:

Train	Can Meet	Siding	Cost
1	3	1	40
1	3	2	30
1	4	3	20
1	4	4	60
2	4	1	20

In the tree structures below, let:



represent a feasible Meet, K, where
I = the siding (1 - 4)
J = the cumulative cost through Meet K



The algorithm accomplishes this by identifying a meet and choosing a feasible siding for it. Given each train's travel time to the siding, the delay and thus cost can be calculated for both trains. A second conflict is then chosen and resolved in a similar fashion. If the additional delay of this second conflict causes either train to be unable to reach its destination within the extended time horizon, an alternative location for the second conflict is considered. Eventually, all conflicts will be resolved such that each train can reach its destination within the extended horizon. The cost associated with this combination of meets and passes becomes a bound with which the cost of all other conflict resolutions will be compared. We can now backtrack and consider combinations of meets only as long as their cumulative cost is lower than the present bound. If all conflicts can be resolved and the cost is less than the present bound, then the new combination is the better solution, and its associated cost becomes the bound. When all combinations have been considered (i.e., the entire tree has been fathomed), the solution associated with the bound is the optimal solution.

BENEFITS

The practical benefits of the Engineering System cannot at present be assessed in financial terms, it is expected however, that the system when fully developed will yield the following benefits:

- More efficient utilisation of Railway Operating maintenance resources, by the use of information on miles/time in service, when allocating work to be done.
- The ability to define Maintenance Intervals by the analysis of component failures and rates of wear.
- A reduction of the number of trains failing in service, by the more effective estimation of component life and the renewal of such assemblies before failure .
- A reduction in stockholdings of components commensurate with deductions on usage and failure rates.
- The achievement of more realistic manning levels, calculated on accurate workloads and based on reduced overhaul frequencies.
- The ability to provide the Management Accountant with accurate costing information for work completed, together with a realistic indication of over/under spending on Revenue and Capital Accounts.
- A reduction in the shunting of trains within Rolling Stock Depots resulting from better planning of train stabling according to maintenance and examination requirements.

The benefits in computing terms have shown that a move from the corporate Mainframe to distributed application specific processors, working in the 4th Generation environment are:

- Software produced in 30% of the time and at 25% of the cost of traditional 3rd Generation Language environment.
- Processor support costs reduced by 30%.
- A high level of user acceptance.
- The ability to adapt quickly to business demands.

31 Dec '87

'Driver-Assist' – Microprocessor Technology to Aid in the Scheduling of Trains

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S/N 7/629417

INTRODUCTION

Iron ore trains operated in the Pilbara region of Australia are among the longest and heaviest trains in the world. Train lengths of typically 180 to 210 cars using head end power and 240 cars using remote controlled locomotives are operated regularly with mean axle loads of 30 to 32.5 tonnes. Gross train masses range up to 30000 tonnes and length over 2.5km. The trains operate continuously over single track railroads some 400 km long.

A reduction in operating costs has been achieved by operating longer and heavier trains which have reduced the fuel consumed per tonne of ore. Whilst this trend will continue, further gains will be realised by increasing the capacity and efficiency of the railway through improved scheduling of trains. A system is currently under development that will enable trains to be scheduled in real time to meet some overall railway objective or strategy. At its simplest, this strategy could lie between the extremes of minimising the operating cost of the railway and of maximising the throughput of the railroad. In the case of the mining companies this relates to the demand for ore at the port. If the demand for the ore is high then there is a need to maximise the throughput to ensure that the ore is transported as fast as possible. If the demand for the ore is low, when the stockpiles are full for example, then the objective may be to transport the ore in the most cost-effective manner.

With the iron ore trains it has been found that different scheduling objectives require quite different driving techniques. This poses a significant problem since large in-train forces can result from a poor driving strategy and cause a broken train. The high in-train forces are a consequence of the length of these trains in relation to the track profile. The train may extend over a number of grade changes, allowing different parts of the train to be in tension or compression. The current driving strategies have evolved from a long and difficult learning process which has progressively aimed at controlling the high in-train forces and brake system response. Consequently, it is not desirable to vary a driving strategy such as occurs when there is disruption in the system. In these circumstances it is desirable to be in a position to implement an alternative driving strategy known to be appropriate. This can now be accomplished using a technology known as 'Driver Assist' (Vanselow, Davis, Duncan [1]) which will:

(i) provide an overall operating system which can dynamically

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accommodating changes in real-time,and still satisfy objectives relating to time and cost. It is this system which sets goals for individual trains by way of the Train Scheduling Algorithm.

(ii) continuously advise the driver of the control actions required to drive the train while meeting goals in areas such as fuel use, in-train forces, or transit times by means of the Driver Assist Algorithm.

BACKGROUND

Current state-of-the-art electronic equipment has been developed, including the 'Locologger' (Idrus, Kurz, Malone [2]) which monitors and records locomotive performance and driver's control actions, Portable Data Loggers and Transportable Data Recorders for in-train measurement and recording of forces or brake system pressures. The suite of sophisticated equipment also includes the Train Driving Simulator (Blair, Norman, Fitzgerald, Mamczak [3]) which can simulate the response of a train to track characteristics and control actions, providing information in real time on speed, fuel use and in-train forces. However, these devices are used in an "off-line" mode, in the sense that the data is collected for later analysis. The intent of 'Driver Assist' is to extend the capabilities of this equipment so that it operates in a real-time, "on-line" predictive mode.

Feasibility Study

It was necessary as a first step to investigate the technical and economic feasibility of implementing such technology in this way (Vanselow, Davis, Duncan [1]). In a technical sense, it was demonstrated that it is possible to:

(i) predict the dynamic performance of a train over a known section of track based on its response to feasible control actions by the driver.

determine which of these control actions make up the best driving strategy to achieve some overall objective for the train.

(iii) develop an operations controller which will continously recognize and assess the state of the rail system and set goals for each train (or track machine) so that some overall system objective, such as operating cost, is optimized. Such a controller needs to respond in real time to any change and reorder the system to meet new conditions.

(iv) develop the necessary hardware, software and systems to acquire, process and transfer data and information on which decisions can be based.

The economic feasibility depended upon estimates of costs and potential benefits. These had to be sufficiently accurate to confirm that 'Driver Assist' would provide a competitive and attractive investment for

the future. The initial estimates of costs and benefits will be validated following testing of the prototype system.

System Development

During the last eighteen months the development has concentrated on algorithms which determine operating strategies. This has involved many hours on the Train Driving Simulator to gain an understanding of the effects that different control actions have on in-train forces and fuel usage. Many of the variables were tested on-track at both Hamersley Iron and Mt Newman, during which in-train forces and brake system pressures were measured. This not only provided information for use in the 'Driver Assist' project but provided useful information validating the Train Driving Simulator and its usage in such investigations.

In addition, it was necessary to define both the long and short term requirements for the hardware to:

(i) enable, the display of the information to the train driver on-board the locomotive

(ii) monitor and record the status of the locomotives to provide input information on train performance

(iii) interface with other systems, such as Centralised Train Control (CTC)

The short term objective is to demonstrate that a 'Driver Assist' system can be made to operate as a railway control system. The longer term requirements will follow on-site testing.

CURRENT SYSTEM OVERVIEW

Development of a prototype system, both hardware and software, has been completed and tested at Hamersley Iron in February/March 1987. The objective of these tests was to demonstrate that operating information can be determined and displayed to both the Train Controller and to the Train Driver in real time.

Hardware Development

Basing the prototype hardware design around existing technology and experience had a significant impact on the design. It was decided very early in the development process to locate the decision-making ability at a centrally based computer in the vicinity of the Train Controller, while equipment on-board the locomotives would display information to the train driver and monitor the status and performance of the train. Communication between each train and central control is by means of a radio link. The testing undertaken at Hamersley Iron used their existing radio link. A schematic of the hardware configuration is shown in Figure 1.

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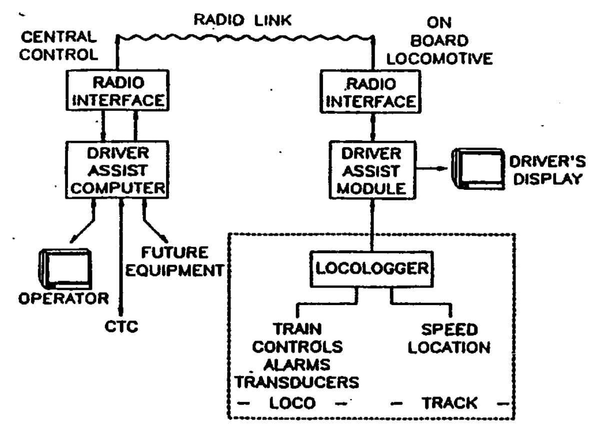


Figure 1 Schematic of Hardware Configuration for the Initial System Tests

Locomotive Based Equipment

Since the existing 'Locologger' incorporated many of the requirements needed in the Driver Assist System, it formed the basis of the on-board equipment. These features include:

(i) Data Acquisition System: contains six microprocessor sub-systems and gathers analogue and digital signals from transmitters and system alarms on the locomotive. Digital pulses from other devices (such as fuel flow meters) are also processed. Track location is monitored by the axle generator, calibrated regularly by means of track mounted transponders. All signals are referenced to geographical positions on track.

(ii) Data Storage Module: stores the data from the Data Acquisition System in solid state memory cartridges for later dumping onto a Data Transfer Unit and analysis by computer.

(iii) Intelligent Display Unit: replaces the conventional locomotive speedometer and displays the results of the driver's control actions immediately they are made, as well as the locomotive's operating condition in real time.

The current display is a 125 mm monochrome CRT. However, for use in the Driver Assist application, a 250mm colour monitor has been developed since a much greater amount of information on different display pages, is required to be displayed.

(iv) Transmitters: measure and transmit gauge and differential pressure, temperatures, linear and rotary displacements, high and low voltages and currents, coupler forces and track location. These are 'ruggedised' devices used to measure and transmit the fundamental signals on train status and train control actions made by the driver.

(v) Power Supply: provides 'clean' distributed power to electronic equipment.The locomotive's on-board supply of 74 volts is used as the primary input to the 400 watt capacity unit, developed for Driver Assist and now standard on the 'Locologger'.

With 'Driver Assist', it was necessary to add additional features and computing power on-board the locomotive, based around a Motorola 68010 microprocessor system with sufficient capacity to meet short term, and many longer term, requirements. Most of the software required on-board the locomotive has been developed in FORTRAN. The hardware can be interfaced to a terminal and disc drives which greatly speeds up the rate of development and testing on-site. Interface with the existing radio link allows information to be transmitted to and from the train.

Prototype hardware has been installed on three locomotives at Hamersley Iron for the purposes of testing.

Central Control

The hardware located at Central Control is based around a Hewlett Packard A900 mini-computer. Allowances are currently being made to interface with other systems, including the CTC signalling systems which exist at Hamersley Iron and Mt Newman.

Radio Link

A 1200 baud radio link allows the transmission of data between the Central Control and equipment on-board the locomotive. Tests have been carried out at Hamersley Iron to determine error rates and identify areas of poor radio coverage. A coverage of about 97% has been achieved.

Software Development

The ability to schedule trains according to some system strategy required developing algorithms that could predict the performance of a train under different operating conditions. In the case of long heavy haul trains, it was necessary to determine control actions that would achieve the required strategy without inducing high in-train forces and a broken train. These algorithms are required to interact with the Scheduling Algorithm which effectively acts as a decision maker under the control of an executive program. Data flows between the software modules, currently under development, and external systems are shown in Figure 2.

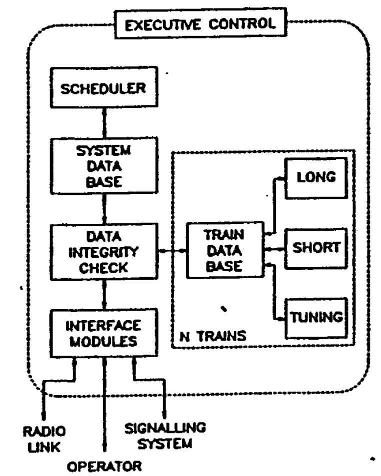


Figure 2 Data Flow Between Software Modules

Long Term Controller

The Long Term Controller (LTC) predicts the cost and travel time for an extensive set of feasible driving strategies over a section of track. In the existing system, the entire length of the track, some 400 km, is considered, with the train stopping or not stopping at passing sidings. For long, heavy haul trains, the difference in travel times between a train stopping or not stopping can be significant. The process is unconstrained, except by imposed speed limits, and the resulting strategies are given in terms of force and velocity profiles. The Train Scheduling Algorithm determines the actual strategy to be implemented using information from the LTC.

To determine the alternative force profiles, which influence fuel consumption, brake wear and coupler fatigue, a dynamic programming technique (Elgerd [4]) is used to systematically examine the effects of different driving strategies and establish a relationship between operating cost and travel time. This relationship, shown schematically in Figure 3, has highlighted a 20% difference in operating costs, primarily fuel, by allowing slower travel times and more efficiently utilising the momentum of the train. The output has been validated against the Train Driving Simulator and by limited on-track testing.

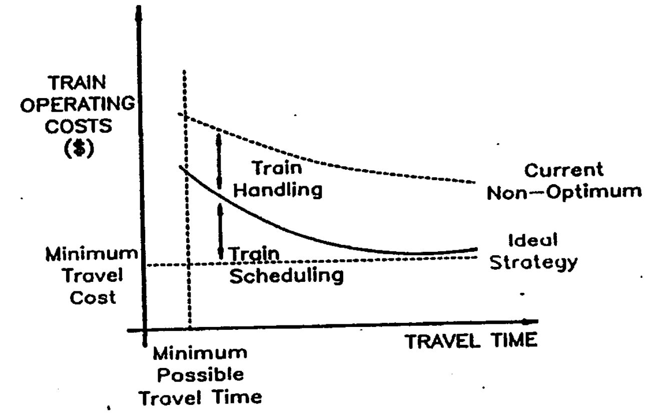


Figure 3 Relationship Between Travel Time and Operating Costs

Short Term Controller

The Short Term Controller is the module within the Driver Assist System responsible for producing the train control actions for display on-board the train. The primary input to the Short Term Controller is a specification of the journey that the train is expected to follow generated by the Long Term Controller. This specification consists of profiles of velocity, time and loco power output, all with respect to distance. The Short Term Controller processes this information to produce a set of control actions which satisfies the given specification while ensuring that consideration is given to the internal dynamics of the train to reduce in-train forces.

Tuning Algorithm

In practice, the performance of an individual train depends upon power and dynamic brake efficiencies, rolling resistance and environmental factors, such as a head wind. All of these need to be considered by any model. In effect the model is required to go through a learning process, similar to a driver obtaining a 'feel' for the train. This is important for the heavy haul situation where experience has shown that there is considerable variation between trains. The computer model is required to compensate for this variability by comparing predicted against actual performance of the train and adjusting its prediction accordingly.

The Tuning Algorithm, based upon unconstrained optimisation, enables the computer models to be adjusted in real-time to improve the subsequent prediction of a train's performance. (Powell [5]). This module has been included in the current system.

Executive Control Module

The above sections have discussed modules of the Driver Assist System which required major development work. Other modules include communication programs and Input/Output programs to interface with operating personnel and other systems including the CTC system. Since these modules exist as part of other equipment, a minimal amount of development work was required. The primary function of the Executive Control Module in the Driver Assist System is to schedule the appropriate tasks or programs at the required times and priorities to enable the overall objective of the system to be met. It continuously monitors the current status of the system and detects when there is a significant difference between predicted and actual performance. It then schedules the appropriate task to resolve the difference. Figure 4 gives a simplified, schematic representation of the interaction between the different modules.

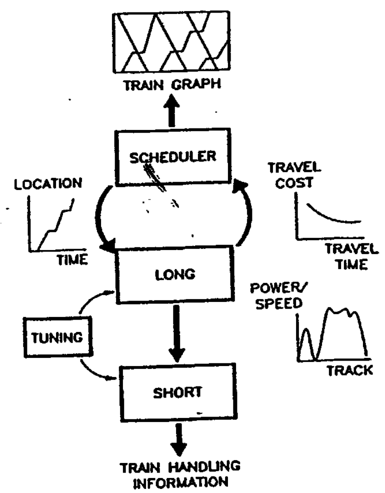


Figure 4 Simpified Schematic Representation of the Interaction Between Software Modules

SCHEDULING ALGORITHM

The aim of the Scheduling Algorithm is to determine the optimum location and time for a train meet, using the information calculated by the Long Term Controller. Clearly, this is subject to information input by the Train Controller and to conditions existing on track. In effect, the Scheduling Algorithm becomes the decision maker to choose the near optimum driving strategy for a particular train from a range of driving strategies after considering the system objective to be achieved and interaction with other trains.

The ability to determine the time and cost of different train-specific driving strategies allows the scheduling of trains to achieve a particular strategy rather than a timetable. Such strategies might include a need to maximise system throughput or to minimise the cost of operating the trains. It offers the ability to alter the schedule in an optimum fashion to meet changes that may have occurred in the system.

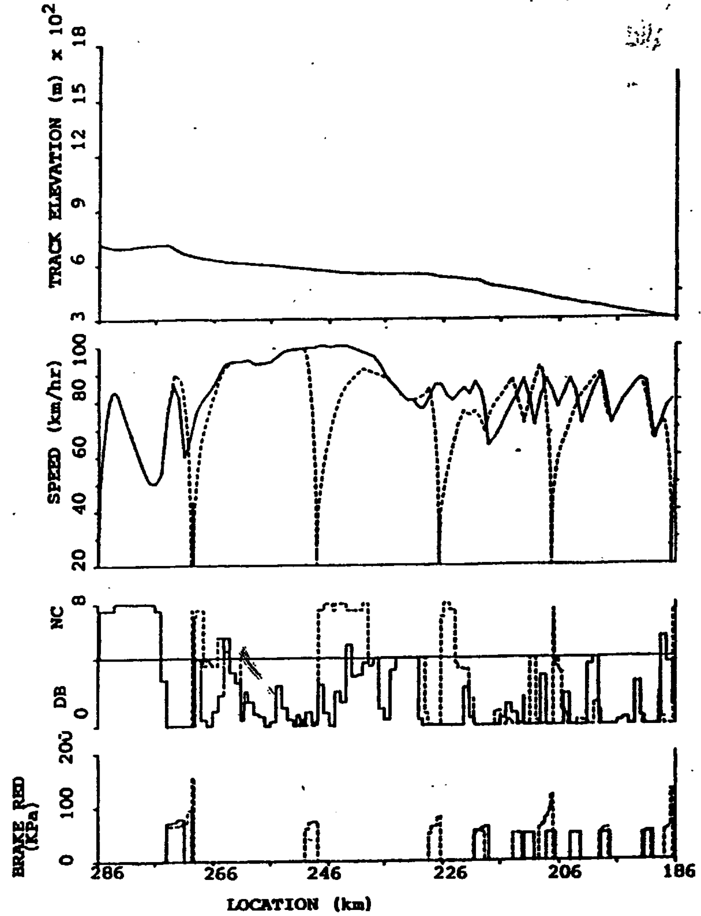
Apart from ore trains, Hamersley Iron and Mt Newman operate hi-rails, light engines and track maintenance equipment under CTC control on single-track railroads. The difficulty with the scheduling of these trains and other vehicles is determining the safest and 'best' utilisation of the system under current operating conditions, and subject to whatever operational constraints are imposed. The purpose of the Train Scheduling Algorithm is to systematically optimise the train schedule and to determine train departure times, the timing and location of train meets and other travel information, while respecting the need for other vehicles to occupy the track.

Composite Train Path

A train journey is initially specified by its start and stop locations, and its passage through the different passing sidings.

The track section between adjacent sidings is considered to consist of two travel subsections separated by an intermediate signal. Travel time and cost information is generated by the Long Term Controller for all feasible driving strategies to stop a train at a siding or to allow the train to have priority. The optimum solution is decided on a global basis by the Scheduling Algorithm after consideration of the total situation, rather than on a local decision criteria for that meet. Examples of the associated travel profiles for a train achieving a minimum time strategy are shown in Figure 5. Similar information and profiles would be determined for a train following a minimum cost strategy.

The Long Term Controller is used to determine this information for the ore trains, while simpler models are used for other vehicles.



NC = Notch (Power Setting)
DB = Dynamic Brake

Figure 5 Travel Time Information Generated by the Long Term Controller

Scheduler Operation

The difficulty in achieving a 'best' schedule is defining what is meant by 'best'. The notion of an optimum suggests that all alternatives considered are not equally efficient or cost effective. Selection of the optimum relies on as complete an evaluation of the alternative viable schedules as possible. Conditions or events that may lead to the combination of travel segments contributing to a full train schedule include:

(i) a meet with another train

(ii) track or operational constraints allowing more than one alternative travel path for a train. For example, a train may be requested to depart earlier or later to avoid the closure of a track section, or it may continue on its current schedule and be forced to wait for a period. (For this purpose, "path" is defined as a series of lines on a time-distance graph).

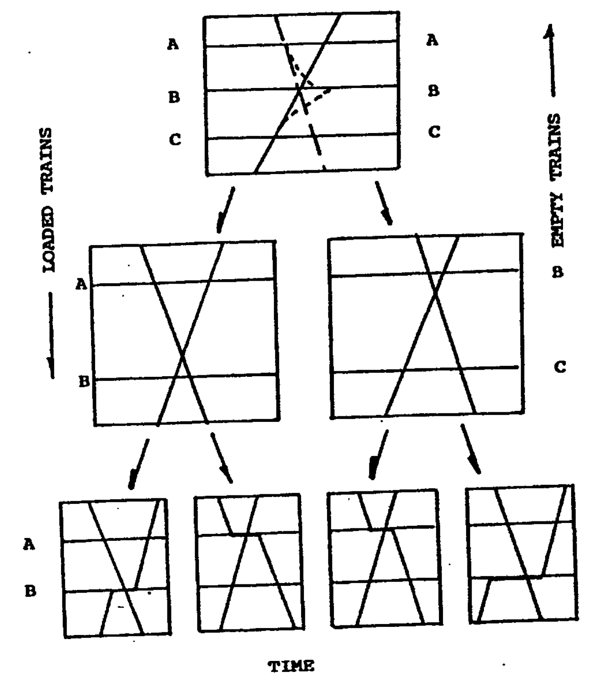


Figure 6 'Tree' Branching Resulting from a Train Meet

A train schedule is actually a composite of the separate, but related, paths for the trains involved. Where two trains meet, their complementary paths contribute to the schedule structure. Examples of this train path branching and the resulting schedule trees are given in Figure 6. The actual schedule which is chosen depends on the strategy to be achieved.

In addition to the travel time and cost information it is is also necessary to input constraints relating to allowable departure and arrival slots for a particular train. Any track "windows" or track sections closed for track maintenance must also be input, as should train crew rosters, since penalty costs resulting from a train being on track for too long have a significant impact on the schedule cost. These constraints, and the objective to be achieved, may also change with time. Furthermore, it may be necessary to recognise circumstances in which an individual train may be required to operate to a strategy which is different from the system strategy. For example, while the system objective may be to minimise the operating cost, a specific train may be required to operate at the highest priority to minimise travel time.

The Scheduling Algorithm then provides the following:

(i) requested journey departure time and the resulting scheduled arrival time. This will be updated in the event that there is a deviation from the predicted schedule.

(ii) the arrival and departure times at intermediate track sidings. These are determined subject to the constraints discussed earlier.

(iii) information to enable a train schedule time-distance graph to be generated for display to the Train Controller who may validate the schedule before it is implemented.

(iv) statistical information that can be archived as required.

v) information relating to the specified journey for use by the Short Term Controller.

Benefits of the Train Scheduling Algorithm

The fundamental reason for developing the 'Driver Assist' System is to reduce the cost of transporting ore between the minesite and the port. In the past an attempt was made for trains to follow a fixed schedule, however this rarely occured due to on-track delays and variabilities in train travel times. Generally trains were scheduled at departure, primarily to satisfy roster requirements, then progressed through the system as facilities, such as passing sidings, became available.

The major benefit of the Scheduling Algorithm currently being developed is that trains are scheduled according to some strategy or requirement, and not just to satisfy a timetable, though this may occur if required. Consequently, as changes occur on track, the system will respond to achieve management's defined strategy which may be stated, for example, as a 10% increase in throughput by reducing the cycle time of trains.

Other situations which frequently occur and can be resolved include:

(i) the early arrival of a loaded train at a passing siding. Generally, there is a higher cost associated with stopping and starting a loaded train compared with an empty train. Hence by slightly delaying the loaded train, the empty train would arrive first, eliminating the need to stop the loaded train. However, analysis and investigations have demonstrated that each situation needs to be considered on its own merits;

(ii) the empty train has a considerable wait. The excess delay time could enable a more cost effective driving strategy to be implemented, such as approaching the passing siding at a lower average speed and coasting to a stop.

(iii) Both trains required to stop at a passing siding.

The Algorithm considers the real time performance of each train operating on track when determining the train schedule. The difference in performance can be significant between what would appear to be similar trains, resulting in significant variations in travel times. The performance of a train could also vary in the event that a locomotive fails, or is low on power. It has also been found that the maximum speed of a train can be reduced by up to 10 km/hr in the event of a strong head wind. Effects that speed restrictions have on travel times are considered by the Long Term Controller when it generates the cost and travel time information.

Whilst the current objective is to implement the Scheduling Algorithm into a railway control system, it can also be used as a planning tool in a stand-alone mode. In this mode it can be used to evaluate different operating procedures, strategies and train configurations.

Sample Schedule Outputs

The process of schedule tree evaluation stops when one of the following end conditions is reached:

- the complete tree has been explored
- the number of feasible schedules to be considered has reached a declared maximum
- the declared maximum elapsed time for Algorithm operation has been reached
- the Algorithm has been externally terminated by the Executive Controllor.

Extensive simulations of different trains, priorities and system objective combinations have been undertaken to determine how the Scheduling Algorithm functions and interacts with the other modules. One of the difficulties found has been to validate the algorithm and establish that it is generating a near-optimum solution.

However, a result of the simulations carried out on one railway has shown that there is up to a 20% difference in operating costs, primarily fuel, between a schedule generated to a minimum time strategy and a schedule generated to a minimum cost strategy. This difference results in potentially large cost savings by operating trains in the most cost effective manner.

A time-distance train graph consisting of five empty trains and five loaded trains is shown in Figure 7(a) according to a minimum operating cost objective. Figure 7(b) shows the schedule resulting from scheduling the same trains according to minimum time objective. Comparison between the two schedules highlights the difference in travel times and the result that this has on the location and timing of train meets.

CONCLUSION

The Driver Assist System presented in this paper refers to a computer-based system and associated subsystems which operate in real time to act as a railway control system. This required the ability to determine all feasible driving strategies for a number of trains operating simultaneously and continuously on a single track railroad to enable trains to be dynamically scheduled, by means of an algorithm, to achieve a defined system objective. The system objective could lie between the extremes of maximising throughput or minimising the cost (including fuel usage, in-train forces, and brake applications) of train operations.

Detailed studies were conducted to investigate the technical and the economic feasibilities of the proposed system. The economic studies showed that there are potentially large operational and capacity related savings to be obtained through Driver Assist, in addition to a number of indirect benefits associated with improved performance data. The technical studies showed that Driver Assist was technically feasible and subsequent development has resulted in system testing on an operating heavy haul railway.

Hardware was developed by extending the capabilities of existing hardware. However, to make Driver Assist a reality the majority of the development effort concentrated on the software. The ability to determine the cost and associated travel times for all feasible driving strategies has enabled the development of a dynamic Scheduling Algorithm which can respond to changes in real time.

Although the development of the Driver Assist system represents a considerable technical challenge, it also represents a massive challenge to the management teams of operating railroads. Driver Assist will either directly or indirectly affect a number of separate groups within the railways, including Train Controllers, Signals and Communications personnel, Locomotive maintenance personnel, Technical support groups and, of course, Train Drivers. Even though the objective of Driver Assist is to provide Drivers with more information and advice to allow them to do their jobs more effectively, it will be necessary to work closely with all affected groups to obtain maximum benefits.

Acknowledgement

The authors wish to express their gratitude to the management of Hamersley Iron Pty Ltd, Mt Newman Pty Ltd, ACET Limited and Australian Industrial Research and Development Incentives Board, for permission to publish this paper.

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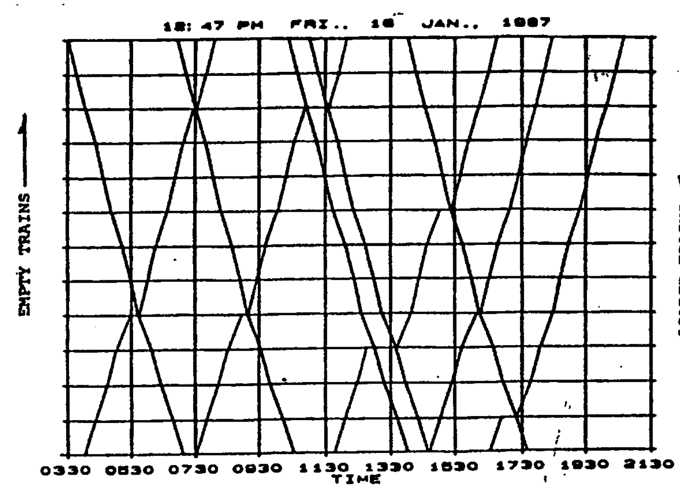

Figure 7(a) Schedule to a Minimum Time Strategy

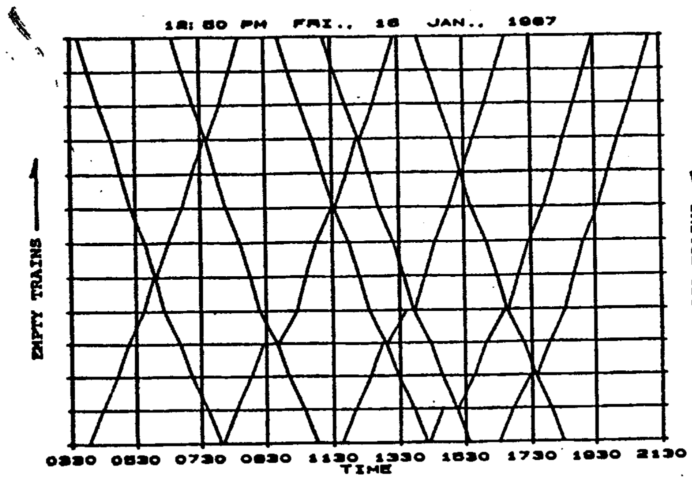

Figure 7(b) Schedule to a Minimum Cost Strategy

Timetables for the Zurich S-Bahn

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Institute of Transportation-, Traffic-, Highway-, and Rail
IVT, Swiss Federal Institute of Technology, CH-8093 Zu

1. INTRODUCTION

Drawing up timetables for the Zurich S-Bahn is a very cor
one hand, the S-Bahn runs on a closely knit network with
and local passenger traffic side by side, for which timeta
up by the conventional graphical methods used in th
disproportional effort. On the other hand, the boun
continually changing or in some cases are not even know
rolling-stock, the Rail 2000 concept of the Swiss Federal
extensions and links between lines, and so on, are typica
of significance for the Zurich S-Bahn and they mak
timetables by conventional methods a very tedious job.

The concentration on manual work which occurs
drawn up by the conventional method and the associated
with the demand for a timetable which takes into accoun
boundary conditions. But this cannot be to the benefi
especially since today there are computer programs avail
timetable planner of the manual work, giving him tin
enabling him to vary timetables and observe the resultant

The data concept presented in an article by P. Gige
simulation of railway networks) is the basis of the railw
RWS[2]. The Zurich S-Bahn will be considered as an exa
description of the manner in which this program function

2. THE ZURICH S-BAHN

Zurich Central Station with its 16 platforms is nowa
terminal point for nearly all local transport routes in the Z
S-Bahn currently under construction is completed, this
fundamentally. This line, which will be 12 km long, wil
strasse station - with 4 platforms situated underground -
the Central Station and, after passing beneath the river Li

Morlock et al.

RAILROAD FREIGHT TRAIN SCHEDULING:
A MATHEMATICAL PROGRAMMING FORMULATION†

by

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and

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and

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† The extensive assistance of persons in various departements of The Chicago, Burlington and Quincy Railroad, is gratefully acknowledged.

ABSTRACT

The problem of scheduling railroad freight trains is one that is of continual interest to the railroad industry. Presently, there is argument as to whether short, fast trains or long, slow trains are the most efficient and profitable way of hauling various traffic in differing geographic and competitive situations. The combinations of train size, speed, power, departure times, scheduled stops, traffic carried, and other variables make the determination of train schedules for even the most simple networks complicated. It seems appropriate, then, to attempt to develop efficient models for assisting decision-makers in the scheduling of freight trains through a railroad network.

The examination of a specific real-life problem led to the development of a general model, which was then tested on an actual, but simple rail network. The model was first formulated as a mathematical programming problem which turned out to be a solvable mixed-integer linear programming problem. The model is constructed so as to answer four important railroad operating questions: the route and intermediate stops of the trains run, their departure times, the cars per train, and the speed of the trains run. Total cost (train operating cost plus intermediate yard cost plus car-time and service cost) is minimized in the model, while a minimum level of service is provided.

The general model yields answers in terms of trains (defined by horsepower-to-tonnage ratio, car limit, route, and departure time), cars per train, and total car-hours used. The model is applied to a specific real-life problem, and results are obtained and compared with existing schedules.

Finally, extensions of the model which will allow it to represent much larger networks and represent networks more realistically are described.

INTRODUCTION

Background

A railroad system can be thought of as a network consisting of nodes connected by links. The nodes represent terminals, and the links represent main-line track which connects these terminals. Freight traffic enters the system at various nodes, and it is moved by road freight trains over the links until its destination node is reached.

Railroad operations may be defined as (1) inter-nodal and (2) intra-nodal.[7] Inter-nodal operations consist mainly of the operation of road trains over the links of the network. Intra-nodal operations include the switching or classification of freight cars, as well as engine servicing, train inspection, changing of crews, and other terminal functions. Classification is the sorting of freight cars into groups with similar destinations or other common characteristics. In most railroad networks, a few important yards perform most of the network's classification function.

In the problem considered in this research, a sub-network of a railroad system is considered, and the freight cars enter this sub-network already classified. The only intra-nodal activity considered is at the one intermediate node in the sub-network where, though no classification takes place, road trains may be originated, terminated, or their make-up changed. The model, then, deals mainly with alternatives of the inter-nodal activity of road train operation.

Railroad Freight Train Operating Questions

The scheduling of freight trains is of growing importance in the railroad industry today. Naturally, it is desirable to minimize total operating cost when moving given traffic. This has often been thought to be accomplished by maximizing the cars per train and minimizing total train miles. But, today there is intense intramodal and intermodal competition for most rail traffic, making necessary the swift and dependable movement of much rail traffic. The cost of new freight cars is increasing, especially with the trend to more specialized equipment. Therefore, the additional operating expense involved in providing faster, more frequent service may sometimes be offset by the decreased cost due to less car time used, and the additional traffic obtained or higher rates allowed.

Various railroad operating questions must be answered in order to determine the optimal train scheduling for a railroad network. Four basic railroad freight train scheduling questions are considered in this study. They are: (1) the route and intermediate stops of the train, (2) the departure time of the train from its initial node, (3) the cars per train, and (4) the power (or speed) of the train.

By considering these questions, the model will be able to choose between direct, non-stop trains and those which stop at intermediate yards. For both these types of trains, the optimal number of cars per train, and the best of various train departure times can be determined.

Previous Work in the Area of Train Scheduling

A small amount of work has been published in the area of railroad train scheduling. Beckmann, McGuire, and Winsten[2] include a chapter on train scheduling to minimize accumulation delay in their book. This chapter involves the development of a train scheduling model for a single line and offers some thoughts on scheduling trains for a more complex network.

Some railroad network simulation models have been developed. Allman's[1] network simulation evaluated alternatives defined by regularly-scheduled trains, their route and cars, as well as the grouping policy for each of the network's yards. Also, a published network simulation performed within the railroad industry was that of Bellman[3] of the Frisco Railway.

Mansfield and Wein[12] attempted to determine the location for a new classification yard by constructing a mathematical model which would choose as optimal the yard location which minimized the total train operating costs and yard construction cost.

A linear programming model to schedule trains for a small, triangular network was developed by Charnes and Miller.[5] Their model assumed that minimizing crew costs would yield the optimal scheduling of trains and crews. There have also been related studies such as Devanney's[6] dynamic programming approach to passenger vehicle scheduling, and empty freight car distribution models such as that of Kloer[9], Boberault and White[4], and Leddon and Wrathall.[11]

Reasons for Attempting a Mathematical Programming Formulation

Any attempt to answer rationally the four operating questions described earlier involves at least four steps. These are: (1) the generation of alternative system schedules, consisting of the route, number of cars, departure time, and power (or speed) of each and every train, (2) the prediction of the consequences of each alternative, consisting of costs in this study, (3) the evaluation of each alternative, consisting of a total variable operating cost, and (4) a comparison of alternatives and selection of the best one. Most previous and current railroad scheduling research concentrates upon the prediction and evaluation, employing simulation-type models. These models can deal effectively with predictions and evaluations with very complex, stochastic interactions. However, each alternative schedule must be generated outside the model, and input to it; and the prediction and evaluation for each alternative may be costly due to voluminous data input.[1] Moreover, there is generally no comparison and selection of alternatives within these models, so that this must also be done separately, usually manually. Thus, these models are not ideally suited to considering a large number of scheduling alternatives and selecting the best one.

The objective of this research was to develop a railroad freight train scheduling model which was efficient in generating, evaluating, and selecting among a wide range of scheduling alternatives. Thus, it would be useful primarily in the search for a good schedule among a very large number of possible schedules, rather than the analysis of and refinement of a particular schedule. Mathematical programming is a technique developed primarily to deal efficiently with such a choice problem among hundreds of alternatives. But it imposes restrictions upon relationships, which may reduce realism relative to that of a simulation. This is the price of being able to look more globally at alternatives. Thus, the mathematical programming model is most useful for initial definition of good alternatives, and then these can be analyzed in more detail and refined with a simulation model.

Study Objectives

The first objective of this research was to solve a train scheduling problem of a particular railroad. This problem was well defined, and much information about this sub-system was available. The specific problem was essentially to answer the four railroad operating questions for a sub-system consisting of a small chain of terminals, considering a wide range of possible alternatives, including slow (drag) and fast (manifest, high power to weight ratio) trains, etc. However, this problem is a particular example of a much more general problem, which is not limited to a small number of terminals, a simple network configuration, etc. Therefore, a second objective was to formulate this problem in a manner such that the same mathematical model and solution technique could be applied to other situations, such as an entire railroad.

This study will include four major areas. First, in the following section, a general theoretical model is developed and described. Then, this general model is applied to a specific real-life example. This example is the one which motivated the study. In the third section, the results of applying the general model to the specific problem are described and analyzed. Finally, conclusions about the efficacy of the model are presented, and extensions that will make the model more realistic are considered.

THE GENERAL MODEL

In this section, a train-scheduling model is developed. In order for it to be applied to a specific problem, this model is a modified form of a more general model. The model described in this section, though, can be easily extended to solve train scheduling problems of much more complexity than the problem solved in this study.

The Network

In developing a theoretical freight train scheduling model, the first consideration is the network through which the trains will operate. A rather small real-life network was in mind at the beginning of this study, and for clarity, much of the discussion of the general model will center around this example problem. However, the abstract formulation is such that any network can be considered.

The network of yards and main lines--the fixed network--of the railroad is shown in Figure 1. The nodes are yards or terminals, and the links are the main lines. Cars come into the system at nodes A and B, and are destined for node C.

Choice Variables

The various alternatives which are to be considered in this train scheduling problem are defined by the model's choice variables. The four operating questions mentioned earlier will be answered when the optimal values of the variables are determined.

There are four groups of choice variables in the model, the first group being the train variables, each of which is a train arc. Each train variable, a binary (0,1) variable, corresponds to a specific train-arc

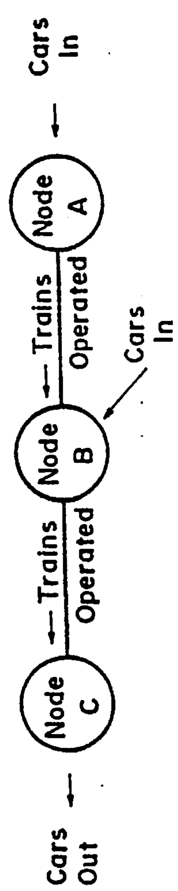

Figure I. General Model Network

and is defined in terms of the train's route and stops, its departure time from its initial node, and sometimes its speed, horsepower-to-tonnage ratio, and car-limit.

When considering only one type of train in the network described in Figure 1, there are three groups of train-arcs over which these trains may operate. In the western direction, the three groups of train arcs include direct trains from node A to node C, trains from node A to node B, and finally trains from node B to node C. A train from A to C stopping at B is considered equivalent to a separate train from A to B and then B to C, with a corresponding time connection at B. By considering this network with three groups of train-arcs, it is possible to compare the total cost of direct train service with service in which cars are delivered from one train to another at an intermediate yard located at node B. Within the three groups of train-arcs, different departure times from the trains' initial nodes further define the total number of train-arcs.

In the model, one option is to consider trains of only one type, such as manifest trains which have a certain schedule which can be maintained only by furnishing a specified amount of horsepower per unit weight, and by not exceeding a certain car or tonnage limit. The model also allows trains of more than one type to be considered, the different types of trains differing in their schedules, and corresponding horsepower-to-tonnage ratios and car limits.

The second group of choice variables in the model consists of variables which represent the cars per train. These variables answer the operating question: what is the optimal number of cars per train? There are the same number of cars-per-train variables as train variables, since each cars-per-train variable corresponds to a particular train-arc in the model.

In order to determine the total car time used by the various train scheduling procedures, two groups of choice variables are required in the model. The first group of variables define the number of cars that are still at the car input terminals and are ready to be moved at midnight. In our network, two of these variables are required, one for each of the two input terminals (node A and node B). These variables allow the cars that remain to be moved at the end of the scheduling day to be added to the cars available at the start of the day, and allow the correct car waiting time to be determined.

Secondly, a single choice variable represents the total car-time, less that car-time already computed by variables representing the cars at an input terminal at midnight. The total car-time is the time that each car spends from the time that it is ready to be moved at one of the input terminals, until it has arrived at the destination terminal summed over all the cars that are input into the network on the day considered. Together, the car-time variable and the variable representing the cars to be moved at midnight give the total car-time for the network, and therefore, allow the total car costs of various scheduling procedures to be determined.

Costs

The train-scheduling model schedules trains so as to minimize total cost. Total cost includes all costs that vary with variations in train scheduling. Those railroad operating costs that vary with different train scheduling procedures will now be included in the model, and expressed in terms of the choice variables that have been chosen for this model.

Total train crew and engine crew costs definitely vary when different numbers of trains are scheduled. The total car costs vary with different train schedules; and locomotive investment, maintenance, and operating costs will vary if trains of different schedules and horsepower-to-tonnage ratios are considered.

Yard costs at intermediate terminals such as node B will vary with alternative scheduling of direct trains or trains which are handled at the intermediate yard. Yard expenses at node A and node C, though, are assumed not to vary, since the same number of cars is handled through each yard no matter what train scheduling procedure is used. This assumes that long trains pose no great hardship on these yards, either in terms of length of receiving and departure tracks needed, or by causing switching work to be concentrated into short time periods surrounding the arrival or departure of the long trains operated. This assumption tends to favor long trains, as yard costs surely increase as traffic is concentrated.

Other costs that are assumed not to vary with varying train scheduling procedures are maintenance of way costs, costs of building and maintaining structures, and general expenses not directly related to train operation.

Four groups of costs, then, are assumed to be the only costs that vary significantly with alternative train scheduling procedures. They are:

1. train and engine crew cost
2. intermediate yard cost
3. car-time cost
4. cost of additional horsepower per car

In order to be used in a mixed-integer programming model, the preceding costs must be expressed as functions of the choice variables of the model. The train and engine crew costs vary with the number of trains run, the total weight of the engines on each train, and the number of cars per train. These costs can be approximated by a linear function varying with the number of trains and the number of cars per train, since for a given type (speed) of train the ratio of horsepower-to-tonnage, and therefore, the engine-to-car ratio will be constant.

The intermediate yard cost that is dependent on different scheduling procedures appears to vary with the amount of switch-engine time required to handle the yard's traffic, since other yard costs are virtually fixed in the short run. Yard office employees, maintenance employees, and at least one switch engine and crew must be available at this network's intermediate yard to switch local trains and local traffic. The additional cost of handling road trains in the yard will be a function of the increased operating and maintenance expenses of the switch engine, which vary with the amount of switch-engine time used. The intermediate yard cost is, then, expressed as a linear function of the number of road trains to enter the yard, and the number of cars on each of these trains.

The actual car-time cost is assessed daily. For foreign cars, the railroad on which the freight car is at midnight is charged the daily per diem rate for that car. If the car is a home-road car, naturally no per diem charge is assessed. But, each car has a time-value, no matter whether it is a home or foreign car. In this study, no distinction is made between home and foreign cars; and an hourly time cost is used which equals the average per diem rate divided by 24 hours, plus an hourly value of service cost. The use of an hourly rate instead of a daily rate has the advantage of rewarding savings of just a few hours, which when accumulated over a car's journey and over a large railroad system increase that railroad's car supply (or reduce car requirements) and reduce the total daily per diem charges as well as car ownership costs.

If trains of different types, that is with different schedules requiring different amounts of horsepower per trailing ton, are considered, train operating costs will vary between the different types of trains. If trains of only one type are operated, one can neglect locomotive costs, since it is assumed that whether two locomotives move a 100-car train at a given speed, or each of the locomotives haul a 50-car train at the same speed, the engine costs are the same, since any small difference in wind resistance can be neglected. But, when one train is operated at a faster schedule than another, it requires more horsepower per trailing ton, or a greater engine-to-car ratio; and the added fuel consumed, as well as the investment and maintenance costs of the added locomotives, make the faster train of the same length have a considerably greater engine operating cost. The additional locomotive cost can be expressed as a function of the number of cars on the different types of trains, since there is a constant horsepower-to-tonnage or engine-to-car ratio for each type of train.

Car-Input Functions

Freight cars are input into the network at node A and node B and are destined for node C. The numbers of cars that are ready to be moved from each of the two input nodes throughout the day are represented by car-input functions, or plots of cars to be moved versus time. There is one such function for each input node-output node combination. The model requires only that the number of cars ready to be moved at the departure time of each train considered be known, but the more precise the car-input function, the more accurate will be the determination of the total elapsed car time in the model.

Available data did not break down freight cars by type, and hence all types of freight cars are considered to be represented by an "average freight car," with a daily value equal to the average freight car per diem rate. No distinction is made between loaded cars and empties, between cars loaded with cargos of different values or priorities, between cars in different per diem categories or charged only on a mileage basis, or between home road and foreign road freight cars. If data of this sort were available, then cars could be distinguished by as many categories as desired. A distinct function of cars available to be moved between each origin and destination would have to be developed for each different per diem rate or car class for which some constraint, such as a time constraint at destination, were desired.

Yard classification of freight cars is not dealt with in this model. Alternate classification policies are not considered, and cars are considered available for input into the model only after they have been classified and are already in their destination's classification track. Also, no local traffic (or cars destined for stations between nodes) is considered. When this type of network model is applied to a real-life problem, all significant traffic-originating or terminating points must be represented by nodes, and some very low volume traffic generators may be omitted.

Mathematical Formulation for One-Direction Problem

The general model can now be formulated in mathematical terms. This presentation of the model will be for scheduling in a single direction with all cars bound for a single destination. Thus ignored is the problem of locomotive availability, though trains of more than one type may be considered. These restrictions greatly facilitate the mathematical presentation of the model, and they result in a model suited to the example application. The model without these restrictions is conceptually not difficult to understand, but it is complex in its mathematical representation. The more general model is presented in the Appendix.

This model can be easily expanded to include train scheduling in both directions, with cars input into the network at any node and destined for any node, with the exception that cars do not originate and terminate at the same node. Also, engines can be included as variables, and car variables can be expanded to include as many freight car categories as one wishes to consider.

In the mathematical formulation with the previously mentioned restrictions, the following notation will be used:

A_i = Cost of running train i, \$

B_i = Cost per car on train i, \$

C = Cost per unit of car-time, \$/car-hour

D_i = Time of departure of train i, hours

E_k = Area under car-input function for node k, car-hours

F_i = Running time of train i, hours

G_{kj} = Cumulative number of cars originating at node k at time of departure of train j, cars

H_k = The total number of cars available to be moved for the entire day at node k, cars

L_k = Set of designations (i's) of trains leaving node k

R_i = Limit of the number of cars per train i, cars

T_k = Set of designations (i's) of trains terminating at node k

L_{kj} = Set of designations of trains (i's) leaving node k before departure of train j leaving node k

T_{kj} = Set of designations of trains (i's) arriving at node k in time for cars to be available for departure on train j leaving node k

i = Train designation, $i=1,2,\ldots,I$

j = Train designation, $j=1,2,\ldots,I$

k = Node designation, $k=1,2,\ldots,K$

I = The total number of train-arcs in the network

K = The destination terminal's designation

z = The total variable cost in the problem

t_i = Choice variable for existance of train i, binary (0 or 1)

w_i = Number of cars on train i, cars

x_k = Cars remaining to be moved from node k at the end of the scheduling period (day), cars

y = The total car hours in the problem, less the product of (24 hours)(the cars remaining to be moved from all nodes at midnight), car-hours

Problem Statement

The freight train scheduling model schedules trains so as to minimize the total cost which will be incurred. This total cost is composed of costs which vary with the number of trains operated, the number of cars per train, the number of cars remaining to be moved at midnight of the scheduling day, and costs that vary with the total elapsed car-hours. Mathematically, the objective of the model is to minimize

$$z = \sum_{i=1}^{I} A_i \cdot t_i + \sum_{i=1}^{I} B_i \cdot w_i + 24C \sum_{k=1}^{K} x_k + Cy$$

subject to the following groups of constraints:

1. The following equation determines the value of y, the car-time variable. Shown in Figure 2 is the computation of that part of y attributable to one example input node, designated node 2.

This example is for the case of one train into node 2 and one train departing node ~~2~~ t_1 and t_2 respectively. The value of y can then be obtained by summing the car-time for each node over all the nodes in the network.

$$y = \underset{(1)}{\sum_{k=1}^{K-1} (E_k)} + \underset{(2)}{\sum_{k=1}^{K-1} \sum_{i \text{ in } T_k} (24-D_i-F_i)(w_i)} -$$

$$\underset{(3)}{\sum_{k=1}^{K-1} \sum_{i \text{ in } L_k} (24-D_i)(w_i)} + \underset{(4)}{\sum_{k=1}^{K-1} \sum_{i \text{ in } L_k} (F_i)(w_i)}$$

The first term in the equation (1) represents the area under node 2's input function, and this is designated as E_2 or A_1 in Figure 2. Added to this is the second term in the equation (2), which is the number of cars (w_1) brought into node 2 by trains terminating at node 2 multiplied by the time between midnight and the trains' arrival time at node 2, here $24-D_1-F_1$. This area determined by the second term in the equation is designated as A_2 in Figure 2. Together, A_1 and A_2 form the total car-input function at node 2, A_1 being determined by external car inputs, and A_2 coming from car inputs from road trains terminating at node 2.

The third term in the equation represents the area formed by the product of the number of cars (w_2) on the train's departing node 2 multiplied by the time between midnight and the trains' departure time (D_2), and this term is subtracted from the area al-

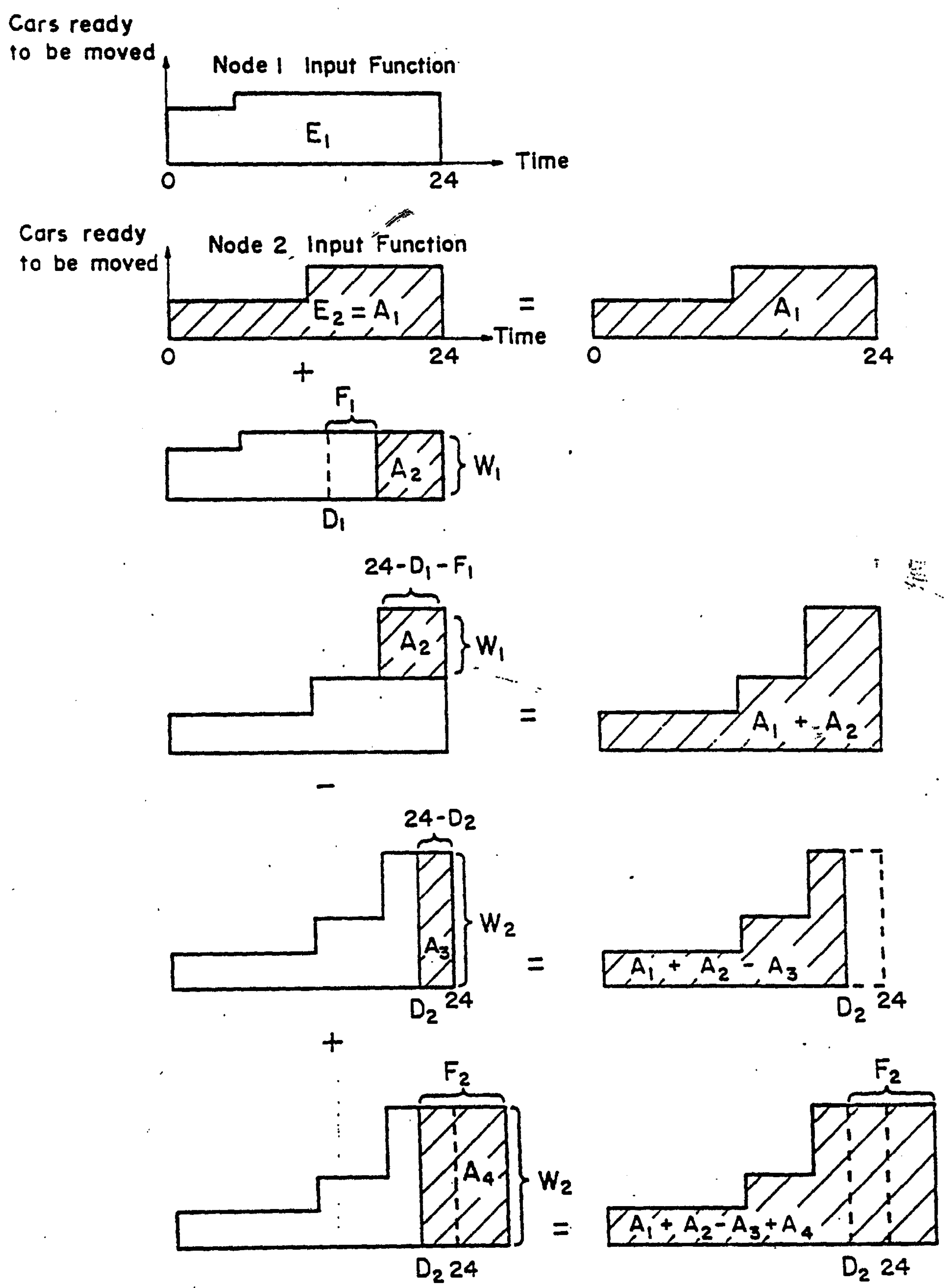

Figure 2. Car Time Determination

ready computed (A_1+A_2). Finally, the fourth term in the equation equals the product of the number of cars (w_2) on the trains departing node 2 multiplied by the running time of the trains (F_2), and this equals A_4. After subtracting A_3 from the total car input area (A_1+ A_2), the addition of A_4 yields the total car time for node 2, since the total area formed is equal to: each car's arrival time at the end of its train-arc minus the time the car was ready for movement at node 2, summed over all cars available to be moved at node 2. The value of y attributable to node 2 in this example is, then $A_1+A_2-A_3+A_4$, and to obtain the total value of y, the above procedure is repeated for all nodes, as indicated by the $\sum_{k=1}^{K-1}$ summation signs preceding all four terms in the equation.

2. The cars which depart each input node on trains between the start of the scheduling day and a given train departure time must be less than or equal to the value of the node's input function at that time, plus the cars that have been delivered to the input terminal by trains terminating at that node since the start of the scheduling day, plus the number of cars that remain to be moved at midnight of the scheduling day, i.e.,*

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* In this model, a one-day time period is used, though a longer one can easily be substituted, if desired. If one assumes that the car-input functions for the day preceding and the day following the scheduling day are the same as that for the scheduling day, then the cars remaining to be moved at the end of the scheduling day will equal the number of cars to be "carried over", and added on to the car-input function at the beginning of the scheduling day.

$$G_{kj} + x_k + \sum_{i \text{ in } T_{kj}} w_i - \sum_{i \text{ in } L_{kj}} w_i \geq w_j \text{ for all } j,\ (j=1,2,\ldots,I)$$
$$\text{for all } k,\ (k=1,2,\ldots,K-1)$$

3. The total cars which depart each input node for the entire scheduling day must equal the number of cars input into the node for the entire day plus the total cars delivered to the node by trains terminating at that node; i.e.,

$$H_k + \sum_{i \text{ in } T_{kj}} w_i - \sum_{i \text{ in } L_{kj}} w_i = w_j \text{ for all } k,\ (k=1,2,\ldots,K-1)$$

4. The cars per train must be less than or equal to the corresponding train value (0 or 1) times the limit of cars per train. The actual function of this constraint is to require that a train be run (t_i=1) if the corresponding w_i>0, i.e.,

$$R_i \cdot t_i \geq w_i \text{ for all } i,\ (i=1,2,\ldots,I)$$

5. In actual railroad operation, certain cars must be delivered to connecting lines before a certain cut-off time. On-time delivery to connecting lines at node C can be accomplished by requiring that at least one of a certain group of trains that arrive at node C before a certain cut-off time be run.

6. Constrained Variables. The train variables are restricted to taking on either a value of zero (the train is not run), or a value of one (the train is operated).

$$t_i = 0 \text{ or } 1 \quad \text{for all } i,\ (i=1,2,\ldots,I)$$

APPLICATION OF THE MODEL TO A SPECIFIC PROBLEM

The theoretical model developed in the previous section will now be applied to a specific actual example. Two different formulations will be explained, and designated as problem A and problem B. Variations of these two formulations, caused by altering certain costs and constraints, will be discussed in the following section dealing with results.

The Network

The network of the theoretical model and this particular example's network are compatible. The actual railroad line considered is 418 miles long, consisting of three crew districts. There is a major yard at each end of the line. At node B, a secondary main line joins the network, and a small yard is located here. The yard is not large enough to do much classification work, but here cars from local trains and from industries can be added to road trains, cars can be taken off road trains, and road trains can be split-up or consolidated. The other intermediate crew-change point is not represented as a node since little traffic originates or terminates there.

The network of this railroad sub-system is shown in Figure 3. Only scheduling in one direction is considered, with cars entering at nodes A and B destined for node C. The line between nodes A and B is single track equipped with Centralized Traffic Control, while the line from node B to node C is primarily a double-tracked line. Considering the volume of traffic over these lines, it does not appear that the capacity of the network's links will be a factor that will limit the number of trains which can be run.

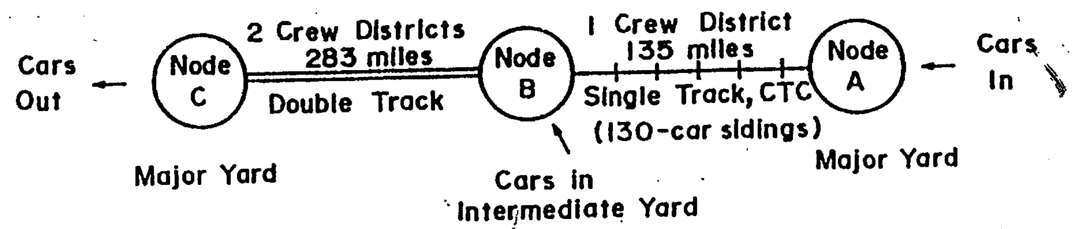

Figure 3. Actual Railroad Network of Example

Car Input Functions

Only westward traffic is considered in the model, and the real-life problem is such that westward traffic other than that destined for the gateway city at node C can be ignored, since it represents an insignificant percentage of the total traffic volume. Cars destined for node C, as well as other cars, arrive at nodes A and B throughout the day.

Various transfer runs bring cars in to the major yard at node A. These cars are inspected and classified in about two hours, and one hour is considered as the additional time required to build the cars into a road train. A time interval of three hours, then, is added to car arrival data (obtained in two-hour intervals) to construct the car input function in Figure 4. This function describes the number of cars ready to be moved from node A to node C versus time for a typical week-day.

Figure 5 describes the car input function at node B for a typical week-day. The three car inputs shown in the function come from the arrivals of two local freight trains, and one road freight train off the secondary main line. Two hours switching time is added to each of the locals' arrival times to obtain the times when their cars are ready for movement, while the cars on the road train are all destined for node C, and are considered as immediately ready to be moved beyond to node C.

Problem A

Problem A is addressed to three railroad operating questions. They are: (1) the route and intermediate stops of the trains run, (2) the departure times of these trains from their initial nodes, and (3) the cars per train. Only manifest-type trains are considered.

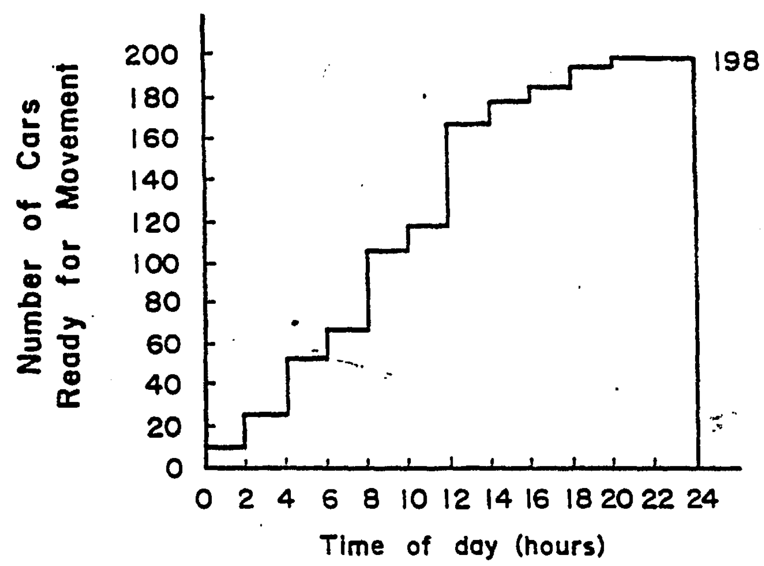

Figure 4. Car Input Function for Node A

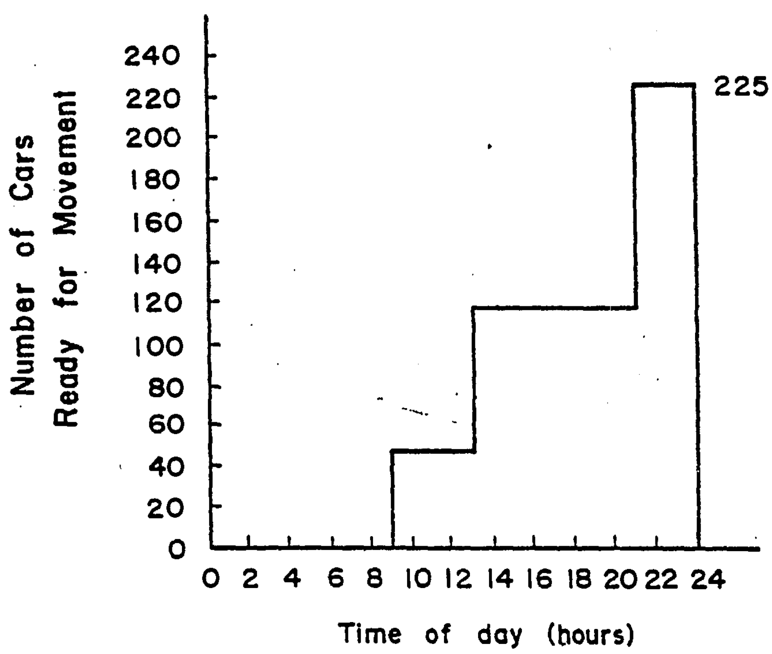

Figure 5. Car Input Function for Node B

There are 21 train variables, or train-arcs. These include seven direct manifest trains from node A to node C, seven non-direct manifest trains from node A to node B, and seven non-direct manifest trains from node B to node C, as shown in Figure 6. All manifest trains are defined to have a car limit of 120 cars, allowing them to fit into the 130-car, CTC-controlled sidings between node A and node B. A horsepower-to-tonnage ratio of 1.67 or equivalently, one engine per 30 cars,* will allow these manifests to maintain their schedules over the network links. Running time for direct manifest trains from node A direct to node C is 11 hours, while between node A and node B it is 4 hours, and between node B and node C the running time is 7 hours. The overall running time of two non-direct trains from node A to node C is 12 hours, though, since the model is constructed to allow one hour handling time at the intermediate yard at node B.

The seven departure times of trains from node A are: 1 a.m., 5 a.m., 7 a.m., 9 a.m., 1 p.m., 5 p.m., and 9 p.m. Departure times for trains which depart node B are: 2 a.m., 6 a.m., 10 a.m., Noon, 2 p.m., 6 p.m., and 10 p.m. These departure times were selected as those that appear intuitively to be the best alternatives. Possible train departure times follow closely in time most large car inputs as illustrated in Figure 7.

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*Assuming an average engine of 2500 horsepower, and an average freight car of 50 tons: $1.67 \text{ Horsepower/Ton} = \dfrac{2500 \text{ Horsepower/Engine}}{(X \text{ cars/engine})(50 \text{ tons/car})}$

$X = 30$ cars/Engine

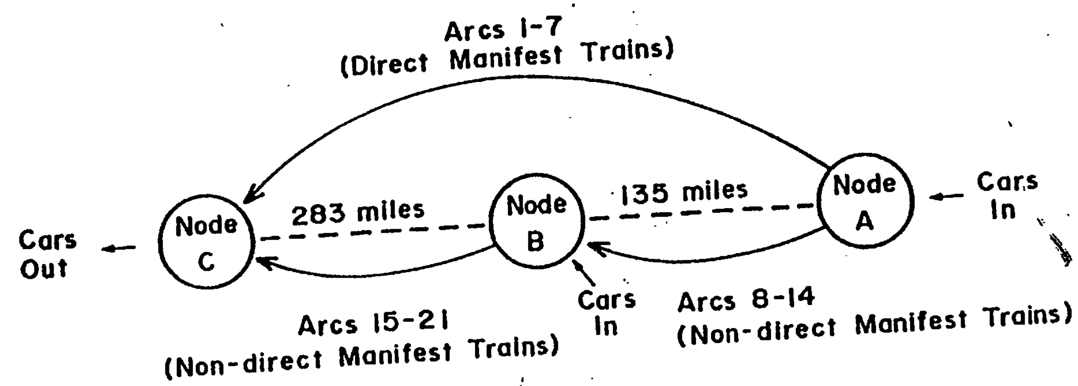

Figure 6. Train Arcs for Problem A

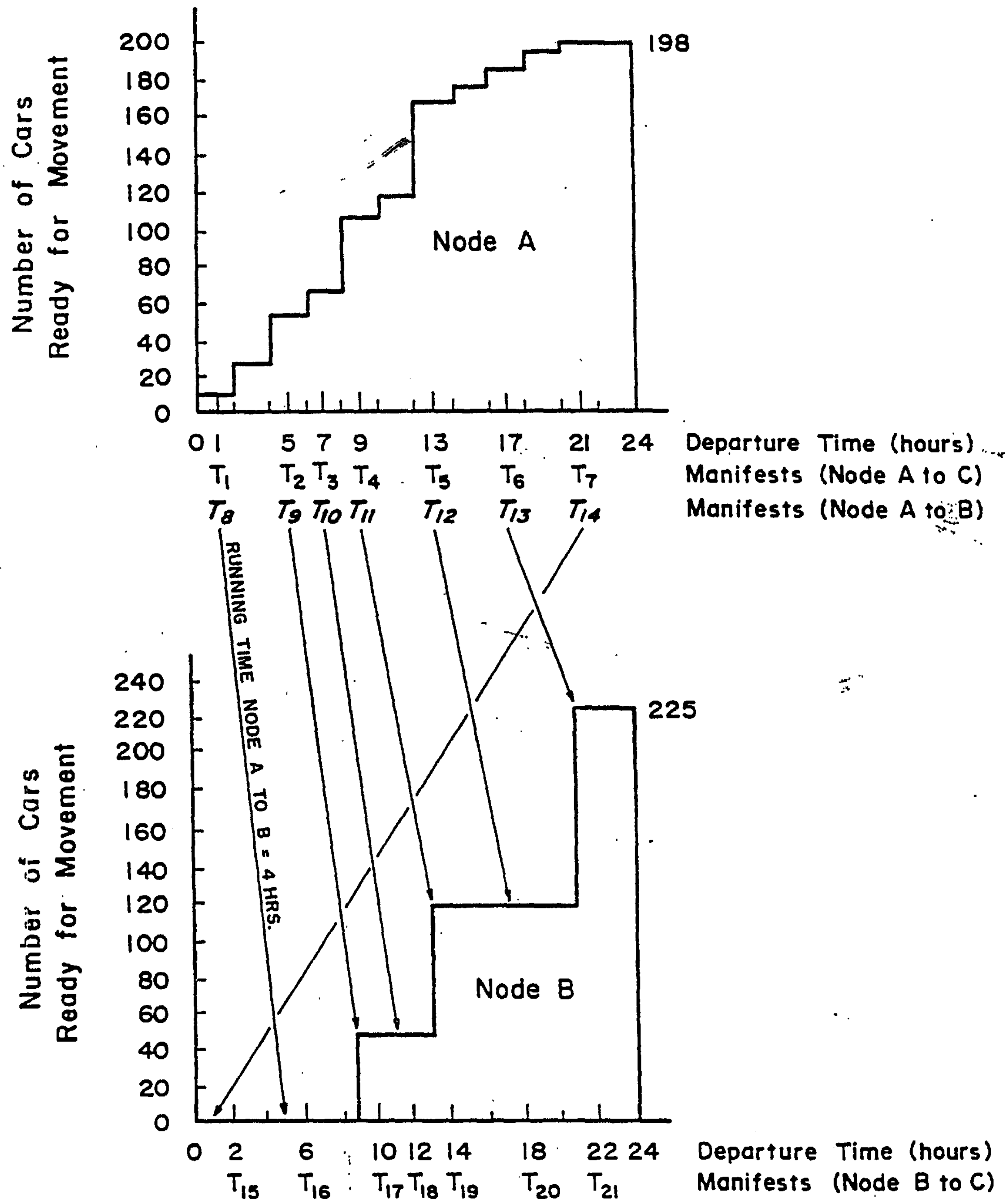

Figure 7. Train Departure Times for Problem A

There are 21 cars-per-train variables which correspond to the 21 train variables in the model. Also, since there are two input nodes, there are two variables which represent the number of cars remaining to be moved from these two nodes at midnight of the scheduling day. Finally, there is one variable representing the total car-hours, less that car-time computed by the previous two variables.

Specific cost figures for problem A can be obtained from the cost functions developed for the general model. These costs are listed in Table 1, and were derived from railroad information.

The linear-programming matrix for problem A is shown in Figure 8. Actual costs and car-input figures are applied to the general model to obtain this matrix. Of the 36 constraint rows (not including the objective function), one is a group 1 constraint, 12 belong to group 2, two are in group 3, and 21 are group 4 constraints.

Problem B

In problem B, four railroad operating questions are considered. These are: (1) the route and intermediate stops of the trains run, (2) the departure times of these trains from their initial nodes, (3) the cars per train and (4) the type (speed) of the trains run.

In problem B, drag trains, as well as manifest trains, are considered. All drags are defined to have a car-limit of 150 cars per train, which is thirty cars longer than the manifest car limit. Drags also have a horsepower-to-tonnage ratio of 1.0, requiring one 2500-horsepower engine for each 50, 50-ton freight cars.

Twenty train variables or train-arcs are used in problem B, allowing four different train departure times for each of five groups of train-arcs.

Table 1

Costs for Problem A

Train and Engine Crew Costs for Manifest trains:

From Node	To Node	Cost/Train	Cost/Car on The Train
A	C	$ 652.80	$ 0.50
A	B	$ 188.40	$ 0.12
B	C	$ 464.40	$ 0.38

Yard Cost at Intermediate Node B (This cost is added to those trains which enter the yard at Node B):

$ 10.00 / train + $ 0.15 / car on the train

Car-time Cost:

$ 6.00 / car-day or $ 0.25 / car-hour

Total Costs:

From Node	To Node	Cost/Train +	Cost/Car on The Train	Cost/Car-hour
A	C	$ 652.80	$ 0.50	
A	B	$ 198.40	$ 0.27	
B	C	$ 464.40	$ 0.38	
				$ 0.25

			Constrained to be Integers																																												
			Direct Manifests							Non-Direct Manifests							Non-Direct Manifests																												
			Node A to Node C							Node A to Node B							Node B to Node C							Node A to Node C							Node A to Node B							Node B to Node C									
Variable			Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	Y10	Y11	Y12	Y13	Y14	Y15	Y16	Y17	Y18	Y19	Y20	Y21	V1	V2	V3	V4	V5	V6	V7	V8	V9	V10	V11	V12	V13	V14	V15	V16	V17	V18	V19	V20	V21	Z1	Z2	Y
Maximum Value			1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	198	225	
Cost			652	652	652	652	652	652	652	198	[illegible]	[illegible]	[illegible]	178	198	198	464	464	464	464	464	464	464	0.5	0.5	0.5	0.5	0.5	0.5	0.5	.27	.27	.27	.27	.27	.27	.27	.38	.38	.38	.38	.38	.38	.38	6.0	6.0	.25
Constraint Group 1	4761	=																						12	8	6	4		-4	-8							-24	15	11	7	3	1	-1	-5			1
Constraint Group 2	8	≥																						1							1														-1		
	53	≥																						1	1						1	1													-1		
	66	≥																						1	1	1					1	1	1												-1		
	102	≥																						1	1	1	1				1	1	1	1											-1		
	166	≥																						1	1	1	1	1			1	1	1	1	1										-1		
	183	≥																						1	1	1	1	1	1		1	1	1	1	1	1									-1		
Constraint Group 3	198	=																						1	1	1	1	1	1	1	1	1	1	1	1	1	1										
Constraint Group 2	0	≥																																			-1	1								-1	
	0	≥																													-1						-1	1	1							-1	
	44	≥																													-1	-1					-1	1	1	1						-1	
	44	≥																													-1	-1	-1				-1	1	1	1	1					-1	
	116	≥																													-1	-1	-1	-1			-1	1	1	1	1	1				-1	
	116	≥																													-1	-1	-1	-1	-1		-1	1	1	1	1	1	1			-1	
Constraint Group 3	225	=																													-1	-1	-1	-1	-1	-1	-1	1	1	1	1	1	1	1			
Constraint Group 4	0	≥	120																					-1																							
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Figure 8. Problem A Matrix

There are four direct manifest trains from Node A to Node C, and there are four direct drags between the same two nodes. Due to problem size limitations, between node A and node B only four manifest trains are considered. Four manifest trains from node B to node C are considered, as are four drags, also from node B to node C. See Figure 9.

The added maximum length and reduced power per freight car of drags means that they operate at considerably slower speeds than manifests. The running time for manifests is eleven hours direct from node A to node C, four hours from node A to node B, and seven hours from node B to node C, while drags require 16 hours to go from node A to node C, and drags take eleven hours to go from node B to node C. The four departure times of trains which depart from node A are: 5 a.m., 9 a.m., 1 p.m., and 5 p.m. Trains which depart from node B, have departure times of: 10 a.m., 2 p.m., 6 p.m., and 10 p.m. These departure times are shown in Figure 10.

There are twenty cars-per-train variables in this problem, corresponding to the twenty train variables. Also, there are two variables representing the cars remaining to be moved from the two input nodes at midnight of the scheduling day, and one total car-hour variable.

Specific cost figures for problem B are listed in Table 2. Many of these costs are the same as for problem A, though costs for drag trains have been added, and additional engine costs are included, since they are greater for manifests than for drags.

The linear-programming matrix for problem B is shown in Figure 11. The matrix consists of 32 rows (counting the objective function), 44 columns (including the right-hand-side), and the twenty train variables are restricted to being integers. Of the 31 constraint rows (not counting the

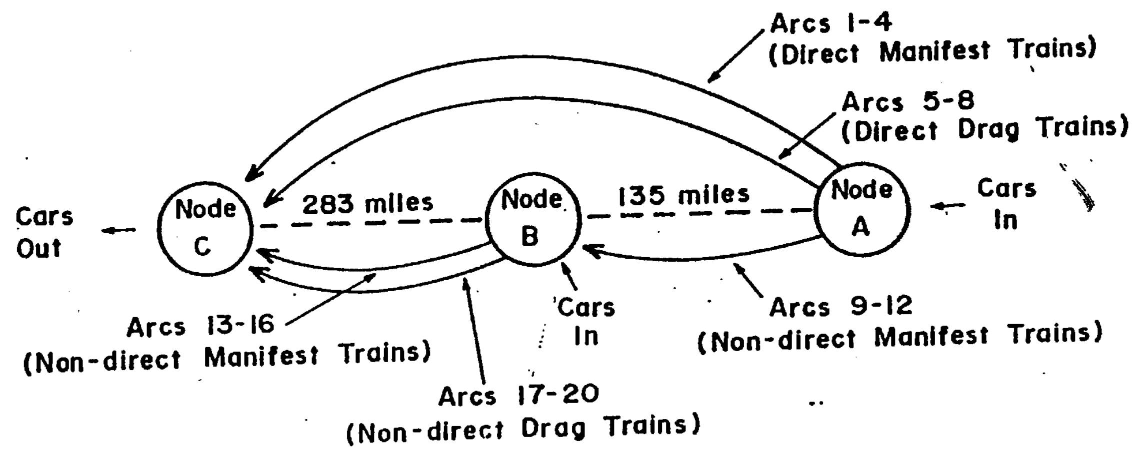

Figure 9. Train Arcs for Problem B

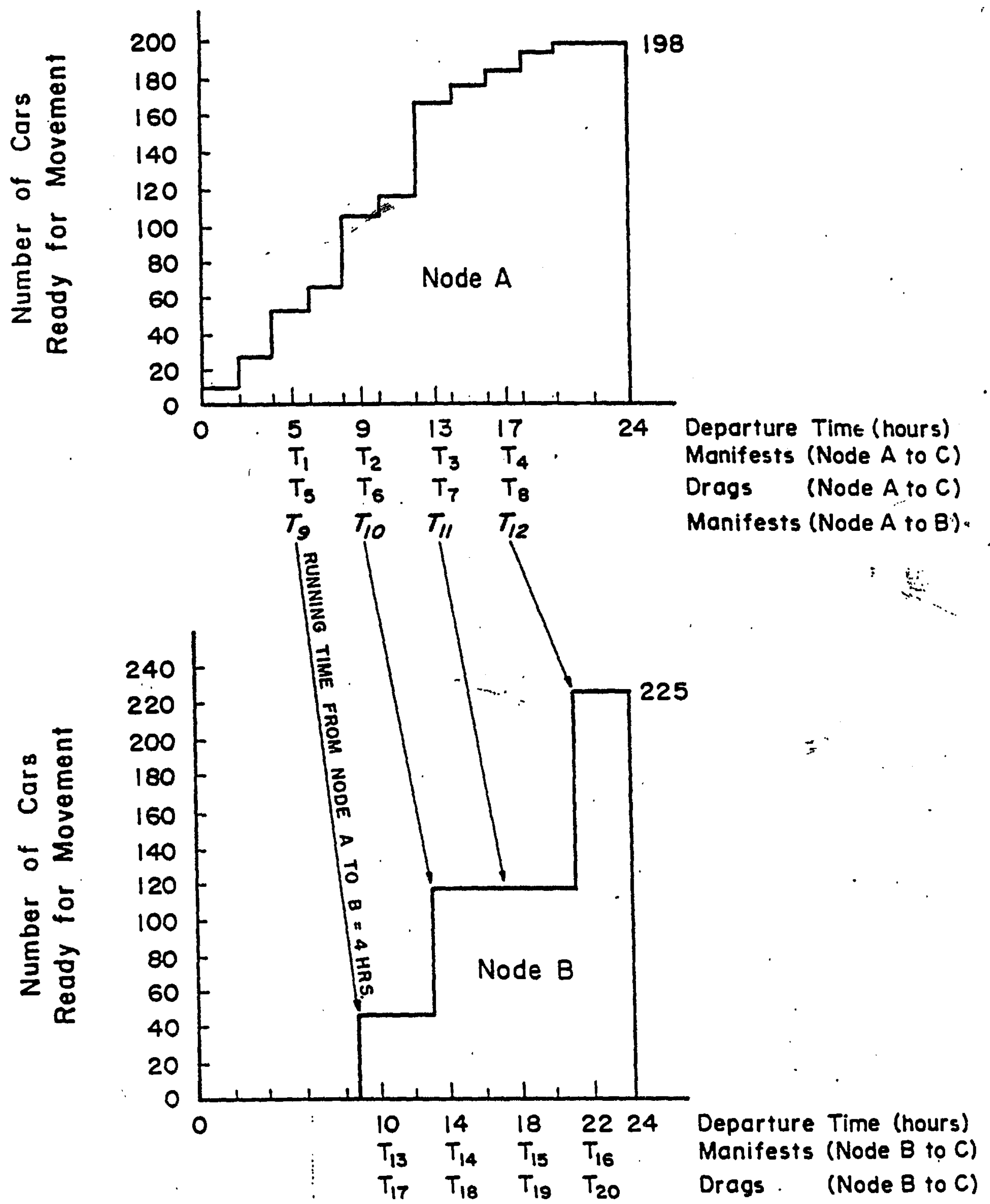

Figure 10. Train Departure Times for Problem B

Table 2

Costs for Problem B

Train and Engine Crew Costs:

	Cost/Train	+	Cost/Car on The Train
(Manifests, Node A to Node C)	$ 652.80		$ 0.50
(Drags, Node A to Node C)	$ 652.80		$ 0.38
(Manifests, Node A to Node B)	$ 188.40		$ 0.12
(Manifests, Node B to Node C)	$ 464.40		$ 0.38
(Drags, Node B to Node C)	$ 464.40		$ 0.28

Additional Engine Costs:

	Cost/Car on The Train
(Manifests, Node A to Node C)	$ 13.20
(Drags, Node A to Node C)	$ 11.50
(Manifests, Node A to Node B)	$ 4.80
(Manifests, Node B to Node C)	$ 8.40
(Drags, Node B to Node C)	$ 7.90

Yard Cost at Intermediate Node B (This cost is added to those trains which enter the yard at Node B):

$ 10.00 / train + $ 0.15 / car on the train

Car-time Costs:

$ 6.00 / car-day or $ 0.25 / car-hour

Total Costs:

	Cost/Train	+	Cost/Car on The Train	Cost/ Car-Hour
(Manifests, Node A to Node C)	$ 652.80		$ 13.70	
(Drags, Node A to Node C)	$ 652.80		$ 11.88	
(Manifests, Node A to Node B)	$ 198.40		$ 5.07	
(Manifest, Node B to Node C)	$ 464.40		$ 8.78	
(Drags, Node B to Node C)	$ 464.40		$ 8.18	
				$ 0.25

			Constrained to be Integers																																										
			Manifest				Drag				Manifest				Manifest				Drag																										
			Node A to C				Node A to C				Node A to B				Node B to C				Node B to C				Node A to C				Node A to C				Node A to B				Node B to C				Node B to C						
Variable			T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15	T16	T17	T18	T19	T20	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13	W14	W15	W16	W17	W18	W19	W20	X1	X2	Y
Maximum Value			1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	120	120	120	120	150	150	150	150	120	120	120	120	120	120	120	120	150	150	150	150	198	225	
Cost			652	652	652	652	652	652	652	652	198	198	198	198	464	464	464	464	464	464	464	464	14	14	14	14	12	12	12	12	5.1	5.1	5.1	5.1	8.8	8.8	8.8	8.8	8.2	8.2	8.2	8.2	6.0	6.0	.25
Constraint Group 1	4761	=																					8	4		-4	3	-1	-5	-9					7	3	-1	-5	3	-1	-5	-9			1
Constraint Group 2	53	≥																					1				1				1												-1		
	105	≥																					1	1			1	1			1	1											-1		
	166	≥																					1	1	1		1	1	1		1	1	1										-1		
	183	≥																					1	1	1	1	1	1	1	1	1	1	1	1									-1		
Constraint Group 3	198	=																					1	1	1	1	1	1	1	1	1	1	1	1											
	44	≥																													-1				1				1					-1	
Constraint Group 2	116	≥																													-1	-1			1	1			1	1				-1	
	116	≥																													-1	-1	-1		1	1	1		1	1	1			-1	
Constraint Group 3	225	=																													-1	-1	-1	-1	1	1	1	1	1	1	1	1			
Constraint Group 4	0	≤	120																				-1																						
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Figure 11. Problem B Matrix

objective function), one is a group 1 constraint, eight belong to group 2, two are in group 3, and twenty are group 4 constraints.

RESULTS

Problem A

The optimal solution of problem A is given in Table 3. In this optimal solution, two trains are operated directly from node A to node C, and two are operated from node B to node C. With a 120-car limit for these trains, the minimum number of trains that must be run to handle the traffic is two trains departing node A, and two trains departing node B, making four trains operating into node C. In the optimal solution, this minimum number of trains is operated, and the best departure times are chosen for these trains to minimize the total car time.

Problem B

In problem B, drag trains are considered, as well as manifest trains, and the solution to this problem is given in Table 4. The inclusion of drags drastically changes the types of trains chosen as optimal. The optimal solution to problem B consists of a direct drag train from node A to node C, and a manifest from node A to node B, whose cars are added to those input at node B to supply the cars for two drags from node B to node C. The total car-time for problem B's optimal solution is 7,512 car hours versus 5,102 car hours for problem A, indicating that the level of service provided by problem A's solution is considerably better than that for problem B's solution. But, the cost savings attained by operating one less train from node B to node C (283 train-miles) are greater than the added car cost and node B yard cost, yielding the minimum total cost of $7,917.*

*The optimal total cost for problem B is greater than that for problem A due to the inclusion of additional engine costs for problem B. Additional engine costs are not included in problem A since only trains of one type are considered and engine operating, maintenance, and investment costs do not vary with different scheduling procedures in problem A.

Table 3

Problem A Optimal Solution

Trains Operated	Departure Time	Cars/Train	Train Type	From Node	To Node
T_2	5 A.M.	78	Manifest	A	C
T_5	1 P.M.	120	Manifest	A	C
T_{19}	2 P.M.	116	Manifest	B	C
T_{21}	10 P.M.	109	Manifest	B	C

Total Cost = Z = $ 3,694

Total Car Hours = 5,102

Y = 4,334 car-hours

X_1 = 32 cars

X_2 = 0 cars

Table 4

Problem B Optimal Solution

Trains Operated	Departure Time	Cars/Train	Train Type	From Node	To Node
T_7	1 P.M.	150	Drag	A	C
T_{12}	5 P.M.	48	Manifest	A	B
T_{18}	2 P.M.	123	Drag	B	C
T_{20}	10 P.M.	150	Drag	B	C

Total Cost = Z = $ 7,917

Total Car Hours = 7,512

Y = 6,984 car-hours

X_1 = 15 cars X_2 = 7 cars

The Effect of Varying Car Costs

For the problem B formulation of the train-scheduling problem, the car costs are varied to determine what effect this will have on the train schedules. Table 5 shows the optimal scheduling procedures for car per diem costs of \$3.60, \$9.60, and \$12.00 per day, as well as the answer previously obtained for problem B using a \$6.00 per diem cost. The optimal scheduling of trains for the \$3.60 per diem value is the same as that for the \$6.00 per diem value. But, by raising the daily car cost to \$9.60, an optimal solution very similar to that for problem A is obtained. The raising of the per diem value from \$9.60 per day to \$12.00 per day does not alter this solution, though. Therefore, between \$6.00 and \$9.60 lies the per diem rate which, for this formulation, divides the optimal solutions into two distinct categories.

At a low per diem rate, it is most economical to provide slow service, in which drags are operated and cars are handled at the yard at node B. At a higher cost level, though, the total cost is minimized by providing much faster service, which is obtained by operating two manifest trains direct between node A and node C, and two manifests between node B and node C. Therefore, once the value of car time becomes great enough, it is most economical to operate faster and more frequent trains, since the added cost of this speed and the cost of operating more trains is more than compensated for by savings in car costs at the higher per diem levels.

Existing Schedules

The approximate train schedules used by the railroad operating the network considered in this study are listed in Table 6, and given in terms of the problem B variables. A manifest is run daily on about the schedule of train T_3 departing node A at 1 p.m. It usually carries only loaded cars,

Table 5

Optimal Solutions of Problem B With Varying Car Costs

1. Car Cost = $ 3.60 per day

Trains Operated	Departure Time	Cars/Train	Train Type	From Node	To Node
T_7	1 P.M.	150	Drag	A	C
T_{12}	5 P.M.	48	Manifest	A	B
T_{18}	2 P.M.	123	Drag	B	C
T_{20}	10 P.M.	150	Drag	B	C

Total Cost = Z = $ 7,165 Total Car Hours = 7,512

Y = 6,984 car-hours X_1 = 15 cars X_2 = 7 cars

2. Car Cost = $ 6.00 per day

Trains Operated	Departure Time	Cars/Train	Train Type	From Node	To Node
T_7	1 P.M.	150	Drag	A	C
T_{12}	5 P.M.	48	Manifest	A	B
T_{18}	2 P.M.	123	Drag	B	C
T_{20}	10 P.M.	150	Drag	B	C

Total Cost = Z = $ 7,917 Total Car Hours = 7,512

Y = 6,984 car-hours X_1 = 15 cars X_2 = 7 cars

3. Car Cost = $ 9.60 per day

Trains Operated	Departure Time	Cars/Train	Train Type	From Node	To Node
T_1	5 A.M.	85	Manifest	A	C
T_3	1 P.M.	113	Manifest	A	C
T_{14}	2 P.M.	116	Manifest	B	C
T_{16}	10 P.M.	109	Manifest	B	C

Total Cost = Z = $ 8,941 Total Car Hours = 5,046

Y = 4,278 car-hours X_1 = 32 cars X_2 0 cars

4. Car Cost = $ 12.00 per day

Train Operated	Departure Time	Cars/Train	Train Type	From Node	To Node
T_1	5 A.M.	85	Manifest	A	C
T_3	1 P.M.	113	Manifest	A	C
T_{14}	2 P.M.	116	Manifest	B	C
T_{16}	10 P.M.	109	Manifest	B	C

Total Cost = Z = $ 9,445 Total Car Hours = 5,046

Y = 4,278 car-hours X_1 = 32 cars X_2 = 0 cars

Table 6

Approximate Actual Train Schedules

Trains Operated	Departure Time	Cars/Train	Train Type	From Node	To Node
T_3	1 P.M.	100	Manifest	A	C
T_{12}	5 P.M.	98	Manifest	A	B
T_{16}	10 P.M.	120	Manifest	B	C
T_{16}	10 P.M.	120	Manifest	B	G
T_{18}	2 P.M.	83	Drag	B	C

Total Cost = Z = \$ 8,508 Total Car Hours = 6,404

Y = 6,044 car-hours X_1 = 15 cars X_2 = 0 cars

and it is generally restricted to 100 cars or less. This schedule is based mainly on forwarding important morning deliveries from connecting lines at node A, and meeting two important connections shortly after midnight at node C. Another manifest is run which picks up cars at node B. This train's schedule is approximately that of train T_{12} departing at 5 p.m. from node A for node B, and of train T_{16} departing at 10 p.m. from node B to node C. This train takes those cars that missed manifest train T_3 , or were excluded because that train's car-limit was reached, and there are connections with connecting-line trains to be made at node C early in the morning.

Another manifest enters the network at node B and runs from node B to node C on approximately the schedule of train T_{16}. This train is scheduled to arrive at node C to meet approximately the same cut-offs as the other manifest train, T_{16}. On most days, an extra drag is operated from node B to node C, leaving node B at approximately the departure time of train T_{18}, 2 p.m. This train handles cars originating at or destined for intermediate points along its route, as well as some through cars. Some of the other trains mentioned also occasionally stop at locations not included in the model to make important pick-ups or set-outs.

The total car time for the railroad's actual scheduling procedure, with the inputs used in the example, is 6404 car hours. This is significantly less than the total car time for the optimal solution to problem B, though it is more than the car time for the case when the per diem rate was raised to $9.60 per day. But this is achieved by operating one more train than in the optimal solution to problem B. The 283 additional train-miles associated with this train cause the present railroad schedule to have a total cost of $8,508, assuming a $6.00 per diem, which is considerably higher, about 8%, that the $7,917 total cost for problem B's optimal solution.

Addition of Cut-Off Constraints to Problem B

An extension of the formulation of problem B was made by adding an additional constraint which requires that either train T_3, or train T_{11} and train T_{15}, be run to protect the important midnight connections at node C. Also, a constraint is added to require that either train T_{16} or train T_{20} be run to allow the cars input at node B during the day to make the early morning cut-off at node C. These additional constraints resulted in the solution listed in Table 7. In this optimal solution, manifests T_3 from node A to node C, and T_{16} from node B to node C are run, as are a drag from node A to node C and another manifest from node B to node C. A total of 5,471 car-hours are used with the additon of these cut-off constraints, while four trains are operated into node C. The connections at node C are protected, and the car-hours are lowered by 2041 over the optimal solution to problem B, while the total cost is increased by $219. This solution is still superior to that presently operated, which has a cost of $8,508 and 6,404 car-hours, in contrast to this optimal solution with cut-offs of $8,136 and 5,471 car-hours.

Implications of Reduced Crew Costs

A reduction in the size of train and engine crews on road freight trains, and the resulting decrease in crew costs, may alter train-scheduling procedures greatly. Such a possibility for reduced crews exists, as has been shown on foreign railroads. With this in mind, additional runs of problem A were made for different per diem rates with the crew costs halved.

Table 7

Problem B Optimal Solution With Cut-off Constraints Added

Trains Operated	Departure Time	Cars/Train	Train Type	From Node	To Node
T_3	1 P.M.	113	Manifest	A	C
T_5	5 A.M.	85	Drag	A	C
T_{14}	2 P.M.	116	Manifest	B	C
T_{16}	10 P.M.	109	Manifest	B	C

Total Cost = Z = \$ 8,136 Total Car Hours = 5,471

Y = 4,703 car-hours X_1 = 32 cars X_2 = 0 cars

The optimal solutions for these runs are listed in Table 8. The optimal solution with the crew cost halved for a per diem cost of $3.60 is the same as that for the full crew cost and a per diem rate of $6.00. This could be anticipated, because relative costs are almost identical. But, when the per diem rate is increased to $6.00 and $9.60 for the halved crew cost, one train which formerly went directly from node A to node C now stops at node B. The additional yard cost for this train is more than compensated for by a reduction of 90 car-hours at the higher per diem rates. By running a 78-car manifest from node A to node B, three trains can depart with cars from node B, which allows train departures after each of the three large car-inputs at node B. This scheduling procedure provides the best service of any of the solutions, and has the lowest car hour figure, 5,012 car-hours.

In Table 9 is shown a possible solution to the problem A formulation of the train-scheduling problem which contains twice as many trains as the model determined to be optimal. When crew costs are halved, twice as many trains may be run for the same total crew expense. Manual computation of the costs and car-time for four direct manifests from node A to node C, and four manifests from node B to node C were made for a car cost of $6.00 per day. The total cost for this scheduling procedure is considerably greater than that for the optimal solution for a halved crew cost, but it is somewhat less than the total cost of the optimal solution using the full crew cost. Therefore, if co-operation between rail management and rail unions could be obtained, twice as many trains could be run as are presently under existing work-rules, each with half as many crew members. The total crew costs would be approximately the same in both cases, the same total number of trainmen and enginemen would be employed, but the service would

Table 8

Optimal Solutions to Problem A With Varying Crew Costs and Car Costs

1. Full Crew Cost, Car Cost = $ 6.00 per day

Trains Operated	Departure Time	Cars/Train	Train Type	From Node	To Node
T_2	5 A.M.	78	Manifest	A	C
T_5	1 P.M.	120	Manifest	A	C
T_{19}	2 P.M.	116	Manifest	B	C
T_{21}	10 P.M.	109	Manifest	B	C

Total Cost = Z = $ 3,694 Total Car Hours = 5,102
Y = 4,334 car-hours X_1 = 32 cars X_2 = 0 cars

2. Crew Cost Halved, Car Cost = $ 3.60 per day

Trains Operated	Departure Time	Cars/Train	Train Type	From Node	To Node
T_2	5 A.M.	78	Manifest	A	C
T_5	1 P.M.	120	Manifest	A	C
T_{19}	2 P.M.	116	Manifest	B	C
T_{21}	10 P.M.	109	Manifest	B	C

Total Cost = Z = $ 1,975 Total Car Hours = 5,102
Y = 4,334 car-hours X_1 = 32 cars X_2 = 0 cars

3. Crew Cost Halved, Car Cost = $ 6.00 per day

Trains Operated	Departure Time	Cars/Train	Train Type	From Node	To Node
T_5	1 P.M.	120	Manifest	A	C
T_9	5 A.M.	78	Manifest	A	B
T_{17}	10 A.M.	120	Manifest	B	C
T_{19}	2 P.M.	74	Manifest	B	C
T_{21}	10 P.M.	109	Manifest	B	C

Total Cost = Z = $ 2,484 Total Car Hours = 5,012
Y = 4,224 car-hours X_1 = 32 cars X_2 = 0 cars

4. Crew Cost Halved, Car Cost = $ 9.60 per day

Trains Operated	Departure Time	Cars/Train	Train Type	From Node	To Node
T_5	1 P.M.	120	Manifest	A	C
T_9	5 A.M.	78	Manifest	A	B
T_{17}	10 A.M.	120	Manifest	B	C
T_{19}	2 P.M.	74	Manifest	B	C
T_{21}	10 P.M.	109	Manifest	B	C

Total Cost = Z = $ 3,235 Total Car Hours = 5,012
Y = 4,244 X_1 = 32 cars X_2 = 0 cars

Table 9

Manually-Computed Solution for Eight Manifest Trains with Crew Cost Halved

Crew Cost Halved, Car Cost = $ 6.00 per day

Trains Operated	Departure Time	Cars/Train	Train Type	From Node	To Node
T_2	5 A.M.	53	Manifest	A	C
T_4	9 A.M.	52	Manifest	A	C
T_5	1 P.M.	61	Manifest	A	C
T_7	9 P.M.	32	Manifest	A	C
T_{17}	10 A.M.	44	Manifest	B	C
T_{19}	2 P.M.	72	Manifest	B	C
T_{21}	10 P.M.	50	Manifest	B	C
T_{21}	10 P.M.	59	Manifest	B	C

Total Cost = Z = $ 3,520 Total Car Hours = 4,406

Y = 4,406 car-hours X_1 = 0 cars X_2 = 0 cars

be vastly improved, as reflected by the total car-hour figure which dropped from 5,102 for the optimal solution of problem A, to 4,406 car hours for the case when twice as many trains are operated resulting in lower total car costs and lower car fleet size requirements. Thus a reduction of crew size which would be matched by a proportionate increase in trains operated would directly benefit both railroads through lower costs and shippers through better service. If rail traffic were to increase, it would probably also benefit rail labor.

CONCLUSIONS AND RECOMMENDED EXTENSIONS

Conclusions

The model constructed in this study is intended to aid in decision-making involving railroad operating questions. This first generation model was designed to answer four railroad operating questions, and it was applied to a small railroad network. The answers to these questions were obtained without undue computer time and effort, with most answers obtained in less than three minutes of computer time (about $20) using the solution code BBMIP* and a Control Data Corp. 6400 computer. The size of problem that can be solved with this code is a function of the computer size and the number of rows, columns, and integers in the problem. Both problem A and problem B formulations are near the size limit for the BBMIP code using a Control Data Corp. 6400 computer.

The model may be used on a daily basis, to schedule trains for an upcoming 24-hour period, or historical data may be used to establish basically unchanging daily schedules. In order for the model to be used daily as a management decision-making tool, a real-time information system is required which can give, in advance, predictions of the number of cars to be moved between terminals for an upcoming time period. Such real-time information systems are now being installed on many railroads, such as Total Operations Processing System (TOPS) on the Southern Pacific system. Without a real-time

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*The computer solution code used to solve the mixed-integer programming problems in this study is BBMIP (Branch and Bound Mixed Integer Programming).

information system, though, basically unchanging daily schedules can be established through the use of historical data.

The model developed in this work deals primarily with the inter-nodal railroad operations and only small-scale yard operations are considered at one intermediate node. The optimal schedules in this study were determined by minimizing the total cost exclusive of the costs of classification yards at both ends of the network, and the effect of these schedules on these major yards was not considered. By not considering the variable costs associated with alternate classification policies, and the physical layout of the yards, the timing of train arrivals and departures, and other factors of yard operations, the model is slightly biased in favor of long trains.

The relative dependabilities of various lengths and types of trains were not considered in this model, and this may bias the model toward long trains, since they may be less dependable than shorter trains. Also, a constant horsepower-to-tonnage ratio may not always insure a given train speed with added train length, since a shorter train may have advantages of more rapid acceleration and deceleration than a longer train.

The development of the model in this study has demonstrated that railroad train-scheduling problems can be formulated in a mixed-integer programming format. Despite limitations, due mainly to size restrictions, the model can accurately and quickly determine which of the two important factors, train cost or car cost, outweighs the other for a given scheduling situation. With refinements and extensions, the model can be made to yield for actual scheduling problems results that are accurate and attainable without great effort or expense.

Recommended Extensions

Other computer codes for solving mixed-integer programming problems besides BBMIP are being developed which will solve, without undue cost, problems with hundreds of integer variables. With codes like these being made available, the model developed in this study can be made more realistic by making certain extensions to it. The problem matrix can be made larger, and this will allow more possible departure times for each type of train. This will also allow large problems, with larger networks, to be considered, with the inclusion of more nodes, and the accompanying increase in the number of train arcs. More local traffic can be considered, since important stops made by local trains can be expressed as nodes with the larger permissible network. Additional types of trains can be considered by the model. Very fast and short trains, and very long, slave-unit trains can easily be included in the present model formulation by considering their appropriate costs, car-limits, and running times, and including more arcs in the model for them.

Other extensions that will add realism to the model will require restructuring of the model. Engines per train can be added as a group of variables, allowing a more accurate representation of costs associated with the number of locomotives. Also, train scheduling can be considered simultaneously in both directions by combining the scheduling problems for each direction. With engines per train as a variable, and scheduling in both directions considered, constraints which specify the total number of engines available and the number of crews available can be added to the model.

Possibly the most important extension that can be made to the model is to refine the definitions of freight cars. In the existing model, an "average car" is considered. The classification of freight cars into many groups--by individual car cost, origin and destination, perhaps priority of shipment, or any other factor--is an extension that will add greatly to the model's realism and usefulness.

If cars are broken down into many groups, based on the value of the car and a value or priority assigned to its contents, and cut-off times for delivery to connections, then it is possible that the optimal solution to a scheduling problem will have cars of different categories handled on different types of trains, operating at different rates of speed. For expensive freight cars loaded with valuable contents, the value of car-time saved by greater train speed is greater than the cost of providing that speed. On the other hand, for empty freight cars in a low per diem group, the cost of attaining car-time savings by increased running speeds will be more than the value of the car-time saved, and these cars will probably operate in slow trains, possibly handled at intermediate yards. The model, then, could determine for a given real-life situation the important and unresolved question of where the optimum trade-off is between the value of car-time savings, and the cost of attaining those savings.

Extensions to the model such as those described above are now being explored and developed.

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APPENDIX

Expanded General Model

Shown below is an expanded formulation of the general train scheduling model. This expanded model is much more comprehensive than the model used in the earlier part of this paper. It explicitly treats car movement in both directions, by car type, as well as locomotive availability.

Notation.

A_i = The cost of running train i, \$

B_{ijn} = The cost per car on train i, with car-arc j in car-group n, \$/car

C_{jn} = The cost per unit of car time for cars with car-arc j and in car-group n, \$/car-hour

D_i = The departure time of train i, hour

E_i = The cost per engine on train i, \$/engine

F_i = The running time of train i, hours

G_{mjn} = The cumulative number of cars in car-group n and car-arc j originating at the origin of train-arc m, at the time of departure of train m, cars

H_{jn} = The total number of cars in car-group n and car-arc j originating at the origin of train-arc m, for the entire scheduling day, cars

L_{km} = The set of designations of trains (i's) leaving node k before the departure of train m from node k

P_{ijn} = The average weight of a car in car-arc j and in car-group n, divided by the tonnage-to-engine ratio for train i, engines/car

Q_j = The set of train-arcs which take cars of arc type j to their final destination (i.e., after a car of type j is assigned to a train in set Q_j, it is definitely taken to its destination)

R_i = The limit of the number of cars per train i, cars

S_{km} = The difference between the number of engines input into node k from outside the network and the number of engines output of the network at node k before the departure time of train m, engines

T_{km} = The set of designations of trains (i's) terminating at node k before the departure of train m from node k

U_{jn} = The area under the car input function for one day at the origin of car-arc j for cars in car-group n, car-hours

e_i = The number of engines on train i, engines

s_k = The number of engines at node k at midnight of the scheduling day, engines

t_i = Choice variable for the existance of train i, binary (0,1)

w_{ijn} = The number of cars on train i, on car-arc j and in car-group n, cars

x_{jn} = The cars remaining to be moved at the node at the origin of car-arc j at the end of the scheduling day for cars in car-arc j and in car-group n, cars

z = The total variable cost in the problem

i = Train-arc designation, i=1,2,...,I

j = Car-arc designation, j=1,2,...,J A car-arc is defined by the origin and destination of a freight car in the network.

k = Node designation, k=1,2,..,K

m = Train-arc designation, m=1,2,...,I

n = Car-group designation, n=1,2,...,N A car-group is defined by the car-time cost associated with the car due to car per diem rate, daily value of contents, service costs, etc.

The objective of this train scheduling model is to minimize the total variable cost. In this formulation, the car-time computation is brought into the objective function to reduce the number of problem variables, engine variables are added, and the car variables are expanded to include all car origin-destination pairs, and as many car-cost groupings as desired. Stated mathematically, the objective is to minimize:

$$z = \sum_{i=1}^{I} A_i \cdot t_i + \sum_{i=1}^{I} E_i \cdot e_i + \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{n=1}^{N} B_{ijn} \cdot w_{ijn} +$$

$$\sum_{j=1}^{J} \sum_{n=1}^{N} C_{jn} (U_{jn} + 24 x_{jn} - \sum_{i \text{ in } Q_j} (24 - D_i - F_i) \cdot w_{ijn})$$

where the terms in the second row compute the total car-time. The minimization problem is subject to the following constraints:

1. $G_{mjn} + x_{jn} + \sum_{i \text{ in } T_{km}} w_{ijn} - \sum_{i \text{ in } L_{km}} w_{ijn} \geq w_{mjn}$ for all j, (j=1,2,...,J) for all m, (m=1,2,...,I-1) for all n, (n=1,2,...,N)

2. $H_{jn} + \sum_{i \text{ in } T_{kI}} w_{ijn} - \sum_{i \text{ in } L_{kI}} w_{ijn} = w_{Ijn}$ for all j, (j=1,2,...,J) for all n, (n=1,2,...,N) where I is the final train departure of the scheduling day.

3. This constraint group requires that the number of cars per train not exceed an imposed limit of train length.

$$R_i \cdot t_i \geq \sum_{j=1}^{J} \sum_{n=1}^{N} w_{ijn} \qquad \text{for all } i, (i=1,2,\ldots,I)$$

4. This constraint group requires that adequate horsepower per train weight be supplied to each train to maintain the train's given schedule.

$$e_i \geq \sum_{j=1}^{J} \sum_{n=1}^{N} w_{ijn} \cdot P_{ijn} \qquad \text{for all } i, (i=1,2,\ldots,I)$$

5. This constraint group requires that the number of engines on a train cannot exceed the number of engines available at the train's departure time.

$$S_{km} + s_k + \sum_{i \text{ in } T_{km}} e_i - \sum_{i \text{ in } L_{km}} e_i \geq e_m \quad \text{for all } m, (m=1,2,\ldots,I) \text{ at each node, } k.$$

The engine variables can easily be expanded to include engines of different types. Also, constraints relating the crews available to the trains run, and train-capacity constraints for various fixed network links in the system can easily be included in this model. No calculation of the number of locomotives required is made in this model, because the railroad costs model assumes that locomotive life is based upon time of operation (hours run), not age. Hence, aside from interest charges, costs are proportional to time of operation. Thus locomotive ownership cost can be included approximately in the terms E_i, each of which corresponds to a unique train and train running time.

(32)

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OPTIMAL TRAIN SCHEDULING ON A SINGLE TRACK RAILWAY

Circulation optimale de trains sur un chemin de fer à voie unique

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Abstract. This paper concerns a single track railroad in eastern Brazil. The basic problem was: Given the routes and departure times of the trains on a single track railway, what are the best crossing and overtaking locations? A detailed description of this problem suggested that it had a structure analogous to the general job-shop scheduling problem developed by Greenberg. A more general formulation is given to the constraints and a more meaningful objective function is adopted. A technique is introduced that significantly reduces the number of nodes created by the branch-and-bound algorithm. Some results of computational experiments are presented at the end.

1. Introduction

This paper concerns a single track railroad in eastern Brazil – Companhia Vale do Rio Doce – where iron ore transportation plays the major role and passenger and freight trains are of lesser significance.

By definition a single track railroad has only one track which is used for circulation in both directions. In our example only at the stations is there additional track, parallel to the main line where trains can cross or overtake. Track between two consecutive stations will be called a *track section*.

During their travels, trains may have to stop for clearance of sections ahead. Such a situation is depicted in fig. 1, by means of a type of graph in common use by railroads to represent train movements. The vertical axis represents the relative positions of the stations and the horizontal the time.

fixed travel times for
trains on segments
minimizing weighted travel time
good branching rules

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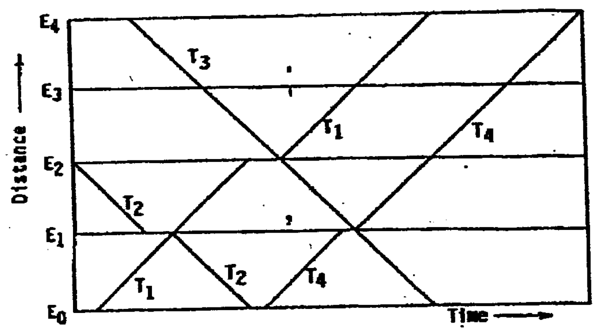

Fig. 1. Graph of train movements.

Fig. 1 displays the movement of four trains in four single track sections. As an example, train T_1, which is running from E_0 towards E_4, had to stop at station E_2 while waiting for train T_3.

Given that two trains must cross, a decision must be made as to where (which station) this is to occur. In general, this decision involves a choice among alternatives that affect differently the movement of other trains.

The selection of crossing points is made as an operational routine in two different operational functions. The first is the *time-table* preparation, which sets a pattern to be followed in the movement of trains. The second function is *train dispatching*, which is required when disturbances of the planned time-table occur.

Train scheduling decisions may have different economic effects. Sequences that reduce travel times may decrease investments in cars and engines as well as crew and fuel costs. Regularity and transportation velocity, which also depend on the schedule, are important factors to the satisfaction of customers needs and thus are related to railroad income.

In any railroad the importance of train scheduling problems increases with the number of trains per day. Decisions can be efficiently made by trained man-power until a certain degree of complexity is reached. From this point on, better means of finding good solutions are required.

2. Model

Train scheduling can be regarded as analogous to the problem of scheduling jobs (train travels) on a set of machines (track sections).

While most reported applications in job-shop scheduling have been based on heuristic approaches several authors [1–4] have formulated mathematical programming models for the "minimize the latest job-completion time" form of this problem. In addition Manne [3] minimizes the average flow (travel) time and Greenberg [4] total machine idle time.

The model described here builds on Greenberg's formulation but includes more general constraints and an objective function which fits better the economic characteristics of the scheduling situation treated in this paper.

2.1. Constraints

Let n be the number of trains to be scheduled on m track sections. The ordered set of track sections that must be travelled by a train to complete a trip will be named a *route*. The route of train i will be represented by a vector with m_i components, where m_i is the number of track sections in this route. Component $r(i,k)$ of this vector is the kth track section to be travelled through by train i.

Let $t_{ir(i,k)}$ be the entrance time of train i into section $r(i,k)$ and let $a_{ir(i,k)}$ be the minimum time interval between the entrances of train i in track sections $r(i,k)$ and $r(i,k+1)$, then

$$t_{ir(i,k)} + a_{ir(i,k)} \leq t_{ir(i,k+1)}\,, \quad k = 1, 2, \ldots, m_i - 1\,, \tag{1}$$

$$t_{ir(i,k)} \geq 0 \quad \text{for all } i \text{ and } k\,, \tag{2}$$

Constraints (1) express the sequence in which track sections must be travelled. Note that a route must be composed of adjacent sections. These sections, however, may be arranged in any form of network.

Constants $a_{ir(i,k)}$ may have different interpretations. The usual one is $a_{ir(i,k)} = d_{ir(i,k)}$, where $d_{ir(i,k)}$ is the time needed by train i to cover section $r(i,k)$. A more general interpretation is $a_{ir(i,k)} = d_{ir(i,k)} + s_{ir(i,k)}$, where $s_{ir(i,k)}$ is a non-negative constant. This is the general case in which a time interval is required between the releasing of a section and the seizing of the following one. Examples of this case are: (1) scheduled stops of passenger trains for embarkation and disembarkation and (2) train lengths considerably shorter than station yards and thus requiring a travel time to reach the following track section.

Departure times are constrained by

$$t_{ir(i,1)} \geq t_{i0} \quad \text{for all } i\,, \tag{3}$$

where t_{i0} is the time when train i is ready.

The ordering of trains i and j in section p are specified by

$$(t_{ip} + b_{ijp} \leq t_{jp}) \quad \text{or} \quad (t_{jp} + b_{jip} \leq t_{ip})\,, \tag{4}$$

the "or" being exclusive.

For convenience of the discussion in section 3 we shall renumber the constraints contained in (4) as

$$t_{ip} + b_{ijp} \leq t_{jp}\,, \tag{4a}$$

$$t_{jp} + b_{jip} \leq t_{ip}\,. \tag{4b}$$

Constraints (4) must be specified in every track section p for any pair of trains that travel through this section.

Constants b_{ijp} also may have different meanings. If a train is not allowed to seize a section while it is occupied by another train this can be expressed by setting $b_{ijp} = d_{ip}$. This is clearly the case for any pair of trains running in opposite directions. For trains running in the same direction it is possible, in some railroads, to have them simultaneously in the same track section, provided they do not get closer than a predetermined safety distance. In these cases b_{ijp} may be less than d_{ip} and its value is defined by the minimum time interval allowed between the passages of trains i and j through any point of section p.

In some railroads, track sections cannot be seized immediately after being released by a train. Examples: (1) Traffic control procedures may be significantly time consuming. (2) Trains at a standstill waiting to seize a section may have to spend time in acceleration. In these cases, constant b_{ijp} can be given a third interpretation: $b_{ijp} = d_{ip} + u_p$, where u_p is the additional time required to clear section p after the passage of a train.

Constraints (4) can be alternatively formulated using 0–1 variables [4]. The present formulation is more convenient for the branch-and-bound algorithm described in section 3.

In this model it is assumed that the station yards can accomodate any number of trains that are likely to be there simultaneously. The importance of this assumption must be analysed for each railroad. In many real cases the constraints on the maximum number of trains in a station are seldom active.

2.2. Objective function

There is no standard objective function for train scheduling problems. The specific conditions of each railroad determine the criteria to be used. The objective proposed below is to minimize the weighted average of train travel times. Let F_i be the travel time of train i, i.e., the time interval between its ready time (t_{i0}) and its arrival at the destination, then the objective function can be expressed as

$$z' = \sum_i c_i F_i = \sum_i c_i [t_{ir(i,m_i)} + a_{ir(i,m_i)} - t_{i0}]\,, \tag{5}$$

or equivalently as

$$z = \sum_i c_i t_{ir(i,m_i)}\,, \tag{6}$$

since t_{i0} and $a_{ir(i,m_i)}$ are constants. Coefficients c_i express the general situation in which trains differ in economic importance or priorities.

Objective function (6) may be applied to some scheduling situations. In particular it is a good objective function when a considerable number of trains travel between the terminals with no scheduled intermediate stops (e.g., ore trains continuously travelling between loading and unloading terminals). It can also represent situations in which, for a relatively small number of trains, previously assigned arrival and departure times at intermediate stations should be obeyed as closely as possible (e.g., passenger trains). This can be achieved by setting high values to the correspondent c_i together with an adequate definition of constants $a_{ir(i,k)}$.

The model proposed in this section is to minimize (6) subject to (1)–(4). This will be named problem P.

3. Solution method

Problem P can be solved by a branch-and-bound algorithm as presented in [4]. In this section a brief description of this solution method is followed by a presentation of some modifications which improve on Greenberg's original algorithm.

The problem associated with the starting node is problem P without constraints (4). Call it problem P'. It is a linear programming problem and can be solved as such. If the solution of P' satisfies P the latter is solved. Otherwise we start the first branching operation by selecting two trains i and *j*, in a section *p* and then creating two new problems: one is P' together with the additional constraint (4a); the other is P'' with constraint (4b). These two problems, which correspond to two new nodes in the branch-and-bound tree, are also linear programming problems. We now select one of the newly[1] created nodes for another branching operation.

For notational convenience we shall write $(i,j;p)$ when referring to trains *i* and *j* in section *p*. The solution method proceeds through a sequence of node selecting and branching. At any point, branching from a selected node creates two problems, each of which will result from the inclusion of one of the constraints (4a) or (4b) in the problem associated with the node currently being branched. These constraints must be associated with an $(i,j;p)$ which has not been fixed for the current branching node. The expression "fixed $(i,j;p)$" will mean that the relative order of trains *i* and *j* in section *p* is fixed.

The solution of the linear programs associated with the nodes provide the lower bounds which are used to guide the selection of nodes for branching and to identify optimal solutions.

3.1. Branching rules

For each iteration the branching rules must specify: (1) which node is to be branched and (2) which $(i,j;p)$ is to be fixed.

3.1.1. Node selection

A node which has not been branched will be named an *open node*. An *active node* will be any candidate for branching. An active node (1) must be an open node, (2) cannot correspond to a feasible solution to problem *P* and (3) cannot have a value greater or equal to the best known feasible solution. The solution method begins with an active node — the starting one — and finishes when there is none. At each iteration the branching node is selected from among the active nodes.

The following rules are compared in our study:

(a) *Select the least value active node* — the rule used by Greenberg [4].

(b) *Select the latest active node created.* In this rule, described by Little [5], open nodes (active or not) are arranged in a list in accordance with its creation time. The node to be selected is the last active one in this list.

(c) *Select the latest node created if it is active. Otherwise, select the least value active node.* This rule may be regarded as a mixture of rules (a) and (b).

Branching rules can be compared in terms of (1) number of nodes created; (2) computer storage requirements; (3) computer time required to obtain the first (good) feasible solution, and (4) computer time required to obtain an optimal solution.

While rule (a) is best, given criterion (1), it is by far the worst, given criteria (2) and (3), which are more important for practical applications. Rules (b) and (c) produce good feasible (and very often optimal) solutions using considerably less time than rule (a). However, they require additional time to ensure optimality.

3.1.2. Selection of $(i,j;p)$ to be fixed

This section describes a technique that significantly reduces the number of nodes explicitly enumerated by the solution method as compared to Greenberg's algorithm.

After defining a node to be branched, we must select two trains *i* and *j* on a track section *p*, to fix their relative order in that section. A simple rule is:

(a) *Select any $(i,j;p)$ which has not been fixed in the node being branched.* This rule leads us to one of these two conditions: (1) Neither constraint (4a) nor constraint (4b) is satisfied; or (2) only one of them is satisfied (and the other is not). There is no other possibility. In the first condition we shall say that trains *i* and *j* are in *conflict* on section *p*. A feasible solution to problem *P* cannot have any conflict. When, for a particular $(i,j;p)$, condition (1) occurs, the inclusion of one of the constraints (4a) or (4b) will eliminate the conflict for this $(i,j;p)$. Where condition (2) occurs, the additional constraint will be redundant for one of the two new problems.

The disadvantage of fixing an $(i,j;p)$ under condition (2) becomes clear when we are branching from a node without conflicts (i.e., the node solution is feasible for problem *P*). This can happen (and it generally does) before fixing all possible $(i,j;p)$. In this case it is pointless to continue fixing $(i,j;p)$ because we already have a feasible solution.

The above discussion suggests the following rule:

(b) *select an $(i,j;p)$ such that trains i and j are in conflict in section p.* This rule requires that we undertake some additional computational work in order to find conflicts. This must be traded off against the additional number of nodes required when using rule (a). As an example, the 3 job-2 machine problem solved by Greenberg after creating 19 nodes under rule (a) can be solved searching only 7 nodes using rule (b). This saving increases with problem size.

3.2. Node evaluation

The problems associated with all nodes are linear programming problems. Two ideas for reducing the computational burden of obtaining their solutions were employed in the computer codes developed to test the model. Problem

P', associated to the starting node, can be easily solved:

$$t_{ir(i,1)} = t_{i0} \quad \text{for all } i,$$

$$t_{ir(i,k+1)} = t_{i0} + \sum_{l=1}^{k} a_{ir(i,l)}, \quad k = 1, 2, \dots, m_j - 1,$$

$$z = \sum_i c_i [t_{i0} + \sum_{l=1}^{m_i} a_{ir(i,l)}],$$

For any other node we can use the dual simplex algorithm, more specifically in Beale's column tableau form [6]. When a new node is created, its related problem results from the inclusion of an additional constraint to a problem (associated to the current branching node) for which a solution is already known. By applying the dual simplex algorithm we can obtain the new optimal solution with few (very often only one) iterations.

4. Computational experiments

The solution method was coded in Fortran and processed in an IBM/360 model 40 computer with 64K of core memory. Three versions were developed, each using one of the branching rules for node selection mentioned in section 3. Version 1, based on rule (a) was considered too inefficient for application purposes and was abandoned before the end of the experiments.

Table 1 illustrates computer codes performance for some test problems. In all problems the railroad is composed of five track sections linking two terminals. All trains travel at the same speed and each one spends the same amount of time in any of the five track sections. In each problem, half of the trains run in each direction.

The maximum size of the problems that we were able to solve was not satisfactory. Fields for future developments could be both suboptimization procedures and ways of increasing maximum allowed problem size. The approach presented in this paper can be further explored in these developments. The interruption of the algorithm after obtaining a good feasible solution is an obvious suboptimization scheme. Furthermore, partitioning a problem into smaller subproblems, as described in [7], can be a useful device to increase problem size.

Table 1
Computational results

Problem	Track sections X trains	Branching rule [a]	Time (nodes created) [b] T1	T2	T3	T4	Feasible solution/optimal solution [c] 1	2	3
1	5 X 4	b	0.5 (8)	*0.6 (10)	0.8 (14)	–	1.018	1.0	–
		c	0.5 (8)	0.8 (14)	*0.9 (16)	–	1.018	1.009	1.0
2	5 X 6	b	1.3 (14)	*1.9 (22)	3.0 (34)	–	1.018	1.0	–
		c	1.3 (14)	*2.6 (30)	3.2 (36)	–	1.018	1.0	–
3	5 X 8	b	1.9 (18)	*4.8 (46)	9.6 (92)	–	1.009	1.0	–
		c	1.9 (18)	*4.4 (42)	9.6 (92)	–	1.009	1.0	–
4	5 X 10	b	3.2 (24)	4.5 (34)	*21.7(160)	39.3 (298)	1.018	1.014	1.0
		c	3.0 (24)	5.4 (44)	*6.9 (56)	29.8 (244)	1.018	1.011	1.0

a) The branching rules are those for node selection in section 3.
b) T1 is the time at which the first feasible solution was obtained; T2, T3 and T4 are the times at which either a better feasible solution was obtained, or the program stopped after having ensured optimality (in this case the correspondent T1 is the last time value recorded for the problem). The time at which the optimal solution was achieved is marked with "*". Times are measured in minutes and are approximate. The values in parentheses are the number of nodes created up to that moment. Example: In problem 1 with rule b, the first feasible solution was obtained after 0.5 minutes, the second one (which is already optimal) after 0.6 minutes but the program stopped after 0.8 minutes.
c) These columns contain the ratios of the value of a feasible solution to that of the correspondent optimal solution for the problem. The order is the same as that in which the feasible solutions were obtained.

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A METHOD OF PLANNING YARD PASS ON A GENERAL NETWORK

Méthode de planification des trains "yar sur un réseau général

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Abstract. One of the most important problems in train forma freight transportation is to determine, considering freight traffi other characteristics, the sections on which direct service of yar so as to minimize the total transit time of freight cars or the total First, the problem in a general yard network is explained an discrete programming problem. Since it is practically impossibl solution of the problem, an approximate numerical method is treat the problem for a general network containing up to fifty computing time. Newly developed graph-theoretic analytical too ting the problem and devising an algorithm for solving it. Althoug out primarily for determining a nearly optimal pattern of yard freight transportation, it can be applied to other types of pla where grouping or batching of freights or passengers are essential.

1. Introduction

In railway transportation trains move freight cars another. Only exceptionally is the demand for transport of stations large enough to warrant running a train betw Therefore, it is a common practice to transport freight in a series of trains. One method of doing so, which scheme, is to construct a number of marshalling yards in

* Yard pass: trains qui passent les dépôts.

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A GOAL-DIRECTED TRANSPORTATION PLANNING MODEL†

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(*Received* 20 *May* 1969)

I. INTRODUCTION

TRANSPORTATION planning has been described as a problem-solving process (Manheim, 1967; Thomas and Schofer, 1967). This process involves the extensive use of formal models, generally computer models, for information processing and predictive purposes. In the search for transportation system improvements, these model systems rely on relatively unstructured search and evaluation procedures. This paper describes an attempt to develop a planning model system which more efficiently explores the range of transportation alternatives in order to find alternatives which are conformal to the relevant societal goals.‡ It involves a merging of the fields of mathematical programming, graph theory and cost-effectiveness in order to achieve this result.

Although there is a wide variation within the field, current transportation planning model systems tend to be very similar to that portrayed in Fig. 1. The basic functions of the transportation planning model system, involving both formal models and human judgement and decisions, are: generation of alternatives, prediction of the consequences of alternatives, evaluating alternatives on the basis of values applied to their respective consequences, and finally the selection of an alternative or a set of alternatives to be presented to the decision-making body. Specific types of information which result from each of these elements of the planning process is also shown in Fig. 1.

Since we are concerned with the implementation of transportation improvements over long periods of time, usually periods of 20–30 years, the model system described above is usually operated so as to portray or replicate the state of the region at various points in such a time period. In order to replicate the state of the region at various points in time, the model system is usually operated iteratively, with each pass through the system representing one such period. Predictions are thus made from one period to the next, on the basis of the state of the region in the last period analysed, assumptions about governmental policies or programs and those of other decision-making units, which are usually largely beyond the purview of transportation planners, and the transportation alternative to be implemented in the time interval to the next period. The reason for the inclusion of other policies and programs as a separate item is that these can have a profound effect on the environment in which the transport system operates as well as the system itself. Since

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these are somewhat uncertain but also subject to the direct choice of various bodies, it is useful to explore the effects of a range of these.

Whereas the process described above seems very well suited to the task of finding feasible transportation alternatives—that is, alternatives which are acceptable to the region—it has not been found possible to examine a wide range of transportation alternatives using such a system. The primary reason for this seems to be the level of efficiency with which

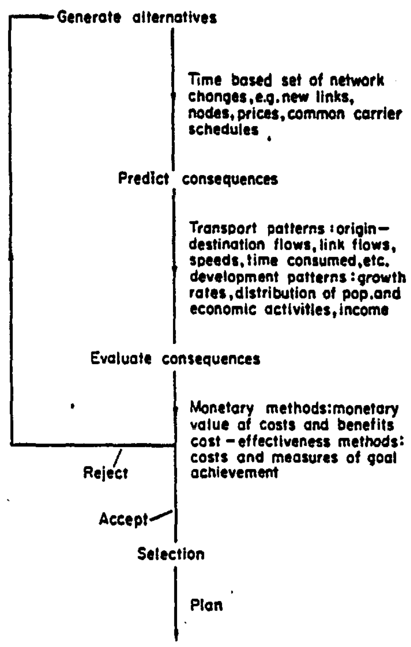

FIG. 1. Transportation planning process.

each alternative can be examined. The examination of each alternative is usually so costly in terms of men and computer time that only a very few alternatives can be explored (Hay, 1966; Harris, 1967). If there existed only a few reasonable transport alternatives in such a study, this would be acceptable. However, quite the contrary is true. For example, consider an admittedly oversimplified situation, in which the alternatives consist solely of the possibility of constructing new highway links, which could be constructed in any combination, over a period of 30 years, which has been divided into nine periods for analysis purposes. The number of alternative plans is approximately $(10)^{20}$—a number which staggers the imagination. More realistic problems would have more alternatives and possibly more time periods, compounding the number of alternative plans among which decisions must be made.

A model system such as the one described above is usually referred to as a forward-seeking model system. The reason for this description is the manner by which the alternative plans, both for each period in time considered and for the entire time horizon of the study, are compared with the goals and objectives set forth for the selection of the transportation of various bodies, it is

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plan. Thus, it is only at the end of the process that the final evaluation and selection of alternatives can be made. This model system proceeds forward in time, the state of the system and region at any one period unfolding after the consideration of the preceding period(s).

The proposed transportation planning model system can be described as a backward-seeking model system, in contrast to a forward-seeking model system. The essential difference between this type of model system and the one previously described is that, in this system one starts with the goals for the selection of transportation alternatives and then tries to proceed backward, as it were, through the consequences of alternative plans to the selection of an alternative plan which will best or at least satisfactorily achieve the desired goals. The significance of this change in posture, with respect to the process of planning, is that it is likely to increase the efficiency with which "good" or optimal alternatives can be found and then selected.

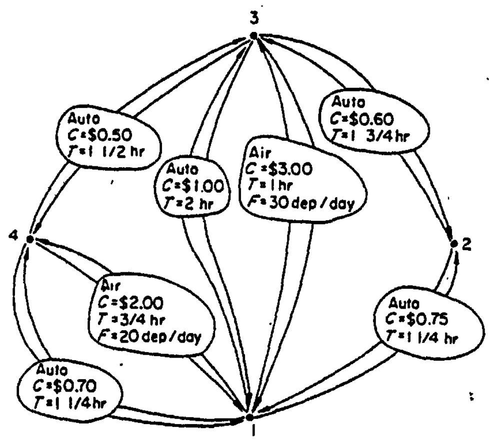
Model systems of this sort have been suggested at least four times in the literature, but, to this author's knowledge, none have ever been implemented. The first explicit reference to this sort of model system appears to be in a recent article by Bruck (1966). Formulations of transportation problems in this way were suggested specifically by Garrison (1960) and Hay *et al.* (1966) in recent papers dealing with relatively simple decision problems, that is, problems which were much less complex in terms of both criteria and number of entities and relationships than the typical problem considered by most transportation planning studies.

This goal-directed or backward-seeking approach to planning has many characteristics in common with the general methodology of mathematical programming. In particular, it is very similar in conception to the general characteristics of dynamic programming. Dynamic programming treats problems as sequential decision problems, in which the search for an optimal solution proceeds from the end stage of the problem back toward the initial stage. If these stages correspond to periods of time, then the program proceeds backward in time. The method suggested in this paper involves a merging of the general area of mathematical programming and, in particular, dynamic programming and linear programming, with graph theory, as it is applied to the description and analysis of transportation networks. Therefore, it is first necessary for us to describe our graph theoretic representation of transportation networks and of the general problem of selecting transportation network improvement schemes.

II. TRANSPORTATION NETWORK

We describe a transportation network as a collection of points and lines or, in graph theoretic terminology, a set of vertices and directed arcs. The vertices represent points between which persons and goods flow, that is, points of origin and destination of traffic. Points also represent the places where goods or persons may change mode or change vehicle, that is, transportation terminals. Arcs represent the connections between these points.

Figure 2 is an example of the representation of the transportation network in this manner. Both types of nodes or vertices are illustrated in this figure. The arcs shown in this graph represent possible paths of travel for persons and goods between the various nodes. The numbers associated with these arcs are used to represent characteristics of the transportation network which are relevant to the perception of the network, and hence the reaction to the network, by users of the network. Each of the arcs connecting two vertices represents a possible mode of travel between those vertices or, more precisely, a possible alternative means of travel between those two vertices. The phrase "possible alternative means of travel" is used to convey the notion of a path which is different from all other such path alternatives. This path alternative is described by such characteristics as travel time, fare, frequency of departures, comfort level, etc., in the case of person movement, and in the case of freight flows, such characteristics as time consumed, price charged, probability of damage, packaging requirements, and so forth, would be the relevant descriptors. It is important to note that each arc on this graph might not necessarily correspond to a different arc in the sense of a fixed facility designed for the movement of vehicles. This arises because there may exist an express train or plane service between a pair of cities which actually



C = out-of-pocket cost, \$

T = travel time, hr

F = departure frequency, departures per day

FIG. 2. Graph—theoretic representation of a transportation network.

passes through a number of intermediate cities without stopping. In this case, one would expect the travel time, at the very least, to be less than the sum of the travel times between these two end cities and intermediate cities at which local trains stop. Therefore, one could not represent the path between these two end cities, which includes the use of this express train, by simply the sequence of the arcs representing travel via the local train(s) serving the intermediate points. A similar situation may exist with respect to other characteristics of the network, especially fare, in which case the fare between any two cities would not necessarily equal the sum of the fares between these cities and some or a set of intermediate cities. In fact, fares generally do not exhibit this additive property. Thus, the graph is very likely to be one of a non-planar nature.

Of course, a graph such as that shown in Fig. 2 does not give us all of the information about a transportation network which would be considered relevant for transportation planning. Specifically, it says nothing about the actual path on the ground or route through the air or in the sea which a vehicle takes; that is, it does not say by what specific links or via which terminal a vehicle travels in taking persons or goods between any pair of terminal points on the network. Thus a second graph is needed in order to describe the transport

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network in terms of the means used to produce transportation. This graph can be considered one which gives information about how the transport service described in a graph such as Fig. 2 is produced, and is termed the transport processor network.

A graph describing a transport processor network is shown in Fig. 3; this portion is the network of flow channels for vehicles referred to as the fixed plant network. Again, the points or nodes on this graph refer to terminals and places of origin and destination of travelers and goods. In Fig. 3 the arcs between these points, however, actually refer to way links on which vehicles may travel, such as railroad tracks, roadways, sea-lanes and air-lanes. Non-vehicular modes, such as walking or conveyor belts, could also be included, but these are not, for reasons of clarity. An additional set of nodes is also shown. These are intersections of such links which do not occur at places corresponding to terminals, and these are termed "way interchanges" or "intersections".

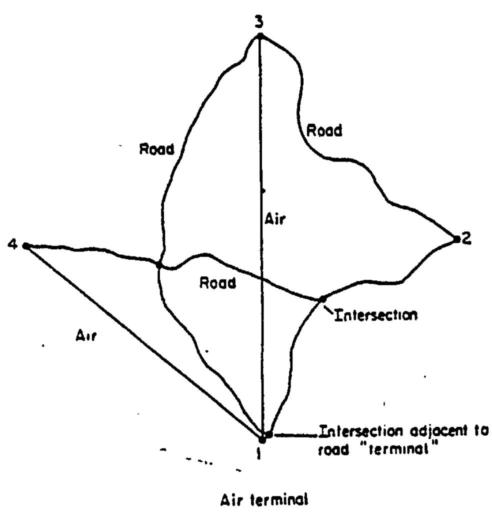

FIG. 3. Transport processor network: the fixed plant.

A graph can be constructed which represents the characteristics of the fixed plant network. These characteristics can vary considerably by mode or technology used, but in general they would provide such information as capacity, the time required for a vehicle to traverse that link or to pass through the node (by vehicle type, if necessary), etc.

Figure 4 describes the flow of vehicles on the fixed plant network. This is described in terms of both the spatial and the temporal aspects of the motion, and hence the diagram is inherently one involving three dimensions. Two of these refer to two-dimensional physical space, and the network of fixed plant can be placed directly into this plane. The location of vertices and arcs corresponds to their actual location in physical space.

The flow of a vehicle in this three-dimensional space is represented by the movement of a point representing the vehicle in time and location. Two vehicles are shown in Fig. 4. The identification of each vehicle can be achieved by associating an appropriate symbol with the line, and other pertinent information, such as seating capacity, range, etc., can also be so associated.

From the information contained in Fig. 4, the service characteristics of each mode can be determined. Such items as travel time, frequency of service, etc., can be obtained from it. A few service characteristics, such as fares, modal transfer privileges and the like are not the result of the vehicle flows in the system and, hence, must be obtained from elsewhere. However, much of the information needed to construct the service network is available from a description such as that contained in Fig. 4, which we shall call the vehicle flow network.

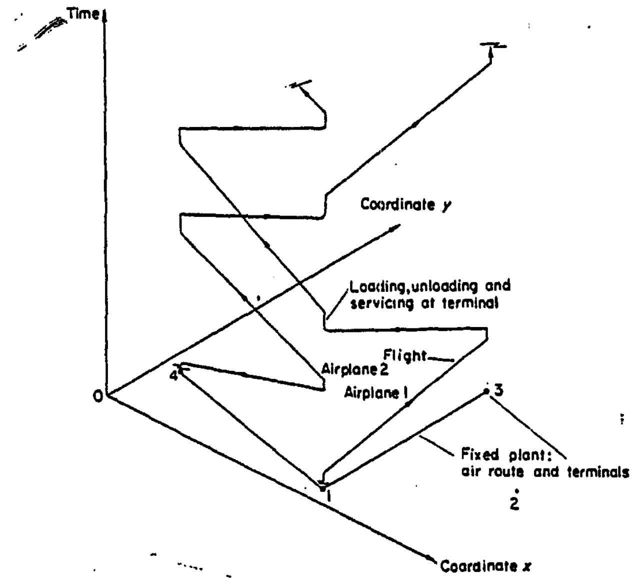

FIG. 4. Transport processor network: the flow network.

It is possible to develop networks identical to those of Figs. 3 and 4 but including all modes of transport. Of course, the plant and vehicles of each mode would have to be identified as such, in order to prevent confusion. Such a network was not drawn in the figures above simply because it would necessarily include so many items (points, lines, associated numbers and designations) that it would probably be incomprehensible.

III. TRANSPORTATION SYSTEM IMPROVEMENTS

There are two aspects of transportation improvements which must be considered at this time. The first is the manner in which they will be described mathematically. The second is the context within which they will be treated, that is, the considerations which are considered relevant to making a decision about selecting particular transportation improvement. The former will be treated first, since it is most strongly related to the immediately preceding discussion about the transportation network description.

As Fig. 5 implies, there exist a large number of types of improvements, at all levels, which are possible. At the simplest level, one could simply change the schedules or certain rules of operation for the transportation system. The effects of this in terms of inputs to the transportation network might be fairly small and readily identified—such things as the need for more fuel, more equipment if it is common carrier, additional labor, and so forth, are the likely input requirement changes. At the next level, one might make improvements to existing links or terminals within the modes which exist. These again are often changes which can be implemented rather rapidly and do not cause very great increases or decreases in inputs to the transportation network. The next level of improvement would be the addition of new links or terminals and associated equipment, fuel, labor and other inputs

ACCESS POINTS
specifies those points to which service is provided, and thereby the area to be served

↓

NETWORK CONFIGURATION
(LINKS, INTERCHANGES)
specifies via what route a vehicle can travel between each pair of access points

↓

VEHICLES AND CONTROL SYSTEM
specifies the minimum time required to travel between each pair of access points, link and interchange capacities and speeds

↓

SCHEDULE OR OPERATING SCHEME
specifies actual service which it is planned to provide, as measured by such characteristics as capacity, travel time and frequency, between each pair of access points, and trade-offs between these

FIG. 5. Hierarchy of network property relationships within a mode.

which are necessary, employing a technology or mode which already exists. These would then be considered additions to the network of that mode. The final level of improvement could be considered the addition of an entirely new mode or new modal technology within the region, with its own associated links, terminals, equipment, employees, control system and so forth.

The above discussion clearly indicates that there exists a very wide range of alternatives which might be considered in any transportation improvement program. This is particularly so if the goals to be achieved by the improvements are very broad in nature, so that it is difficult if not impossible to immediately narrow the search to a particular mode, or a particular area of the region in which the improvement should be made. Further complicating the analysis problem, however, is the fact that there exist choices as to when improvements can be made—especially if the time horizon of the study is 20 or 30 years, as is common in transportation planning. Clearly, because of the economies or diseconomies of scale in construction and operation, it is not necessarily optimal to simply make those improvements which are absolutely necessary in order to meet needs which are immediately impending.

The representation of these improvement possibilities in mathematical terms is not a conceptually difficult problem, although the resulting description does in fact cause certain mathematical problems which will be treated later on. Some of the choices, clearly, are binary choices. For example, the choice as to whether to introduce a new arc in the network of a particular mode, or the choice to use a particular technology, and the decision to construct a new terminal for a particular mode in a particular city are binary choices. These choices can be represented as binary variables, the associated variable either taking the value of zero or one.

Other choices, mainly those within each modal technology, can be represented as continuous choices within a range of values. These choices are with respect to variables whose value can be chosen once it has been decided to introduce a particular set of links and terminals and to use a particular modal technology on these. These choices refer to such characteristics of the system as the capacity of a link, the travel time for vehicles (of a particular type) on a link, the price or fare to be charged for travel between two places, the nature of the scheduled service which will be provided on these links, and similar items.

It is very evident from the description of these variables that these are the transportation variables which are primarily responsible for the explanation of traveller and freight flow behavior on the system, with respect to the choice of places to go and the particular path or mode to be used. Specifically, the demand models developed to date (Quandt and Baumol, 1966; McLynn, 1966) seem to have treated the variables time, price and frequency of service in the case of person flow, and time (including variance), price and measure of damage in the case of goods flow (Mathematica, 1967), for the sensitivity of travel patterns to network properties. We shall, hereafter, deal with just these three variables—time, price and frequency—since we are dealing primarily with a person travel network. It is these same variables, incidentally, which are presumed to be primarily responsible for the impact of transportation network improvements upon regional developments patterns and especially upon economic development patterns (Bruck *et al.*, 1966).

IV. COST EFFECTIVENESS

The framework within which transportation network improvements will be considered is that of cost effectiveness, which was suggested by Thomas and Schofer in their recent report on strategies for the evaluation of alternative urban transportation plans (Thomas and Schofer, 1967). This framework is specifically designed to array good alternatives before decision-makers, so that they can in fact evaluate intangibles which are nevertheless relevant to the consideration of the selection of a particular set of transportation network improvements.

The basic concept involved is that of arraying the costs incurred by a system along with the effectiveness of that system in terms of achieving goals. The costs can be multi-dimensional in nature, reflecting different viewpoints as to the incidence of cost and importance of costs. The effectiveness measures are measures of the extent to which the various alternatives achieve objectives which are held within the community and assumed by the planner for purposes of evaluation. These objectives can relate specifically to transportation system descriptors; however, it is most likely that they will reflect such things as life style, opportunities for employment and recreation, economic development and similar items which are related to the transportation network, but for which the relationship is not at the present time very well understood. For brevity, we shall designate these measures of effectiveness measures of the social state.

V. MATHEMATICAL PROGRAMMING

The general problem with which we are dealing is one of finding the minimum cost set of transportation network improvements during the period of analysis for each level of effectiveness. The general form of the problem, then, is one of a constrained extremal problem. The levels of effectiveness or social state desired for any one example, in the cost-effectiveness framework, are specified at the outset, and then a feasible set of transportation network improvements, which will achieve that level of effectiveness at a minimum

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cost, is desired. As can be realized from the discussion in the first few paragraphs of Section III, there in general will exist a very large number (precisely, an infinite number) of transportation improvements which will achieve any given level of effectiveness. The infinity, of course, arises from the fact that some of the choices are continuous choices and that there exist trade-offs between these.

Figure 6 illustrates the general form of the problem, specifying the types of variables included and their relationships. The costs (discounted) which are to be minimized are

$$\min Z = \min \sum_{t=1}^{Y} \hat{C}_p{}^t(P^t, P^{t-1}) + C_0{}^t(O^t, F^t) \qquad \text{(F6-1)}$$

subject to

$$\hat{T}_k{}^t(P_k{}^t, O_k{}^t, F_k{}^t) = T_k{}^t \qquad \text{(F6-2)}$$

$$\hat{P}_k{}^t(P_k{}^t) = \hat{P}_k{}^{t+1}(P_k{}^{t+1}) \qquad \text{(F6-3)}$$

$$\hat{D}_{ijk}{}^t(P^t, O^t, S^t) = D_{ijk}{}^t \qquad \text{(F6-4)}$$

$$\hat{F}_k{}^t(D^t) = F_k{}^t \qquad \text{(F6-5)}$$

$$\hat{S}_g{}^t(P^t, O^t) = S_g{}^t \qquad \text{(F6-6)}$$

where

Z = total discounted costs;

P^t = vector of binary network plant variables for time period t; $P^t = (P_1{}^t, \ldots, P_k{}^t, \ldots, P_m{}^t)$, where $P_k{}^t$ = binary plant variables for mode k; $P_k{}^t = (p_{k1}{}^t, \ldots, p_{kh}{}^t, \ldots, p_{kn}{}^t)$;

O^t = vector of operational variables for time period t; $O^t = (O_1{}^t, \ldots, O_k{}^t, \ldots, O_m{}^t)$, where $O_k{}^t$ = operational variables for mode k; $O_k{}^t = (o_{k1}{}^t, \ldots, o_{kh}{}^t, \ldots, o_{kn}{}^t)$;

$D_{ijk}{}^t$ = demand for travel from city i to city j via mode k in time period t;

$F_k{}^t$ = vector of flows in links of mode k in time period t;

S^t = vector of social state descriptors of the SMSA's in the region; $S^t = (S^t{}_1, \ldots, S_g{}^t, \ldots, S_e{}^t)$, where $S_g{}^t$ = social state descriptors of SMSA labeled g; $S_g{}^t = (s_{g1}{}^t, \ldots, s_{gf}{}^t, \ldots, s_{gr}{}^t)$.

The letters with the symbol ^ are used to designate the associate function.

FIG. 6. Choice of network improvement scheme, given a target level of effectiveness.

functions of the fixed plant of the transport system, the choices made as to system operations at each point in time, and the flows on the network at each point in time. The first of these is represented by the function $\hat{C}_p{}^t(P^t, P^{t-1})$, in which P^t is a vector, the elements of which represent the existence or non-existence of way links, terminals and interchanges for each mode. The cost at each time period is then a function of both the improvements made from the preceding time period and the plant in existence at the time considered. The other costs are considered only functions of attributes of the system at that moment in time. The variables included are ones describing the operating choices made, O^t (such items as schedules, prices and trip capacities) and F^t, the person flows on the network.

The constraints on the problem include ones imposed by technological considerations, demand relationships and general social state-transportation system relationships. The first of these are represented by equations (F6-2) and (F6-3) in Fig. 6. Equation (F6-2) would include such relationships as those required for internal consistency within the problem, such as the inability to choose a non-zero capacity on a non-existent way link, and those which indicate bounds on the operation of a transport technology, such as limits on speeds. Each of these relationships refers to a single time period, as the superscripts indicate. Equations (F6-3) refers to constraints across time periods, namely those which refer to consistency in the choice of plant improvements. For example, these would preclude making improvements (say, adding lanes) to a non-existent freeway or prevent the selection of two necessarily mutually exclusive plant configurations.

The next set of constraints, represented by equations (F6-4) and (F6-5), refer to demand relationships. The first states that demand between two places via a particular mode is a function of network properties—potentially over the entire network—and of site properties—the social state at all places. In this case, undoubtedly only a few of the social state measures would be relevant, such as population, income, employment, scale of shopping or recreational area and similar items. Equation (F6-5) indicates that flows on individual elements of the network are a function of these values of the quantity of travel demanded.

The final set of constraints includes the relationships between transport system properties and the social state vector. This set includes the usual economic impact relationships, as well as others which deal with non-economic variables. The exact form of these relationships, even all the variables, are not known at the present time, as these will (hopefully) emerge from analysis of time series and cross-section data from the Northeast Corridor region from 1940 to 1960.

In addition to the above constraints, certain non-negativity and perhaps other similar constraints will also be present. It should be added that this representation of the relationships is necessarily tentative, because the exact form will emerge from both the theoretical grounds used to generate the above and empirical work.

It is very evident from the descriptions of the problem in Fig. 6 that this problem can be treated as a mixed integer programming problem, that is, a problem in which one is choosing both integer variables and values of variables which lie on a continuum within an allowable range. The problem is further complicated by the fact that the constraints are very likely to be non-linear, and in particular this would be the case with respect to possible new technologies, new arcs and new terminals, where the constraint set which describes continuous variable choices and trade-offs exists only if the associated integer variable takes on the value of one. It is well known that solutions to this sort of problem are very difficult to obtain by the use of the methods of convex programming. In fact, the experience with just integer programs, much less mixed integer programs, has been far from satisfactory.

Because of these considerations, a search was made for methods which would combine known mathematical techniques which were capable of solving portions of the problem. For example, dynamic programming is well known for its robustness with respect to handling binary or integer variable problems (Bellman and Dreyfus, 1962). Similarly, linear programming has achieved distinction in the area of solving very large, complex mathematical programming problems which are characterized by continuous variables (Charnes and Cooper, 1961). If means can be found to formulate our problem so as to make use of dynamic programming for the choice of binary variable values and of linear or or other very efficient programming methods for the continuous variable values, then a reasonably efficient computational scheme might emerge.

IV. THE GOAL-DIRECTED FORMULATION

This problem has been formulated as a mathematical programming problem involving the joint use of dynamic programming and linear programming in a manner which makes feasible the efficient solution of the problem using standard methods. This formulation involves the use of dynamic programming in order to make choices regarding the integer variables, and uses the linear programming portion of the problem to make choices regarding the values of continuous variables. The linear program is imbedded within the dynamic program in such a manner that the combination finds the optimal set of integer and continuous variable values.

Each stage of the dynamic program corresponds to one time period, in which there exists a certain fixed network for the transportation system. The alternatives to be considered by the dynamic program at each stage correspond to different sets of this transportation fixed plant. For each such fixed network, there exists a large number of choices of service variables and other transport system variables which are continuous in nature, and this choice is made with the use of the linear program. A distinct linear program is run for each transportation fixed plant alternative. This formulation of the problem is described in Fig. 7.

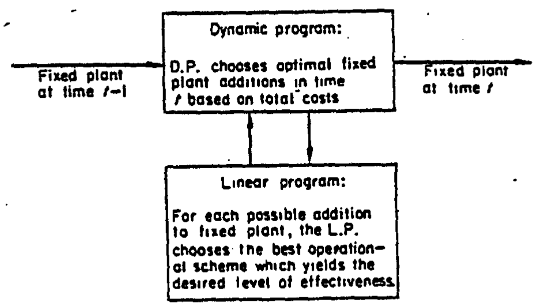

Fig. 7. Relationship of the dynamic programming and linear programming portions of the problem.

In describing the details of this formulation, it is most convenient to begin with the linear programming problem. This portion of the problem takes as given the values of the transportation fixed network variables. Given these variables, certain choices regarding the service to be provided on each arc of each mode must be made. These choices relate to such items as frequency of service, price to be charged, travel time between terminals or interchanges and capacity level. As shown in Fig. 7, certain constraints involving these variables must be met. Some of these constraints relate the choices of transportation system properties to levels of effectiveness, which are given at the outset of the problem for each time period. Other constraints will typically refer to such things as: capacity equalling or exceeding demand, level of service, the level of transport technology presumed to exist and the usual non-negativity constraints. The cost function refers to the marginal cost, over and above the cost of the fixed plant, which is implied by any choice of the set of continuous variables. Costs are the amounts incurred at each stage, discounted to present values, of course.

The linear program is then run for each alternative fixed plant for each time period, and it selects the optimum characteristics of the transportation system given the constraints of the fixed plant and the effectiveness level to be achieved. If, given the fixed plant, there is no possible feasible combination of transportation system properties which will yield the desired level of effectiveness (that is, satisfy the constraint relationships), then the program will automatically indicate this infeasibility. This linear program will be run for each fixed plant alternative and each stage. The fixed plant alternatives which are deemed feasible by this analysis are then retained.

The results of the preceding analysis are then entered into the dynamic programming problem. For each stage and for each feasible fixed plant alternative, a cost, including the cost of capital investments to be made and the cost of operating the system, is entered.

The cost associated with construction of the fixed plant at each stage of the dynamic program will, of course, be a function of the fixed plant which exists during the preceding stage and which must be upgraded to yield the desired fixed plant at the stage in question. Again, these capital costs will be discounted to present values.

Thus, the costs at any particular stage will depend not only upon the fixed plant and the value of continuous variables chosen at that particular stage, but also upon the nature of the fixed plant at the preceding stage. This relationship is incorporated into the dynamic program by means of the transformation matrix, which gives information on feasible fixed plant alternatives, given any fixed plant existing at the time of entry into the particular stage in question. Given any fixed plant while entering into a particular stage, the costs of additions to that fixed plant, to yield a new fixed plant, are uniquely determined. Feasible changes over time are indicated by this transformation matrix, an example of which is given in Fig. 8.

From \ To		1	2	3	4	5	6	7
Link 1*	1	1	0	0	1	1	0	1
Link 2	2	0	1	0	1	0	1	1
Link 3	3	0	0	1	0	1	1	1
Links 1 and 2	4	0	0	0	1	0	0	1
Links 1 and 3	5	0	0	0	0	1	0	1
Links 2 and 3	6	0	0	0	0	0	1	1
Links 1, 2 and 3	7	0	0	0	0	0	0	1

* The state of the network (links in existence) listed in this column is designated by the number to the right.

An entry of unity in a cell i, j indicates that it is feasible to pass from state i to state j; a zero indicates that this is not feasible.

FIG. 8. Example of a fixed plant transformation matrix.

This combination of a dynamic program and linear program operates in such a manner as to choose the (cost) optimal set of transportation improvements and operational variables over a period of time in which a number of distinct time periods and their interrelationships are considered. The initial starting point is, of course, given by the existing network and the existing level of service on that network.

Either a single fixed network or a number of possible fixed networks existing at the end of the planning horizon can be considered. These presumably would be chosen in such a manner as to yield a desired level of flexibility with respect to possible future paths of network development.

Different government policies with respect to level of transportation system service can be represented in the problem by changing the level of service constraints in each of the linear programs. As this change is made, the effect of these policy changes upon the selection of network improvements and the cost of network improvements can be readily obtained. This will permit the arraying of various government policies and the consequent costs of the transportation system. In this manner, various levels of government can examine the effectiveness of various transportation programs and the costs of the optimal program to achieve each objective to varying degrees, and thereby make an intelligent policy choice among the effectiveness levels to be achieved.

This arraying of alternatives in a cost-effectiveness framework then enables the analyst to perform his analysis without making the difficult value judgements which can only be made by representatives of society in general. The final decision thus rests with the political leaders, but the analyst has given these governmental leaders the information upon which to base an intelligent decision. In addition, political leaders can be given the opportunities to examine various policies and effectiveness levels which the analyst does not analyse himself, merely by rerunning the goal-directed model for a different policy or set of effectiveness levels. Thus, the political leader can experiment with various policies using this model system.

An important consideration in any predictive endeavor is the consideration of uncertainty regarding the future. This uncertainty exists with respect to human preferences and behavior, with respect to costs of doing various things, with respect to levels of activity in the economy and with respect to the technology which will be available. This uncertainty will continue to exist regardless of how refined our predictive models become, because human preferences and human values seem to continually change over time. Moreover, the environment within which a region of the United States or the United States as a whole exists is continuously changing and changing in a manner which is in itself not wholly predictable.

Therefore, it is desirable to try to accommodate this inevitable uncertainty within the planning process. An important consideration in this regard is the flexibility of any transportation system plans and programs with respect to responding to unforeseen changes in the environment. If such flexibility is built into our plans and programs, then we insure that we are able to respond at least in part to these changing needs of the world. To date, the desire for flexibility has been frequently pointed to in the literature and mentioned in most transportation planning studies, but to our knowledge it has never been incorporated into these studies as an operational criterion for the selection of particular plans and programs.

The goal-directed transportation planning model described above lends itself to a definition of flexibility and to an operational measure of the extent to which any particular set of system improvements are in fact flexible. This consideration of flexibility is provided by varying various givens or various parameters which are input to the model system at the outset. For example, with respect to human preferences regarding modal choice, the value of travel time, etc., one can change the parameters of the demand and modal choice model in order to see how varying human values and preferences affect the amount of travel on various modes. This enables one to see how varying values and preferences of these sorts can cause variations in the desired investment program and operating scheme of a particular transportation network.

Certain aspects of the network improvement program involve purchasing items of high costs, which items cannot be diverted or adapted to alternate uses if the predicted use does not materialize. The most conspicuous examples of this type of item are the elements of the fixed plant. One can see how the optimal network changes with respect to the fixed plant called for as parameters of the model are varied. If there are no changes in the fixed plant, then the optimal network from a cost sense is also a very flexible network, because usually those physical changes which are required change only the items described by continuous variables in the problem (frequency, price, capacity and travel time), which can generally be instituted without difficulty, whereas changes in the fixed plant are very difficult to institute. This results from the fact that the fixed plant is usually, as the name implies, fixed in space and cannot be used for other purposes, or sold, but the changes in the flow network are easily accommodated by selling of equipment, changing the fare level, and similar, relatively readily implemented means.

Other aspects of this uncertainty involve costs, particularly the costs of new technologies and also the availability of various new technologies. This can readily be explored in the model by varying the cost parameters and the parameters involved in the various technological constraints. It can also be explored by removing from the model system the possibility of instituting a sub-system involving the use of a new technology at some point in the future. One can then rerun the program without the availability of this new technology and examine whether the fixed plant for other technologies would change very much as a result of this change in the constraint set. In this case, it would be hoped that the only changes would be changes involving additions to, but not deletions from, the fixed plant of other modes. If this were the case and if these changes could be instituted without great cost, then the system leading up to this particular stage would be considered a flexible one.

Similar changes reflecting uncertainty, represented in the model system by variations in parameters of the model, can be explored. These can be accomplished in a similar manner and the conclusions regarding system flexibility would be similar to those described above.

Of course, in the above discussion we have not defined the value of flexibility; we have merely given an operational definition to it and given an indication of how one would compare various systems with respect to their flexibility properties. At this point in time, it does not appear as though a value of flexibility can be given. In fact, it appears that the value of flexibility is essentially a value derived from the flexibility and cost of one system relative to the flexibility and cost of alternatives which might be instituted. It seems that subjective judgements as to the value of flexibility will have to evolve from the consideration of various alternatives and their properties with respect to flexibility.

V. CONCLUSIONS

The model system described above is now being developed at the Transportation Center at Northwestern University. It is still in its embryonic stages, but from initial experience in running various programs, it appears that the goals implied by the description above can be achieved. Applications will be made to the problem of selecting alternative transportation investment and operational schemes for the Northeast Corridor.

It is hoped that this model system will represent a step forward in the science of transportation planning. We have attempted to take into account, to the extent possible, real-world considerations and issues, with respect to transportation investment and operational schemes. Our motivation has been primarily one of responsiveness to the real-world problem, not necessarily the development of an elegant mathematical model. With this motivation, we have attempted to take into account the problem of investment in a multi-mode network, the problem of the sequencing of investments or the selection of the time at which investments are to be made and the problem of uncertainty with respect to the future environment in which the transportation system will find itself. The test of whether our efforts are successful will of course come from the application on which we are now working. Comments and suggestions about our approach to transportation planning are welcomed.

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MODELS FOR RAIL TRANSPORTATION

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Abstract—Railroads constitute an important mode of transport for both freight and passengers. In the United States, for example, railroads are responsible for 35.6% of total intercity freight transport and enjoy approximately 30% of total revenues of all carriers. However; due to severe competition from other modes, the rail industry is eager to improve its operational efficiency and rationalize its planning decisions further. The role of analytical models in supporting managerial decision-making thus assumes renewed importance. This paper reports on the existing literature models for rail transportation with two goals in mind: (a) to collect and categorize rail modelling efforts, and (b) to position the rail-related literature in the context of other transportation models and provide an introduction to this field for nonspecialists. Optimization, queueing, and simulation models are all treated with particular emphasis on optimization. The role of each class of models is discussed in relation to its function and its position within the total planning activity of a railroad. A concluding section outlines the major modelling obstacles and promising areas for future development.

Railroads constitute an important mode of transportation for both freight and passengers. In the United States, for example, railroads handle over 35% of all freight measured in ton-miles. The railroad industry has a large investment in equipment and a sizeable number of employees. Its management faces a complex decision-making environment where a broad spectrum of planning and operational issues have to be settled. This complexity calls for decision-support systems in the form of analytical models. The potential of significant financial returns from even small percentages of savings motivates a serious interest in such models. The competition from other modes of transport acts as a further impetus in this direction.

Fortunately North American and European railroads have been historically receptive to the use of analytical planning models. The increasing computerization of rail systems provides rail managers with an information system data-base for the implementation of planning models. The past decade has witnessed the efficacy of optimizing planning models in several areas of transportation (see, for example, the survey by Magnanti and Golden (1978) of network models). It is thus not unreasonable to hope that optimization-based models will assume a similar importance in the rail environment. As a result, we feel that a survey of the existing literature on analytical models for rail systems is timely. Our experience suggested that the extant work in this area has not received sufficient exposure and is somewhat scattered. This paper, therefore has two objectives: (a) to provide the analyst familiar with rail systems a synopsis of the known modelling approaches to planning and operational issues, and (b) to acquaint modellers in the fields of transportation science and operations research with issues in rail planning that currently present challenging opportunities for model formulation and implementation.

The next section briefly reviews the institutional background and terminology specific to rail systems. This description of basic rail operations is supplied with goal (b) in mind and is referred to in the remainder of this paper. Section 1 also seeks to provide a context for various planning models and their relation to other areas of transportation. The following sections categorize the literature on rail modelling according to the issues addressed by each class of models. Optimization, queueing, and simulation models are all treated although there is an admitted emphasis on optimization models since, in the author's opinion, these hold a significant developmental potential. Since in many countries freight transport constitutes the major use of railroads, the issues relating to freight are treated in greater detail although we discuss passenger transport whenever appropriate particularly in Section 7 on scheduling trains.

1. INSTITUTIONAL BACKGROUND

As in many other transportation environments, one may regard the rail transportation system as a network. The links of this network refer to lines of track where long haul movements of traffic take place. The nodes refer to stations where carriers pick up or deliver traffic to. In the case of rail freight transport the nodes represent *classification* or *marshalling yards*. The major function of yards is to reorganize the incoming traffic for departure on outbound trains leaving that yard. We call the various operations performed in a yard, *yard activities* to distinguish them from *line activities* that refer to decisions affecting the journey of a train between yards.

One source of complication in rail systems is the intricate nature of yard or node activities. The incoming traffic may undergo major reorganizations at a yard before it is assigned to the next carrier. As opposed to, say, airline systems, most freight shipments do not proceed directly from origin to destination, but generally visit a number of intermediate yards. Studies indicate that the major portion of delays occur at such intermediate yards thus suggesting that yard policies and operations largely influence the line movement of traffic. Modelling the interaction between line and yard policies

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is a challenging issue that is discussed at various points of this paper. A brief overview of the basic yard and line activities follows:

Yard Activities. A typical car visits classification yards at intermediate points of the trip from its origin to its destination (from the shipper to the consignee). At such an intermediate yard, cars are taken off the train and placed on receiving tracks of the yard. The main activity at the yard is a sorting or *classification* activity whereby incoming cars are grouped together according to their outbound destinations. Cars in the same group will share some initial leg of their subsequent trips out of the yard towards their destination. This consolidation of cars into *blocks* or *groups* allows railroads to take advantage of the economies associated with full trainloads. The decision as to what cars should be grouped together is called the *grouping* or *blocking policy.* Blocks including cars with diverse destinations have to be broken up at a later yard and reclassified. Thus there is a tradeoff between reclassification costs and delays and the advantages of utilizing trainload economies. Given the highly combinatorial nature of the problem, the determination of optimal blocking policy constitutes a complex issue.

Cars in the same group are placed on classification or departure tracks to await the departure of an outbound train. Physically this sorting is accomplished in two ways:

(i) In *hump yards* the cars roll down an incline (or a hump) and are then automatically switched onto the appropriate track allotted for that group.

(ii) In *flat yards* cars are moved onto the tracks by a switching engine. Most modern classification yards are automatic hump yards.

Any outbound train at a yard has a *take-list* that specifies, in the order of preference, the groups or blocks of cars it may pick up from the classification tracks. We may call this the *make-up* policy for that train insofar as it determines the composition of the train. Thus, if the number of cars waiting for departure in the most preferred group on the take-list is insufficient to warrant the trip, cars from the next preferred group are added on to the train until an acceptable trainload is achieved.

One may view a classification yard as a service station (or better yet, a collection of servicing facilities) through which a car passes. A car suffers various delays in the reception yard, for the inspection activities, and on the departure tracks. The departure delay has two possible sources: (i) A car may have to wait for the next outbound train to arrive thereby incurring a *connection delay*, or (ii) If the train's departure is predicted upon the accumulation of a sufficient number of cars, there will be an *accumulation delay.*

A typical case of this latter delay arises when a yard uses a *dispatching rule* of the following kind: "Train No. 124 departs at 10:00 a.m. if 100 cars are ready for departure, at 11:00 if 80 cars are ready and so on." Dispatching rules, therefore, involve a tradeoff between trainload economies and traffic delay. This problem has a dynamic component that makes the derivation of optimal policies very hard, especially if one considers the effect of delaying a train departure on subsequent yards. O[ne] may also investigate issues of centralized versus dece[n]tralized control according to the extent these rules a[re] derived locally by the yard personnel as opposed to [a] central decision-maker.

Section 3 reviews the literature on yard modelling. Fo[r] more information on classification yards the reader ma[y] consult Troup (1975), Beckmann *et al.* (1956, Chaps. [7] and 8), and Folk (1972).

Line policies

Line policies affect the movement of carriers on the tracks. As such, they interact with the overall *routin[g]* decisions that determine the flow of traffic on the ra[il] network. Key line policies include:

Scheduling. Which routes of the network should b[e] provided with service and with what frequency. We tak[e] the scheduling problem to include the issue of specifyin[g] train itineraries. That assumes major importance in th[e] context of passenger services.

Timetabling. A timetable provides arrival and depar[-]ture times for each yard (station) included in a train itinerary. There are two basic considerations in esta[b]lishing a timetable: (i) efficient use of track capaci[ty] and (ii) prompt delivery of traffic along a certain leg of [its] journey. The latter issue leads us to examine tradeoff[s] between accumulation delay and connection delay. [A] number of other factors may constrain timetables: In[-]spection requirements, crew and motive power availab[il]ity, minimum headway considerations, etc.

Track priority rules. If track capacity is limited, [a] priority scheme is necessary to set protocols for mee[ts] and passes or right-of-way. These rules will in turn affe[ct] the over-the-road delay trains experience. For an enu[-]meration and discussion of line-haul delays, the read[er] may consult Belovarac and Kneafsey (1972). Li[ne] models are reviewed in Section 4.

Certain decisions, which one may call *network-wi[de] policies*, impact the rail network as a whole interact[ing] with both line and yard policies. A prime example is t[he] *routing* decision that determines the flow pattern [of] traffic between origin-destination (OD) pairs. Rout[ing] models are widely used in other areas of transportat[ion] such as airline systems, traffic equilibrium, and vehi[cle] routing. When stated in terms of a network these mod[els] share the basic multi-commodity flow structure (Assad, 1978). However, in the case of rail freight tra[ns]port it is necessary to consider the sequence of block[s a] certain shipment enters when travelling from its or[igin] towards its destination. Since various classes of tr[affic] that share certain legs of their flow paths on the netw[ork] may combine to form common blocks, an additi[onal] combinatorial complexity enters the routing decision [which] must be fully specified by a *network-wide blocking [pol]icy.* The interaction between this policy and yard w[ork]loads becomes important when preblocking is used [as a] device to reduce congestion at yards operating near capacity levels. In this option, a yard with extra cap[acity] will perform some of the classification work norm[ally] performed by another yard further downstream th[at is] overloaded to near-capacity levels. Modelling the va interactions between line movements of traffic and the yard policies is a key factor in the development of rail network models in Sections 5 and 6.

Car and engine distribution constitutes another network-wide problem in the operation of railroads. Various studies TRB (1975), CTS (1975) point to poor car utilization due to faulty operating policies and distribution procedures. The basic issue involves redistributing empty cars and engines from locations with surplus to those with insufficient supply that arise due to imbalances in the pattern of freight shipments. In view of the cost of capital tied in cars and engines, rail management is seriously concerned with increasing the productivity of this equipment. Clearly, effective distribution and control systems not only improve the availability of cars and carriers for shipment but also offer opportunities for greater utilization and a possible reduction in fleetsize. Section 8 describes distribution models developed for this purpose.

The context of rail planning

The issues addressed by various analytical models reviewed in this paper may be categorized according to their positions in the hierarchy of planning decisions. Here, one may take the strategic/tactical/operational classification of Anthony (1965) as a guide as in an earlier paper by the present author (Assad, 1980): Briefly, strategic planning addresses resource acquisition in the long term. Changes in the link structure of the rail network and the location or expansion of classification yards may be viewed as strategic issues.

Tactical planning focuses on resource allocation in the medium term. Rail network models generally operate on the tactical level. Here the general pattern of traffic flow on the network is derived from basic demand data on OD requirements taking yard and link capacities into account. It is important that network models be responsive to changes in the requirements pattern arising, for example, from seasonal shifts. Tactical models can also be used to evaluate the network-wide effects of certain operating policies such as the institution of particular blocking strategies at certain yards.

Network models may use both yard and line models (see Section 3 and 4) as components. On the other hand, they may be used as components of a more aggregate strategic model. An example of this arises in network design problems where various network structures are evaluated and compared by investigating their traffic load patterns for given demand requirements through a tactical network model.

Once the flow of traffic over the rail network is known, the assignment of traffic to carriers constitutes the train scheduling problem. The determination of the number and frequencies of train services and their itineraries forms another tactical planning problem. Indeed, in the case of passenger transport, this tends to be the major tactical issue. We devote Section 7 to a discussion of scheduling models.

Lastly, operational decisions reflect the day-to-day activities of the railroad. Empty car distribution, engine scheduling, timetable setting and dispatching policies may be quoted as examples. Generally these models use the information provided by tactical models as a basic guideline and respond to the dynamic changes in the environment. Certain operational decisions in a railroad may not derive from centralized planning at all and simply be decided by yardmasters locally. Indeed, the internal operations of a rail classification yard are somewhat similar to the activities of a job-shop. Empty car scheduling models as described in Section 8 have been successfully implemented and used on the operational level.

The following sections of the paper review the arsenal of models for railroad activities. Although the structure of these models and the corresponding solution techniques are emphasized, we do not wish to imply that any one model acts as a panacea and effectively captures all the complexities of the rail environment. There are severe barriers to effective implementation of the models discussed: on the input side, data-gathering and particularly cost information require substantial effort. Costing has been a notorious difficulty in railroads (see Kneafsey, 1975; Murphy, 1976; Poole, 1962; Stenason and Bardeen, 1965; and TRB, 1975, pages 190–194).

We conclude this section by citing some references providing useful institutional background that the modeller will find useful: the papers presented at the Railroad Research Study conducted by TRB (1975) address the basic questions and research needs for the railroads in the period 1975–80. A series of international symposia on the use of cybernetics in railways (see Proceedings, 1963, 1967, 1970) address a wide range of issues on management information and planning systems for railways. The Association of American Railroads (AAR, 1974) prepares and periodically updates a collection of models used by North American railroads each summarized in a one-page abstract.

The MIT group on reliability in rail transportation directed by Sussman (1972) has published a series of reports running through some 17 volumes. These studies contain valuable insights into yard and line operations and policies and culminate in a case study of Southern Railway (see Sussman and Martland, 1974) containing specific recommendations for improving reliability.

Finally, the reader is referred to the recent bibliography by Rakowski (1976) for information on railroad economics, a topic that the present paper omits. For overviews of rail modelling in particular countries, he may consult Wilson (1966), Urabe (1966), Yabe (1967), and Truskolaski (1973) in addition to the proceedings quoted above.

2. FACILITIES LOCATION AND INSTALLMENT

Facilities acquisition or installment decisions for a rail network generally lead to aggregate network design or improvement problems. However, relatively few studies have documented the use of such optimization-based models to the rail environment:

Pierick and Weigand (1976) formulate the selection of train routes on a rail network as a network design problem. The choices range from providing direct service between any two yards to "local" itineraries which serve a number of yards on a given route. The objectives are: (a) use shortest routes: (b) minimize the number of routes used: (c) maximize the number of passengers (or cars) who can use direct routes (i.e. require no connections). The authors propose a branch-and-bound procedure to solve this problem.

Leblanc (1976) considers a network improvement problem where the coefficient of shipping costs on each link is lowered by link improvements (such as track maintenance and upgrading) at a known cost. As the degree of improvement of each link is reflected in the shipping costs per unit flow, these coefficients, together with the usual flow variables, are treated as decision variables. Minimization of shipping (routing) plus maintenance costs over the network results in a nonconvex-nonconcave trans-shipment problem which Leblanc then transforms to a concave minimization problem. The paper also includes computational results for 40 test problems with parameters randomly generated on a 10 node network.

Kondratchenko and Turbin (1977) view track improvement as a stagewise process. A series of actions can be taken to improve the capacity of a single line, given a projection of future demand requirements over time. The objective function consists of investment necessary to go from one "state" to another and the maintenance costs for each state. The authors provide a graphical method for finding the optimum sequencing of improvements (transitions to improved states of capacity).

Another major facilities installment decision involves the location of a new classification yard or planning for the prospective technical profile of an existing yard. Mansfield and Wein (1958a) describe a deterministic simulation model for yard location. The set of feasible sites, the traffic flow, and the changes in grouping policies form the inputs. Total costs are computed for each site (using analytic formulae) and the least expensive site is selected. This model is interesting in that it considers the effect of routing and grouping policies on the location decision. However it relies upon managerial judgement to prescribe the new routing and grouping policies resulting from the location of a new yard. Gulbrandsen (1963), too, uses a simulation model to plan the profile, technical equipment of reception and sorting yards, and the number of tracks in the reception yard of a marshalling yard. For each choice of the above three factors, the model calculates the total costs (fixed, service, and waiting costs) to find the least costly combination. Sotnikov (1974) reviews the large number of factors influencing the optimal choice of yard profile and suggests simplifying assumptions which result in expressions for operating costs as a function of yard throughput. Thereupon a sequential improvement program viewed as a transition between different technical states is proposed to plan for the optimal profile. The tradeoff, naturally, lies between numerous reconstructions and the early installment of equipment (which would not be in full use for some initial period of their life). It is also possible to search for the optimal profile of some subsystem of the classification yard instead of considering the whole yard in all its complexity.

3. YARD AND TERMINAL MODELS

Yard models analyze the operation of a given classification yard (or terminal) or some subsystem thereof. Such models provide estimates of mean delay or operating costs and point to congestion and bottleneck effects associated with yard operations. They may also be of use in evaluating the effects of certain policies on yards or serve as aids to the allocation of yard resources and equipment. As one of the important uses of yard models is the prediction of delay characteristics of various yard operations, it is important to isolate the main sources of delay in a yard. The unit of transaction passing through a yard is a *cut*, that is a string of cars with the same final destination, that does not need to be sorted at any point of its trip. A given cut encounters the following delays in its passage through a yard: (a) Reception and Inspection Delays; (b) Classification or Sorting Delay; (c) Connection Delay; (d) Train Assembly Delay; (e) Outward Inspection and Departure Delay.

The modeller may correspondingly break up the yard into subsystems involving the above operations. The yard manager must divide the physical resources of the yard; that is tracks, engines, and crew, among these operations. In smaller yards some of the above activities may share the same resources: for example, some classification tracks may also serve as departure tracks. Once the yard subsystems are clearly defined, queueing or simulation models may be used to provide information on the behavior of each subsystem.

Yard queueing models

A number of studies apply basic queueing theory to specific yard processes in railroads. The yard is viewed as a composite service facility with each of the operations (a)–(e) listed above, modelled as a queueing system with a given arrival process and service function. Naturally, it is important to determine the degree of interdependence among various subsystems and to ascertain whether parallel or series modelling is appropriate for linking the operations together. For simple inter-arrival and service time distributions (such as exponential), analytical formulae are available for certain system characteristics such as average queueing time, average length of the queue, and the probability of overloading the system (see, e.g., Kleinrock, 1975). A series of papers by Petersen provides a systematic analysis of the delay terms (a)–(e). For the yards under investigation, Petersen concludes that operations (a) and (e) are not bottlenecks and can therefore be modelled realistically by fixed service times. The classification and train assembly operations, however, exhibit congestion effects and are modelled as $M/G/s$ queues. Here, M denotes Poisson arrivals for the cars, G is a general service-time distribution, and s is the number of service channels. The class of distributions G for which the resulting queueing systems is analytically tractable is somewhat limited. In fact, one may use a deterministic (D), exponential (M), or Erlang distributions of order k (E_k) for G. It is important to take the yard type into account when choosing G (Petersen, 1977a). The connection delay may be modelled as an $M/E_k/1$ (bulk) queue as in Petersen (1971b). This means that cars arrive according to a Poisson process and are periodically pulled out and assembled into outbound trains. These trains depart according to an Erlang distribution of order k. The parameter k may vary between $k = 1$, corresponding to completely random train departures, to $k = \infty$ which implies a regular pick-up schedule. Such a model provides information about the waiting time for the pick-up or collection process at a yard. Petersen compares the predictions of these models with actual data from two hump yards.

In a follow-up paper, Petersen (1977b) relates the service rates of the classification and train assembly processes to the number and configuration of classification tracks, the available yard engines, as well as the yard grouping policies and traffic intensities. (We comment on the role of grouping policy on switching delays later.) Petersen's co-workers, Schwier *et al.* (1976) have prepared codes for the models described above, now available as a user's manual.

Other researchers have used queueing models for specific yard subsystems: Hein (1972a) gives an approximation for a two-stage model of the approach side of a marshalling yard: cars are placed on the arrival sidings and are processed through the hump as soon as it becomes available. Thus the cars wait for inspection and also for the sorting process. Let m be the number of arrival sidings. Then the delay approaching the arrival sidings decreases as m increases. Conversely, the delay before the hump increases with m. Hein (1972b) studies this trade-off analytically to determine the optimum value of m. A similar use of queueing results for yard design is the work of Fotea (1976). He uses an $M/M/s$ queue to calculate the load on a set of reception sidings for a given sorting rate. Specification of a certain range of acceptability for the load factor determines the required number of sidings.

Brandalik and Kluvanek (1966) analyze the occupancy distribution of reception sidings using an $M/M/S$ queue. This allows them to determine the required number of sidings graphically. Kluvanek and Brandalik (1966) carry out a similar analysis for the locomotive change sidings which usually form an independent subsystem of the yard. These authors have also studied the car collection process at classification tracks. In Kluvanek and Brandalik (1974), cars follow Poisson arrivals, and two collection policies are studied: (i) Fixed collection periods; (ii) Variable collection periods governed by fixed trainloads. The second policy differs from the first in that trains pull out cars from the track as soon as a given number of cars (corresponding to a desirable trainload) accumulates. Brandalik & Kluvanek (1976) extends this analysis, under policy (i), to incorporate a fixed departure delay in addition to the collection cycle time (which, in turn, is set by train departure frequencies). The authors study the capacity of classification tracks for the above process and also discuss the time-phasing of train departures within a collection cycle.

Yard simulation models

Yard simulation models simulate the movement of a typical input to the yard as it undergoes various yard operations. The cars move through the yard according to a set of mathematical or logical rules specified by the modeller or user. There is a large number of possible rules or input parameters for a typical classification yard-track assignment, grouping rules, schedules for outbound movements, car length restrictions, crew assignment and shift procedures, to mention a few. The model provides information on the delays and costs associated with a given set of rules, allowing the modeller to evaluate their feasibility and efficacy. The power of such a model lies in its capacity to capture a large amount of detail. As a result, most railroads now use a yard model to evaluate the yard capacity and resource requirements as a final check before actual adoption of a policy. Yard models are usually used in conjunction with larger rail network models (discussed in Section 5) where a given yard is linked with other yards in the rail network so that the global impact of a set of policies is not ignored.

The work of the Batelle Memorial Institute on the development of simulation models for railroads is reviewed in Shields (1966a, 1966b) and Koomanoff and Bontadelli (1967). In particular, Shields (1966a) describes two deterministic simulation models at different levels of aggregation. One model deals with the input on a car-to-car basis thereby incorporating great detail. To overcome the slow running time of this model the other model operates on a more aggregate level to simulate a 10-day period in several minutes of running time. The RSRG Terminal model is described in three papers of RSMA (1966, pp. 169–193) where its use in the Chesapeake and Ohio Railway is also discussed. Nadel and Rover (1967) discuss the simulation model in GPSS used at New York Central Systems (NYC) for a large classification yard. Wunderlich and Wiedenbein (1972) outline a simulation model used for the Berlin yard. We do not wish to enter into the details of yard simulation models and consider the above citations as only representative. We comment further on simulation models when we review network models in Section 5.

Yard production functions

A question of basic interest to the modeller is the nature of a classification yard's production function. By this we mean a certain aggregate measure of the yard's capability to process incoming traffic. This might take the form of an aggregate service function relating the processing time and dollar costs to the volume of traffic the yard handles as in the work of Sotnikov (1974). Alternatively, one may try to calibrate production functions for specific subsystems of the yard as implied in Peterson (1977a). In either case, it is important to note that both queueing and simulation models of a classification yard must rely on such relations to determine the *service rates* of specific yard operations. Unfortunately this research area has received comparatively little attention in the rail environment.

Since a *cut* refers to a string of cars that do not require intermediate reclassification or sorting, we expect blocks of cars with a high cut/car ratio to require less classification work. Clearly the more homogeneous a string of cars in terms of its final destinations, the larger the cut/car ratio. Beckmann *et al.* (1956, Ch. 8) first used a relation of the form $t = a + b \cdot (m/n) + c \cdot n$ to estimate the sorting time/car t. Here, n is the number of cars in the string to be sorted and m is the number of cuts with which it is separated. Beckmann *et al.* found values for a, b and c through regression for two classes of data involving hump and flat yards. Note that this relation is important in deciding the yard grouping policy as this policy determines the number of cuts incoming traffic is separated into. Indeed Beckmann *et al.* (1956, *Chap.* 10) use a service function based on cuts to set the optimal grouping policy at a hump yard followed by a flat yard. Assad (1978b, Chap. 5) discusses an extension of this approach dealing with several yards of different productivities. Petersen (1977b) also relates the service for the sorting operations to the grouping policy of the yard.

Not all trains are completely reclassified at a marshalling yard and the volume of cars handled by a typical yard is substantially larger than the volume of cars actually sorted at that yard. As a result, it is important to determine service rates (barring congestion) for processing trains with a variety of make-ups at a given yard. The two papers by Alexander (1968) and Shinohara (1963) contain some results and comments in this regard. Finally, we mention that a number of different schemes exist for sorting a given input of traffic, especially when the number of sorting tracks is significantly less than the number of outbound groups formed at that yard. Bourgeois and Valette (1961) and Siddiqee (1972) have studied the suitability of each scheme.

4. LINE MODELS

Line models analyze train movements and dispatching activities over the track sections. They investigate the capacity of track sections, identify the related bottlenecks, and evaluate priority rules in meets and overtakes over the line. The capacity of a rail line can be evaluated through the delays encountered by trains under different operating assumptions. Petersen (1977c) provides a very useful survey of the basic issues of line capacity and reviews some of the available literature in this area.

Petersen (1974, 1975) develops analytical models for the prediction of the average interference delay over a single track line and a partially double-tracked line. His study involves priority rules for meets and overtakes for three classes of traffic (way-freight, fast freight and passenger). Based on the assumption that trains within each class are independently and uniformly distributed over the given time period, Petersen computes the expected interference delays. English (1977) refines this approach and develops delay expressions in greater detail. These models are used to predict delay as a function of traffic intensity over the line thus forming a component of the Railcar Network model (see Section 5 below). However, they are appropriate for low to moderate traffic intensities only. As the intensity increases, dispatching delays become predominant with respect to section run-out time and switching delays. This means that trains tend to queue for dispatching at yards waiting for track capacity to become available. In general terms, the dispatching decision is similar to a machine scheduling problem where trains correspond to jobs and machines to track sections. Various priority and order restrictions constrain the scheduling decision. As with machine scheduling, it is possible to formulate this problem as a 0–1 integer program with the objective to minimizing total travel time as in the work of Szpigel (1972). However, the resulting programs are hard to solve and must be limited to a very small number of sections. This calls for simpler models of line capacity. Frank's paper (1966) serves as a basis of such a model that captures the essential features of train paths on a single line for periodic schedules. He considers the simplified case of a line with equally-spaced sidings on which all trains travel with same speed. Petersen (1977c) uses Frank's result to show that the availability of double vs single sidings strongly influences line capacity while it has little influence on the number of trains (or cycle time) required for different patterns of train movement. He also extends this idealized model to derive the probability distribution of the section track time needed to process the traffic. The extensions incorporate switching times, headway allowances, variable section lengths and variations in the train patterns. Next he combines these ideas with the earlier over-the-road delay model of Petersen (1974) to extend its applicability to high traffic intensities. This means that dispatching delays have a substantial effect on train transit times due to queues building up at yards for train dispatches. Dispatching delays depend on train transit times over the bottleneck track section, the availability of double sidings (as in Frank's analysis), and the pattern of train movements.

As mentioned earlier, the above models function as planning models and are, of necessity, aggregate in scope. For actual operations, railroads simulate line activities in great detail. For instance, Wilson *et al.* (1963, 1967) describe two simulation models used by Canadian National Railways (CNR): The Train Performance Calculator (TPC) simulates train movement over the track, based on the train's length, horsepower, speed, etc. but neglects interference with other trains. This program actually performs a step-by-step solution of the differential equations governing the train's motion. The Single Track Capacity Analyzer (STCA) simulates the details of meets and passes following a given schedule and priority rule. A new program SIMTRAC, which later replaced STCA, handles train dispatching over a single track for a period of 10 days. This paper also describes a siding-to-siding simulation of loaded car moves for the purposes of analyzing service time variability, i.e. reliability. The Chessie system used a simulation model of over-the-road operations to prepare train schedules meeting the U.S. federal 12 hours of service law. Another well-known simulation model is the Peat, Marwick and Mitchell (PMM) model which was used to determine the effect of varying track and signal configuration or train operating policy on line capacity. For a more detailed discussion of line capacity models, we refer the reader to Petersen (1977c) who notes the utility of simulation models in the calibration of analytical models described earlier.

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5. RAIL NETWORK MODELS

Network models integrate line and yard activities to provide a routing of traffic over the rail network as well as an allocation of work to classification yards and may be classified into two groups—optimization models or simulation models. Folk's (1972c) early survey of both these types serves as a useful introduction to rail network modelling.

Optimizing network models

Optimizing models search for an optimal routing of traffic through the rail network with respect to some objective function such as total costs or total delay. The basic input to such models is forecasted O–D requirements for traffic flow.

The prime example of this class of models is the Railcar Network Model developed at Queen's University at Kingston and the Canadian Institute of Guided Ground Transport (CIGGT). This research effort, documented in Petersen and Fullerton (1973a, 1973b, 1975), evolved over a period of five years into a comprehensive set of models of line and yard operations in the context of Canadian railways. The object of the model is to find the optimal routing minimizing total yard and line delays. In the yards, the delays are the five listed in Section 3 in our discussion of yard models. The inbound and outbound inspection delays per train are taken to be constant. The analytic queueing formulas allow one to express the average delay in the remaining operations as a function of traffic flow through the yard (node-throughput). Similarly, Petersen's over-the-road model (see Section 4) provides an average transit time to traverse a given link as a function of link flow. This corresponds to the usual service function, in the language of traffic planners, that incorporates congestion effects due to other trains. If the yard and line delay functions are all convex, then the routing problem assumes the structure of a minimum flow problem with convex costs. This nonlinear multi-commodity flow problem is algorithmically equivalent to a traffic assignment problem for which a number of efficient algorithms already exist (see Assad, 1978). Petersen (1975) uses a primal-dual assignment algorithm to solve the Railcar model. Schwier *et al.* (1976) document the component programs and the codes of the Railcar Network model.

The work of Thomet (1971a, b) constitutes another optimization approach to freight routing. Here, the objective function is the sum of delay costs and operating costs that take the cost of providing train services into account explicitly. The model addresses the trade-off between customer service (or the delay the customer suffers) and operating costs to the railroad in a heuristic manner: Thomet starts with a schedule that provides direct train service between all O–D pairs with nonzero demand. Clearly this solution involves a large operating cost but minimizes the traffic delay since no intermediate classification is necessary. The heuristic then proceeds to cancel some of these trains. Indeed a train from some yard i to yard j may be cancelled by moving its traffic to the two trains i to k and k to j for some intermediate yard k. This cancellation will reduce the operating costs (crew and motive power requirements) while the delay and classification costs will increase due to the intermediate switching at yard k. If one calculates a net savings for each cancellation, the train yielding the largest savings is cancelled at each step of the algorithm. We may readily observe the analogy between Thomet's heuristic and certain "savings" procedures for solving vehicle-routing problems (see Eilon *et al.*, 1971).

Assad (1980) discusses rail network models as planning tools from the viewpoint of hierarchical decision-making by distinguishing between tactical and operational issues. He also provides a critical review of the two models discussed above and suggests a network model that integrates the routing and make-up decisions. This is done by explicitly considering the effect of train composition on the classification delay at a yard. The resulting model has the structure of a multicommodity flow problem with certain nonlinearities in the objective function.

Our discussion of blocking models, in Section 7 includes other issues shared by network models. Indeed, a rail network model may be viewed either as a train scheduling problem or as a blocking problem for traffic, depending on whether train movements or car movements are emphasized. For instance the paper by Ackermann (1969) is very similar to Thomet's work.

Network simulation models

Rail network simulation models simulate the movement of trains and cars through the network taking a given set of train schedules and line or yard policies as input. Thus the user has to input the grouping policy at each yard, a complete set of train itineraries, and the traffic flow requirements, among other data. The output of these models includes operating costs (train haul and classification) and information about the distribution of transit times for traffic. Based on these outputs, the user may evaluate a given policy decision in detail, or search over several policy alternatives by repeated simulation if the running time requirements are not prohibitive.

Allman (1966a, b, c, 1967) initiated much of the work on rail network simulation models in the U.S. His early model (1966a) was used to perform a 10-day simulation of an 11-yard network with 28 scheduled trains. The inputs include demand data, train schedules, and yard policies, as well as cost information (on hauling, switching, and so forth). The "Frisco" Railway expanded this model to deal with 25 nodes and 51 trains, Bellman (1967). Allman's later papers report a 10-day simulation of a 20 yard network with 85 trains. The Canadian National Railways (CNR) network model also evolved from Allman's work. Wilson and Hudson (1970) provide a useful synopsis of this model with the results of a run involving 41 nodes and 100 trains. Folk's survey (1972c) gives an overview of other simulation models used by Southern Railway (1970) called SIMTRAN, Southern Pacific, and the AAR model. All these models use the SIMSCRIPT language, except Simtran which is in GPSS. Presently simulation models can handle a large number of nodes and train movements. For example, CONRAIL has used the SRI blocking model for networks with over 500 nodes (see Hoppe in TRB, 1975).

6. BLOCKING AND TRAIN FORMATION

Simply stated, the blocking problem concerns the repetitive regrouping of traffic on a rail network in its movement from the yard of origin to the destination yard. As mentioned before, there is strong interaction between the blocking problem (which refers to car movement) and carrier movement on the rail network. In particular train formation and make-up plans have to take blocking or grouping policies into account. This interaction is especially salient in the context of scheduling special direct or long-haul trains whose purpose is to avoid frequent intermediate reclassification for certain classes of traffic. The literature in this area varies widely in the degree of integration attempted between train scheduling or make-up and the network-wide blocking policy. In particular the network models described in Section 5 operate on an aggregate level and could provide rough guidelines for blocking strategies. On the other hand, the models of Bodin *et al.* (1980) and Holecek (1971) described below concentrate on the blocking strategy and abstract away from the scheduling problem.

The work of Holecek (1971) is one of the earlier optimization approaches to the blocking problem. He formulates a linear programming model to minimize the total routing and classification delays on a rail network. Each yard in this model services as an outlet for a set of destinations (e.g. local yards or sidings serviced by that yard). A grouping is an amalgamation of a subset of such destinations. Each yard classifies traffic into a number of groups that correspond to blocks composed of cuts of cars for any one of the destinations in the group. Thus, for example, if a given group has the form {1, 4, 5, 7}, cuts of cars for destinations 1, 4, 5 and 7 are consolidated into a single block or group on their outbound journey from the yard. A group composed of a single destination reflects a completely classified set of cars. For a class of traffic to exit the network, such a single destination group must be formed at the yard serving that destination. The decision variables, denoted x_{npd}^{gh}, refer to the number of cars with destination d that arrive at yard n in a grouping g and depart for another yard p in the grouping h. Any car following this course suffers a classification delay, measured as the time per car to transform from group g to group h; and a routing delay involving the running time from yard n to p plus an average waiting time for the outbound train at yard n. Flow balances and upper limits on the total amount of switching time available at each yard form the constraints of the linear program. Knowledge of the values of all variables x_{npd}^{gh} determines the car movement on the network (routing) as well as the sequence of groups (or blocks) cars become part of successively. Clearly, such a formulation leads to a very large number of variables if all possible groupings at a given yard are considered. Consequently Holecek reports computational experience for only two networks with 3 and 4 nodes.

The blocking model of Bodin *et al.* (1980) is somewhat similar but includes important refinements. In the Holecek model, all conceivable blocks may be formed with no further restrictions. The authors, however, impose upper and lower bounds on the number of cars in a block and define 0–1 variables specifying whether a given block (traversing a given path) should be formed at a yard. This leads to a more realistic model since very short blocks are not economical and are avoided in practice. The continuous variables x_{ijk}^{p} in the model, give the number of cars shipped from yard i to yard k along path p which are next reblocked at an intermediate yard j. These interact with the 0–1 variables y_{ij}^{q} that specify if a block is formed to go from yard i to j (where it's next reblocked) along path q. As in Holecek (1971), there is a constraint reflecting yard capacity, formulated here in terms of the total number of cars handled at the yard. The total number of blocks formed at any yard i is also constrained by an upper bound. The model is further complicated by the introduction of some special restrictions on the blocking policy dictated by the practice of the particular railroad under study. Another difficulty is the piecewise linear form of the delay function giving the waiting time on a given classification track of each yard. This requires the introduction of additional variables acting as breakpoint weights in the separable programming approximation to the objective function. The total delay, a sum of accumulation and connection delays, processing time for cars, and over-the-road travel time, forms the objective function to be minimized. The final report by Bodin and Berman (1979) describes the solution technique. The model involved 33 yards and was reduced to a mixed integer program with 1500 constraints, 1000 binary variables, and 5000 continuous variables and was solved by successive relaxations of the original problem.

The European literature on rail contains a number of other optimization approaches to the blocking problem from the viewpoint of train formation and makeup. Martens (1967) formulates a joint blocking/train scheduling problem. Given a skeleton of existing train services, he considers changes in the schedule to accommodate fluctuations in the load pattern. Thus, each train service may be duplicated to carry additional traffic, run as normally scheduled, or cancelled for want of traffic. An integer variable y_i reflects these choices by taking values 0, 1, and 2. Another set of integer variables determine the assignment of cuts onto the trains thus addressing the blocking/makeup aspect of the problem. Martens enumerates all possible assignments of a cut *a priori*. In addition to the classification costs, the objective function now includes the costs of operating train services explicitly (in terms of the y_i's). The paper draws a contrast between the two assumptions of divisible vs indivisible cuts. With the latter, a cut must be assigned to a train in its entirety and cannot be subdivided. In the former case we may divide cuts between different trains and thus obtain a model more like Holecek's. One should note that the divisibility assumption influences the computation of classification or processing costs for cuts.

Achermann (1969) gives a comprehensive report of a train formation program for the Swiss Federal Railways.

The objective is to schedule trunk-haul freight trains to reduce intermediate classification activities and train transit times. Indeed, Achermann allows only one intermediate classification. This results in a two-phase procedure for train formation: In Phase I traffic may move to its final destination or an intermediate classification yard. In Phase II, all traffic should move directly to its final destination. Each train is identified by a given make-up (or take-list). This could also be viewed as the formation of a block containing traffic with destinations in the make-up list. Achermann gives an integer programming formulation in which 0–1 variables govern the decision to run a given train. The costs of train formation and intermediate classification are explicitly incorporated into the objective function. Moreover, these are constraints on train weights and required motive power. The paper proposes branch-and-bound to solve the model and discusses the case of Swiss Railway's network involving 20 yards and 340 possible trains. We recommend this report especially for its clear discussion of the issues arising at each stage of the planning process.

Two Russian papers by Duvalyan (1973) and Kozloukova and Markov (1963), also address the issue of train formation and make-up as a tradeoff between classification time and the accumulation delay involved in dispatching direct trains. Truskolaski (1968) considers a similar problem and aims to determine an optimal assignment of direct trains to traffic flows as well as an optimal reclassification policy for the remaining traffic—the objective is the minimization of total car-hours spent at yards. Both papers rely on heuristic search methods that, unfortunately, suffer from cryptic expositions.

7. TRAIN SCHEDULES AND TIMETABLES

As in the planning of bus operations, train scheduling involves both space and time: the spatial dimension refers to the selection of train itineraries. For a given forecast of traffic loads, one needs to search for the optimal allocation of train services. This search usually calls for zoning decisions (that is, dividing the area under consideration into convenient zones) and the assignment of yard or station stops to different train services. Along the temporal dimension, a complete timetable should be devised for each train service. This step generally involves the specification of arrival/departure times at each station of the train's itinerary. The general train scheduling decisions, when viewed both in space and time, form a massive problem that is further complicated by a variety of other constraints such as track, crew and engine availability.

Most of the scheduling literature for rail has developed in the context of rail passenger and commuter systems. Although the results and contributions carry over naturally to the rail freight environment, the emphasis is somewhat different in the latter context: line activities are dominant in passenger train systems. Stops at different yards (stations) do not involve major node activities as in classification yards, or the regrouping of traffic. Moreover, timetable construction is of great import for commuter trains. Passenger trains are expected to adhere to a set of globally determined timetables and interferences on the local level with the overall plan are generally discouraged. For freight transport, however, yard operations are of great significance and, accordingly, local decisions tend to influence the global flow of traffic. Trainload economies and yard delay considerations affect the timetabling decisions. The dispatching rule "train leaves when 100 cars have accumulated" is an example of a local yard decision that affects the train's schedule over the course of its subsequent stops.

Because of its great complexity, the scheduling decision is usually carried out in two stages: the first explores tradeoffs in various zoning schemes, in express vs local service, and in the number or size of trains in the light of operating costs and customer service. The essential outcome of this step is the determination of the number of services to be operated and allocation of pick-up and delivery activities (along a given route) among these services. Transportation planners have studied a number of specific schedule plans, such as all-stop, skip-stop and zone-stop schedules in this regard (see Eisele, 1968). In the next stage, the planner may proceed to construct a detailed timetable and evaluate the costs of the resulting plan more precisely. Timetable construction involves the reconciliation of a given schedule plan with other constraints such as minimum headway (spacing train departures) and line interference effects arising from limited track capacity.

Morlok *et al.* (1973) adopt this two-stage approach in planning suburban railways. The schedule plan affects the number of carriers required in the fleet, total carrier-miles, and the crew requirements. For timetable construction, the authors use an extension of the model in Bisbee *et al.* (1966, 1968). This approach uses dynamic programming, with stage variables corresponding to discrete train arrival times, to dispatch the trains. Morlok *et al.* (1973) also include an application to a Chicago commuter railroad where 250 trains operate each weekday over a line of some 30 miles in length. Petersen and Merchant (1977) also propose the two-stage approach for train scheduling on a line and concentrate on an algorithm for the first stage. There, each of m possible trains has the 3 options of bypassing, stopping for classification, or stopping to terminate at a given yard, at a given cost for each option. Thereupon a dynamic programming formulation is used where the dynamic programming stages refer to the yards on the line. The authors propose special feasibility tests and bounding arguments to limit the number of choices in the dynamic program. The solution determines the optimal stop-schedules for all m trains.

The work of Salzborn (1969) on scheduling for a suburban transit system also reflects this two-stage planning approach. The network configuration for suburban systems usually involves rays emanating from a Central Business District (CBD) and may therefore be viewed as a set of single-line problems. Given values for the stop-time and required minimum headway, Salzborn shows how the timetable is largely determined by the stop-schedule of each train. Next he proposes two minimization criteria: (i) total carriage miles (TCM) and;

(ii) total number of passenger stops. (For each passenger, each intermediate stop before his final destination counts as 1 passenger stop.)

Each carriage has a fixed capacity of w passengers. Salzborn uses dynamic programming to find the optimal schedules. Moreover, if the number of passengers going from the CBD to each station i on the line is an integral multiple of w, Salzborn shows that some zone-stop schedule is indeed optimal. (A schedule where each train stops at a sequence of adjacent yards or only at a single yard is called a zone-stop schedule, Eisele, 1968). Clearly this qualitative result allows us to limit the search for the optimal policy to the much narrower class of zone-stop schedules. In a later paper, Salzborn (1970) studies the effect of the stop-schedule on the fleetsize required for a suburban rail system. A single train serving a line of stations has to travel to the end of the line before returning. However, as the demand tends to decrease for the tail of the line (i.e. far downstream) it might be advantageous to divide the service between two trains one of which "cuts-back" to the CBD before reaching the end. This results in shorter turnaround times and higher utilization rates for the carriage fleet. Taking the yard at which the train cuts back as his decision variable, Salzborn formulates a 0–1 integer program minimizing the required number of carriages at peak hours. Salzborn performed a case study for the City of Adelaide (South Australia) involving 4 lines.

Saha (1975) extends the above results in his doctoral dissertation. Assume that in addition to the CBD, each station i $(1 \leq i \leq n)$ is a source of traffic for subsequent stations along a line of n stations. Saha maximizes the total number of transported passengers by a train of capacity w. The decision variables in his integer programming formulation are the number of passengers boarding the train at station i with destination j. He shows that the technology matrix of this program is totally unimodular so that the linear program provides integral optimal solutions. His dynamic programming solution results in a simple loading rule: at each station load the passengers in the order of their destination—furthest destination first—until the train is full. He further shows that an optimal solution for the problem with m trains may be obtained by solving a single train problem with capacity mw.

Saha extends Salzborn's results on zone-stop schedules for the case of a general traffic pattern where p_i, the number of passengers travelling to station i from the CBD, is no longer a multiple of w. His algorithm proceeds as follows: first, for each i, send direct trains with $[p_i/w]$ carriages to station i. Next, revise traffic demand to account for the remaining passengers only. This policy results in new values $p_i < w$ for $i = 1, \ldots, n$. Then, starting with the last destination n, assign its passengers to the train moving back through yards $n-1$, $n-2$, etc. until train capacity is exhausted. Again, revise the demand requirements and repeat the above process for the next train starting with the last yard of nonzero current demand. This procedure clearly constructs "almost zone-stop" schedules where two trains share at most one yard in their schedules.

Vuchic and Newell (1968) study the line problem from the viewpoint of design. The problem is to determine the number and locations of stations on a line emanating from a CBD so as to minimize total passenger travel time. Demand data is available in the form of the passenger distribution along the line. The solution of this problem via dynamic programming leads to a set of simultaneous linear equations.

Assad (1979) considers a different approach to the question of setting stop-schedules for the line problem. Suppose we schedule one extra train in addition to a local service that stops at every yard. Given the traffic volumes and the delay caused by stopping at any yard as data, Assad sets up an objective can be posed as the maximization of a submodular set function with the stop schedule S as the argument. Under mild assumptions on the data, he can then show that the greedy heuristic is optimal for this problem. Assad then extends these results to the case where two trains compete for traffic delivery and thus divide the set of yards between themselves. Further computational experience points to the efficacy of the greedy heuristic even when it could fail to provide the optimal solution. This work relates the train-scheduling problem to the research by Nemhauser *et al.* (1978).

Timetable construction

Given a schedule of stops and the number of trains operating on a line of track sections, timetables should be constructed to specify the detailed operations. Timetables are subject to a number of constraints including headway and safety requirements between successive dispatches and bottleneck problems on limited track capacity.

In Section 4 we remarked how such track scheduling problems result in formidable optimization programs. Indeed, the largest problem Szpigel (1972) solves via a branch-and-bound approach in his "machine-scheduling" formulation only 5 track sections and 10 trains. Amit and Goldfarb (1971) discuss a similar problem in the context of the Israeli railway: they allow train movements in both directions on a line and set up constraints reflecting track availability, and timing restrictions (e.g. earliest and latest start times, maximum waiting times, and overall passage times). The track availability constraints are nonlinear in this case unless trains in one direction are given absolute priority. Therefore the authors propose a heuristic technique to solve this complex model.

Young (1970) develops timetables by maximizing and objective function based on operating costs, revenues, and traveler's benefits (based on a model specifying traveler's willingness-to-pay). A dynamic programming algorithm constructs timetables for each vehicle in a fixed schedule passenger transport system.

It is also possible to view the train schedule over a single track probabilistically: for example, if interstation running times are governed by probability distributions, then a certain time reserve period (leeway) should be allocated to each yard to decrease the probability of missed connections. Cerny and Vasicek (1977) devise a probabilistic method of assigning such reserve times and contrast the results to the usual method of choosing reserve times proportional to interstation running times.

Beckmann *et al.* (1956, Chap. 11) considered a different aspect of the timetable scheduling problem, namely the minimization of accumulation delays plus connection delays. Consider a line of stations where each station dispatches trains to the next yard downstream. Assume that at each station, cars accumulate for subsequent stations at a linear rate. This means that the delay in car-hours will be a quadratic function of the time elapsed since the last collection. Clearly an evenly-spaced schedule of trains will minimize the accumulation delay at the first yard. However such a schedule might not match the dispatching frequency at the second yard and cause substantial connection delays. This latter consideration provides an incentive to schedule trains as runs, i.e. train going from 2 to 3 leaves (exactly after the minimum required period) after the arrival of the train from 1 to 2. These two opposing tendencies (spacing train dispatches evenly vs synchronizing them with dispatches of subsequent yards) lead to a quadratic objective function if we choose the train departure times at each yard as the decision variables. Additional constraints should be imposed on the order of dispatches. As the objective function may fail to be convex, the authors are restricted to local searches. We feel, though, that a network formulation for a discrete-time analogue of this problem is amenable to algorithmic development.

Special and express vs local services

A special case of the train scheduling problem arises when special or express trains are scheduled to supplement a normal operating schedule. This is common practice in commuter systems during peak hours or periods of high demand to reduce the passenger waiting time. In freight systems, too, the use of by-pass trains reduces classification work at congested yards and increased service reliability.

A number of papers in the literature can be viewed in this light. Salzborn's procedure (1970) for cutting back trains somewhere midstream is one example. Suzuki (1972) formulates the problem of scheduling by-pass trains as an integer program. He considers the tradeoff between speedier transport provided by by-pass trains vs increased accumulation delay in making up such trains.

Nemhauser's paper (1969) is an insightful instance of the service selection problem. On a given route, two kinds of service are available—a local service that stops at every station on the route, and an express service that operates non-stop between the first and last stations of the route. The problem is to find the optimal pattern of dispatching express and local trains over a given time horizon to maximize revenues. Passengers have earliest departure and latest arrival times for their trips. If no service is available to them meeting these requirements they will leave the system and must be considered as lost sales to the system. Otherwise they opt for the service that gets them to their destination earliest. Nemhauser provides an efficient dynamic programming solution to this problem based on a judicious choice of state-space.

8. CAR AND ENGINE DISTRIBUTION

As the movement of engines and empty freight cars should respond to the highly dynamic environment of day-to-day operations: models for this process should explicitly incorporate timing considerations. Indeed, the physical rail network may be expanded into a time-space network in which the nodes correspond to a given location at a specific time and also reflect possible movements between such points. The resulting network is acyclic because of unidirectional movement in time.

To take the case of empty car distribution, starting with a distribution of cars on the network at the beginning of a planning cycle; the flow of goods over the network may produce imbalances in the distribution of empty cars by the end of the cycle. This means that the cars should be redistributed over the network to ensure availability for the next cycle. Thus empty cars should be moved from points where they are in surplus to others in need of empty cars. Consequently we may formulate a transshipment problem on the space-time network with the objective of minimizing transshipment costs. Cars are allowed to move along scheduled train paths represented by arcs on the network. Leddon and Wrathall (1967) and White and Bomberault (1969) were among the first in the U.S. to propose using linear programming for the empty car problem. Indeed, if the empty car fleet is homogeneous, one may use the out-of-kilter method or the recent implementations of primal network flow codes that are capable of solving very large network problems (see Magnanti 1976, 1978 for a review). The linear programming model soon found acceptance in the rail community and variants of this model now form part of the analytical arsenal of many railroads. See AAR (1974), Herren (1973, 1977), Gottfried (1968), Truskolaski and Grabowski (1963) and Wyrzykowski (1961).

For an inhomogeneous fleet of cars, Gorenstein *et al.* (1971) noted that the problem becomes a multicommodity flow problem which is considerably more difficult to solve (see Assad 1978). Martens (1967) also treats this inhomogeneous case as a special case of his model. More recently, Fromovitz *et al.* (1978) have been engaged in integrating distribution model within a larger operational model that uses forecasts of car supply and demand to control the empty car inventory at each terminal. This research also investigates the interaction of operational policies with the optimum car fleet size and the ratio of supply to demand for empty cars.

The engine scheduling problem involves moving locomotives on the network to ensure that all scheduled train movements have the requisite motive power. In fact, some very early work in rail modelling addressed this problem: Bartlett's paper (Bartlett, 1957) contains a method for allocating motive power units to departing trains which minimizes the required fleet size. This method essentially pairs arrivals and departures at stations, regarding motive units as flows on a space-time network. The recent paper by Gertsbach and Gurevich (1977) discusses a formal procedure of constructing an optimal periodic fleet schedule that bears much resemblance to the work of Bartlett and Charnes.

Surmont (1965) uses the out-of-kilter method to minimize the costs attached to fleet size and deadheading in the movement of locomotives to meet train schedules on a rail network. McGaughey *et al.* (1973) use a similar approach for locomotive and caboose distribution. Tounge (1970) describes the work of French Railways (SNCF) on the same problem but uses the "assignment method" to allocate locomotives to train services. Holt (1973) gives an overview of "Bashpeak"—the system of programs British Rail uses for engine scheduling.

Algorithmically, the most sophisticated work on engine scheduling to date, is the paper of Florian *et al.* (1976). This research considers an inhomogeneous engine fleet and aims to find the best mix of engines meeting motive-power requirements of all trains. The cost function includes economic depreciation and maintenance costs (expressed as an hourly rate). The problem has a multicommodity flow structure over the space-time network with additional variables y_{ij}^k denoting the number of engines of types k, used to provide motive-power over an arc (i, j) (a lag of train movement). Note that this number is not the same as engine flow since trains may be assigned engines in excess of power requirements in order to redistribute engines over the network. Once these variables are fixed, the problem decomposes into a series of minimum cost flow problems, one for each engine type, which may be solved by the out-of-kilter algorithm. Therefore the authors propose a Benders Decomposition scheme. The Benders Master problem is a mixed integer program with one continuous variable and the integer variables y_{ij}^k. To solve this problem, the authors use an approach based on Dantzig–Wolfe decomposition for block angular systems. The advantage of this method is that the integer lattice points of each block can be generated *a priori* by searching over possible engine mixes. As this study considers only two engine types, this search is not prohibitive. This algorithm was applied to a region of Canadian National Railways (CNR) involving a space-time diagram of 718 nodes and 986 arcs of which 216 represent train movements. Satisfactory results were obtained after 9 iterations of the Master Problem. However, on a larger network with 2000 arcs and 430 train movements, the upper bound used in Benders' scheme behaved somewhat erratically thus precluding rapid convergence. Nevertheless, we view the above work as an outstanding example of modelling and algorithmic effort in the rail environment. Finally, we should note that elaborate simulation models exist to deal with the details of motive-power fleet operations. For example, Bontadelli and Hudson (RSMA · 1966, pp. 109–121) describe the RSRG Motive-Power Systems Model.

Freight car management gives rise to a host of complex problems when viewed as an inventory/distribution system with network structure. Johnson and Kovitch (1963) describe pathologies that may arise in the absence of a rational inventory control system for freight car distribution. In practice, faulty flow of information between yards could cause serious fluctuations in freight car buffer inventories. In fact the car distribution problem also includes stocking decisions, i.e. the levels of car inventories to be maintained at the yards. This suggests that a general multilocation distribution model might be appropriate for rail systems. Feeney's early work (1956) in empty car distribution does address the stocking decisions by setting up a dynamic inventory/distribution model with a nonlinear objective function. Konya (1967) presents a similar viewpoint. He argues that the future status of car demands (viewed as stochastic) should be taken into account in deciding the number of cars moving daily between various zones of a rail network. A procedure estimating car availabilities of each zone over an n-day planning cycle is given. Next Konya formulates a linear program to maximize routing and shortage costs. This model exhibits a block-angular structure suitable for Dantzig–Wolfe decomposition.

The allocation of freight cars is further complicated by the structure of per-diem costs. A railroad choosing to use freight-cars of a different railroad for shipment must pay rental fees for such cars. Allman (1974) uses linear-programming to determine the optimal mix of cars for shipment maximizing the rental fees receivable. This approach results in an assignment model for the allocation of cars to orders. He also discusses an interesting aggregation technique whereby individual cars are aggregated into order types to reduce the size of the model.

Finally Avi-Itzhak *et al.* (1967) construct a model for a railroad car pool system subject to stochastic demand. The authors find the distribution of the number of busy units for a class of consignees with small orders and several consignees with bulk orders. This information is then used to derive the number of cars required in the pool.

CONCLUSION

This paper has reviewed and classified the current literature on rail modelling. It is apparent that a noteworthy body of methodology is available in the way of both models and algorithms to aid the planning process for railroads. We feel that future research can draw upon these results with profit although there is still substantial potential for new developments.

The advances in analytical modelling should be matched by a better understanding of the rail environment along several directions: the available costing information leaves much to be desired for modelling purposes. The assessment of operating costs that are policy sensitive and further insights into the dominance economic tradeoffs rail activities will be valuable inputs for model-building and deserve greater attention. For example, the performance criteria for blocking models need further clarification. The calibration and validation of aggregate production or service functions for yard and line operations forms another worthwhile enterprise in which Petersen (1977a, b) has taken the first steps. Ultimately it is desirable to have production functions that can be easily used by and incorporated into global optimization models.

The congestion effects at the nodes of a rail network, and possible routing and pre-blocking strategies that may be attempted to relieve these problems, constitute a decision-making environment that is different from what the usual traffic equilibrium models address. Indeed, it may prove to be fruitful to consult the literature on computer communications networks (see, e.g. Schwartz, 1977) and investigate its applicability to rail problems. The issue of centralized vs decentralized control (and routing) especially comes to mind, since rail management might prefer some degree of decentralized decision-making at the yards.

The development of rail network optimization models has been encouraging. The work of Florian *et al.* (1976) and Bodin *wt al.* (1979) demonstrate that sophisticated mathematical programming models can be solved for large networks. We expect more progress in this direction over the coming years. Nevertheless, due to the size of the problems encountered, it is improbable that routing, blocking, and scheduling decisions could all be addressed by a single monolothic model. Instead, there seems to be a need for an integrated system of models at various levels of aggregation for rail planning efforts. Thus, for example, the information from an aggregate routing problem could feed into and guide a more detailed model handling the blocking problem. Since rail simulation models are fairly advanced and incorporate vast detailed information, these could be used at the highest level of detail to interact with and evaluate the policy recommendations of more aggregate optimization-based models. We feel that such hybrid optimization/simulation models hold much promise.

An alternative approach to very large problems is the development of heuristic techniques. Even if exact models are computationally tractable, there is still much to be said from the practical viewpoint in favor of effective but simple heuristic rules: these rules can be easily understood by rail managers and form valuable guidelines for decentralized decision-making on a local basis (say, within yards). Unfortunately heuristics have received little attention from rail modellers. We feel that the areas of train scheduling and blocking could benefit from developments in this direction.

We hope that this paper has communicated the flavor of rail modelling and the nature of the currently available tools. We would also feel gratified if the discussion has managed to interest transportation analysts in the area of rail so that their combined efforts with rail managers would result in increased implementation and use of such models for railroads.

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SCAN: A DECISION SUPPORT SYSTEM FOR RAILROAD SCHEDULING

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Abstract

This paper presents an overview of a decision-support model for the tactical scheduling of railroad traffic which is meant to support the medium-term issues facing a railroad. This initial version of the *Schedule Analysis (SCAN)* system is based upon notions from both simulation and combinatorial optimization, and is designed to provide schedulers with a tool for scheduling which provides real-time response. After describing the conceptual and algorithmic underpinnings of the SCAN system and its associated user interface, examples taken from a major railroad are used to illustrate the capabilities and limitations of the current system. Preliminary results from the use of this system at a major railroad are also discussed.

1. Introduction

Recent years have seen a renaissance of North American railroads, both in terms of economic indicators (ton-miles, revenues) and the development of new "space age" communication, information, navigation, and electronic control systems ([10,11]). Increased traffic volumes, new technologies and stronger competition have put pressure on railway companies to rethink their management strategies and operating practices in order to make use of the wealth of information and control capabilities provided by new systems and, in turn, to increase the level of service offered. It became apparent that decision-makers need new methodologies and tools in order to make better decisions from a system-wide perspective. The model described in this paper is designed to fill the gap in the area of operations research (OR) models applicable to the problem of medium-term (tactical) scheduling of trains.

1.1 Tactical Rail Scheduling Problem and OR Models

Tactical train scheduling is defined as the determination of planned (scheduled) train arrival and departure times at important points (yards, terminals, junctions) along a train's route; these times are then published in timetables intended both as marketing information for railroad customers and official guidelines (or goals) for the railroad employees. Train routes, car-blocking and yard polices are determined at a higher (longer term) planning level, and they are assumed as given inputs to the tactical scheduling process, along with marketing considerations (i.e., the train arrival/departure times most attractive to the customers).

The main issue involved in tactical train scheduling is a trade-off between the train arrival/departure times desired from the marketing point of view, and the reliability of actual schedule performance (i.e., on-time train arrivals) as influenced by over-the-line and yard delays incurred by trains. Shorter transit times are more attractive to the customers and can result in better equipment utilization; however, these gains can be more than off-set by the resulting higher frequency of late train arrivals and the deterioration of the reliability of the transportation service offered. It is hard to overemphasize the importance of on-time shipment arrivals in today's transportation market, and the fact that the trains' schedule performances play a vital role in the overall reliability of railroad services [3]. In practice, train schedulers have almost no means (aside from their past experience) to predict the on-time performance of their new or revised schedules. The adjustments of schedules are usually myopic in nature and dictated by historic train performance; in other words, rather than setting goals, the tactical scheduling function is simply a summary of the actual train operating practices defined by the oftentime uncoordinated actions of train and yard dispatchers and engineers. The methodology embedded in the SCAN system takes a somewhat different perspective; namely, the basis for reliable rail operations are achievable goals set at the tactical scheduling level. The main purpose of SCAN is to enable schedulers to produce schedules which are consistent with the physical constraints of over-the-line train operations or, in other words, to produce *robust* schedules that contribute to reliable operations.

1.2 Current State-of-the-Art in Railroad Scheduling

No existing model of rail operations was appropriate for task of tactical rail scheduling; however, we can learn from the shortcomings of the existing models. A large number of models developed to support railroad operations (for comprehensive, though somewhat dated review see [1]) can be categorized as either *goal-* or *action*-oriented, borrowing the classification given by [9]. Representative of the goal-oriented models are optimization models which, in the context of rail operations, are either network oriented models (the most recent and successful example is described in [4]), or focus on the real-time operations of a single

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railway line. While network optimization models are useful in determining yard and blocking policies and train routes, these models do not implicitly deal with schedules; they instead use train frequences. In the real-time category, there are few operational models of optimal line operations (or train dispatching) to date (see, for example, the description of the Norfolk Southern Railroad's proprietary dispatching system described in [10]). Even if more such real-time systems were available, the short-term scope of such a model would make it impractical for planning purposes. Another problem with the optimization models, both network- and line-oriented, is that they are usually based on relatively rigid and simplified mathematical formulations of the problem; at present it is a challenge just to understand and define all the intricacies involved in the tactical train scheduling problem, let alone produce a detailed mathematical formulation of the problem.

Action-directed models are usually discrete-event simulation models and are used to assess the impacts of various proposed actions. These models, depending on their scope, can accomodate a great level of detail. Network-oriented simulation models, however, either ignore or use overly simplified representations of over-the-line train interference; this interference is one of the main sources of delays that trains incur and thus, directly influences schedule performance. Simulation models of line operations, on the other hand, are usually stochastic and incorporate train interference — meets and overtakes — in great detail (a somewhat dated review of these models can be found in [2]). However, because of the level of detail incorporated and the large number of iterations required to get a statistically significant sample, these models are too slow and cumbersome to be used interactively; e.g., so as to allow the analyst to make iterative improvements to the alternative plans being evaluated within a reasonably short period of time. An additional shortcoming of most simulation models in the area of rail transportation is that, besides being data intensive, they require extensive preparation and knowledge of the software from their users; the final output must be processed by the technical people with a thorough understanding of the particular simulation package *and* rail operations before it can be presented to a decision maker.

2. SCAN System Design

Although the SCAN decision support system is being developed within the scope of a broader research effort aimed at the optimal control of railroad operations [5], it was designed so that it can serve as a useful stand-alone tool for railroad management, independent from any real-time control systems which may be implemented on the railroad. In order to achieve this goal, several design objectives were chosen:

- **Ease of use and user independence.** The system was intended to be used directly by the decision-makers, without extensive training requirements and without need for technical consultants, such as programmers and MIS experts, to process system input and output. Both the inputs to and the outputs from the model should be easily and quickly comprehended by the users. This goal prompted the use of the interactive-graphics and menu oriented user interface.
- **The system should be interactive.** Closely connected to the ease of use, the realization of this objective is necessary in order to make the system truly useful in supporting the decision-making process. After the invocation of any command, the user should receive a meaningful response from the system in a reasonable amount of time (e.g., before he forgets what he asked from the model). This objective required the use of fast-response algorithms and adequate computational power.
- **Modular design.** The algorithms used in the model, data input-output to the algorithms, initialization routines and user interface should be designed and coded as relatively independent modules. This goal allows different algorithms to be added or substituted in the model as the research progresses and the users' needs and enviroment change.

The choice of the computing enviroment for the SCAN system was dictated by the above objectives; we needed more computational power than a PC could offer and better graphics and real-time response capabilities than a time-sharing mainframe could offer. Therefore, we chose a graphics-oriented, multiple-window, mouse-controlled Apollo DN 3000 workstation.

3. SCAN Methodology

3.1 Model Philosophy, Scope, Assumptions and Data Needs

As discussed in the Introduction, the purpose of this model is to *help* in the design of robust (reliable) train schedules, not to provide an "optimal" schedule. Accordingly, the model starts with given train schedules and evaluates their feasibility; if a given set of schedules is found to be infeasible, the system offers interactive or automatic procedures to modify the given schedules until they are feasible. Once the set of schedules are proven feasible, their reliability can be estimated. All the remaining objectives (besides reliability) imbedded in the tactical scheduling process are the domain of the user; the scheduler follows these objectives through the proposed initial set of schedules and by controlling the subsequent interactive modification of that set.

Reliability of train schedules is a system-wide issue; i.e., because of interactions among trains, it is not possible to consider the reliability of a single train's schedule while ignoring the schedules of the other trains. Consequently, the SCAN methodology has a system-wide scope. However, in order to ensure the fast model response required for the interactive nature of the SCAN system, the railway network over which the schedules are analyzed was disagregated into basic units of analysis called *traffic lanes*. A lane is defined as a railway line between two points on the network termed *reporting stations* (usually yards, terminals and junctions) where trains are scheduled to arrive and/or depart at a certain time.

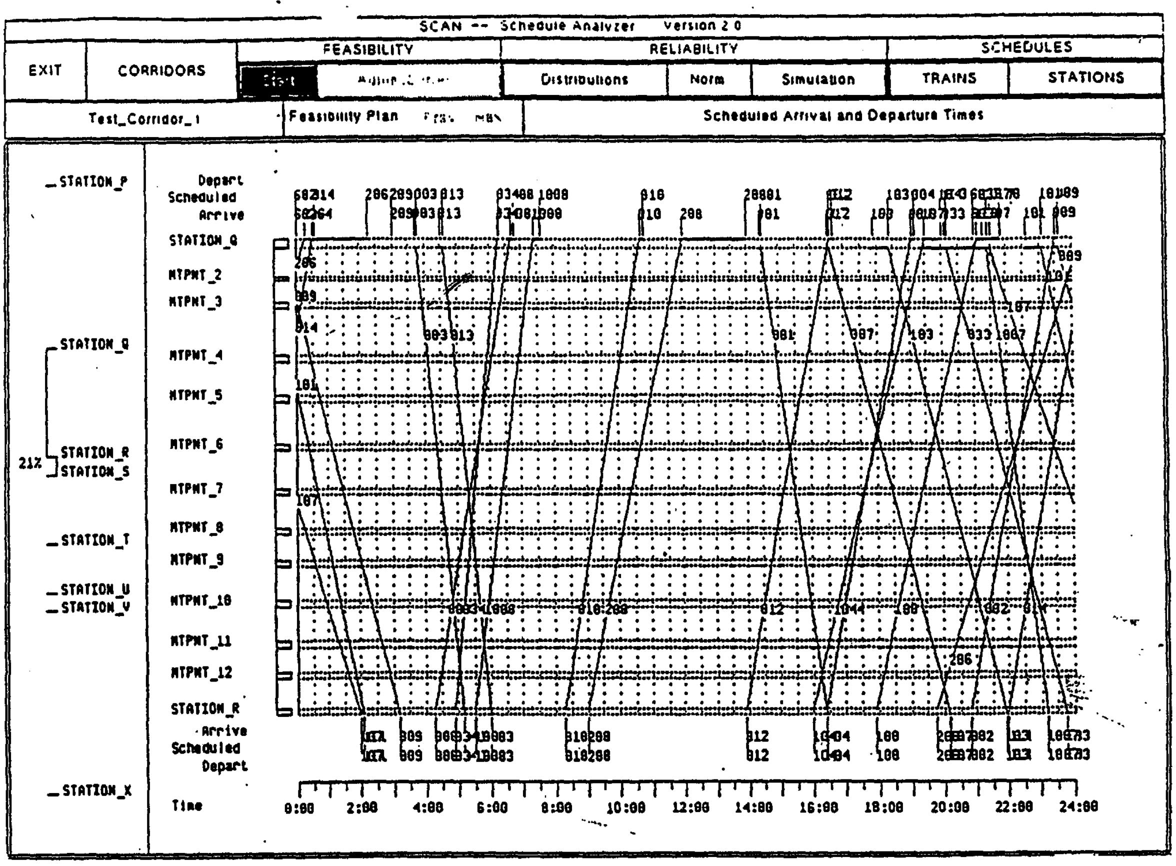

Figure 1: Station_Q–Station_R schedule diagram.

This methodology incorporates two basic assumptions: (*a*) all trains are scheduled, and (*b*) all the trains going through a reporting station are scheduled at that station. The first assumption is a major one and does not mirror the current practice of North American railroads: there is a substantial number of regional and local trains that are not scheduled at the tactical level. However, the philosophy embedded in the SCAN system maintains that on-time performance is a system-wide issue and thus, in order to improve it, planners at the tactical level should have some control over the operation of unscheduled trains rather than leaving it to the discretion of train dispatchers. A system of scheduled slots, similar to those employed by the airline industry, could be used for this purpose so that unscheduled trains can be incorporated within the SCAN system using the slots allocated to them.

The 24 hour time horizon of the model was chosen as natural for a tactical scheduling model since that represents the practical cycle of most train schedules (viewed from a particular reporting station. not from a train).

The data required by the model can be classified into three basic categories: track description, train travel times, and, of course, proposed train schedules (for a detailed description of all the information required by SCAN I package see [6]). The track description for a given traffic lane lists all points, termed *meetpoints*, where trains can meet or pass (i.e., overtake) each other; such points are side tracks, yards, and points at the ends of double-track sections. Travel time files list free-running (i.e., without interference from other trains) transit times between adjacent meetpoints for various train types classified according to their performance. Statistical distributions of stochastic input parameters are also needed for the schedule reliability estimation (e.g., variance of free-running times influenced by locomotive health, etc.).

3.2 SCAN Algorithms

There are three algorithms incoporated within the SCAN I system: one that evaluates the feasibility of a given set of schedules over a given lane, one that modifies the infeasible schedules until feasibility is achieved, and one that estimates a measure of reliability of a given set of schedules. The schedule feasibility evaluation algorithm attempts to find a feasible meet-pass plan that satisfies given schedules (i.e., that enables all trains to arrive on time to their reporting stations within the lane). A feasible meet-pass plan specifies the time-space coordinates (when and where) of train paths and their interactions in such a way that

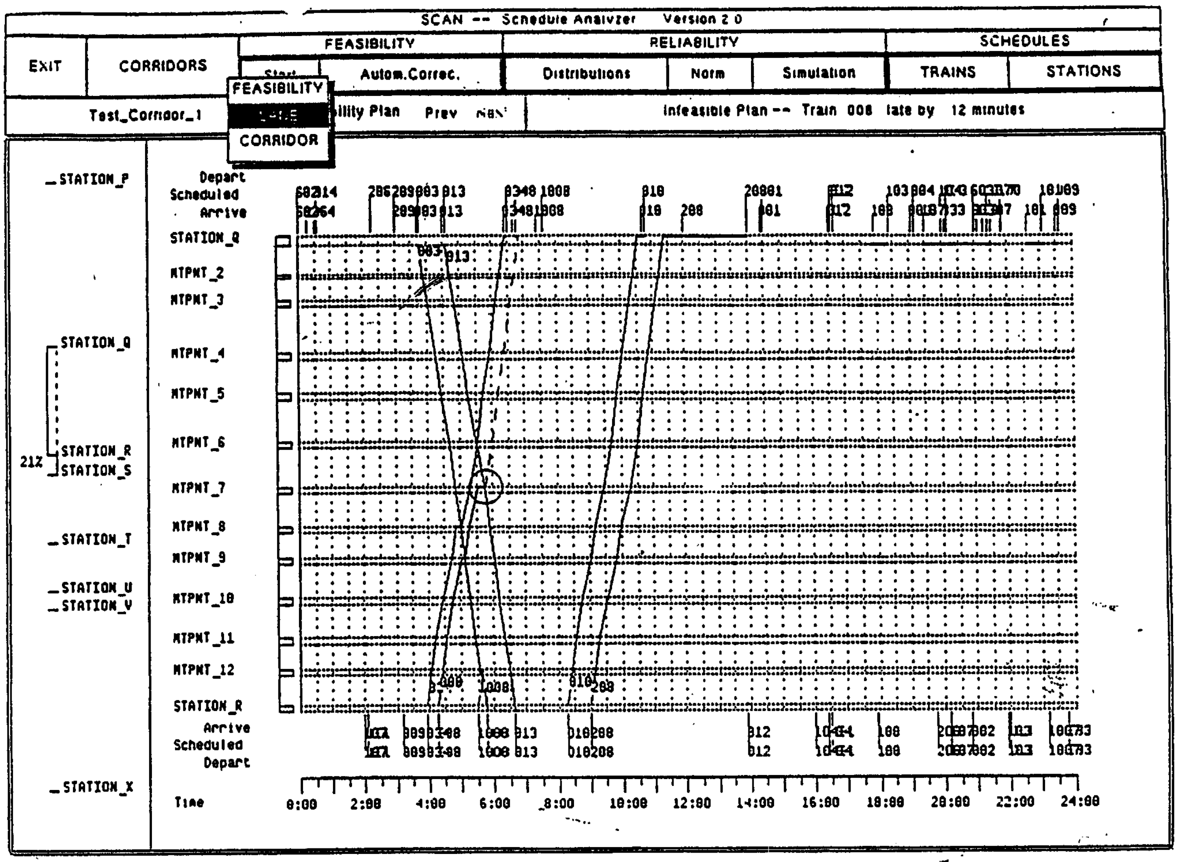

Figure 2: Station_Q–Station_R: an infeasible meet-pass plan.

no physical constraints of the train motion and interaction are violated; e.g., two trains travelling in opposite directions cannot meet on a piece of single track, only at a siding, yard or double-track section.

The feasible meet-pass plan generation problem can be formulated as a mixed-integer mathematical programming problem, where the integer binary variables determine the location of train meets and continuous variables represent train arrival and departure times at each meetpoint in the lane. There is no explicit objective function in this problem; i.e., the goal, as described by Jovanović and Harker [8], is to find a feasible solution(s) that meets the schedule. This problem is NP-complete, and in many ways is similar to a job-shop scheduling problem. However, some features of the problem enabled the design of an efficient implicit enumeration algorithm. The special structure of the problem allows, for fixed binary variables, the resulting problem in the continuous variables to be solved trivially. This characteristic allowes for the design of an implicit enumeration-like rather than an LP-based branch-and-bound technique. Node generation is performed using process-interaction simulation techniques to actually move the trains over the lane in a manner which ensures that only feasible nodes are generated. Thanks to the availability of 32-bit integer variables in the Apollo workstation enviroment, there is no need for floating point operations; in fact, only integer addition and comparison were used in the implementation of the algorithm. Computationally inexpensive node evaluation (200 nodes/sec on Apollo DN 3000), coupled with a strong initial bound (no train can be late) and depth-first search resulted in satisfactory running times for most real-world data sets encountered. Typically, it takes under 10 seconds on the Apollo DN 3000 for the SCAN I system to derive a meet-pass plan that satisfies the schedules or to prove that the given set of schedules is infeasible. However, for some rare test data sets involving a substantial number of overtaking trains, the problem size was so large that it required almost 30 minutes of Apollo DN 3000 CPU time for the algorithm to prove that the schedules are infeasible.

If no feasible meet-pass plan that meets the schedules can be found, the schedule modification module returns the "best" partial meet-pass plan with indication of the unresolved train conflict (cf. Figure 2); the "best" in present version of SCAN is defined as that plan which corresponds to the deepest node generated in the search tree before the schedules were proved to be infeasible. The scheduler may then choose to let the heuristic embedded in the schedule modification algorithm render given schedules fea-

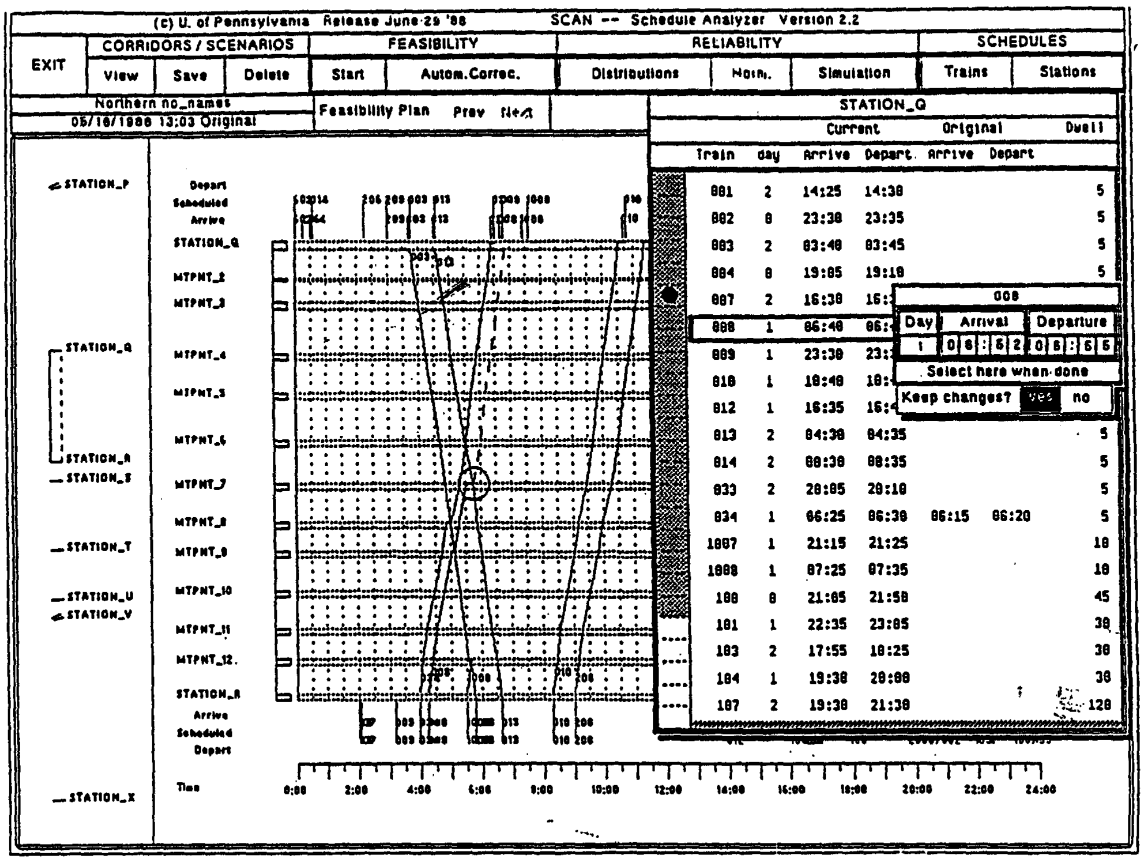

Figure 3: Menu-controlled modification of train's 008 schedule.

sible or he may do it interactively by resolving infeasible train conflicts one by one.

Finally, if the set of schedules is feasible, the scheduler can invoke the reliability estimation module to obtain a measure of the 'robustness' of the schedules. In SCAN I, this measure is defined to be probability that all trains in the given set will arrive on time. This probability is estimated by a Monte Carlo simulation where each sample point represents one run of the feasibility evaluation routine with different values of the stochastic input parameters. In the present version, the stochastic parameters are limited to free-running train travel times.

4. SCAN User Interface

The SCAN user interface was designed to be mouse-controlled and menu driven, with some elements of graphics-oriented direct manipulation [7]. The menu system allows a novice user to start using the system immediately, eliminating syntax errors or the need to memorize the commands, without inhibiting the expert user (due to the relatively small number of commands available in SCAN I). Examples of direct manipulation include the choice of a traffic lane to be analyzed (the user positions the cursor on the desired lane on the railway line diagram in the left window shown in Figure 1 and clicks on the mouse button) and the input of statistical distributions for the stochastic parameters (the user positions the cursor at the desired coordinates on the frequency histogram). An illustration of the success of the interface is that when the prototype SCAN system was delivered to a major railroad for field testing, it was not accompanied by a user manual and none of the users seemed to require one.

For the presentation of output, we continued the railroad tradition of using time-distance diagrams to represent the movement of trains. SCAN I uses two types of diagrams: schedule diagram (Figures 1 and 5) in which the scheduled (desired) train departure and arrival times at the reporting stations are connected by a straight line, and the meet-pass plan diagrams (Figures 4 and 6) which represent one possible realization of the schedule or show why it is not possible to achieve the given schedule (Figure 2). All meetpoints on the analyzed traffic lane and their names are displayed on the vertical axis alongside the track schematic. Color is used to differentiate among various types of trains in the diagram, with red reserved for late trains. An important asset of the graphical output of the algorithmic results is that it proved to be an invaluable tool not only for the end users, but also for the algorithm developer during the testing and debugging of the

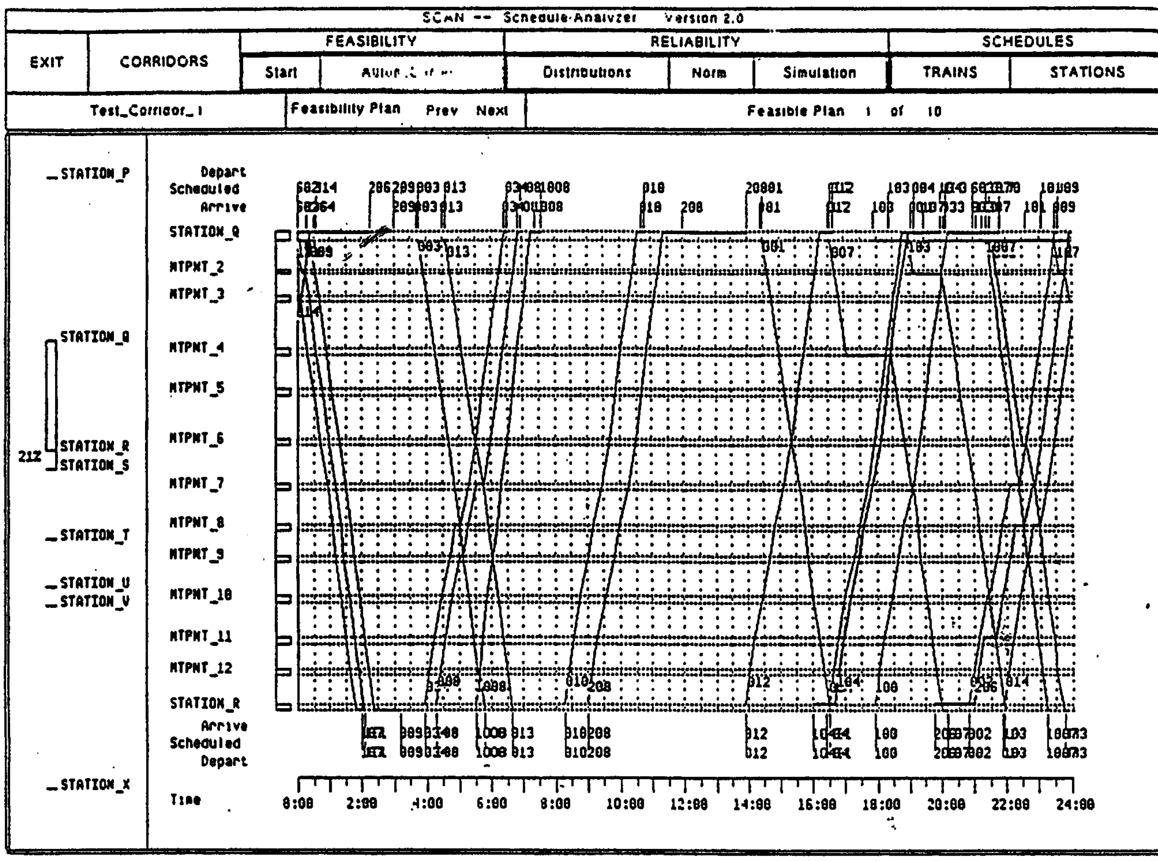

Figure 4: Station_Q–Station_R: a feasible meet-pass plan.

code.

Coding of the interface was substantially accelerated through the use of Apollo Domain *Dialogue* user interface management system (UIMS). Dialogue provides a library of menu building and control routines that can be called from a standard procedural language such as Pascal (the entire SCAN system was coded in standard Pascal augmented by the procedures from Dialogue and Domain 2D-graphics libraries).

5. Examples

In this section we present examples of the evaluation of the proposed schedules over two traffic lanes. Figure 1 presents a schedule diagram for the Station_Q-Station_S lane; note a straight line connecting these two stations in the left window which indicates which lane is being analyzed. By simply looking at the diagram, one would be tempted to conclude that this set of schedules would be easy to meet since there are several 'holes' in the schedule and the majority of trains seem to meet or pass each other at a meet-point (i.e., a siding). However, invocation of the feasibility checking option reveals a series of infeasible train conflicts. One such conflict is shown in the Figure 2. The conflict can be resolved by the schedule-modification procedure or by manually changing the scheduled arrival or departure time of one of the trains involved in the meet; manual modification of a train schedule is illustrated in Figure 3. Finally, after the schedules of eight trains have been interactively modified by the analyst, the given set of schedules has been rendered feasible, as illustrated by a feasible meet-pass plan in Figure 4.

The schedule diagram for a second example, the Station_V-Station_X lane in Figure 5, on the other hand, suggests a barely achievable set of schedules since the train paths are dense and interconnected, and many of them do not intersect at a siding or a double track section. The feasibility algorithm, however, discovers over 500 meet-pass plans that can achieve the given set of schedules; one is presented in Figure 6.

The above examples illustrate the type of added information that the SCAN system presents to the decision-maker; simply collecting data and presenting it in a nice graphical form can often be misleading if it is not accompanied by adequate analysis.

6. SCAN I IN Practice

The SCAN I system is currently being used at a major U.S. railroad in order to obtain achievable schedules. SCAN has refocused this railroad's efforts on increasing the level of service offered to their customers by highlighting the role of proper scheduling of trains. As is preached in Operations Research classes but often-

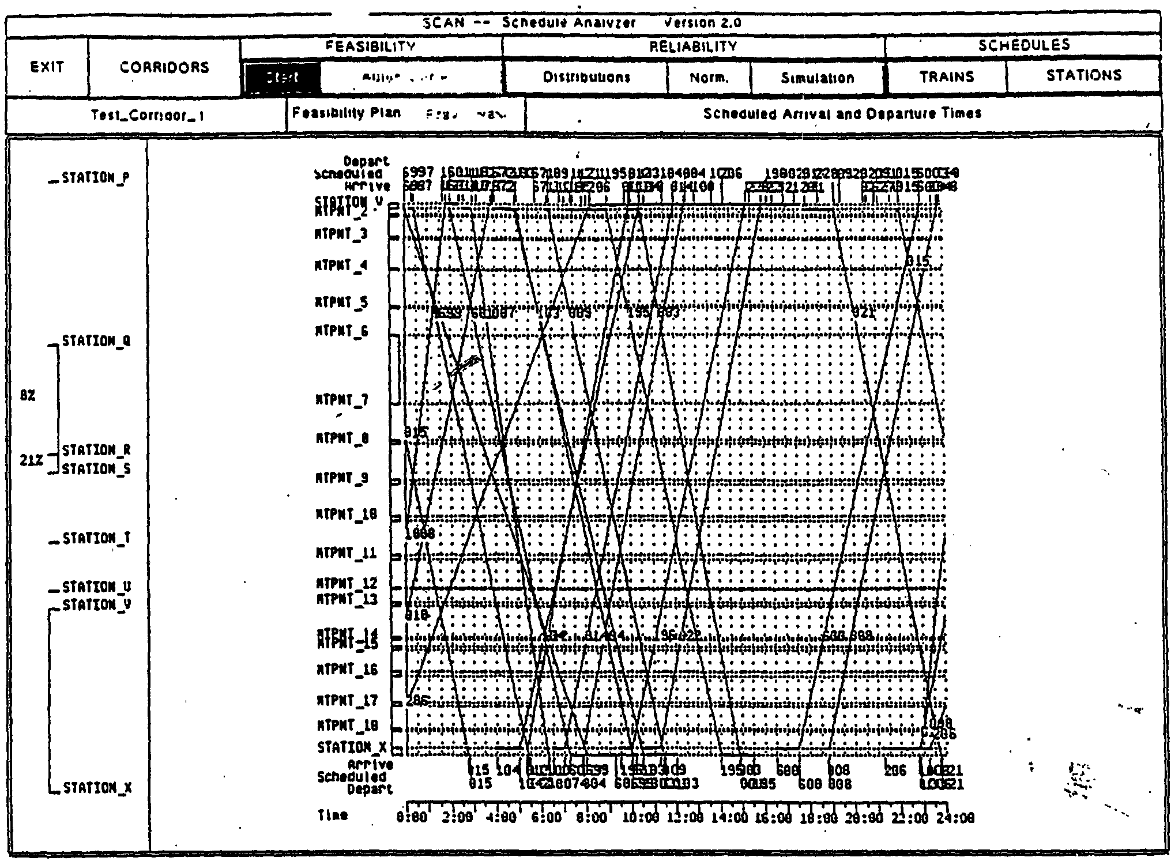

Figure 5: Station_V–Station_X schedule diagram.

time not believed, it was the *act of modeling* more than the model itself that has made the biggest impact on the railroad: they are beginning to believe in scheduling! In this sense, SCAN has already been a success, given its acceptance by the schedulers. This can be illustrated by quoting one of the SCAN users:

> "...calling up the software, running feasibility checks and changing the schedule data...was accomplished with minimal effort and confusion. This is very important as we would like to see 'non-programmer types' able to access the system and use it for analyzing and improving operations. Many non-analysts were eager to '*try it for themselves*'. ...The graphic representation of the schedules is a strong asset. Without it, the analysis would essentially produce *just a bunch of numbers that don't mean anything to me and don't allow me to get any real work done.*"

As for the quantitative measures of the impact of SCAN I, statistics are being collected to provide the numerical evidence of the system's impact on the operations of the railroad as the system is being used to analyze larger and larger portions of the network.

7. Future Directions

In order to provide the scheduler with even greater sophistication in the support of tactical scheduling, several research issues concerning the methodology employed in SCAN I remain to be solved. Among these are the issues of cyclic schedules, introduction of the *measure* of schedule infeasibility rather than just stating that the given set of schedules is infeasible, and better measures of the reliability of schedules. Improved, faster algorithms are required in order to accomodate these new methodologies and enable the system to be used over larger, aggregated, traffic lanes, while retaining interactive nature of the system.

Besides these algorithmic and methodological issues, one of the challenges for the future development of SCAN system will be to retain the positive features of the existing user interface while supporting the more sophisticated flow of information between the user and SCAN which will be required by the new methodologies. For example, the user should be given greater control over the feasibility evaluation algorithm in the fashion of the interactive optimization: results of each iteration of the algorithm should be displayed immediately with the user having the option to stop the algorithm, examine the 'best' solution so far, and either accept that one or restart the algorithm with the option

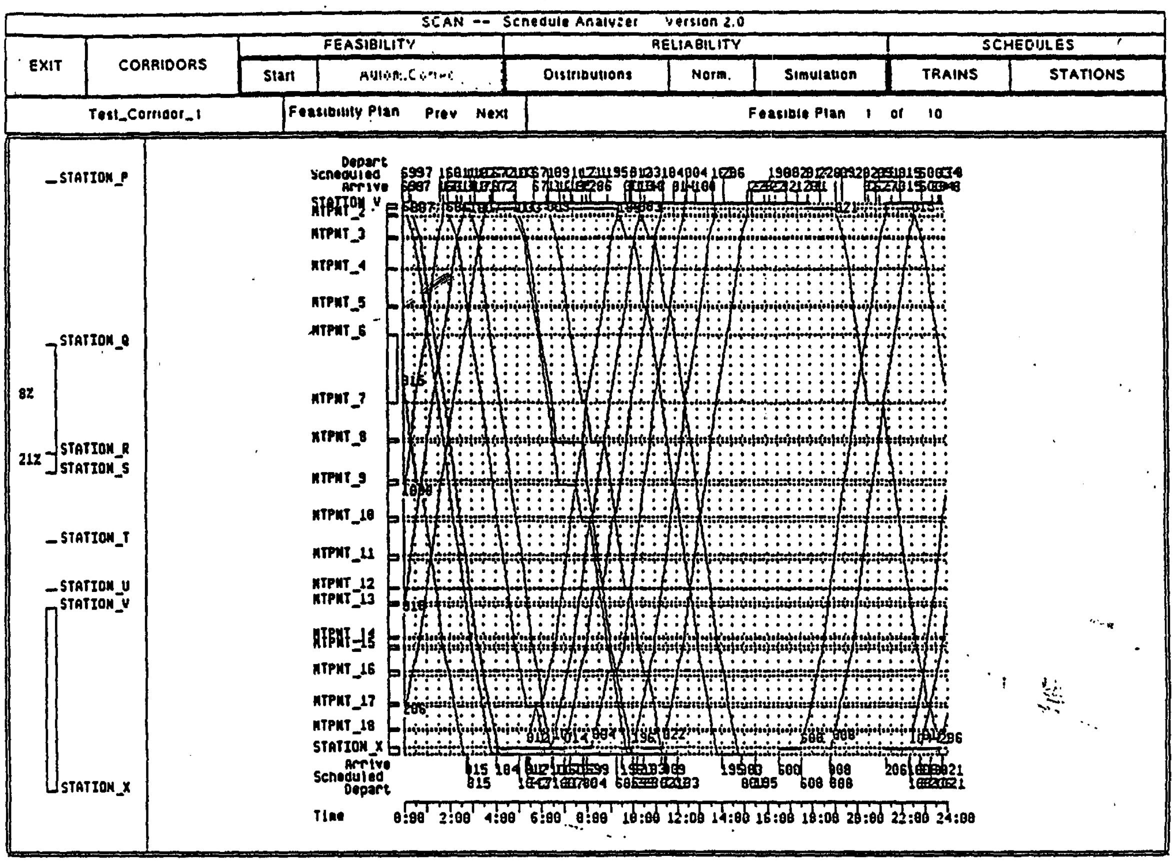

Figure 6: Station_V–Station_X: a feasible meet-pass plan.

of directing the algorithm towards better solution. The "Dialog" type of UIMS has the necessary flexibility for the concurrent package architecture where both the algorithm modules and UIMS can concurrently control the display, as opposed to the current SCAN architecture where an external UIMS has control over the display and invokes algorithmic modules as necessary; however, this architecture is not only difficult to implement but may also compromise the modularity of the package. Another challenge lies in increasing the role of direct manipulation as the mode of user interface. An obvious example would be to allow the user to modify schedules directly in the time-distance diagram by moving the path of the train using the mouse.

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A COMPARISON OF TWO METHODS FOR TACTICAL PLANNING IN RAIL FREIGHT TRANSPORTATION

Comparaison de deux méthodes de planification tactique pour le transport ferroviaire de marchandises

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Abstract: We examine two different methods which may be used to assist the tactical planning process in rail freight transportation : a deterministic simulation method based on decison-making input from the planner and a network optimization model. The first has been designed at a large Canadian company, while the second has universitary origins. We compare the two methods and the characteristics of the solutions obtained and discuss the possibilities offered by a method combining the two approaches.

Résumé: Dans cette présentation, nous examinons deux méthodes conduisant à des outils d'aide à la planification tactique pour le transport ferroviaire des marchandises. La première méthode, développée par une grande compagnie canadienne de chemins de fer, est basée sur une simulation déterministe des opérations suivant le contrôle continu de l'utilisateur. La seconde est construite autour d'un modèle d'optimisation de réseau que nous avons développé. Nous comparons les deux méthodes ainsi que leurs résultats et examinons les avantages qu'un processus combinant les deux approches pourrait présenter.

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1. INTRODUCTION

A freight rail transportation system is a complex entity, larger than the sum of its parts and displaying intricate relationships and trade-offs between the policies affecting its different components. It is also a system where changes to the physical structure may take years to perform. It is therefore imperative to be able to forecast such changes and analyze their effects on the operations and performance of the system. Scenario evaluation is thus an essential part of the planning process of a railway company.

These characteristics are reflected in the complexity of the planning process, especially at the level of the medium (tactic) to long term (strategic) planning and good, fast and efficient tools are needed to assist the planner in his task.

In this paper we present two different approaches at building such tools. The first has been designed and implemented at the Canadian National Railways (C.N. Rail), a large Canadian company and it is based on a deterministic, interactive simulation model. The second is based on a network optimization model and has been developed at the Centre de recherche sur les transports of the Université de Montréal, with the support of C.N. Rail.

We begin by rapidly reviewing the problems associated with tactical planning in rail freight transportation. The two methods are then described and their main characteristics are emphasized. The following section contains results and comparisons between the two approaches and we conclude with a discussion of the perspectives opened by a possible combination of the two methods.

2. THE PROBLEM

The physical framework of any large railroad company consists of a complex network of small stations and large terminals interconnected by main and secondary lines. At any given time, a large number of cars (more than 100,000 C.N. and foreign cars, in the case of the C.N. Rail System) are in the network, and each may have an independant objective.

The cars, however, move in convoys called trains. In addition, cars are generally grouped into blocks, a block being a group of cars, with possibly different final destinations, arbitrarily considered as a single unit (for handling purposes) from the yard where it is formed till its destination, where its component cars are to be resorted. Rail companies use blocks as a mean to take advantage of some economies of scale and thus decrease the number of car manipulations in yards.

To monitor the individual cars and train movements, rail companies use a number of detection and identification devices in connection with computer based systems, also used to collect data on those movements, as well as on train and block composition, yard workloads, etc.

To control the activities related to these individual movements, on the lines and through the yards, rail companies establish a series of operational policies, dynamic in nature, which deal, in great detail, with the local operations : train time-tables, track priority rules, dispatching policies in yards, engine and empty car scheduling and so on.

All these policies follow, however, the guidelines established at a higher level of decision-making, where general, network-wide operating strategies are generated : the tactical (medium-term) planning level. At this level of decision making, planners are mainly concerned with :

. classification policies : at each yard, what blocks to build (what are the yards for which blocks may be formed) and what cars to put into each block? How to distribute the workload among the yards of the system to fully use their capacities and avoid congestion?
. make-up policies : what blocks may be carried by each train?
. train routing policy, or how to establish the design of the service network and the level of service : what train services to run, on what routes and with what frequencies?
. traffic routing policy : determine for each origine-destination pair (possibly by commodity also) the routing pattern for its traffic : the train sequence used to travel and the yards where the cars are to be classified.

These policies have network-wide impacts and are strongly interconnected in both their economic aspects and their space-time dimensions. Trade-offs between the operating costs implied by a certain policy and its impact on the quality of the service (as reflected, in most cases, in the delays imposed on both freight and trains) have to be considered. The same trade-offs have also to be considered when the relationships between the four mentioned policies are examined.

The purpose of tactical planning is to specify an efficient and rational allocation of existing resources to improve the performance of the whole system. Day to day operations are not analyzed at this level of planning and decisions are sensitive only to broad variations in system parameters and data such as seasonal changes in traffic demand or modifications to the physical lay-out of the network.

The planner must then be provided with a tool which allows him to analyze, from a network point of view, the effects on the various elements of the rail system of changes in the configuration and characteristics of the physical network (such as new or improved installations or the abandonment of lines), in external factors (such as energy prices or safety regulations), or in the global operating philosophy of the company (priority to intermodal COFC/TOFC transportation, for example). Thus this planning tool may be used for the tactical planning of the next season or to answer "what if" questions raised during strategic planning.

The tool must be flexible enough to facilitate the analysis of different scenarios and manageable enough to allow to experiment many strategies in a reasonable period of time. It may contain evaluation modules to analyze various attributes (capacity, congestion, costs) of individual units (yards and lines) but it must treat the system as a whole, at the network level. This also implies the capability to aggregate the network and the data according to the level of detail of the analysis.

We present, in the next two sections, two different approaches toward such a planning tool.

3. THE "CANAT" SYSTEM

We first consider the CANAT system, designed, developed and implemented at C.N. Rail with the goal of assisting transportation planners to measure the effects of changes in freight traffic on yards and lines from the perspective of the entire network [1]. This system, called CANAT for Computer-Assisted Network Analysis Tool, was designed as a macro tool for medium-to-long term planning, with an emphasis on the study of yard workloads.

Schematically, CANAT is a modular, interactive, deterministic simulation system and it requires the decision-making input of the planner about the rail system operations, capacities and structure.

CANAT is composed of a number of discrete steps, grouped into, currently, three modules (additional modules are in development).

The first module, Module 0, is used to generate the traffic forecast data, from historical car-trip data and from the long term forecasts established by the Marketing Department. These traffic forecasts are then reduced and organized on a quarterly basis by traffic type and origin-destination zones.

Module 1 is used to select the traffic data and to define the network for the study. For CANAT use, the more than 5000 original C.N. Rail stations are reduced to approximately 650 zones. Each zone represents a large terminal or an aggregation of a group of small yards, a particular line (with, possibly, a range of small stations) or a junction point. Then, for a particular study, a network of about 100 yards and 150 lines (the traffic demand originating from or with destination in a line zone is either eliminated or aggregated into a single pick-up/delivery point) is selected, boundary nodes are defined and the traffic data is reduced accordingly.

The third module is used to define the traffic movements to satisfy the demand and is made up of two parts. Each of the elements of the network, yards and lines, may have a number (from 5 to 30) of capacity-related parameters, such as yard capacity in number of trains originating/ending/working at the yard, maximum train length, line length, tonnage limits and so on. The first step of Module 2 is then used to fix these parameters and some other system elements such as standard routes for trains.

The second stage is used to interactively create trains to satisfy the demands for traffic movements and to check yard workloads. The traffic must be moved such as not to dramatically exceed the capacities defined in the previous stage. Trains are defined in terms of train class, speed class, pick-up/set-off stations, traffic blocks carried and routes. The system may display informations about the status of the traffic demand, yard and line workloads, train blocks and so on. The user may create, modify or delete trains until satisfactory results are achieved and all traffic is successfully transported. A wide range of reports complete the system.

4. THE OPTIMIZATION METHOD

Our approach is to regard the tactical planning process for rail freight transportation as an optimization problem that we can model and solve by mathematical programming techniques.

The formulation is that of a network optimization model which aims to integrate the relationships and trade-offs between operating policies in train and traffic routing and classification and make-up policies in yards, at a tactical planning level. The purpose of the model is not to specify a detailed schedule but rather to generate economically sound global operating strategies ensuring a good level of service, in terms of transport delays and reliability.

A complete description of the formulation may be found in [3]. Here we only present the general modelling framework.

The physical network is aggregated following the same general rules as in CANAT. The line capacity-related parameters that we have retained include the line type (single, double), length, number of sidings, plus some train operational parameters such as a minimum headway for each train type. For each yard, one has to define an average service time for the classification operation. Presently, it is estimated from the capacity (maximum number of cars that may be classified during the planning period, usually a week) of the yard as the mean through-time of a car being classified at that yard.

The traffic demand is specified for each traffic-class, defined as an origin-destination-type of commodity combination for which a positive number of cars (or any equivalent measure of tonnage) has to be moved.

Based on the physical network, the service network specifies the set of feasible routes on which train services may be operated. A train service is characterized by its type (defined by a speed-priority combination) and route (origin, destination, intermediate stops) in the physical network. The frequency of the service is defined as the number of trains operated on its route during the planning period and will be determined by the model.

An itinerary completely specifies a feasible journey for the traffic of a given traffic-class : the service path followed in the service network and the sequence of (re)classification yards along this path. The distribution of the traffic of each traffic-class among its itineraries will also be determined by the model.

The frequencies and itineraries are the central elements of the formulation, because fixing the values of the frequencies determine the services to be offered and the level of service, while by selecting for each traffic-class its best traffic distribution (for that level of service) between its itineraries, one solves the traffic routing problem and also determines network-wide classification and make-up strategies.

Schematically the model may be written as follows :

$$\text{Minimize} \quad \sum_m \sum_k Z_k^m (X,T) + \sum_h [Y_h(T) + P_h(X,T)]$$

$$\text{subject to} \quad \sum_k x_k^m = d^m \qquad \text{all } m$$

$$x_k^m > 0 \qquad \text{all } m, \text{ all } k$$

$$t_h > 0 \text{ and integer} \qquad \text{all } h$$

where h, m, k index respectively services, traffic-classes, itineraries for each traffic-class and

x_k^m : quantity of the traffic of the traffic-class m using the itinerary k

X : vector of x_k^m for all traffic-classes, all itineraries

t_h: frequency of the service h

T : vector of frequencies

Z_k^m : total cost, operations and delays, for the itinerary k of the traffic-class m

Y_h : total cost, operations and delays, for the train service h

P_h : penalty cost, for the service h if the number of cars assigned to it exceeds the capacity of the service.

It is in the objective function that the relationships and trade-offs are considered. One important feature is the consideration of the delays incurred by trains and traffic due to congestion and operational policies in yards and on the lines. The delays are converted into costs via unitary delay costs defined for each type of service and each traffic-class. The major elements of the objective function are :

. Classification delays (for cars) : by means of queueing models (presently a M/M/1 model : Poisson arrival, exponential service, one server) expressing the mean classification delay as a function of the yard characteristics (the yard mean service time) and the total yard workload. For each yard, the number of admissible classification-destinations (and thus of blocks) is controlled via a penalty on small blocks.

. Handling costs for cars and trains on the road and in the yards.

. Over-the-road delays to train and cars. The mean delay is computed as a function of the characteristics of the link and the train congestion (by service type) on the link. We use formulae calibrated at C.N. Rail [5].

. Frequency delays, counting the time cars have to wait at yards until the designated service is available.

The resulting mixed integer, nonlinear, multiflow, multimode problem is solved by a decomposition algorithm working alternatively on the following sub-problems :

. For a fixed traffic distribution, modify (if possible, stop otherwise) the frequencies to improve the global objective. A method of finite differences is used to determine the frequencies to modify.
. For a fixed level of service, determine an optimal traffic distribution. The problem is solved by a decomposition procedure which cyclically considers each traffic-class, all others variables being kept at their present values. For each subproblem, a new itinerary is first generated by shortest-path-like techniques, followed by the optimization of the traffic assignment done by descent methods.

The algorithm and its performance are analyzed in more details in [4]. Considering the size and complexity of the problems it proved to be a very effective algorithm. Some figures supporting this claim are also shown in Table 1 in the following section.

5. HOW THE METHODS COMPARE

Let's begin by summarizing the main characteristics of the two methods we just described. Il will help explain the observed differences in the behaviour of the methods and in the results obtained.

CANAT uses no explicit objective whatsoever, neither does it consider congestion or other time related functions. Neither operating costs, nor delay costs are considered and no automatic traffic assignment is performed. The planner has to specify each train and its workload, in this way effectively performing the traffic assignment and establishing the yard classification and make-up policies. He uses his judgment and experience and help from the status reports generated by the system. In this way, a detailed simulation of operations may be included into the system and the control of the planner over the form of the final results is total and continuous. The system however is unable to suggest new alternatives and the time necessary to build a solution is quite long (of the order of several days) which may limit the number of different strategies that may be examined.

The optimization approach do explicitely consider the delays in yards and over the roads and the costs attached to them and combines them with the operating costs (and some capacity-related penalties) in a global objective. Note that the formulation is flexible enough to allow the replacement of some or all cost and delay models presently included with other, more pertinent formulae. The model generates and evaluates a high number of operating strategies until it finds "the" best over-all strategy with respect to the general objective. At that moment, one obtains the services to be run, their frequencies and make-up, the traffic routing for each traffic class and the workload for each yard together with its classification policy. The proposed algorithm is quite efficient and may be decomposed into several procedures that may be used individually to do a traffic assignment for example, or to analyze the length of some train or the frequency of some service and so on. Of course, this method requires a large amount of data, some of which may not be readily available, such as yard mean service times or, especially, delay costs by commodity. Also, being an optimization procedure, an important amount of detail and realism may be lost. Of course, details might be included but then the flexibility and rapidity will be lost. Therefore, a compromise has to be found.

When comparing the two methods, it rapidly becomes clear that the optimization approach is much faster but probably less precise. But, the comparison, in more detail of the results generated by the two methods proved to be a more difficult task.

First, as emphasized by the characteristics we just mentioned, it is not possible to directly compare the two solutions on the basis of some objective function/economic criteria.

Second, due to technical differences (derived from the differences in the scope and methods of the two systems) in the outputs and the input requirements of the two computer programmes, we experienced significant difficulties in transfering the results of one system to the other. In fact, the only transfer that proved practically possible, was that of the service network generated through the use of CANAT.

We then conducted three types of experiments :

i) Generate the optimal traffic assignment using the CANAT service network and frequencies. We call this the "CANAT solution".

ii) Optimize using the CANAT service network.

iii) Optimize using a service network that we have generated.

We used two sets of data supplied by C.N. Rail, together with the service networks obtained by CANAT on them, as well as the passenger trains in operation on the network and estimations for the other parameters.

The first data set contained traffic demand forecasts for the year 1990 for the western part of the C.N. Rail's network. We had 735 traffic-classes (after aggregations and counting only the traffic-classes with at least 10 cars/week ; in this way, we had over 95% of the total demand) and a network of 71 yards, 36 junctions and 95 links. The CANAT service network had 191 services and we generated a service network of 399 services. The three experiments on this data set will be refered to as Experiment 1, 2 and 3 respectively.

The second data set represented traffic demand forecasts for the year 1991 for the B.C. North Line, a subregion of the previous network on which an extensive study has been conducted at C.N. Rail. We had a network of 18 yards, 6 delivery/pick-up stations, 53 junctions and 41 links and 281 traffic-classes (capturing 99.32% of the total traffic demand). The CANAT service network had 47 services, while ours had 44 services. On this data set were conducted the Experiments 4, 5 and 6 respectively.

Some typical time-related figures for the resolution of the six problems are shown in the first table. They are in Cyber 173-equivalent C.P.U. seconds and the variations are explained by, among others, the size of the networks and of the service networks and the number of traffic-classes.

	Exp 1	Exp 2	Exp 3	Exp 4	Exp 5	Exp 6
frequency modification procedure	---	40	133	---	1.1	0.9
traffic distribution	392	596	2277	76	105	87
itinerary generation	245	266	519	20	22	25
optimization	129	277	1443	37	55	34
total time	480	774	2518	91	126	108

Table 1 : Typical execution times for the various experiments

Table 2 shows the improvements obtained in the values of some performance parameters by the optimization procedure with respect to the respective CANAT solutions. Tables 3 and 4 display the level of service and the composition of the service networks obtained on the two data sets by the various experiments. Table 5 shows, for the three experiments conducted on the second data set, the distribution of the number of trains with respect to the length of the routes, while Table 6 contains, for the same problems, the distribution of the number of traffic classes according to the number of itineraries used.

system performance measures	Exp 2	Exp 3	Exp 5	Exp 6
total cost	5.48	1.01	6.90	10.43
ton-miles	0.37	- 0.39	2.65	2.06
car-miles	0.33	- 0.38	1.75	2.29
car costs				
delay	0.48	- 1.90	- 1.73	2.53
operation	0.28	- 1.20	2.02	1.90
total	0.31	- 2.92	1.35	2.00
train-miles	12.82	15.58	11.89	9.41
train costs				
delay	11.93	5.44	13.33	19.90
operation	11.55	5.76	12.48	18.97
total	11.63	5.69	12.67	19.17

Table 2 - Improvements (in %) in some system performance measures with respect to the CANAT solutions

type of service	Exp 1		Exp 2		Exp 3	
	#services	#trains	#services	#trains	#services	#trains
normal	177	1178	121	807	110	497
rapid	14	105	11	122	106	667
total	191	1285	132	929	216	1164

Table 3 - Service levels determined for the first set of data

type of service	Exp 4		Exp 5		Exp 6	
	#services	#trains	#services	#trains	#services	#trains
unit	4	68	4	68	4	68
normal	40	863	38	859	32	1080
rapid	3	49	2	16	0	0
total	47	980	44	943	36	1148

Table 4 - Service levels determined for the second set of data

length of the route in miles	Number of trains Exp 4	Exp 5	Exp 6
less than 200	79	52	36
less than 300	22	29	28
less than 400	170	150	278
less than 500	355	350	311
less than 1000	131	116	314
less than 2000	93	102	181
over 2000	157	144	0

Table 5 - Train distribution according with the route length

number of used itineraries per traffic-class	Number of traffic-classes Exp 4	Exp 5	Exp 6
1	255	236	270
2	28	15	13
3	11	7	2
4	12	7	0
5	9	12	0
6	0	8	0
total number of itineraries	407	423	304

Table 6 - Distribution of the number of traffic-classes according to the number of itineraries used

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As these figures amply demonstrate, our method compares very advantageously with the CANAT system both in the speed of resolution and the quality of the solutions obtained.

The sixth experiment examplifies extremely well the differences between the two methods. In the CANAT approach, the main study was concentrated on the B.C. North Line, and thus all other traffic was moved by trains generated without much care. Our method however, had to optimize the transportation of all the traffic and thus achieved some very impressive improvements.

But, even for the other experiments, we obtained significant improvements. This is due to the characteristics of the optimization procedure which took full advantage of the economies of scale implied by larger blocks and full trains. The system also explored the possibility of using alternate routes for certain services and choose to operate, on certain services, shorter, more frequent trains to shorten the frequency delays and so improve the quality of service (and the overall objective).

One also notes that due to the cost structure C.N. Rail supplied us with, train costs (operation and delay) were much more significant than car costs. Consequently, the model optimized the rail system trying to save as much as posible on train service related costs, even if sometimes that meant increasing the car-costs.

There was a price to be paid for these performances, however, and it was the loss of some operational details. Thus some traffic-classes were put together in a block or a train in contradiction with some policy or operational rules.

Of course, these problems may be corrected, either by imposing more explicit or implicit constraints on the model and accepting the consequent loss of flexibility and efficiency, or by using a system in which the planner takes the solution as input and interactively modifies it to arrive at a valid policy. It is this second option that, in our opinion, has the better chances of success.

We see several possible utilization modes for our method when integrated in a comprehensive planning tool. In an exploratory mode, the system could be used to seek out possible operating strategies to respond to various scenarios developed during the strategic planning process. Costs and strategies could be produced and analyzed very rapidly with much less effort than currently. The system could also be used in an operating mode to help produce the set of policies to be implemented and used in the next planning period. The manager could interact with the system to modify a solution or to choose from several different solutions with basically the same objective function value. He could also modularly use the various procedures of the algorithm to analyze different parts of the system, such as the optimal traffic distribution for a given level of service or the train length on some of the routes offered.

Thus a system built upon our method may prove to be a valuable tool for the medium to long term management of a rail freight transportation system.

CONCLUSION

We have presented two different systems aimed at assisting the medium to long term planning process in rail freight transportation : the deterministic simulation approach presently in use at C.N. Rail and an optimization method presenting a comprehensive and flexible model together with an efficient algorithm. The optimization approach was much faster and generated very interesting results, suggesting that it might advantageously complement the methods presently in use.

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An Optimal Scheduling System for the Welland Canal

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The problem of real time scheduling of vessels through the Welland Canal is discussed. A mathematical programming scheduling algorithm is presented. The problem is formulated as a master schedule selection problem and a schedule evaluation subproblem. The schedule evaluation subproblem is a linear programming model, which, due to special structure, can be solved using an efficient dynamic programming algorithm. The schedule selection algorithm is a heuristic that employs optimal dynamic programming submodels for scheduling the individual locks. Sensitivity information from the schedule evaluation model is used in a greedy type of algorithm to fine tune the schedule. An example of a schedule for the Welland Canal is presented.

1. INTRODUCTION

The St. Lawrence Seaway is a navigable link between the Atlantic Ocean and the Great Lakes, into the heart of the North American continent. Part of this route, between Lake Ontario and Lake Erie, involves bypassing a major obstacle, the Niagara Falls. The Welland Canal was constructed for this purpose. In the early 1980s it appeared that the Canal would soon reach its capacity limit. Subsequently, lower traffic levels have postponed this problem, but efficient operation of the canal reduces the transit time for the vessels, thereby increasing the competitiveness of the seaway.

The Welland Canal,[1] sketched in Figure 1, is 38 kilometers (23.5 miles) long and contains 8 locks which raise (and lower) vessels by 97 meters (326 feet). The first three locks upbound from Lake Ontario are individual locks with stretches of canal, called "reaches," between them. Locks 4, 5 and 6 are combined into a single flight with one lock leading directly into the next one. Each of these locks is twinned to permit simultaneous movement of vessels upbound and downbound. Lock 7 is a very short reach above Lock 6, at the top of the Niagara escarpment, and is considered to be the major bottleneck in the Welland Canal. Finally, the narrow stretch of canal between Lock 7 and Lock 8, 5.4 kilometers long, does not permit vessel meets over its length. (The term "meet" refers to two vessels in opposite directions passing each other.) The canal is also crossed by several lift bridges, at which meets are not permitted due to the narrowness of the canal. Limited capacity tie-up walls, below and above each lock, are used for temporarily mooring vessels as they wait for the lock to accept them.

There were 4750 transits through the Welland Canal in 1984, with a cargo volume of 14.1 million tonnes upbound and 39.8 million tonnes downbound, over a navigation season from April to December. Bulk cargo accounted for 92% of the traffic. Although many vessels pass through both the St. Lawrence and the Welland Canal on "through" trips, there is a substantial amount of local traffic, grain and coal, between Great Lakes ports which involves only the Welland Canal. For example, in 1984 the Welland Canal traffic was 8.4 million tonnes greater than that reported for the Montreal-Lake Ontario section.

In normal operations, it is most efficient to have upstream and downstream traffic alternate through a lock, so that the lock contains a vessel every time it fills or empties. This is possible only if the traffic is balanced in each direction, which happens less than 60% of the time. When traffic is unbalanced, the locks must be occasionally cycled with no contained vessel. We call such a nonutilized lock cycle a "turnback."

Although vessels arrive at the canal randomly, their expected times of arrival (ETA) are usually known well before arrival and updated as the canal is approached. Smaller vessels and pleasure craft are grouped together at the canal entrance and move through the canal as a unit, which we will hereafter consider to be one vessel.

Once a vessel enters the canal, it proceeds through the canal in its order of entry, with overtakes occurring only if a vessel encounters mechanical difficulties.

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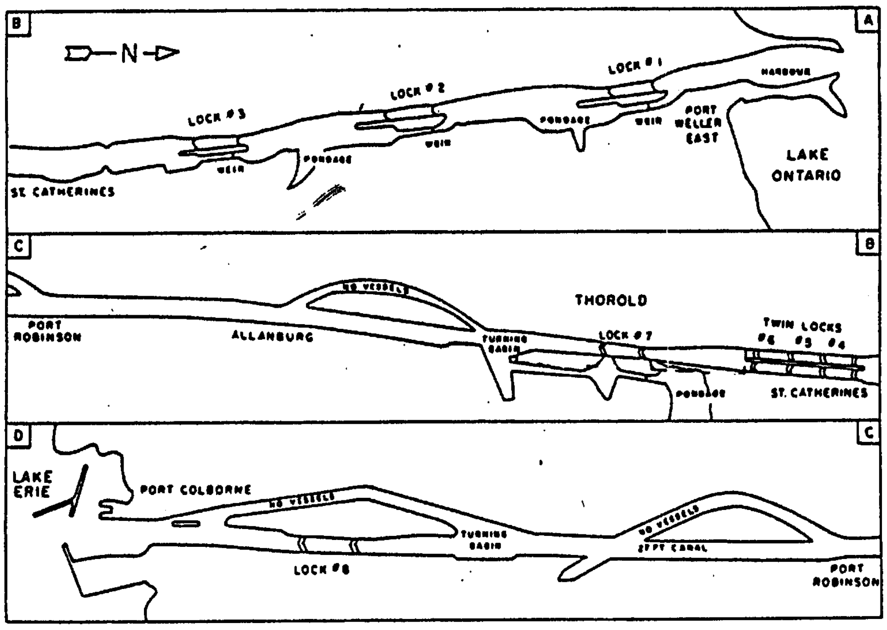

Fig. 1. Schematic of Welland Canal Locks (not to scale).

2. THE VESSEL SCHEDULING PROBLEM

THE Seaway Traffic Control System provides for safe and efficient transit through the canal. The System operates from a central control office, which maintains visual surveillance of the canal via closed circuit television, and issues traffic control instructions to ship captains using a system of lights augmented by radio communications. A traffic control superintendent is in overall charge of the central dispatch office, and is responsible for strategic decisions with respect to traffic flow (in particular, with order-of-turn decisions at locks and control points). To assist him, traffic controllers are responsible for tactial decisions in controlling detailed movements of vessels within subsections of the canal. According to the *Traffic Control Manual*,[2] the objective of the system is to maximize the throughput capability of the system (i.e., optimize lock utilization), subject to the maintenance of safe passage.

The current scheduling system has been developed from experience with the canal operation over time, and is summarized in the *Traffic Control Manual*. In effect, the system consists of rules designed to ensure a supply of vessels at canal bottlenecks, so that the flow of vessels through the canal is maximized. The effectiveness of the system rests to a large degree on the traffic superintendent's experience and capabilities. Although the traffic superintendents are very able, it is humanly impossible to project all the future vessel movements to ensure that the optimal dispatch decisions are made. (This is a particular problem on shift changes of traffic superintendents, as differing operating strategies give rise to different vessel movement patterns and delays are incurred during the adjustment period.) A common tool for predicting future vessel movements would help to reduce the vessel delays within the canal system, and so improve its capacity.

Predicting vessel performance in the system requires knowledge of the direction of travel of the vessel, canal characteristics (lockage times, speed restrictions), vessel characteristics (dimensions, acceleration performance, load), and environmental special considerations (time of day, weather). These characteristics are known in advance, knowing the vessel ETA and through the call-in procedure, and are independent of the schedule.

In addition, vessel performance depends on situational factors, such as the type of lock entry or exit to be executed, and the type of meet when vessels encounter one another (for example, in poor weather it may be necessary for one vessel to tie up while the other passes). These variations occur only in adverse weather conditions, and so can be treated as variations from normal performance. The traffic superintendent would adjust the schedule locally to compensate for these changes.

Simulation techniques have been used to study canal operations. DAWSON et al.[3,4] and BROWNE and LIOU[5] used simulation effectively to study and improve the dispatch decisions involved in moving vessels in and out of locks. To some degree, simulation could be used to study scheduling rules. However, due to the combinatorial nature of the scheduling problem, the use of a simulation model is limited.

This paper described a vessel traffic scheduling system based on the use of mathematical programming. This system provides the traffic superintendent with:

1. The optimal (or near optimal) schedule (order of turn for each lock and restriction);
2. A measure of the total delay encountered by vessels in the system;
3. The relative sensitivity of each movement, pinpointing the bottleneck moves;
4. Identification of the existence of slack: delays that can occur without affecting the schedule or the performance of the schedule;
5. Identification of how much a schedule can slip and the cost of such slippage;
6. The information necessary to draw string (time-distance) diagrams to display the evolution of movements through the canal.

The scheduling problem is formulated in the next section. Key to obtaining a workable solution is the decomposition of the problem into a master schedule selection programming problem and a schedule evaluation problem. These models are described in the next sections.

3. THE SCHEDULING MODEL

THE SCHEDULE dictates the order-of-turn for vessels for each lock and each stretch of canal where meets are not permitted. We shall refer to the locks and canal restrictions as facilities (which must be scheduled) and number them $f = 1, 2, \ldots, F$ in the upbound direction. The flight locks are considered to be a single facility. Facilities are separated by reaches in which vessels in opposite directions can meet.

The movement of traffic through the canal is controlled at a number of control points (cp) in the system. These cp's are located at the entrances to the canal and at the upstream and downstream end of each facility and are numbered, in the upbound direction, $k = 1, 2, \ldots, K$ where $K = 2(F + 1)$. The downstream cp for any facility f is numbered $2f$, and the upstream cp $2f + 1$. The downstream canal entrance cp is numbered 1, and the upstream entrance cp is K.

The scheduling algorithm looks ahead over a specified scheduling horizon and considers all vessels currently in the canal and those that will arrive at the canal during the horizon. Suppose there are I upbound and J downbound vessels. The traffic in each direction is ordered in the sequence that the vessels or groups of vessels would normally proceed through the canal (e.g., FIFO) and are numbered $i = 1, 2, \ldots, I$ for the upbound traffic and $i = I + 1, I + 2, \ldots, I + J$ for the downbound traffic.

For each vessel i, the following information will be available to initialize or update the scheduling model:

A_i = current cp or next cp if vessel is between cp's or arriving at the canal,
B_i = exit cp (normally 1 or K),
t_i = current time if at cp $= A_i$, or expected time of arrival (ETA) at next cp.

Vessel performance along the canal can then be summarized as

$t^i_{k,k+1}$ = time for upbound vessel i to transmit from cp k to cp $k + 1$, $i \leq I$, and
$t^i_{k,k-1}$ = time for downbound vessel i to transmit from cp k to cp $k - 1$, $i > I$.

where the detailed information on vessels and the canal is used to calculate these timing data. In addition, we define the minimum headway permitted between two vessels, due to operational and safety considerations, as

h^k_{ij} = the minimum time that is required from when the reference point (bow) of vessel i passes cp k before the reference point of vessel j can proceed past cp k when vessels i and j meet at cp k. This includes the time for a vessel to transit its own length plus safety headway before the next can proceed.

Finally, we let $t_1(f)$ and $t_2(f)$ be the time to empty and fill a lock, respectively, when no vessel is present in the lock (i.e., a turnback).

The schedule, which specifies the order in which vessels will be processed at each facility, is subject to a variety of constraints. We describe the schedule by an $((I + J) \times F)$ matrix S, where element $s(p, f)$ is the index of the pth vessel to be processed by facility f.

Feasibility of a schedule requires that if a vessel i precedes vessel j at some facility f, then i must precede j in the list at all facilities previously visited by i. To formalize, suppose $s(p, f) = i$, $s(q, f) = j$ and $p < q$. Then,

$$\begin{aligned} &\text{for } (i \leq I \text{ and } m < f) \quad \text{or } (i > I \text{ and } m > f), \\ &\text{if } s(r, m) = i \qquad \text{and } s(t, m) = j, \qquad (3.1) \\ &\text{then } r < t. \end{aligned}$$

Let $x_{i,k}$ be the time vessel i departs control point k. The set of times is constrained by the time required to complete operations, the required separation when vessels follow each other through locks, and by the schedule which dictates the order vessels are processed at each facility. These constraints are:

3.1. Timing Constraints

These constraints specify the minimum time for a vessel to move from one cp to the next. They require that the earliest departure time from the next cp is the departure time from the previous cp plus the minimum transit time. Thus,

$$x_{i,A_i} \geqslant t_1$$

for $i = 1, 2, \ldots, I + J$;

$$x_{i,k} \geqslant x_{i,k-1} + t^i_{k-1,k}$$

for $i \leqslant I$ and $k = A_i + 1, \ldots, B_i$; (3.2)

and

$$x_{i,k} \geqslant x_{i,k+1} + t^i_{k+1,k}$$

for $i > I$ and $k = B_i + 1, \ldots, A_i - 1$.

3.2. Following Constraints

The geometry of one vessel following another through a lock is illustrated in Figure 2. A following vessel can enter a lock only after the vessel ahead has cleared the lock and the lock has been turned back. If the facility is a restricted reach, then vessels can platoon through the reach maintaining a minimum headway or separation between vessels. The following constraints for a reach may be written in the same form as for a lock if we define the turnback time to be the headway minus the transit time for the following vessel, which may be negative in this case. Letting $g_u(f)$ and $g_d(f)$ be the minimum vessel separation in the upbound and downbound direction respectively, the constraints are

$$x_{i+1,2f} \geqslant x_{i,2f+1} + t_1(f) \quad \text{for } f = 1, 2, \ldots, F;$$
$$i = 1, 2, \ldots, I - 1; \quad \text{and } A_i \leqslant 2f \leqslant B_i$$

where

$$t_1(f) = \text{time to empty lock} \quad \text{if } f \text{ is a lock;}$$
$$= g_u(f) - t^{i+1}_{2f,2f+1} \quad \text{if } f \text{ is a reach.}$$

or

$$x_{i+1,2f+1} \geqslant x_{i,2f} + t_2(f)$$

for $f = 1, 2, \ldots, F$; $i = I + 1, \ldots, I + J - 1$; and $B_i \leqslant 2f + 1 \leqslant A_i$,

where

$$\begin{aligned} t_2(f) &= \text{time to fill lock} \quad \text{if } f \text{ is a lock;} \\ &= g_d(f) - t^{i+1}_{2f+1,2f} \quad \text{if } f \text{ is a reach.} \end{aligned} \tag{3.3}$$

3.3. Schedule Constraints

Figure 3 illustrates the geometry that must hold when opposing vessels are sequenced through a facility. The resulting constraints, which hold for $f = 1, 2, \ldots, F$ and for $m = 1, 2, \ldots, I + J - 1$, are

$$x_{s(m+1,f),2f+1} \geqslant x_{s(m,f),2f+1} + h^{2f+1}_{s(m,f),s(m+1,f)}$$

if $s(m, f) \leqslant I$ and $s(m + 1, f) > I$, and (3.4)

$$x_{s(m+1,f),2f} \geqslant x_{s(m,f),2f} + h^{2f}_{s(m,f),s(m+1,f)}$$

if $s(m, f) > I$ and $s(m + 1, f) \leqslant I$.

The objective of minimizing total vessel delays within the canal is equivalent to minimizing the sum of exit times for each vessel.

The scheduling problem is now formulated as a master (combinatorial) problem that selects the schedule, described by the $((I + J) \times F)$ matrix S, with the objective function evaluated using a linear

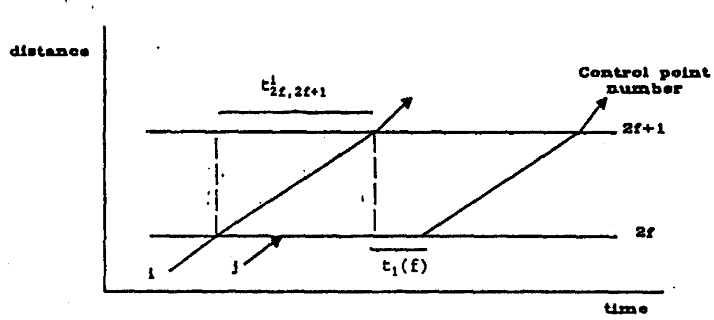

Fig. 2. Following contraints at a lock.

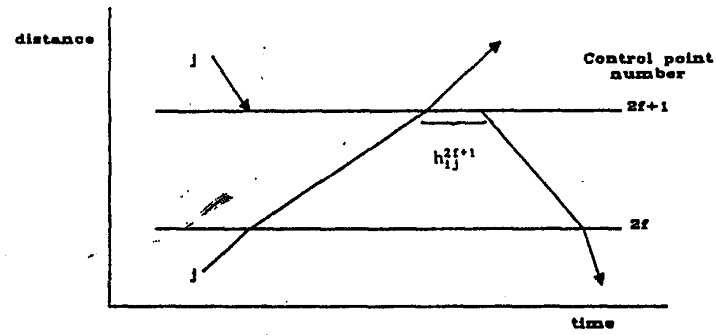

Fig. 3. Schedule constraints at a facility (f).

programming submodel. That is:

Master Problem

$$\min_{S} z(S) \qquad \text{(MP)}$$

subject to (3.1).

Subproblem

$$z(S) = \min \sum_{i=1}^{I+J} x_{f,B_i} \qquad \text{(LP)}$$

subject to (3.2), (3.3) and (3.4).

Since all the variables are non-negative, the subproblem is a linear programming model. In Section 5 we show that (LP) has a special structure that leads to a very fast algorithm. First we shall illustrate (LP) using a simple example.

4. A DEMONSTRATION EXAMPLE

CONSIDER A canal consisting of two locks with three reaches, and two upbound and three downbound vessels are to traverse the entire length. Assume the time to process vessels through each lock is 40 minutes, with transit times of 10, 20 and 30 minutes in each direction for the reaches below the first lock, between the locks and above the second lock, respectively. The turnback times are 10 minutes to empty and 20 minutes to fill each lock. A safety headway of 4 minutes is assumed between all vessels. Finally, the two upbound vessels enter the canal at time 0 and 30 minutes, while the downbound vessels enter at time 5, 10 and 40 minutes.

Assume we have a feasible (but not necessarily optimal) schedule described by

$$S = \begin{bmatrix} 1 & 3 \\ 3 & 4 \\ 2 & 1 \\ 4 & 2 \\ 5 & 5 \end{bmatrix}.$$

The resulting (LP model is given in Table I.

Solving yields $z(S) = 1209$, corresponding to 424 minutes delay in the canal. The primal variables describe the movement of each vessel through the canal. The best way to illustrate these movements is by a time-distance (string-diagram) as shown in Figure 4. Vessel delays appear as non-zero slack variables in the timing constraints.

The dual variable associated with each timing constraint is the rate of change of the objective function if the time to transit a link is increased by one unit. These have been plotted on each arc of the string-diagram. For example, observe that upbound vessel 1 can take longer during the first lockage or on reach 1 or 2 without affecting the total system performance as the increased operating time only decreases the waiting delay. Also observe that if downbound vessel 3 were to take 1 additional minute to transit reach 2, this would cause a total of 4 minutes delay to the system, as upbound 2 and downbound 4 and 5 are also delayed by 1 minute. Conversely, if the operation can be altered so that downbound vessel 3 takes 1 minute less to transit reach 2, then a total of 4 minutes of delay will be saved. This pricing or sensitivity information tells the traffic superintendent where to focus attention to expedite a schedule.

In Section 6 the dual variables associated with the meet constraints are used to search for an improved schedule. In the next section we show that the LP subproblem has a special structure that leads to a very fast algorithm for its solution.

5. SCHEDULE EVALUATION

THE MOVEMENT of vessels through the canal can be represented as an acyclic directed graph. Nodes in the graph represent the departure of a vessel from a control point. Each directed arc corresponds to a precedence requirement with a required time for the intervening activity to take place. Figure 5 is the graph for the two lock example of the previous section.

TABLE I

Demonstration example

Min X16 + X26 + X31 + X41 + X51

Subject to

2)	X12	−X11	≥ 10	
3)	−X12	+X13	≥ 40	
4)	−X13	+X14	≥ 20	
5)	−X14	+X15	≥ 40	
6)	X16	−X15	≥ 30	
7)	X22	−X21	≥ 10	
8)	−X22	+X23	≥ 40	
9)	−X23	+X24	≥ 20	
10)	−X24	+X25	≥ 40	
11)	X26	−X25	≥ 30	
12)	X35	−X36	≥ 30	
13)	−X35	+X34	≥ 40	timing
14)	−X34	+X33	≥ 20	
15)	−X33	+X32	≥ 40	
16)	X31	−X32	≥ 10	
17)	X45	−X46	≥ 30	
18)	−X45	+X44	≥ 40	
19)	−X44	+X43	≥ 20	
20)	−X43	+X42	≥ 40	
21)	X41	−X42	≥ 10	
22)	X55	−X56	≥ 30	
23)	−X55	+X54	≥ 40	
24)	−X54	+X53	≥ 40	
25)	−X53	+X52	≥ 20	
26)	X51	−X52	≥ 10	
27)	−X13	+X22	≥ 10	
28)	−X15	+X24	≥ 10	
29)	−X34	+X45	≥ 10	following
30)	−X32	+X43	≥ 20	
31)	−X44	+X55	≥ 20	
32)	−X42	+X53	≥ 20	
33)	−X13	+X33	≥ 20	
34)	X22	−X32	≥ 4	
35)	−X23	+X43	≥ 4	schedule
36)	X14	−X44	≥ 4	
37)	−X25	+X55	≥ 4	
38)	X11	≥ 0		
39)	X21	≥ 30		initial conditions
40)	X36	≥ 5		
41)	X46	≥ 10		
42)	X56	≥ 40		

The graph is constructed by listing the nodes for all vessels at each control point. The horizontal arcs correspond to the timing constraints. For example, the first arc represents the relation

$$x_{12} \geq x_{11} + t_{12}^{1}.$$

The slanted arcs correspond to the lock turnback constraints for following vessels. The first arc of this type, for example, corresponds to the requirement that the second upbound vessel cannot leave control point 2 (entering the lock) until the first has left cp 3 and the lock is turned back:

$$x_{22} \geq x_{13} + t_1(1).$$

Schedule constraints are represented by the vertical arcs in Figure 5. For example in the schedule matrix S, $s(1, 1) = 1$, $s(2, 1) = 3$ says that the first upbound vessel is processed before the first downbound vessel at lock 1. This implies that upbound vessel 1 leaves control point 3 before downbound vessel 3 can leave cp 3, or

$$x_{33} \geq x_{13} + h_{13}^{3}.$$

The resulting graph has a number of nodes equal to the number of variables in (LP), and a number of arcs equal to the number of constraints.

It is easy to demonstrate that the directed graph in Figure 5 is acyclic (otherwise some activity would have to be completed before it could be initiated). DENARDO[6] shows that for any acyclic graph, the shortest path can be found using a one-pass dynamic programming algorithm. We extend this to finding the earliest completion times for each vessel. This results in a very efficient two-pass dynamic programming algorithm for solving (LP). The first pass solves for the optimal vessel times, while the second pass solves for the shadow prices.

Consider the acyclic graph $G(N, E)$ with nodes $r = (i, k) \in N$ and arcs $(r, s) \in E$. (Each node is represented by (i, k) where i is the vessel number and k is the control point.) Let c_{rs} be the time on arc (r, s). Then the following algorithm calculates the earliest completion times:

Step 0. Let X and $\bar{X}$ be sets. Set $X = N$; $\bar{X} = \emptyset$
for $i = 1, 2, \ldots, I + J$

label node (i, A_i) with $x_{i,A_i} = t_i$
add (i, A_i) to $\bar{X}$ and remove from X.

Step 1. Select a node $s = (i, k) \in X$ which is not a successor node to any other node in X. (It is easy to show that if X is non null that there always exists such an s is an acyclic graph).
Label this node as

$$x_{ik} = \max(x_r + c_{rs}), \quad \text{for } r \in \bar{X}$$

Add node s to $\bar{X}$ and delete s from X.
If $X = \emptyset$ stop; otherwise repeat step 1.

The vessel times x_{ik} solve (LP).

A similar "backward" algorithm is used to calculate the dual variables in (LP). First, we calculate node numbers using the algorithm:

Step 0. $X = N, \bar{X} = \emptyset$
for $i = 1, 2, \ldots, I + J$
label node (i, B_i) with $v_{i,B} = 1$
add (i, B_i) to $\bar{X}$ and remove from X.

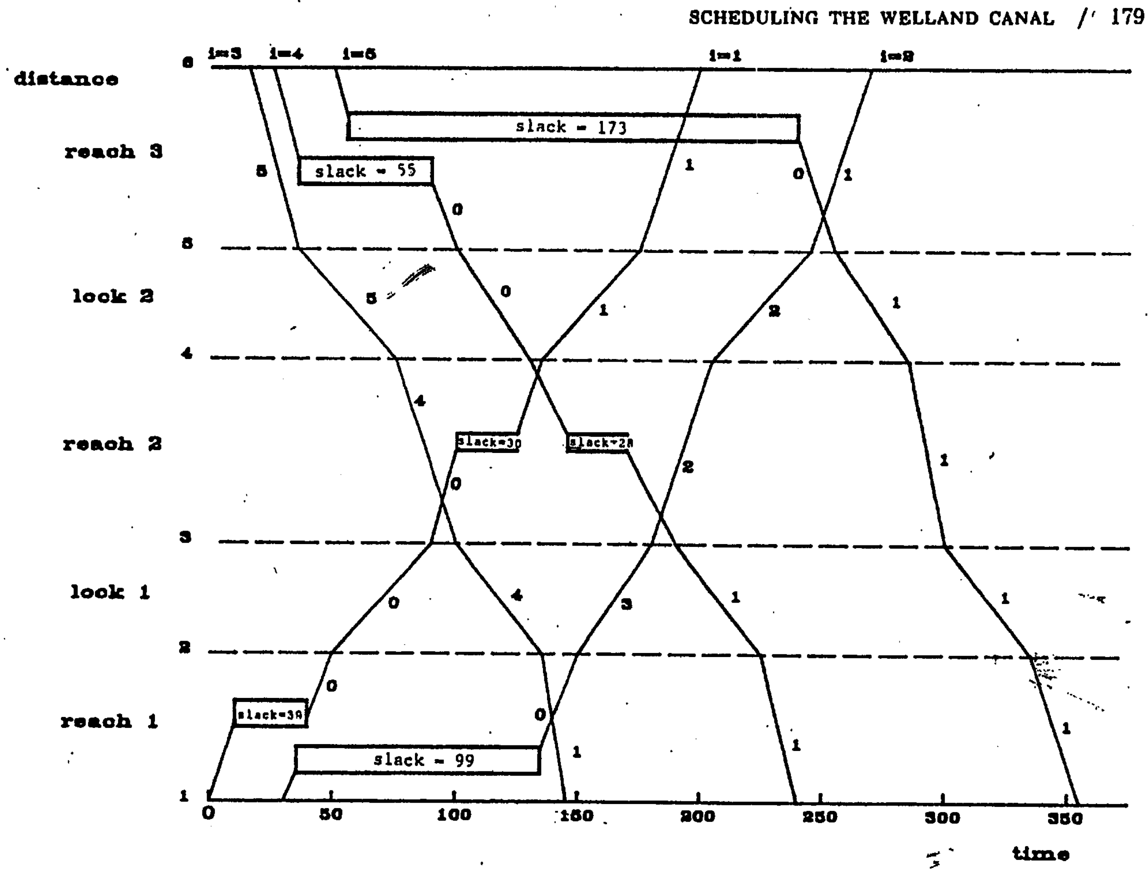

Fig. 4. Vessel movements in the demonstration example.

Step 1. Select a node $r = (i, k) \in X$ for which all of r's successor nodes are in X. (Again it is easy to show that there always is such an r for $X \neq \varnothing$ in an acyclic graph). Label this node

$$v_r = \sum v_s \quad \text{for } (r, s) \in E \quad \text{and } x_r - x_s = c_{rs}$$

(Set $v_r = 0$ if $x_s - x_r > c_{rs}$ for all $(r, s) \in E$)
Add node r to $\bar{X}$ and delete it from X.
If $X = \varnothing$ stop; otherwise repeat Step 1.

These labels are the dual variables associated with each node, and each binding arc (r, s) has a dual price equal to the label of node s. The dual price of the nonbinding arcs is of course zero. Thus the dual solution to (LP) is

$$y(r, s) = v_s, \quad x_s - x_r = c_{rs};$$
$$= 0, \quad x_s - x_r > c_{rs}.$$

This very efficient algorithm, linear in the number of variables, determines the optimal vessel times at each control point and the dual price associated with each constraint. We now examine the master schedule selection problem.

6. OPTIMAL SCHEDULING

SOLUTION OF the master problem for an optimal schedule S is a large integer programming problem. The observation that direct solution of this problem would require exponentially increasing time as the problem size increases suggests a heuristic procedure. This section describes such a procedure, based on optimal submodels, which yields a strategy which is similar in principle to that used by traffic superintendents.

The basic model used in calculating optimal schedules is a dynamic programming model of a single facility. (Recall that a facility to be scheduled is a lock or canal restriction.) Given the estimated time of arrival for each vessel at the facility, the model

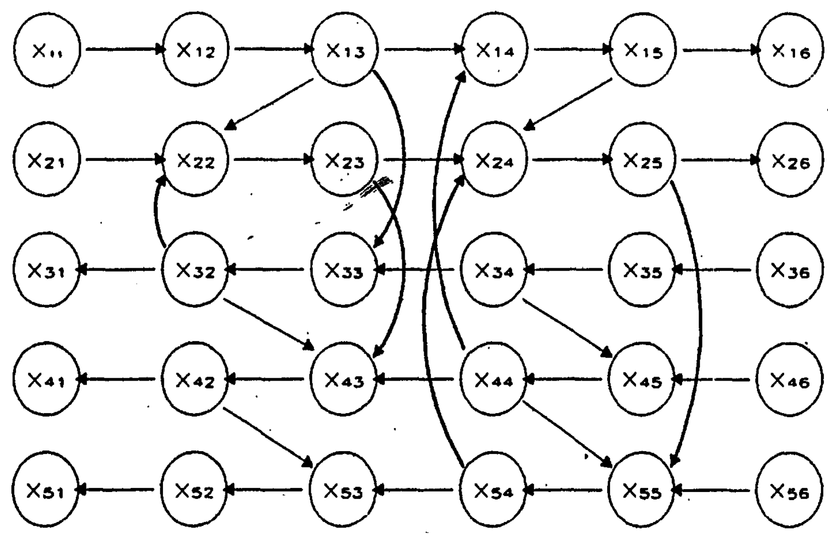

Fig. 5. Network for demonstration example.

determines the order-of-turn for that facility to minimize delays. If the canal had only one lock, this would be the optimal schedule. Even with multiple facilities, this is the key model in calculating a schedule since it determines when a facility should be turned-back.

Given the vessel location information, vessel characteristics, expected demand, canal characteristics and estimated vessel performance, the first step in forming a canal schedule is to determine which facility is contributing the most to vessel delay (i.e., the "bottleneck" facility, the location of which may change with varying loading and traffic patterns). To identify it we successively schedule each facility separately assuming traffic can flow unimpeded to and from the facility. The facility that yields the greatest delay when scheduled is the bottleneck. Delays due to the bottleneck facility also form a lower bound on the optimal solution. An initial order-of-turn for the bottleneck facility will be determined by this procedure.

The second step examines the facility on each side of the bottleneck, with the objective of scheduling these adjacent facilities to minimize any disruption to the schedule determined for the bottleneck. For each adjacent facility, we determine the "ready time" for each vessel, which is the time of arrival of that vessel at the adjacent facility assuming no delays from other vessels except at the bottleneck facility (i.e., vessels proceeding away from the bottleneck lock may have been delayed by other vessels at the lock). For vessels proceeding toward the bottleneck facility, we compute the "due time," which is the latest departure time from that facility to permit arrival at the bottleneck facility on schedule as determined in step one. If a vessel departs x minutes after its due time, we say the vessel is tardy by x minutes. The single lock dynamic programming model is now used to calculate the order-of-turn for the vessel at each adjacent facility so as to minimize the sum of the vessel tardy times.

The procedure is repeated for the next adjacent facilities (upbound and downbound) as we move away from the bottleneck facility, until the ends of the canal are reached. We note in passing that this procedure has the effect of filling up the reaches to try to keep the bottleneck facility busy, and is similar in purpose to the scheduling strategies currently in use. While we allow vessels to be platooned across the long restricted reach, the over-riding requirement is to keep the locks fully utilized. This tends to keep the number of turnbacks, and hence platooning, to a minimum.

The resulting schedule for each lock and restriction is a good but not necessarily optimal schedule.

The third step improves upon this schedule using a greedy algorithm. Using the sensitivity information obtained from the linear programming submodel, candidate changes to the schedule are identified which could yield an improvement. These are tested and when improvements are found, the schedule is updated, sensitivity information is recalculated and the process continues until no further improvements can be found. This procedure has the effect of "fine tuning" the schedule.

The next sections describe the details of these submodels.

6.1. Dynamic Programming Model for a Single Lock

Relax the schedule constraints in (LP) and calculate the vessel times in the canal. The ready times at facility f are

$$R_u(i) = x_{i,2f}$$

for the upbound vessels $i = 1, \ldots, I$ and

$$R_d(j) = x_{I+j,2f+1}$$

for the downbound vessels $j = 1, \ldots, J$. Facility f is scheduled to minimize the sum of completion times at the facility.

Formulating as a forward dynamic programming model, we define the stages $n = 1, 2, \ldots, I + J$, to be the number of vessels scheduled through the facility. The state of the system is described by the ordered pair (m, q) where m is the number of upbound vessels processed and q is the lock position defined as

$q = 0$, lock down and last vessel processed was downbound,
$q = 1$, lock up and last vessel processed was upbound.

(The number of downbound vessels processed is $n - m$.) Now define

$f_n(m, q)$ = the sum of completion times if an optimal path is followed to state (m, q) stage n,
$c_n(m, q)$ = completion time for last vessel if in state (m, q), with

$$f_0(0, 0) = 0, \quad c_0(0, 0) = 0,$$
$$f_0(0, 1) = 0, \quad c_0(0, 1) = 0.$$

For $n = 1, 2, \ldots, I + J$ and $m = \max(0, n - J), \ldots, \min(n, I)$:

$q_n = 0$:
if $m = n$
$f_n(m, 0) = \infty$
$c_n(m, 0) = \infty$
otherwise compute

$$c_0 = \max[c_{n-1}(m, 0) + t_2(f), R_d(n - m)] + t^{n-m+I}_{2f+1,2f}$$

$$c_1 = \max[c_{n-1}(m, 1) + h, R_d(n - m))] + t^{n-m+I}_{2f+1,2f}$$

where

$$h = 0; \quad m = 0$$
$$= h^{2f+1}_{m,n-m+1}; \quad \text{otherwise}$$

with

$$f_n(m, 0) = \min_q \{f_{n-1}(m, q) + r_q\}$$

$$c_n(m, 0) = c_{q^*}.$$

where the contribution to the objective function $r_q = c_q$, the completion time of the last vessel, and q^* is the optimal predecessor state.

$q_n = 1$:
if $m = 0$
$f_n(m, 1) = \infty$
$c_n(m, 1) = \infty$
otherwise compute

$$c_0 = \max[c_{n-1}(m - 1, 0) + h, R_u(m)] + t^m_{2f,2f+1},$$

$$c_0 = \max[c_{n-1}(m - 1, 1) + t_1(f), R_u(m)] + t^m_{2f,2f+1},$$

where

$$h = 0; \quad n = m$$
$$= h^{2f}_{n-m+I,m}; \quad \text{otherwise}$$

with

$$f_n(m, 1) = \min_q \{f_{n-1}(m - 1, q) + r_q\}$$

$$c_n(m, 1) = c_{q^*}.$$

The optimal predecessor state is recorded for each state. The minimum-time ending state is selected, and the optimal order-of-turn for the facility is found by tracking back through the dynamic programming tables. The resulting schedule constraints for the facility are added to the relaxed (LP) model. Evaluating this new (LP) model gives a lower bound z_f for the scheduling problem. This is repeated for all facilities. Then

$$z_0 = \max_f z_f = z_{f^*}$$

is the best lower bound for the problem, and f^* is the bottleneck facility.

The two-lock example from the previous section is used to demonstrate the model. Table II is the dynamic programming tabulation for lock 2, the bottleneck lock, giving a lower bound of $z_0 = 1085$.

The optimal order-of-turn, and entry and exit times at lock 2 are given in Table III. We note that this algorithm has computation time that is quadratic in the total number of vessels, $I + J$.

TABLE II

Lock 2 Optimal Schedule

Stage n	State m	$q = 0$ Lock Down			$q = 1$ Lock Up		
		$f_n(m, 0)$	$c_n(m, 0)$	q^*_{n-1}	$f_n(m, 1)$	$c_n(m, 1)$	q^*_{n-1}
1	0	75	75	0, 1	∞	∞	—
	1	∞	∞	—	110	110	0
2	0	210	135	0	∞	∞	—
	1	264	154	1	194	119	0
	2	∞	∞	—	354	160	1
3	0	405	195	0	∞	∞	—
	1	357	163	1	389	179	0
	2	558	204	1	363	169	1
4	1	580	223	0	644	239	0
	2	576	213	1	564	207	0
5	2	815	251	1	847	267	0

TABLE III

Optimal Order-of-Turn, and Entry and Exit Times at Lock 2

Vessel	Entry Time	Exit Time
Downbound $j = 1$	35	75
Upbound $i = 1$	79	119
Downbound $j = 2$	123	163
Upbound $i = 2$	167	207
Downbound $j = 3$	211	251

6.2. Multiple Lock Scheduling

In the previous section we calculated the bottleneck facility and the optimal single facility schedule. The multiple facility scheduling model schedules the adjacent facilities to minimize disruptions to the schedule at the bottleneck. As mentioned previously, this is achieved by calculating the due times at adjacent facilities for each vessel proceeding toward the bottleneck, and minimizing the tardiness, or total amount by which these due times are exceeded.

Suppose we have recursively constructed a schedule for facilities $f = f_1, f_1 + 1, \ldots, f_2$. Now we relax the schedule constraints in (LP) at facilities $k < f_1$ and $k > f_2$ and evaluate the schedule. Select an adjacent facility $f = f_1 - 1$ or $f = f_2 + 1$ with control points $2f$ and $2f + 1$. Then the due and ready times at the facility are

$$D_u(i) = x_{i,2f+1}$$

$$R_u(i) = x_{i,2f}$$

$$R_d(j) = x_{I+j,2f+1}$$

$$D_d(j) = x_{I+j,2f}$$

for every $i = 1, 2, \ldots, I$ and $j = 1, 2, \ldots, J$.

The single lock dynamic programming algorithm of the last section minimizes total tardiness if we define:

$$r_q = \max(0, c_q - D_d(n - m)), \quad q_n = 0;$$

$$= \max(0, c_q - D_u(m)), \quad q_n = 1.$$

$f_n(m, q)$ is now the optimal total tardiness.

To demonstrate this algorithm, we continue with the two lock example. Given the schedule for lock 2 from the previous section the ready and due times at lock 1 are

$$R_u(1) = 10 \quad D_u(1) = 59$$

$$R_u(2) = 40 \quad D_u(2) = 147$$

$$R_d(1) = 95 \quad D_d(1) = 135$$

$$R_d(2) = 183 \quad D_d(2) = 223$$

$$R_d(3) = 271 \quad D_d(3) = 311.$$

Table IV tabulates the tardiness, completion time and optimal predecessor state for each state. The resulting schedule calls for processing the two upbound vessels first, followed by the three downbound vessels. This schedule has a tardiness of 9 minutes.

This schedule for the two locks has a sum of vessel transit times of 1094 minutes. While not guaranteed to be the optimal schedule for the canal, it is in this example. Note that the schedule evaluated in Section 5 had a value of 1229 minutes, while the lower bound generated using the optimal single lock scheduling model had a value of 1085 minutes.

In the next section we present an algorithm which searches for schedule improvements.

6.3. Solution Improvement

We cannot guarantee that the multilock schedule will be optimal. However, we now describe a greedy algorithm which examines all potentially beneficial

TABLE IV

Lock 1 Minimum Tardiness Schedule

Stage n	State m	$q = 0$ Lock Down			$q = 1$ Lock Up		
		$f_n(m, 0)$	$c_n(m, 0)$	q^*_{n-1}	$f_n(m, 1)$	$c_n(m, 1)$	q^*_{n-1}
1	0	0	135	0, 1	∞	∞	—
	1	∞	∞	—	0	50	0, 1
2	0	0	223	0	∞	∞	—
	1	0	135	1	120	179	0
	2	∞	∞	—	0	100	1
3	0	0	311	0	∞	∞	—
	1	0	223	0	208	267	0
	2	9	144	1	32	179	0
4	1	0	311	0	296	355	0
	2	9	223	0	120	267	0
5	2	9	311	0	208	355	0

switches in the order-of-turn at each facility. Candidate switches are identified using dual variable information from the schedule evaluation algorithm.

Suppose at facility f vessel i precedes vessel j, where i and j represent vessels moving in opposite directions through the canal. The resulting schedule of constraints is

$$x_{j,k} \geq x_{i,k} + h^k_{ij}$$

where

$$k = 2f, \qquad i \leq I,$$
$$= 2f + 1, \quad i > I,$$

and has a dual variable of, say, λ_0. If we allow j to precede i, $x_{j,k}$ will decrease by some amount s_0, until the next most binding constraint is encountered. Then the maximum improvement attainable by advancing vessel j is $\lambda_0 s_0$.

As vessel j is advanced, vessel i is slowed. Let λ_1 be the dual variable associated with the timing constraint for vessel i on the next reach (upstream from facility f if $i \leq I$, downstream if $i > I$). In addition, define T_f to be the loop time for facility f, which is the time to cycle the facility with vessels i and j. For example, if $i \leq I$,

$$T_f = t^i_{k,k+1} + t^j_{k+1,k} + h^k_{ij} + h^{k+1}_{ij}.$$

Then if vessel i is delayed so it follows vessel j, the minimum decrease in the objective function is

$$\lambda_1(T_f - s_0).$$

Combining the maximum improvement in objective if we switch the order-of-turn so vessel i follows vessel j through the facility is

$$D = (\lambda_0 - \lambda_1)s_0 - \lambda_1 T_f.$$

If $D > 0$, the order-of-turn for the two vessels is reversed and the new schedule is evaluated in the search for an improved schedule.

This algorithm requires at most [min(I, J)*F] evaluations to determine that no further improvement is possible. If we start with a poor schedule, then the number of improvements could be exponential and the algorithm is poor. However, the dynamic-programming models generate an optimal or near optimal schedule, and in practice, very few improvements are found using this greedy algorithm.

TABLE V

Welland Canal Configuration

CP	Description	Mileage
1	Call in Point 15	0
2	Lock 1 Downstream LA2	1.4
3	Lock 1 Upstream LA2	1.9
4	Lock 2 Downstream LA2	3.0
5	Lock 2 Upstream LA2	3.4
6	Bridge 4 Downstream LA	4.85
7	Bridge 4 Upstream LA	4.95
8	Lock 3 Downstream LA2	5.3
9	Lock 3 Upstream LA2	5.8
10	Bridge 5 Downstream LA	6.05
11	Bridge 5 Upstream LA	6.15
12	Lock 4 Downstream LA2	6.6
13	Lock 6 Upstream LA2	7.1
14	Lock 7 Downstream LA2	7.3
15	Lock 7 Upstream LA2	7.7
16	Guard Gate Cut Downstream LA	8.25
17	Guard Gate Cut Upstream LA	8.35
18	Bridge 10 Downstream LA	9.2
19	Bridge 12 Upstream LA	12.6
20	Ramey's Bend	20.0
21	Turning Basin No. 4	20.8
22	Lock 8 Downstream LA2	21.0
23	Lock 8 Upstream LA2	21.4
24	Bridge 20 Downstream LA	21.9
25	Bridge 21 Upstream LA	22.0
26	Call in Point 16	23.5

The other routines are all low-order polynomial time algorithms. The dynamic programming algorithm requires $2F(I + J)^2$ operations to generate a schedule for the canal. The schedule evaluation algorithm requires $2(I + J)K$ operations.

7. WELLAND CANAL EXAMPLE

IN THIS section we demonstrate the model for the Welland Canal. The configuration of control points along the canal is given in Table V. There are 26 control points, numbered from $k = 1$ at Lake Ontario to $k = 26$ at Lake Erie. Although there are 8 locks along the canal, operational practice does not permit vessels to be simultaneously raised and lowered on each side of the twinned lock 5. The flight locks 4, 5 and 6 can thus be considered to act like a single lock. Meets are not permitted under bridges, so that bridges behave very much like locks with a short operational cycle and minimum following headway. The canal between bridge 10 and mile 12.6 allows only one-way passage (unless the combined vessel beam is less than 30 m) as does the reach between Ramey's bend and Turning Basin No. 4. This gives 12 facilities to schedule, 6 representing locks and 6 restrictions along the canal.

Vessel transit times are calculated using models developed by ENSTROM, LANDRY and WONG.[7] For the reaches between locks, average transit times in each direction are used. (In using the model, the traffic superintendent can, at will, modify this average for a specific vessel by adjustment of a "reach transit pegging factor" to reflect experience with that vessel.) For locks, it is difficult to forecast precisely the nature of the lock entry and exit. That is, if no vessel is in the lock, an entering vessel proceeds directly into the lock (a "fly" entry). With a vessel in the lock, the entering vessel either continues to move toward the

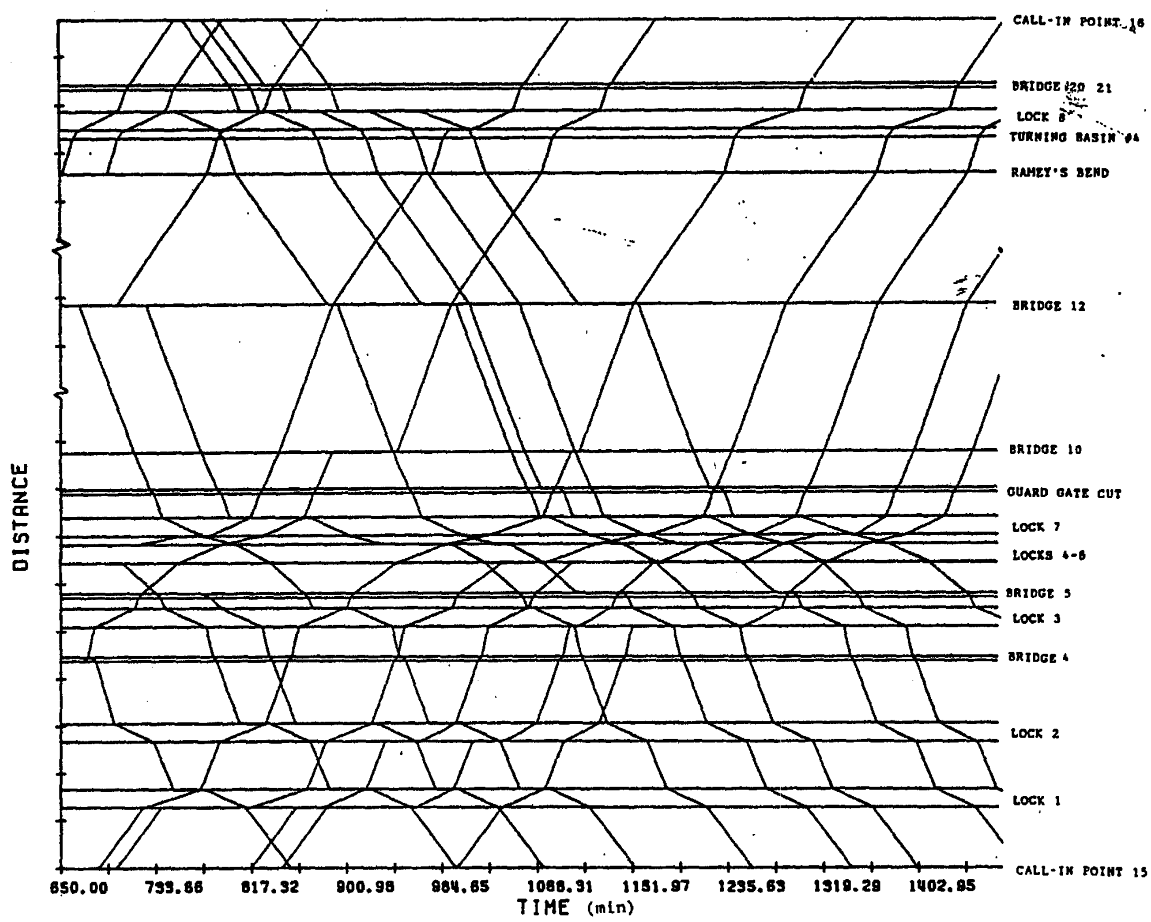

Fig. 6. Time-distance diagram for the Welland Canal.

lock (a "passing" entry), moors briefly before the leaving vessel departs (a "modified passing" entry), or remains moored until the leaving vessel is fully clear (a "moored" entry). Under advice from Seaway personnel, we adopt the following convention for lock entry and exit under normal weather conditions:

(a) Lock 1 upbound: moored entry downbound: modified passing entry
(b) Locks 2 and 3: modified passing entries, both directions
(c) Locks 4 and 8: moored entries both directions.

To compute the lockage times, equations based on vessel cross-sectional area are used. These times may also be adjustable through a "lock pegging factor" by the traffic superintendent to reflect experience with any particular vessel.

Traffic for a typical June day is used to demonstrate the scheduling procedure. Ten vessels are transiting the canal in each direction. Computation of a schedule required 4 seconds on an IBM 4341 computer. Figure 6 shows a typical time-distance diagram for a computed schedule.

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Optimal Pacing of Trains In Freight Railroads: Model Formulation and Solution

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Abstract

Recent developments in location systems technology for railroads provide a train dispatcher with the capability to improve the operations of a rail line by *pacing* trains over his territory; i.e., to permit trains to travel at less than maximum velocity so as to minimize fuel consumption while maintaining a given level of performance. Traditional railroad dispatching models assume that the velocities of the trains moving over a dispatcher's territory are fixed at their maximum value and thus, are incapable of dealing with a pacing situation.

This paper presents a mathematical programming model for the *pacing problem* and describes alternative solution procedures for this model. Both analytical and numerical evidence are presented which confirm the applicability of a heuristic solution procedure for this problem, as well as providing evidence that a pacing approach versus the traditional dispatching approach is an efficient and potentially cost-effective method for the control of train movements.

Key Words. 581–scheduling of rail traffic, 655–heuristic for large-scale, mixed integer convex programs, 835–control of freight railroad traffic.

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1 Introduction

Most of the United States' and the world's rail network consists of single mainline track with passing sidings, although there does exist a fair amount of double track and to a lesser degree, multiple mainline trackage. Over such a railroad which is dominated by non-multiple track lines, dispatchers play a vital role in planning and executing the meeting and passing of trains. Effective meet-pass planning is a critical factor in:

- fuel conservation,
- the mechanical reliability of locomotives, trackage and rolling stock,
- the reliability of the arrival times of trains and hence, of the connection of cars to outbound trains,
- customer satisfaction via the reliability of transit time.

In this paper, we present a model which addresses the problem of fuel conservation while maintaining reliability by satisfying time windows on the departure and arrival times of the trains. The major benefit of this technique is the ability to achieve fuel savings while the system performance is being improved through the "smoothing" the traffic over the lines and through the yards. The model developed herein is the first component of an overall modelling system to define *system-wide* schedules via a method which is similar in spirit to the work by Crainic et al. [7], [8], and then to pace the trains over each dispatchers' territory in accordance with these schedules. It is important to note that the entire model assumes that feasible time windows are chosen, which will require a real-time scheduling system as another component of the overall modelling system [17].

Traditional dispatching practices and models of the meet-pass planning function typically assume that trains will travel at maximum velocity when the dispatcher creates the meet-pass plan. The *pacing problem* takes a different approach to the problem of the meet-pass planning by allowing velocity to be determined endogeneously; that is, the *pacing problem* involves finding the meet-pass plan *and velocity profile for each train* which minimizes some cost measure for the system (e.g., delay, fuel consumption, etc.) while obeying the time windows of departure and arrival for each train. As stated in Eck et al. [9], "...all trains should be operated at the lowest speeds consistent with their required performance levels." Such an operating policy overcomes the *hurry up and wait* philosophy embraced by many dispatchers in which trains are moved over the system as quickly as possible so that they become "someone else's problem". However, one cannot simply run trains at their lowest speeds compatible with the time windows ignoring the meet-pass aspects of the problem since the delays caused by the interactions between the trains would most likely force the schedules to be violated.

The ability to even consider a modelling system such as that described above has been made possible by recent technological advances in railroading. New methods of train tracking and control via satellite or ground-based location and communication systems such as the Advanced Railroad Electronics Systems (ARES) [37] being developed at the Burlington Northern Railroad and Rockwell International provide a wealth of information to train controllers which heretofore has not been available. Given this wealth of data, how can it be used to increase the productivity of the railroad? This paper, through the consideration of the pacing problem and its solution, is the first component of a control system which effectively and efficiently employs the data from ARES-like technology to operate a railroad [17]. In particular, this paper describes an attempt to develop a tool to aid the dispatchers in grappling with the complex relationships and conflicts which are evolving on the rail line, and to suggest possible resolutions of these conflicts.

The model and solution heuristic presented in this paper were tested on 16 lanes of a major railroad and produced average fuel savings of 5%. In addition to the fuel savings is the idea that through the use of time windows, the focus is changed. The dispatcher is no longer trying to get trains across and out of his territory as fast as possible but instead, have the trains meet the time windows and run as efficiently as possible. The time windows need to be decided on a system-wide basis to help smooth traffic across the system. Finally, the pacing concept can increase on-time performance. In the empirical tests on the 16 test lanes, the standard deviation in train arrival times decreased by more than 19%.

The remainder of this paper is structured as follows. In the next section, the literature dealing with computer-assisted train dispatching will be critically reviewed. Section 3.0 presents the mathematical formulation of the pacing model and discusses its relationship to currently proposed pacing systems. Two solution procedures are described in Section 4.0 along with a performance analysis of one proposed heuristic; numerical results on hypothetical and real-world examples are presented in Section 5.0. The paper ends with a summary of the findings of this study along with a list of future research directions.

2 Literature Review

The modelling of train operations has a history almost as old as that of operations research itself; Assad [2] provides a comprehensive review of the literature dealing with the mathematical modeling of rail operations. In the particular case of modelling single-line operations, two general approaches have been employed: Monte-Carlo simulation and mixed-integer or pure integer programming. The simulation models attempt to describe the operations of the rail line via a detailed representation of the line and of the random events which could possibly occur on this portion of track; simulation is an *action-directed* approach as defined in [5]. The main purpose of the simulation approach is to ascertain the likely outcome of a *particular* operating policy on the performance of the rail line. One of the first such models is described by Frank [13], and the paper by Petersen and Taylor [30] provides a general modelling framework for use in simulating rail operations. As stated in the Introduction, the purpose of the pacing model is to define a good operating policy for the dispatcher (to be a *goal-directed model* [5]). In such a situation, pure simulation models are inappropriate since they treat the operating policy as fixed and not as a decision variable; however, these models are essential in the calibration of a goal-directed model.

In terms of previous goal-directed (optimization) models for rail line operations, the early works by Brettman [6] and by White and Westerman [38] are integer programming models which seek an optimal operating policy while treating the velocity of each train as fixed. Kraft [22] presents a simulation-based optimization system for the design of operating policies which is capable of incorporating many real-world concerns, although this approach appears to be inapplicable to real-time scheduling due to its computational complexity. Szpigel [35] also presents an integer programming model for this problem and is the first to recognize in print that the planning of meets and passes on a rail line with velocity treated as fixed is a generalization of some well-known job-shop scheduling problems.

The most successful, published optimization model for the planning of meets and passes is the system developed at the Norfolk-Southern Railroad [34]. The Norfolk-Southern computer-aided dispatching system has been implemented on a portion of the railroad and estimates place its generated annual savings for the company at $3 million. This model is a simple partial enumeration scheme for generating an optimal meet-pass schedule for a single-track rail line and evidence suggests it has been very effective in practice. For a more comprehensive review of the literature dealing with computer-assisted dispatching, the reader is referred to the recent review article by Petersen *et al.* [31].

All of the above simulation and optimization models assume that trains will traverse each track segment at maximum velocity whenever physically possible and thus, no consideration has been given to treating velocity as a decision variable (pacing). With the advent of the type of location systems described in the Introduction, such models must either be extended to include velocity as a variable, or totally new modelling approaches must be generated. One simple extension of the Norfolk-Southern approach is to treat velocity as fixed in order to derive a meet-pass plan (deciding *where* trains will meet), and then find a velocity profile for each train which minimizes some measure of cost (deciding *when* the trains will meet) [14]. While this sequential approach is intuitively appealing and simple to implement, Section 3.3 illustrates the conceptual and practical problems which arise with its use.

Thus, no model exists which can truly be called a *pacing model* in which the pattern of meets and passes (the *where* question) and the velocity profile of each train (the *when* question) are treated simultaneously. In the next section, such a model will be defined.

3 The Pacing Problem

In this section the basic pacing model will be defined. We shall start with the simplest track configuration (single track with passing sidings) which will be generalized in Section 4.2. In Section 3.1 the problem will be defined and its relationship to other dispatching models will be considered in Section 3.2. Finally, Section 3.3 contains an analysis of the pacing model and the sequential approach for this problem which was outlined at the end of Section 2.

3.1 Problem Definition and Formulation

We begin with the case of single track with passing sidings due to the facts that the majority of rail lines are of this type and that these portions of the railroad are where the majority of the difficult dispatching situations arise. However, this assumption will be relaxed in Section 4.2. The following data is assumed to be known by the computer-aided dispatching system:

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- time windows for the departure and arrival of each train which appears on the dispatcher's territory during the planning horizon
- speed limits for each train on each segment of track which comprises the dispatcher's territory
- objective functions for each train which depend on velocity and arrival times; components of this function might include fuel consumption, deviations from the stated arrival window (delay), etc.

(iv)

- priorities of each train in the form of a weight which is assigned to the objective function for that train.

Given this data, the *pacing problem* is to find the velocity profile (speed over each track segment) for each train and the meet-pass plan for the line which *simultaneously* minimizes the weighted sum of the objective functions for all trains. Thus, the pacing problem differs from the sequential methodology described at the end of Section 2 by simultaneously solving for the velocities and the meet-pass plan. The fact that the sequential solution of this problem may lead to a poor operating policy in terms of the objective function is illustrated in Section 3.3.

The basic assumptions which underlie the single-track version of the pacing model are:

A-1 The dispatching territory consists of a single track with passing sidings; double track segments are treated as a single track with a long siding.

A-2 Safety concerns are handled via a fixed safety margin in terms of the minimum permissible time between trains; signal blocks are not explicitly considered. This assumption is not perfectly applicable to the current operating environment on railroads (although it is a reasonable approximation), but it will be applicable when an ARES-like system is implemented throughout a railroad due to the fact that the satellite information will permit the implementation of a safety rule which is based on minimum headways.

A-3 At either end of the dispatching territory, infinite track capacity exists.

A-4 On any segment of track with a siding, at most two trains can be present at any point in time.

A-5 At most one train can occupy any single track segment at any point in time.

The last three assumptions are the most disturbing in terms of their realism. However, assumption A-3 can be removed through a judicious choice of the time windows for each train. For example, the time windows can be defined so that the number of trains which arrive at an endpoint (yard) does not exceed the capacity of that yard. Assumption A-4 can also be relaxed, although the complexity of the mathematical program will greatly increase (this assumption will be dropped in Section 4.2). Furthermore, violations of this assumption can be handled by the careful definition of the track segments which comprise the dispatching territory. Finally, Assumption A-5 can also be handled through the careful definition of the track segments and will be relaxed in Section 4.2.

Given the above assumptions, let us examine the general form of the pacing model; a detailed description of the model is given in Appendix A. Define:

Z $\equiv$ the array of time variables which determines when each train crosses each of the n segments comprising the lane, each row of Z represents one train's times across the lane,

D $\equiv$ a set of logical variables defining which trains enter which sidings,

A, B, C $\equiv$ a set of logical variables defining at which sidings the trains meet and overtake.

The *pacing model* has the following constraints:

$$lb_1 \leq Z^1 \leq ub_1 \tag{1}$$

$$lb_n \leq Z^n \leq ub_n \tag{2}$$

$$\ell(D) \leq E \cdot Z \leq u(D) \tag{3}$$

$$F \cdot Z \geq b(A, B, C) \tag{4}$$

where lb_1, lb_n, ub_1, ub_n represent the lower and upper bounds at the initial (1) and terminal (n) reporting stations.

Therefore, the *pacing model* is defined by the following nonlinear, mixed integer program:

$$\begin{array}{ll} \underset{Z,A,B,C,D}{\text{minimize}} & f(Z) = \sum_{i \in I} \omega_i f_i(Z_i) \\ \text{subject to:} & \\ & \text{Constraints (1)-(4)} \end{array} \tag{5}$$

Constraints (1)-(2) are the departure and arrival time windows. Constraints (3) are the speed limit or travel time constraints for these trains; these limits are a function of D since sidings may have different speed limits than the main track. The final constraints (4) ensure that a feasible meet-pass plan is followed, with the logical variables A,B, and C determining which meet-pass plan is chosen. The complete form and description of these constraints is contained is Appendix A. The only additional assumption which is required for most solution techniques to converge is that $f(Z)$ be a convex function. In Appendix B, a description of one possible objective function involving fuel consumption and a linear term induced by the arrival time is defined which meets the convexity criterion.

3.2 Relationship to Alternative Dispatching Models

The pacing model described above is capable of simultaneously solving for the location and the timing of each meet or overtake over the dispatcher's territory during the stated planning period. Traditional dispatching models such as the Norfolk-Southern computer-aided dispatching system treat velocity as fixed in (5) and simply solve for the integer components which describe where various meets will occur. Thus, the pacing model has in some sense generalized the traditional dispatching models to include velocity as a decision variable.

However, the pacing model is more than a simple generalization of the traditional approach due to the introduction and explicit use of time window constraints. The traditional models typically attempt to minimize the weighted delay of the trains and thus, time window constraints are never specified. The pacing model could also remove these constraints and add them to the objective function, but they are kept in the mathematical program for an important reason. If we consider the fact that we will be solving this problem in real-time for each dispatching territory, it would be very difficult to come up with the cost for a train being late. If the time windows are considered a hard constraint chosen by a real-time scheduling model [17], then each of the dispatching problems can be solved independently.

A simple extension of the traditional dispatching model to include pacing is described at the end of Section 2:

- Assume velocities are fixed and solve (5) for the meet-pass plan (for the variables A, B, C, D). The solution to this step includes the location and time at which each meet or overtake will occur.

- Fixing the location and time of each meet, pace the train which arrives early at each meet point so that it arrives at the meet point just as the train it is to meet also arrives. That is, fix A, B, C, D *and the times* corresponding to the "critical train" (the train which arrives last) at each meet point, and solve the resulting nonlinear programming problem. Since the location and time of each meet is specified, this nonlinear program can be solved by simply reducing the speed of the "slack train" (the train which arrives first) at each meet point; i.e., the nonlinear program is trivial to solve.

While this *sequential algorithm* is simple to implement relative to solving (5) exactly and seems relatively intuitive, the next section illustrates the problems inherent in its usage.

3.3 Benefits of Simultaneity in Meet-Pass Planning

In order to illustrate the possible benefits of solving the pacing model (5) rather than employing the sequential algorithm described in the previous section, consider the simple example with five track segments depicted in Figure 1 and five trains: the first three trains are eastbound and the remainder move westward. The objective function is simply fuel consumption which we simplify to be a quadratic function of velocity with no constant term:

$$\psi_p^i(Z) = [\beta_p^i v_p^i + \gamma_p^i (v_p^i)^2] d_p;$$

Table 3 in Appendix B lists the data for this example.

The first point which arises in the analysis of this example is that with the objective function consisting solely of fuel consumption, *all feasible meet-pass plans with velocity fixed are optimal* due to the fact that the objective is solely a function of velocity. With the velocities set equal to their maximum, the objective function value for this example is equal to 10,840. The sequential algorithm described previously would choose *any* feasible meet-pass plan in this case and thus, the algorithm will not greatly aid the dispatcher in discerning between good and bad meet-pass plans. In reality, some weight on the arrival times will make the objective function vary with the chosen meet-pass plan, but this still does not resolve the problem that fuel consumption is invariant.

To compute the solution obtained by the sequential approach, we chose the meet-pass plan depicted by the solid lines in Figure 2 and paced the trains to achieve an optimal solution of 10,376–a 4% savings from running the trains at maximum velocity. We then solved the complete pacing model (5) by the approach described in Section 4.2 and achieved an optimal solution of 5,947–a 45% savings. As shown by the dashed lines in Figure 2, the complete pacing model is able to choose a slightly better meet-pass pattern (note the difference in the meet between train 1 and 4) and is able to "stretch" the pattern in order to conserve fuel.

Therefore, this small example illustrates two important points. First, one must be careful in employing a simple sequential algorithm such as that described in the previous section since the fuel consumption component of the objective will be invariant with respect to the chosen meet-pass pattern. Second, the simultaneity of the meet-pass problem and the pacing of trains which is embodied in (5) can theoretically yield significant improvements over the sequential approach. These savings are achieved in the pacing model by taking a "global" versus "local" view in determining the meet-pass plan: the pacing model considers more information than the sequential approach when determining the meet-pass pattern. However, the pacing model is significantly more complicated in terms of its solution; the next section describes various approaches for solving the problem in realistic, large-scale situations.

4 Solution Procedures

The pacing model described in the previous section presents a challenge in terms of the development of solution algorithms due to its inherent nonlinearity and enormous number of integer variables. Given the complexity of the model, one must resort to some type of heuristic approach. However, the need for an exact procedure was not completely ignored due to the facts that such a procedure provides a benchmark from which to judge the heuristics and a basis for the development of algorithms for parallel/supercomputing environments.

In what follows, an exact cutting plane-like approach will be presented and in Section 4.2, a method based on a set generation approach is detailed. Due to the complexity of the above two methods, a heuristic is proposed for this nonlinear, mixed integer program and a limited performance analysis is presented in order to provide some insight into its theoretical behavior.

4.1 An Implicit Enumeration Approach

We will discuss the partial enumeration/cutting-plane approach for the pacing model using the formulation given by (5), the correspondence to the full description in Appendix A is direct. The basic idea of the partial enumeration scheme is to first assume that no train interaction occurs and that all trains travel over the mainline track ($A, B, C, D \equiv 0$). Under these assumptions, an initial solution which is feasible with respect to the time window and velocity constraints is obtained by linearizing $f(z)$ about some point z^0 and solving the linear program:

$$\begin{aligned} \text{minimize}_{x,y} \quad & \nabla_z f(z^0)^T x + constant \\ \text{subject to:} \quad & \text{Constraints (1)-(3).} \end{aligned} \tag{6}$$

Since there exist no train interactions, problem (6) decomposes by train into simple linear programs which can be solved with a sorting routine and a trivial linesearch procedure [1]. Thus, the initial solution and lower bound for the optimal value of the pacing model (this is a lower bound since $f(z)$ is convex) is very easy to obtain.

Once (6) is solved, not all meets and overtakes will occur at the sidings or obey the logic encoded into the constraints (3),(4). At this point, one can invoke a branch-and-bound scheme which is similar in spirit to the Norfolk-Southern algorithm [34]. Using the solution from (6), one resolves infeasible meets and overtakes by searching over the finite set of possible points (sidings) at which these meets can be accomplished. This resolution is achieved by iteratively adding the appropriate constraints (cuts) from (3),(4); i.e., by setting the variables (A, B, C, D) in such a way so as to force a meet at a particular siding. Thus, we are not employing a traditional branch-and-bound scheme based on linear programming relaxation due to the enormous size of the resulting linear program but rather, use cutting planes to generate the bounds at each node of the enumeration tree. The linear program which results from the addition of the cuts is:

$$\begin{aligned} \text{minimize}_{x,y} \quad & \nabla_z f(z^0)^T x + constant \\ \text{subject to:} \quad & \text{Constraints (1)-(3)} \\ & \text{A subset of the constraints (3), (4).} \end{aligned} \tag{7}$$

Again, the convexity of $f(x)$ ensures that (7) provides a lower bound for a particular node of the enumeration tree; see [24] for a general discussion of this approach to solving mixed integer mathematical programs.

Obviously, each step of the enumeration tree involves the addition of a set of cuts or constraints to the linear program (6). Thus, the dual simplex method [24], [23] can be used to quickly update and recompute the solution to this linear program when the additional constraints (3), (4) are added.

Once one reaches a node in the enumeration tree which yields a feasible meet-pass plan whose lower bound is less than the current candidate for the optimal solution, the nonlinear program (5) must be solved with fixed values of the integer variables (A, B, C, D) in order to compute the optimal value for this node. This nonlinear program can be solved with a general-purpose nonlinear programming algorithm such as MINOS [27], or by a specialized algorithm such as simplicial decomposition [36], [18], [26]. In particular, the restricted simplicial decomposition algorithm by Hearn *et al.* [18] may prove to be very effective due to the structure of the polyhedral feasible set in (5).

In summary, the implicit enumeration algorithm described above is very similar to the Norfolk-Southern computer-aided dispatching system [34] in terms of its branching logic; however, a linear or nonlinear program must be solved at each node of the enumeration tree for the pacing model due to the fact that velocity is variable rather than fixed at a prespecified value. Given the success of the Norfolk-Southern system, there is some hope that this extension may be computationally feasible; Section 5 will test this hypothesis.

4.2 A Set Generation Approach

As stated above, the implicit enumeration algorithm is appealing in that it is based on well-known mathematical programming theory and, given the Norfolk-Southern experience, is potentially efficient. An alternative approach for solving the pacing model is to generate a list of feasible meet-pass plans (i.e., setting the values of (A, B, C, D)) and then evaluate their optimal values through the solution of the nonlinear program (5). At first glance, this approach seems inferior to the implicit enumeration scheme since a very large number of feasible plans may be generated. However, this method has four major advantages over the implicit enumeration scheme:

1. Much more complex logic in terms of the feasible trains movements can be incorporated into a feasible meet-pass plan generator than can be practically reflected in the constraints of a formal mathematical programming model. Thus, various side-constraints such as dispatcher's work rules, various crew considerations, etc. can be easily incorporated into the set generation logic [19]. Previous experience in the vehicle routing and scheduling area [12], [11] with a set generation approach provides evidence of the potential flexibility and power which this approach can yield in practice.

2. The set generation component of the dispatching system can be tied together with an expert system or heuristic to filter the meet-pass plans. The heuristic or expert system can be used to "weed out" those plans which either violate certain conventions, or are clearly nonoptimal given the dispatcher's expertise.

3. The set generation approach will not provide a single solution but rather, will provide a rank-ordered list of meet-pass plans which the dispatcher can then consider for implementation. The provision of a rank-ordered list is a major factor in having the system accepted and used by the dispatchers in day-to-day operations.

4. This approach readily lends itself to a parallel computer architecture due to the decomposibility of the problem by meet-pass plan.

The major disadvantage of the set generation approach is the potential for high computational times. Theoretically, the implicit enumeration scheme is a special case of the set generation approach since it implicitly considers all feasible meet-pass plans. However, the advantages of the former method over set generation is unclear due to the facts that (a) each must solve a series of nonlinear programs, (b) the set generation logic can be efficiently encoded in integer arithmetic whereas the enumeration scheme must work with slower floating point operations, and (c) the evidence from vehicle routing is that this approach can work well. In Section 5, a numerical comparison of the two approaches will be presented in order to address this issue of computational complexity.

The first step in the set generation algorithm is to generate a list of feasible meet-pass plans. Many different methods can be used for this generation step: artificial intelligence, combinatorial optimization, simulation, etc. The approach taken in this paper is to use the logic encoded in the Schedule Analysis (SCAN) system described in Jovanovic and Harker [19]. As described in [19], the purpose of the SCAN system is to analyze whether or not a given set of schedules is feasible, where feasibility is defined as the ability to find a meet-pass plan which can be used to operate the given schedules. Thus, given a set of schedules (time window constraints), SCAN will generate all feasible meet-pass plans or will conclude that no such plans exist. The inference engine in SCAN which generates these plans is an implicit enumeration scheme very similar to the Norfolk-Southern system in that it treats velocity as fixed at its maximum value in order to generate feasible (not necessarily optimal) plans, and is capable of handling double as well as single track segments, can deal explicitly with the physical capabilities of trains with respect to their maximum attainable velocity through the use of train performance simulations, and can easily incorporate complex dispatching logic and various dispatching rules/policies which cannot be violated in the meet-pass plan. Thus, assumptions A-4 and A-5 can be dropped in the set generation context due to the ability of a SCAN-like algorithms to deal with these situations.

The obvious problem with a SCAN-like set generation approach is that a large number of feasible plans could be generated. The probability of this occurring is a function of the "tightness" or "looseness" of the time window constraints; the more time each train is given in the schedules to traverse a segment of track relative to its minimum travel time, the greater the number of feasible plans. The evidence from the schedules of a major railroad [19] and from Section 5, however, is that the time windows are typically tight and thus, an exponential number of feasible meet-pass plans are unlikely to be generated in practice.

Once the set of meet-pass plans are generated, one must evaluate the optimal velocities for each plan. Thus, one must solve the nonlinear program (5) with the integer variables held fixed. The same algorithms as described in the previous section can be employed for the solution of these nonlinear programs. However, note that in this case, each nonlinear program is independent of the others and thus, they can be solved in parallel. Therefore, the set generation approach is ideally suited for a parallel computing environment. The only linkage between the nonlinear programs will be in the "warm-starting" of the nonlinear programming algorithm with the previous solutions in order to reduce the amount of time necessary to solve each optimization problem.

After the solutions to the nonlinear programs are generated, these solutions are rank-ordered and presented to the dispatcher for selection. Obviously, the dispatcher may not always select the optimal meet-pass plan due to mitigating circumstances. This approach will provide the dispatcher with the capability to scan the top candidates in order to choose the plan to be implemented; this capability to generate such a rank-ordered list is more difficult with the implicit enumeration scheme.

In order to reduce the number of nonlinear programs which need to be solved and thus, the amount of computational effort, various heuristic schemes can be devised which remove meet-pass plans that appear to be nonoptimal; in the next section, one such heuristic is proposed and analyzed.

4.3 A Heuristic Rounding Approach

As discussed above, one needs some heuristic procedures to reduce the computational burden of solving the pacing model (remember, this is a real-time model which must be solved, for example, every fifteen minutes or less). In fact, the heuristic may perform so well in practice that it alone could be used to solve the model. In this section, a "rounding" procedure is defined and a limited performance analysis is presented in order to provide some insight into the potential performance of this procedure.

4.3.1 Definition

Let us assume that one has used a SCAN-like procedure to generate a (potentially large) set of feasible meet-pass plans. Clearly, one does not wish to solve a nonlinear program for each such plan but rather, would like to first filter the plans. A simple rounding procedure may work very well in this context. First, ignore the fact that trains interact with each other over the line and solve for the optimal velocity profile for each train in isolation. That is, solve the following nonlinear programs for each train i (where $D \equiv 0$):

$$\begin{aligned} \underset{x^i}{\text{minimize}} \quad & f_i^e(x^i) \\ \text{subject to:} \quad & \text{Constraints (1), (2), (3).} \end{aligned} \tag{8}$$

The solution of the above nonlinear programs (which are relatively simple to compute given the generalized network structure of their respective constraint sets) provides an optimal "unconstrained" velocity profile for each train. In fact, this solution will provide a lower bound on (5) due to the fact that this solution is the best each train can perform independently. However, when these profiles are plotted on a time-distance (stringline in railroad parlance) diagram such as Figure 2, they may intersect at infeasible points; e.g., they may intersect in the middle of a single track segment, at a siding at which each train cannot physically fit, etc. If no such conflicts exist, then this solution must be optimal since each train was paced optimally. Otherwise, this unconstrained solution will provide the basis for filtering the feasible meet-pass plans. The intuition is that those feasible plans which are closest in some sense to the unconstrained solution have a greater probability of being feasible than those which are further away. Thus, if one "rounded" the unconstrained solution to the closest feasible plan, the resulting solution should be nearly optimal.

After solving the above nonlinear programs for each train, one then locates all the intersections of the train profiles on the time-distance diagram; i.e., all of the points where the trains meet or overtake any other trains. As discussed above, not all of these points will be located at a valid meet-pass location. One then generates a set of feasible meet-pass plans by the type of SCAN-like algorithm described above. Note that one can significantly reduce the amount of computational work (the number of plans generated) by first generating those plans which are closest to the unconstrained solution; i.e., begin the set generation algorithm at the point closest to the unconstrained optimum. This reduction in the plan generation phase can be accomplished by altering the rules used in the branch-and-bound algorithms which are used in this step [20]. Once the plans have been generated, compute the distances of each meet-pass point in a feasible plan to the meet-pass locations in the unconstrained solution. Note that one can use any measure of closeness, but that it is only the physical distance coordinate that matters since the time dimension will be altered through the solution of the nonlinear program (5) after the appropriate cuts arising from the definition of a specific meet-pass plan have been added. Thus, one computes a metric for the "goodness" of a given meet-pass plan by computing the distance of each meet point in the plan with the corresponding point in the unconstrained solution. Once the distance metrics for each feasible meet-pass plan have been generated, the plans can be rank-ordered in ascending order of this metric and the first N plans can be solved to completion by computing the solution to the nonlinear program (5), where N is a prespecified upper limit on the number of nonlinear programs which can be solved in the time available (remember that the pacing model is a *real-time* control model which implies that one must impose an upper limit on the time needed to obtain a good solution). While this heuristic is not perfect, it should be fairly good at "weeding out" the clearly nonoptimal meet-pass plans and may often uncover the optimal plan as having the lowest value of the distance metric; the next section and Section 5 provide, respectively, theoretical and empirical evidence to support this claim.

In order to illustrate the workings of the heuristic procedure, consider the five train example given in Section 3.3 and depicted in Figures 1 and 2. In the first step, we compute the unconstrained solution for each train which yields an objective function value of 4,792 which is 19.4% below the optimal value of 5,947 reported in Section 3.3; Figure 3 depicts this solution. As illustrated in Figure 3, several train pairs do not meet at valid points (train pairs 1-4, 1-2, 2-4, 3-4). Thus, this solution is not feasible. The first attempt one could make to resolve these conflicts is to round the infeasible meet-pass points to the closest point at which they could occur (either the sidings or the ends of this track segment). Thus, we would round the conflict between trains 1 and 4 to the siding between mileposts 70 and 80 along with the conflict between trains 2 and 4, the conflict between trains 3 and 4 to milepost 0, and the conflict between trains 1 and 2 to the siding between mileposts 130 and 140. Consider, however, the situation at the siding between mileposts 130-140 after such rounding. At this point train 1 is scheduled to meet train 5, train 2 is scheduled to meet train 5, and train 2 is scheduled to overtake train 1. Given that the siding capacity allows only two trains to meet or overtake at a time in this example, this situation is infeasible. Thus, the simple rounding procedure will not yield a feasible solution. The problem stems from the fact that the track capacity in this example and the tightness of the schedules will simply not permit train 2 to overtake train 1; there exists no feasible meet-pass plan which permits this overtake to occur. Except for this overtake, the location of the train meets uncovered by the rounding process is identical to the optimal solution represented in Figure 2. By removing the possibility of the overtake from the schedule, the algorithm described above will in fact compute the optimal solution given in Figure 2. Thus, while the rounding procedure may not always find a feasible solution, it should provide a good measure for ranking the set of feasible meet-pass plans. Theoretical evidence is given in the next section which tends to support this claim along with the numerical results of Section 5.

4.3.2 Performance Analysis of the Heuristic

In the working paper version of the current study [21], a detailed analysis of the performance of the rounding heuristic is presented in order to generate some theoretical understanding of how well one can expect this method to work in practice. This analysis assumed (a) no overtaking of trains is permitted, (b) there exist an equal number of eastbound and westbound trains, (c) the departure and arrival times of these trains are uniformly distributed over the planning horizon, (d) the track segment consists of a single track with equally spaced sidings, and (e) the objective is to minimize fuel consumption.

When only one siding is present, the analysis in [21] showed that the rounding heuristic is guaranteed to lead to an optimal solution at least 75% of the time. In the case of multiple sidings, the analysis is more complex. However, this analysis establishes that the heuristic will be optimal more than 50% or the time, with the actual percentage being much higher in special cases. Furthermore, as the number of sidings goes to infinity, the probability that the rounding heuristic is optimal goes to one, thus confirming the intuition that for double track lines (an infinite number of sidings), the rounding heuristic will always be optimal.

This theoretical investigation provides evidence that the intuition underlying the rounding heuristic is sound in the sense that it will most likely lead to an optimal or near optimal solution; the numerical investigations in the next section confirm this finding.

5 Numerical Examples

In order to empirically test the relative efficiency of the algorithms presented in the previous section for the pacing model as well as to ascertain the potential applicability of the pacing model in realistic situations, the results of a series of numerical tests are reported in this section. The next subsection describes the results of running the implicit enumeration and set generation algorithms on a series of hypothetical examples, and Section 5.2 contains the results of applying this model to several portions of a major railroad's operations in order to test the real-world applicability of the model and algorithms.

5.1 Hypothetical Examples

In this section, three hypothetical examples are analyzed in order to compare the implicit enumeration versus set generation algorithms; Appendix C contains a description of the data for these three examples. The examples use the same track configuration and number of trains but differ in the scheduled times for each train. The three cases–tight, medium, loose–reflect the "tightness" of the schedules with respect to the amount of time a train is given to traverse the track segment relative to the minimum time in which it can do so given the physical characteristics of the track and train. Intuitively, the "looser" the schedule, the easier it should be to solve the problem since there exists greater flexibility in the schedule set.

The implicit enumeration algorithm was implemented with the XMP software system [23] for the dual simplex pivoting operations and MINOS 5.0 [27] for the solution of the nonlinear programs. The set generation algorithm employs the SCAN generator described above and MINOS 5.0 for the solution of the nonlinear programs. All work was performed on an Apollo DN3000 workstation, which is approximately 100 times slower than an IBM 3090 using only scalar arithmetic [39].

Note that the essential difference in the two solution approaches lies in the generation of the feasible meet-pass plans. As illustrated in Table 1, the SCAN algorithm generates all of the meet-pass plans in less than one-tenth of the time for the implicit enumeration algorithm to generate the first such plan. Thus, as in the case of vehicle routing and scheduling, the set generation approach appears to be computationally superior to branch-and-bound schemes. Also note that due to the small differences in the ratio of the maximum to minimum objective function values, the implicit enumeration scheme must solve essentially the same number of nonlinear programs as does the set generation method. Thus, the set generation method appears to be very effective relative to the implicit enumeration scheme when one considers that the set generation approach also provides the user with the advantages listed in the previous section.

In order to test the rounding heuristic described at the end of Section 4, the solution of all of the nonlinear programs associated with the meet-pass plans for the tight and medium cases were computed in order to yield a rank-ordered list of the optimal objective values for each plan. The heuristic was then run using the sum of the squares of the differences in the distance dimension in the stringline diagram between the unconstrained and feasible operating policies to rank the meet-pass plans. Table 1 presents the results of calculating the correlation of the values of the sum of squared differences obtained by the heuristic and the optimal values of each plan which were obtained by solving the nonlinear program (5) with the fixed values of the integer variables A, B, C, D. As one can see, the heuristic provides a fairly high correlation with the true ranking. In particular, it appears to be very good at distinguishing the top plans as shown by the last line in Table 1. This result is somewhat striking given the low value of the ratio of the maximum to minimum objective values for these problems; the heuristic appears to be a very promising approach for quickly locating the optimal meet-pass plan, an empirical result which supports the theoretical discussion in the previous section.

Table 1: Results of Hypothetical Examples

	Problem Case		
	Tight	*Medium*	*Loose*
Implicit Enumeration Algorithm			
Time to calculate first meet-pass plan			
(CPU seconds on an Apollo DN3000)	58	71	55
Set Generation Algorithm			
Time to calculate all meet-pass plans			
(CPU seconds on an Apollo DN3000)	6	5	3
Number of plans generated	56	24	270
Average time per nonlinear program			
(CPU seconds on an Apollo DN3000)	.45	.64	.49
Optimal objective function value	1.37	1.23	1.09
Ratio of the max. to min. solution	1.12	1.18	1.28
Heuristic Rounding Procedure			
Correlation between heuristic and			
actual rankings (R^2)	0.865	0.832	not applicable
Rank order from heuristic	1,2,3,6,5,...	1,2,4,5,3,...	not applicable

5.2 Examples from a Major Railroad

In order to provide a further test of the pacing algorithms, a realistically sized and heavily congested section of a major railroad was analyzed. This lane is 102 miles in length and contains 13 passing sidings. For this analysis, 22 trains were used which collectively have 34 meet-pass conflicts. Thus, this example provides a realistic setting for a computer-aided dispatching system.

Table 2 contains a listing of the results. The first observation is that the implicit enumeration algorithm was unable to generate a single feasible meet-pass plan in 360 times the computational effort for generating *all* the meet-pass plans using the SCAN algorithm (note that this example was not solved to completion by the implicit enumeration algorithm due to excessive CPU time). Thus, the implicit enumeration scheme appears to be practically infeasible relative to set generation.

In order to obtain some insight into the performance of the heuristic and the computational feasibility of solving the nonlinear programs resulting from the set generation method, the rounding heuristic was used to rank-order the plans and the top ten plans plus a random sample of the remaining plans were solved to completion. As shown in Table 2, the heuristic does very well at finding a meet-pass plan which is close to the minimum found in the sample of 33. Furthermore, the average time of 6.36 minutes on the Apollo workstation translates into approximately 4 seconds on an IBM 3090 [39]. Thus, this model can be used in near real-time to create a usable and efficient computer-aided dispatching system.

In addition to the above example, several traffic lanes from a major U.S. railroad were analyzed as a part of a study on the benefits which one can expect to achieve from the implementation of computer-aided dispatching. The results of this study suggest that one can expect up to a 5% decrease in fuel consumption *and* up to a 17% decrease in train running times using the pacing model. Translated into dollars using the cost of fuel, the cost of the equipment, and the increased market share due to faster delivery of cars, these results suggest that the pacing model can yield significant improvements in railroad operations.

5.3 Summary of Results

To summarize the numerical experiments, one can conclude:

- the set generation method with the heuristic filtering procedure appears to be the most promising algorithm for the solution of the pacing model. The implicit enumeration algorithm may be improved through the use of more sophisticated logic and solution procedures for the linear/nonlinear programming subproblems, but this research is unlikely to make this approach competitive with set generation. In addition, the set generation approach contains all of the advantages listed in Section 4.2 and thus, appears to be the best way to approach solving the pacing model.

- the CPU time necessary for the computation of a solution to the model, as illustrated in the realistic example, is not excessive. In fact, the solution of the unconstrained problems plus

Table 2: Results of a Real Dispatching Example

Implicit Enumeration Algorithm	
Time to calculate first meet-pass plan	
(CPU minutes on an Apollo DN3000)	≥ 90
Set Generation Algorithm	
Time to calculate all meet-pass plans	
(CPU minutes on an Apollo DN3000)	0.25
Number of plans generated	235
Number of plans solved to completion	33
Average time per nonlinear program	
(CPU minutes on an Apollo DN3000)	6.36
Optimal objective function value	8.053297×10^4
Heuristic Rounding Procedure	
Optimal solution found by heuristic	8.059578×10^4
Percent optimality	99.92201%

the top ten meet-pass plans would take only 70 minutes on the Apollo, which translates into less than 1 minute on an IBM 3090 using only one processor. Given the parallel nature of the set generation approach, multi-processor computing environments would allow one to solve this problem in a fraction of a minute. Therefore, the pacing model can be solved in such a way so as to provide near real-time response to dispatchers.

- the simple rounding heuristic appears to be very effective both theoretically and empirically; future research should be devoted to a further understanding of this heuristic's performance in other real-world situations.

- the benefits from the use of the pacing model seem to be very large in terms of both fuel savings and the reduction in train travel times.

6 Summary and Future Research

This paper has presented a new model of railroad operations which is a direct outgrowth of new technological advances in this industry. Given the ability to locate all trains operating over the railroad, one is provided with a unique opportunity for productivity enhancement through better scheduling of the line operations. Since traditional dispatching models and algorithms were born in an era in which the location and velocity of trains could not be known with a high degree of accuracy, the question of pacing never arose. The model presented in this paper provides a new way of looking at the dispatching of trains. As shown in Section 3.3, this simultaneous consideration of where *and when* trains should meet is important and, as the empirical results of Section 5.0 suggest, this model can be applied to real-world situations. Finally, this model should prove to be useful in helping the dispatchers in large-scale railroads to become "system conscious" in order to achieve Eck *et al.*'s [9] call for dispatchers to become fuel conservers.

Obviously, further research is needed before the pacing model can be put into routine use on a railroad. One needs to develop more efficient algorithms for the solution of this model and, just as important if not more so, one needs to develop the methodology and software to represent the "unquantifiable" constraints which dispatchers face in the scheduling of rail traffic; i.e., future research must be devoted to the development of the necessary filters for the set generation approach. Also, this model must be extended to include an explicit representation of the random events which occur on the rail line. This research is similar in spirit to the stochastic job-shop scheduling field [32], [33] in that "robust" schedules are the goal. In addition, the current pacing model truncates the set of schedules to be considered on the line by simply not considering the trains which will enter the territory outside the stated planning horizon. The "end effects" caused by this truncation must be dealt with formally, although the techniques will have to be different than those used in [16] due to the way in which the pacing model defines its time horizon through a fixed set of schedules. Finally, the pacing model is simply the first step in an overall development effort of a control system for the entire rail network. For example, how are the time windows at the ends of the dispatching territory defined? Ongoing research is being devoted to the development of methods to smooth the production process throughout the rail network by a judicious choice of these windows [17]; the pacing model is the building block in that it smooths this process over a single line.

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A Mathematical Formulation of the Pacing Model

In this appendix, we give the complete description of the mathematical model used throughout this work. The only significant change in notation is that the matrix Z of train variables is separated into a vector x for eastbound train times, and y for westbound times.

Given the assumptions stated in section 3.1, let us define the notation necessary to formulate the pacing model. The territory under consideration is to be decomposed into a set of P homogeneous track segments ($n = |P|$) in which each track segment has essentially the same track configuration (e.g., the same number of tracks, grade, curvature, etc.). Let $P_1 \subseteq P$ denote those segments with single track only, and $P_2 \subseteq P$ as those segments with passing sidings. Thus, $P = P_1 \cup P_2$ and $P_1 \cap P_2 = \emptyset$. On each track segment $p \in P$, let d_p denote the length in miles of the segment. Without loss of generality, we shall assume that the territory is oriented in an east-west fashion.

To describe the trains which move over this territory during the planning period, let I denote the set of eastbound trains and J the set of trains which travel westward. By convention, the trains will be consecutively numbered with the first $|I|$ trains being eastbound and the remaining $|J|$ trains being westbound. For each train $i \in I$ or $j \in J$ let us define:

$\omega_i, \omega_j \equiv$ the scalar priority weight assigned to each train,

$\overline{v}_p^i, \overline{w}_p^j \equiv$ the upper speed limit for each train i, j on segment $p \in P_1$ (m.p.h.),

$\underline{v}_p^i, \underline{w}_p^j \equiv$ the lower speed limit for each train i, j on segment $p \in P_1$ (m.p.h.),

and for each segment $p \in P_2$ which contains a siding

$\overline{v}_{p_m}^i, \overline{w}_{p_m}^j \equiv$ the upper speed limit for each train i, j on segment $p \in P_2$ when the train travels over the mainline track (m.p.h.),

$\overline{v}_{p_s}^i, \overline{w}_{p_s}^j \equiv$ the upper speed limit for each train i, j on segment $p \in P_2$ when the train travels over the siding (m.p.h.),

$\underline{v}_{p_m}^i, \underline{w}_{p_m}^j \equiv$ the lower speed limit for each train i, j on segment $p \in P_2$ when the train travels over the mainline track (m.p.h.),

$\underline{v}_{p_s}^i, \underline{w}_{p_s}^j \equiv$ the lower speed limit for each train i, j on segment $p \in P_2$ when the train travels over the siding (m.p.h.).

Thus, different speed limits are provided for each train and for each type of track segment. Finally, let $p_o \in P$ denote the first track segment on which a train travels and $p_f \in P$ be the last segment in the trip. Since the train leaves the territory at p_f, this segment can be considered as a receiving yard, the next track segment in the train's itinerary, or an industrial or switching siding. Note that this model does not assume that all trains must enter and leave the territory at the same points; individual entrance and departure points are defined for each train. These points for each train are simply defined as the *reporting stations* over which the time windows (schedules) are defined.

Let us now define the decision variables for the pacing model:

$$
\begin{aligned}
x_p^i &\equiv \text{the entry time of eastbound train } i \in I \text{ into track segment } p \in P; \\
&\quad\ \text{i.e., the time that the train arrives at the west end of segment } p \text{ (hrs.)}, \\
x^i &\equiv (\ldots, x_p^i, \ldots)^T, \\
x &\equiv (\ldots, x^i, \ldots)^T, \\
y_p^j &\equiv \text{the time that the westbound train } j \in J \text{ enters track segment } p \in P; \\
&\quad\ \text{i.e., the time that the train arrives at the east end of segment } p \text{ (hrs.)}, \\
y^j &\equiv (\ldots, y_p^j, \ldots)^T, \\
y &\equiv (\ldots, y^j, \ldots)^T.
\end{aligned}
$$

The time windows for train movements can be defined in terms of the times x, y at which the trains depart segments p_o and p_f. Defining

$$
\begin{aligned}
\underline{x}_{p_o}^i, \overline{x}_{p_o}^i &\equiv \text{the earliest and latest departure times for eastbound train } i \in I \text{ (hrs.)}, \\
\underline{x}_{p_f}^i, \overline{x}_{p_f}^i &\equiv \text{the earliest and latest arrival times for eastbound train } i \in I \text{ (hrs.)}, \\
\underline{y}_{p_o}^j, \overline{y}_{p_o}^j &\equiv \text{the earliest and latest departure times for westbound train } j \in J \text{ (hrs.)}, \\
\underline{y}_{p_f}^j, \overline{y}_{p_f}^j &\equiv \text{the earliest and latest arrival times for westbound train } j \in J \text{ (hrs.)},
\end{aligned}
$$

the time window constraints are

$$\underline{x}_{p_o}^i \le x_{p_o}^i \le \overline{x}_{p_o}^i \quad \forall i \in I, \tag{9}$$

$$\underline{x}_{p_f}^i \le x_{p_f}^i \le \overline{x}_{p_f}^i \quad \forall i \in I, \tag{10}$$

$$\underline{y}_{p_o}^j \le y_{p_o}^j \le \overline{y}_{p_o}^j \quad \forall j \in J, \tag{11}$$

$$\underline{y}_{p_f}^j \le y_{p_f}^j \le \overline{y}_{p_f}^j \quad \forall j \in J. \tag{12}$$

Note that crew change rules can be enforced by imposing conditions such as $\overline{x}_{p_f}^i - \underline{x}_{p_o}^i \le H_i$ when defining the time windows; i.e., the maximum time the train may travel with the same crew is limited in the dataset of the mathematical program to some prespecified number of hours H_i.

Since x_p^i is the time train i arrives at segment p and x_{p+1}^i is the time the train arrives at the next segment (which is equivalent to when it leaves segment p), the average velocity v_p^i of train i over segment p is given by

$$v_p^i = \frac{d_p}{x_{p+1}^i - x_p^i}.$$

In a similar fashion, the velocities of the westbound trains w_p^j can be defined as follows:

$$w_p^j = \frac{d_p}{y_p^j - y_{p-1}^j}.$$

The velocity constraints for each train depend on whether or not the particular segment contains a siding. For those segments $p \in P_1$ which do not contain sidings, the following constraints are imposed:

$$\underline{v}_p^i \le v_p^i \le \overline{v}_p^i,$$
$$\underline{w}_p^j \le w_p^j \le \overline{w}_p^j,$$

or substituting the definitions of velocity as a function of travel times as given above:

$$\frac{d_p}{\overline{v}_p^i} \le x_{p+1}^i - x_p^i \le \frac{d_p}{\underline{v}_p^i} \quad \forall i \in I, p \in P_1, \tag{13}$$

$$\frac{d_p}{\overline{w}_p^j} \le y_p^j - y_{p-1}^j \le \frac{d_p}{\underline{w}_p^j} \quad \forall j \in J, p \in P_1. \tag{14}$$

Note that one will typically have $\underline{v}_p^i = \underline{w}_p^j = 0$ and thus, the upper bounds on the times given in (13)-(14) will not exist.

For those track segments which contain sidings, the speed limits depend on whether the train travels over the mainline or over the siding. Obviously, the particular situation depends on one's routing choice for that particular train. Therefore, let us define a zero-one decision variable D_{ip}^e to represent this choice

$$D_{ip}^e = \begin{cases} 1 & \text{if eastbound train } i \in I \text{ enters the siding on segment } p \in P_2, \\ 0 & \text{otherwise,} \end{cases}$$

and $D^e = (\ldots, D_{ip}^e, \ldots)^T$. Defining M to be a large positive scalar, the eastbound speed limits for segments with sidings can be represented as:

$$-MD_{ip}^e + \frac{d_p}{\overline{v}_{pm}^i} \le x_{p+1}^i - x_p^i \le \frac{d_p}{\underline{v}_{pm}^i} + MD_{ip}^e, \quad \forall i \in I, p \in P_2, \tag{15}$$

$$-M(1-D^e_{ip})+\frac{d_p}{\overline{v}^i_{p_s}} \le x^i_{p+1}-x^i_p \le \frac{d_p}{\underline{v}^i_{p_s}}+M(1-D^e_{ip}) \quad \forall i \in I, p \in P_2.$$

The set of constraints for the westbound trains are defined in an analogous manner:

$$D^w_{jp} = \begin{cases} 1 & \text{if westbound train } j \in J \text{ enters the siding on segment } p \in P_2, \\ 0 & \text{otherwise,} \end{cases}$$

with $D^w = (\ldots, D^w_{jp}, \ldots)^T$, and

$$-MD^w_{jp}+\frac{d_p}{\overline{w}^j_{pm}} \le y^j_p - y^j_{p-1} \le \frac{d_p}{\underline{w}^j_{pm}}+MD^w_{jp} \quad \forall j \in J, p \in P_2, \tag{16}$$

$$-M(1-D^w_{jp})+\frac{d_p}{\overline{w}^j_{p_s}} \le y^j_p - y^j_{p-1} \le \frac{d_p}{\underline{w}^j_{p_s}}+M(1-D^w_{jp}) \quad \forall j \in J, p \in P_2.$$

Finally, various conditions such as siding length, the orientation of the switching equipment at the siding, etc. will limit the access of a particular train to a siding. Defining $D \equiv (D^e; D^w)$, the set of constraints on the ability to enter sidings can be represented as:

$$\begin{aligned} \Omega \;= \{D:\; & D \text{ is a vector of zero-one variables,} \\ & D^e_{ip} \equiv 0 \text{ for some } i \in I, p \in P_2, \\ & D^w_{jp} \equiv 0 \text{ for some } j \in J, p \in P_2\}. \end{aligned} \tag{17}$$

Constraints (9)-(17) represent the conditions which each individual train must obey in the pacing problem. The next set of constraints deals with the meeting and overtaking of trains. One must first ensure that two trains do not occupy a track segment $p \in P_1$ at the same time in order to avoid collision. Defining:

$s \;\equiv\;$ a time safety margin which is used to ensure that trains leave sufficient time for other trains to clear a track segment before entering this segment. This safety margin could also be defined by segment s_p and/or train pair $s_{kl}, k, l \in I \cup J$.

$$A_{ijp} = \begin{cases} 1 & \text{if eastbound train } i \in I \text{ traverses segment } p \in P_1 \text{ before westbound train } j \in J, \\ 0 & \text{otherwise,} \end{cases}$$

$$B^e_{k\ell p} = \begin{cases} 1 & \text{if eastbound train } k \in I \text{ traverses segment } p \in P_1 \text{ before eastbound train } \ell \in I, \\ 0 & \text{otherwise,} \end{cases}$$

$$B^w_{k\ell p} = \begin{cases} 1 & \text{if westbound train } k \in J \text{ traverses segment } p \in P_1 \text{ before westbound train } \ell \in J, \\ 0 & \text{otherwise,} \end{cases}$$

$$A = (\ldots, A_{ijp}, \ldots)^T,$$

$$B^e = (\ldots, B^e_{k\ell p}, \ldots)^T,$$

$$B^w = (\ldots, B^w_{k\ell p}, \ldots)^T,$$

$$B = (B^e; B^w)^T,$$

the following conditions ensure that the time between trains is sufficient so as to avoid collisions:

$$s + y^j_{p-1} \leq x^i_p + MA_{ijp} \quad \forall i \in I, j \in J, p \in P_1, \tag{18}$$

$$s + x^i_{p+1} \leq y^j_p + M(1 - A_{ijp}) \quad \forall i \in I, j \in J, p \in P_1, \tag{19}$$

$$s + x^\ell_{p+1} \leq x^k_p + MB^e_{k\ell p} \quad \forall k, \ell \in I, p \in P_1, \tag{20}$$

$$s + x^k_{p+1} \leq x^\ell_p + M(1 - B^e_{k\ell p}) \quad \forall k, \ell \in I, p \in P_1, \tag{21}$$

$$s + y^\ell_{p-1} \leq y^k_p + MB^w_{k\ell p} \quad \forall k, \ell \in J, p \in P_1, \tag{22}$$

$$s + y^k_{p-1} \leq y^\ell_p + M(1 - B^w_{k\ell p}) \quad \forall k, \ell \in J, p \in P_1. \tag{23}$$

Conditions (18)-(19) state that if train i traverses segment p before train j ($A_{ijp} = 1$), then train j must enter segment p after train i has cleared this segment (19). Conversely, $A_{ijp} = 0$ implies that train j must clear the segment of track before train i enters (18). Conditions (20)-(23) rule out the overtaking of trains on segments without sidings. For example, if train k traverses a segment of track before train ℓ, then $B^e_{k\ell p} = 1$ and condition (21) states that train ℓ cannot enter this segment until train k has sufficiently cleared. A similar interpretation can be provided for the other conditions.

The final set of logical conditions for the pacing model deal with those segments $p \in P_2$ on which meeting and overtaking of trains is permitted. Define:

$$C_{k\ell p} = \begin{cases} 1 & \text{if train } k \in I \cup J \text{ completely traverses segment } p \in P_2 \\ & \text{before train } \ell \in I \cup J \text{ enters this segment,} \\ 0 & \text{otherwise,} \end{cases}$$

and $C = (\ldots, C_{k\ell p}, \ldots)^T$. Thus, C is defined for all combinations of eastbound and westbound trains. The first condition to be ensured is that on a segment with a siding, one of four possibilities must exist for any pair of trains $k, \ell \in I \cup J$: either train k completely clears this segment before train ℓ enters ($C_{k\ell p} = 1$), trains ℓ clears the segment before k ($C_{\ell kp} = 1$), train k enters the siding ($D_{kp} = 1$), or train ℓ enters the siding ($D_{\ell p} = 1$). Writing these conditions in a constraint form we have:

$$(1 - C_{k\ell p})(1 - C_{\ell kp})(D_{kp} + D_{\ell p} - 1) = 0 \quad \forall k, \ell \in I \cup J, p \in P_2. \tag{24}$$

Note that Assumption A-5 is used to limit (24) to pairs of trains; if more than two trains are permitted to fit into a siding, then a condition similar to (24) would have to be derived for all three train combinations, four train combinations, etc. Also, this condition is nonlinear. However, the pacing model cannot be solved by traditional branch-and-bound techniques based on linear programming relaxations due to its size and thus, (24) is more a statement of the model logic than an actual constraint in a mathematical program.

The second set of constraints dealing with train interactions at sidings links the logical precedence relationships embodied in C with the travel times:

$$s + x_{p+1}^k \leq x_p^\ell + M(1 - C_{k\ell p}) \quad \forall k, \ell \in I, p \in P_2, \tag{25}$$

$$s + x_{p+1}^\ell \leq x_p^k + M(1 - C_{\ell kp}) \quad \forall k, \ell \in I, p \in P_2, \tag{26}$$

$$s + y_{p-1}^k \leq y_p^\ell + M(1 - C_{k\ell p}) \quad \forall k, \ell \in J, p \in P_2, \tag{27}$$

$$s + y_{p-1}^\ell \leq y_p^k + M(1 - C_{\ell kp}) \quad \forall k, \ell \in J, p \in P_2, \tag{28}$$

$$s + x_{p+1}^k \leq y_p^\ell + M(1 - C_{k\ell p}) \quad \forall k, \ell \in I \cup J, p \in P_2, \tag{29}$$

$$s + y_{p-1}^\ell \leq x_p^k + M(1 - C_{\ell kp}) \quad \forall k, \ell \in I \cup J, p \in P_2. \tag{30}$$

For example, if train $k \in I$ completely traverses the segment $p \in P_2$ before train $\ell \in J$, then $C_{k\ell p} = 1$ in (29) and the time of train ℓ's arrival must be greater than that of train k's departure. Note that it is not the case that $C_{k\ell p} = 0$ implies $C_{\ell kp} = 1$; by condition (24) the other possibility is that neither train completely traverses the segment before the other arrives but rather, one train enters the siding and the other takes the mainline track.

The final constraint needed to fully specify the meet-pass logic simply states that for any segment $p \in P_2$, at most two trains can occupy this segment in accordance with Assumption A-5:

$$C_{k\ell p} + C_{\ell kp} + C_{kmp} + C_{mkp} + C_{\ell mp} + C_{m\ell p} \geq 1 \quad \forall k, \ell, m \in I \cup J, p \in P_2. \tag{31}$$

That is, for any three trains, at least one must fully clear the segment before the other train arrives.

As in condition (17), logical relationships concerning which trains can meet or overtake other trains can be encoded into the following set of constraints:

$$\begin{aligned}\Lambda \;= \{(A,B,C):\;\; & (A,B,C) \text{ is a vector of zero-one variables,} \\ & A_{ijp} \equiv 0 \text{ for some } i \in I, j \in J, p \in P_2, \\ & B^{e}_{k\ell p} \equiv 0 \text{ for some } k, \ell \in I, p \in P_2, \\ & B^{w}_{k\ell p} \equiv 0 \text{ for some } k, \ell \in J, p \in P_2, \\ & C_{k\ell p} \equiv 0 \text{ for some } k, \ell \in I \cup J, p \in P_2\}.\end{aligned} \tag{32}$$

Having defined the constraints (9)-(32) for the pacing model, the final component is the objective function. In general, any convex function $f(x,y)$ of the vector of travel times (x,y) can be employed. However, let us consider a specific example of this function for the purpose of discussion. For each train $i \in I$ or $j \in J$, let $\lambda^e_i \in [0,1]$ and $\lambda^w_j \in [0,1]$ denote, respectively, the relative weight placed on fuel consumption versus delay for an eastbound and westbound train. Let $\psi^i_p(v^i_p)$ and $\psi^j_p(w^j_p)$ be the fuel consumption function for an eastbound or westbound train traveling over segment p which is a function of the velocity over that segment; an example of this function will be provided in the sequel. In general, this function will be nonlinear due to the increased fuel consumption at high velocity. For a particular train $i \in I$ or $j \in J$, the objective function can be represented as:

$$f^e_i(x) = \lambda^e_i[\sum_{p \in P} \psi^i_p(d_p/(x^i_{p+1} - x^i_p))] + (1 - \lambda^e_i)x^i_{p_f}, \tag{33}$$

$$f^w_j(y) = \lambda^w_j[\sum_{p \in P} \psi^j_p(d_p/(y^j_p - y^j_{p-1}))] + (1 - \lambda^w_j)y^j_{p_f}. \tag{34}$$

Using the priority weights for each train which were defined previously, the overall objective function is given by:

$$f(x,y) = \sum_{i \in I} \omega^e_i f^e_i(x) + \sum_{j \in J} \omega^w_j f^w_j(y). \tag{35}$$

Therefore, the *pacing model* is defined by the following nonlinear, mixed integer program:

$$\begin{aligned} \underset{x,y,A,B,C,D}{\text{minimize}} \quad & f(x,y) = \textstyle\sum_{i \in I} \omega^e_i f^e_i(x) + \sum_{j \in J} \omega^w_j f^w_j(y) \\ \text{subject to:} \quad & \\ & \text{Constraints (9)-(32).} \end{aligned} \tag{36}$$

The solution of problem (36) will yield *in a simultaneous manner* an optimal meet-pass plan *and* velocity profile for each train traveling over the specified corridor during the planning period.

The constraint set of (36) is polyhedral in (x, y) and hence, convex. In order to establish that (36) is a convex program in (x, y), one need only establish the convexity of the objective function. The objective function will be convex if each fuel consumption function ψ^i, ψ^j is convex and monotone since $f(x, y)$ is simply a convex combination of these functions and the linear term induced by the arrival time. The following proposition establishes a set of sufficient conditions which ensure that $f(x, y)$ is convex with respect to (x, y):

Proposition A.1 *Let $\psi_p^i(v_p^i), \psi_p^j(w_p^j)$ be convex and monotone functions of v_p^i, w_p^j respectively for all $i \in I, j \in J, p \in P$. Then $f(x, y)$ is a convex function of (x, y) and hence, (36) is a convex program in (x, y).*

Therefore, under reasonable conditions on the fuel consumption functions, problem (36) is a well-defined convex mathematical program in the continuous variables (x, y).

B Fuel Consumption Function

In order to illustrate the complete mathematical description of the pacing model, let us define a possible instance of the fuel consumption function. In practice, fuel consumption is directly related to the amount of work (lb.-ft.) performed in moving the train. In order to find an approximate formula for this work, let us use the well-known Davis formula [25] for the resistance R_p^i (lbs.) facing train $i \in I$ as it traverses segment $p \in P$ at velocity v_p^i (m.p.h.); R_p^j is defined in an analogous manner:

$$R_p^i = \alpha_p^i + \beta_p^i v_p^i + \gamma_p^i (v_p^i)^2 \tag{37}$$

where

$\alpha_p^i \equiv$ resistance due to grade which is constant with respect to velocity

$= a + (G_p + 0.8r_p)W_i$

$a \equiv$ a scalar parameter

$G_p \equiv$ grade of segment $p \in P$ (degrees)

$r_p \equiv$ radius of curvature of segment $p \in P$ (feet)

$W_i \equiv$ weight of train $i \in I$ (lbs.)

$\beta_p^i \equiv$ resistance due primarily to rail friction

$= bW_i$

$b \equiv$ a scalar parameter

$\gamma_p^i \equiv$ resistance due primarily to air friction

$= cA_i$

$c \equiv$ a scalar parameter commonly called the body coefficient

$A_i \equiv$ effective cross-section of train $i \in I$ (sq. ft.).

Typical values of the above coefficients for freight trains are: $a = 1.4W_i + 16n_i$ where n_i is the number of axles on train i, $b = 0.015, cA_i = 0.001$ [25]. If $R_p^i \leq \tau_i$ where τ_i denotes the collective idle resistance of the locomotives on train i, then no excess fuel needs to be consumed in order to achieve the velocity v_p^i; e.g., negative grade resistance is sufficient to overcome the other sources of resistance. Thus, the total work involved in moving train i over segment p is given by

$$\max\{\tau_i, R_p^i\}d_p.$$

Other sources of fuel consumption such as changes in the kinetic energy of the train as it accelerates can also be included. The kinetic energy of the train is defined as one-half the mass of the train times the square of velocity. The positive change in kinetic energy is given by

$$\Delta KE_p^i = \rho W_i \max\{0, [\frac{d_p}{x_{p+1}^i - x_p^i}]^2 - [\frac{d_p}{x_p^i - x_{p-1}^i}]^2\} \quad (38)$$

where ρ is a scalar constant (note that this formulation assumes that dynamic braking or negative changes in kinetic energy consumes no energy). This term, besides being a proxy for the energy consumed in acceleration, will tend to smooth the velocities between adjacent track segments in accordance with the advice given [9].

Thus, one (but not the only) possible formulation of the fuel consumption function ψ_p^i is given by:

$$\begin{aligned} \psi_p^i(x) = \; & \max\{\tau_i, \alpha_p^i + \beta_p^i[\frac{d_p}{x_{p+1}^i - x_p^i}] + \gamma_p^i[\frac{d_p}{x_{p+1}^i - x_p^i}]^2\} d_p \\ & + \rho W_i \max\{0, [\frac{d_p}{x_{p+1}^i - x_p^i}]^2 - [\frac{d_p}{x_p^i - x_{p-1}^i}]^2\}. \end{aligned} \tag{39}$$

Note that this function does not completely satisfy the assumption of Proposition A.1 since it is not continuously differentiable. However, one approximation to (39) which will satisfy these conditions is to simply ignore the $\max\{\cdot\}$ functions; another approximation would involve replacing these functions with $\max\{\cdot\}^{1+\epsilon}$ where $\epsilon > 0$ is a small positive constant. The actual function which should be used to model fuel consumption is a matter for future empirical research.

C Data for Numerical Examples

Table 3: Data for Illustrative Example

$\beta_p^i d_p$ or $\beta_p^i d_p^r$						$\gamma_p^i d_p$ or $\gamma_p^i d_p$					
	Track Segment						Track Segment				
Train	1	2	3	4	5	Train	1	2	3	4	5
1	4.0	3.0	3.0	3.0	2.0	1	0.100	0.020	0.020	0.020	0.010
2	4.0	3.0	3.0	3.0	2.0	2	0.100	0.020	0.020	0.020	0.010
3	3.5	2.8	2.8	2.8	1.8	3	0.100	0.015	0.015	0.015	0.010
4	2.0	3.0	3.0	3.0	3.7	4	0.010	0.020	0.020	0.020	0.080
5	2.0	3.0	3.0	3.0	3.7	5	0.010	0.020	0.020	0.020	0.080

Time Windows (hours)				
Train	Earliest Departure	Latest Departure	Earliest Arrival	Latest Arrival
1	0.0	1.0	3.0	5.0
2	1.0	2.0	4.0	4.5
3	3.0	4.0	6.0	7.0
4	0.0	0.7	3.3	4.0
5	2.0	3.0	5.0	6.0

The hypothetical examples described in Section 5.1 use the same track profile as above. The three cases are defined by the differences in the time window constraints for each train: tight, medium and loose. The track profile consists of five segments with two passing sidings plus the end sidings (yards). The track is assumed to possess no curvature; the other track data is listed in Table 4. Ten trains operate over this track segment and are classified into either a Type I or Type II train depending on their Davis (resistance) formula [25] coefficients:

Type I: Weight= 5000 tons

Davis formula $= 5000 + 4000v + 30v^2$

Type II: Weight = 10,000 tons

Davis formula $= 2000 + 10000v + 25v^2$

The objective function employed in these examples is given by (39) with $r_i = 8000$ for all $i = 1, 2, \ldots, 10$ and $\rho = 0$. Table 5 lists the other necessary data for this example.

Table 4: Track Data for Hypothetical Examples

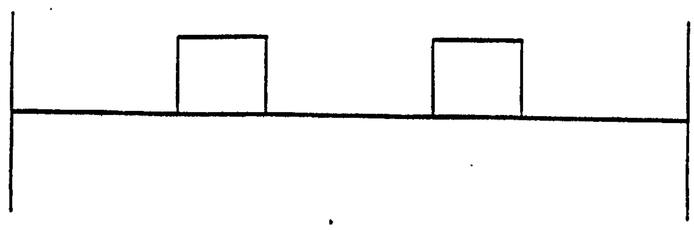
Track Segment p	Grade G_p (%)	Length d_p (mi.)	Max. Velocity $\overline{v}_p$ (m.p.h.)
1	-0.59	8	50
2	+0.53	9	50
3	0.00	12	50
4	+1.18	8	50
5	-1.18	8	50

Table 5: Train Data for Hypothetical Examples

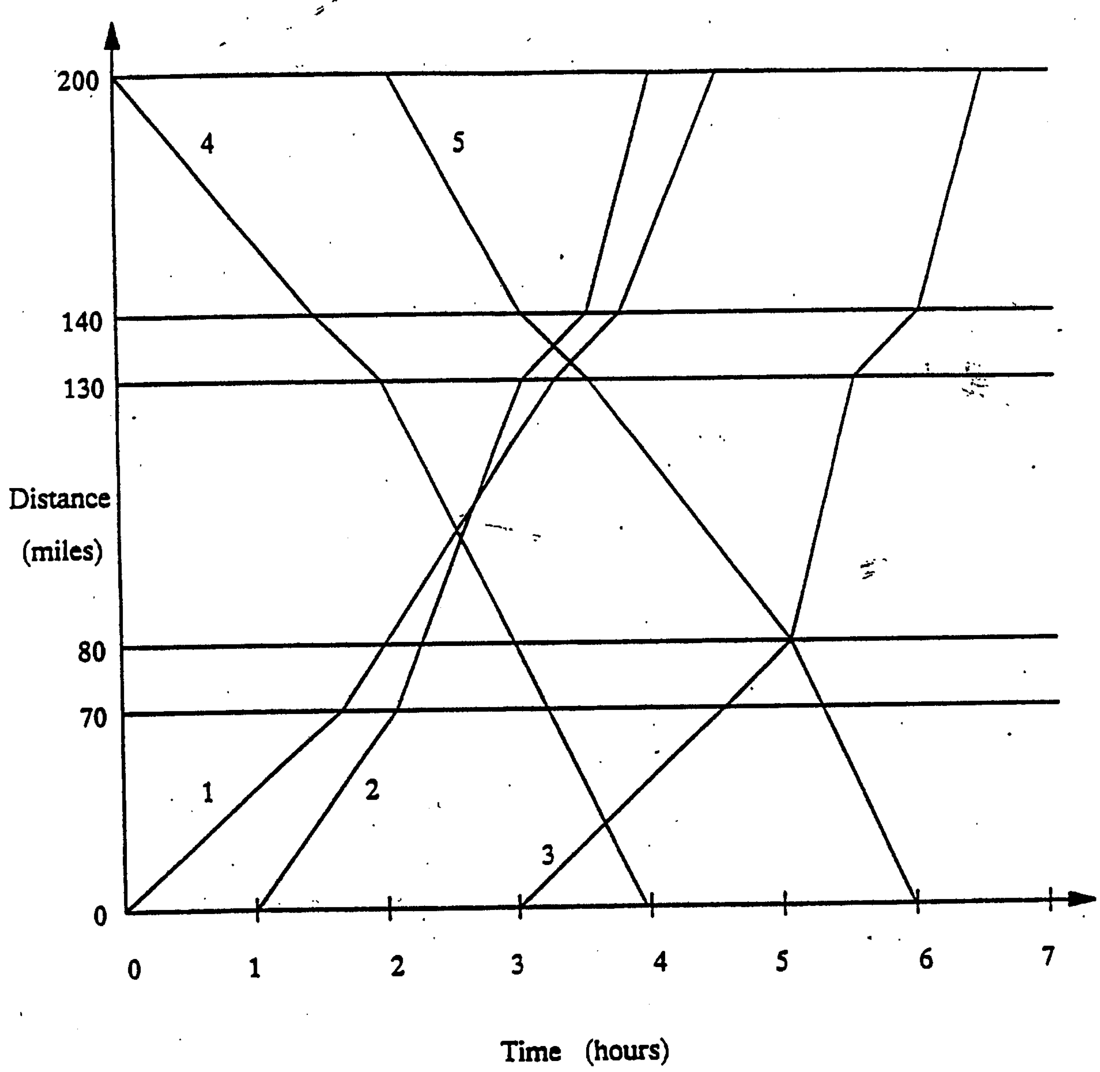
Train No.	Type	Travel Direction	$(x^i_{p_o}, x^i_{p_f})$ or $(y^j_{p_o}, y^j_{p_f})$ Tight Case	Medium Case	Loose Case
1	II	west	1.00, 2.08	1.00, 2.35	1.00, 2.53
2	I	west	1.40, 2.48	1.60, 3.13	1.90, 3.25
3	II	west	3.80, 4.79	5.00, 6.44	5.00, 6.71
4	I	west	4.60, 5.87	6.30, 7.74	6.80, 8.51
5	II	east	1.70, 2.96	2.40, 3.39	2.70, 3.87
6	I	east	2.30, 3.38	3.10, 4.18	3.50, 4.85
7	I	east	2.90, 4.25	3.80, 5.24	4.00, 5.35
8	I	east	3.20, 4.46	4.30, 6.10	4.70, 5.96
9	I	east	4.40, 5.75	5.80, 7.51	6.00, 7.62
10	II	east	5.10, 6.36	7.30, 8.38	7.40, 8.84

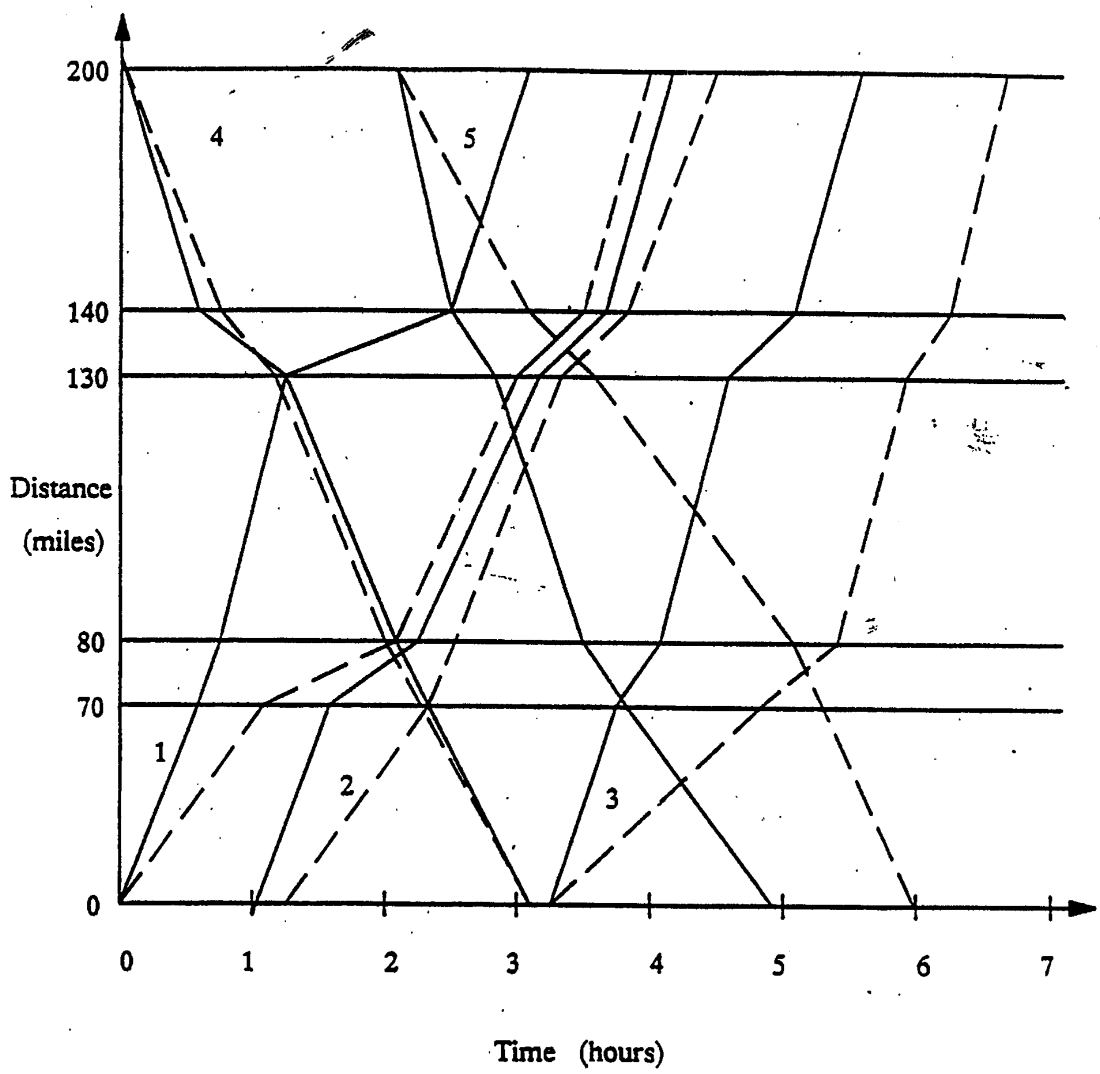
Figure Captions for Kraay, Harker and Chen

- Figure 1: Track Profile for Illustrative Example
- Figure 2: Solutions for Illustrative Example
- Figure 3: Unconstrained Solution for Illustrative Example



Segment no.	1	2	3	4	5
d_p , miles	70	10	50	10	60
$\overline{v}_p$ or $\overline{w}_p$, mph	100	40	80	20	100
$\underline{v}_p$ or $\underline{w}_p$, mph	10	1	10	1	10


200
140
130
Distance
(miles)
80
70
0
4
5
1
2
3
0
1
2
3
4
5
6
7
Time (hours)


200
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(miles)
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0
1
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3
4
5
6
7
Time (hours)

ATCS: On time, on target

The U.S.-Canadian program to develop advanced train control systems, helped mightily by individual railroad efforts, is starting to point the way to more efficient, less costly operations.

By GUS WELTY,
Senior Editor

If the absence of nasty surprises is a reasonable measure of a project's success, then the railroad industry's Advanced Train Control Systems project has thus far been a success.

Much remains to be done, before ATCS is a reality. But much has already been done by the cooperating group at the top level and much is being done by a few individual railroads to prove-out ATCS under real-world operating conditions.

It will be at least a few years before significant numbers of trains are operating under an ATCS system, and it's going to be each railroad's decision as to what level of ATCS would be best. But major test programs are going on, the inevitable glitches are being worked out. Estimated returns from ATCS vary from road to road, but nobody is backing away, including Union Pacific which months ago was estimating that a $100 million investment in ATCS could produce a return of about $60 million annually.

Union Pacific, now considering a system-wide transponder-based system, expects a 60% annual return on a $100-million investment.

• **What comes next.** System specifications are being worked on, and these are some of the developments to look for as the joint U.S.-Canadian team continues its efforts:

—A number of transponders have been under test at the Association of American Railroads' Transportation Test Center at Pueblo, Colo., in an attempt to determine optimum standards for frequency and message protocol. Results of these tests are expected to be available by the end of June and decisions could come by the end of July.

—Major work has been underway to put together control flows for the system. Essentially, this is a detailed description of how ATCS would work and of what should be done where. It's a matter of determining the messages and decisions and logic that would be required, and determining how central and onboard and wayside system components should work together. Project design goes from so-called Level 10 up through Level 40, depending upon the sophistication and complexity of the system desired, and current efforts are looking toward a control-flow determination for Level 30. That should be completed by the end of June. Similar work will then be done for Level 20 and possibly for Level 10, and that assignment should be done by early autumn. These are no small tasks. Control flows identify, in effect, every function that has to be performed. At Level 30, some 60 high-level flows have been identified, and there are possibly even more at a lower level.

—Safety is the first order of business, and system designers are also putting together control-flow arrangements to handle the failure of any system or any component. Their job: To determine how safe operation will be maintained if, for example, an onboard computer fails or if a data radio link fails. This is a vital effort to identify fall-back procedures, in order to preserve safe operation under any conceivable set of circumstances.

—At the same time, system designers are working on rules and procedures that will govern operations under ATCS. This is not really a rewrite of the code of rules that every operating officer and operating employee is, or should be, familiar with. Rather, it's an attempt to write a set of rules and procedures specifically for operations conducted under ATCS.

—The top level of ATCS, Level 40, will get attention after flows are determined for Levels 30, 20 and 10, and that's logical. Level 40 of ATCS involves integration of ATCS with existing ctc, and that can pose problems. Each is a "control" system, and there can be only one. Functionally, system designers say, Level 40 is similar to Level 30 so far as ATCS itself is concerned. But control flows will have to be developed to determine how the systems can be made to work together.

—In the ongoing work on system and component specifications, designers are trying to determine how tight the specs have to be, how detailed they have to be, to insure that there will be reasonable fit, rea-

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Burlington Northern, moving fast with its ARES system, has just started a new series of tests designed to improve the accuracy of satellite positioning of land-based vehicles.

sonable interchangeability.

But, will problems develop as the design work continues?

As one participant in the job puts it, "Probably. As we get deeper into design, no doubt there will be questions raised that haven't been answered, questions that maybe weren't foreseen in high-level studies. That's one reason why pilot projects are going to be valuable—so that we can identify problems before they get built into the system."

• **The key players.** With Burlington Northern going toward a satellite-based control system and with the ATCS project team going toward a ground-based (transponder-interrogator) system, it appears now that the joint project will be relying to a large extent upon tests on Canadian National, CP Rail and Union Pacific.

UP, which had already done extensive ATCS testing on its heavy-traffic North Platte Subdivision, is now into Phase 2 of a new series of tests.

And UP is already seeing positive results from its setting up of the company known as Automated Monitoring and Control International, Inc.

AMCI started with a tiny staff, but it's grown. AMCI started with UP as the sole "partner," but as of late May it seemed sure to be getting minority participants. Participation by another company had cleared its board of directors and awaited only completion of paperwork, while two other potential partners were scheduled to put the proposition before their directors in May. In the meantime, AMCI had won a contract for a pilot ATCS project from another railroad and it held contracts for a couple of non-rail companies for projects in the communications area.

And assuming that all goes well with the new series of operational tests, UP is looking at the potential for applying ATCS to its entire 21,500-mile system within the next five years. It has had, in the venture thus far, cooperation from a number of suppliers, among them GRS, Motorola Communications and Electronics, Pulse Electronics and Tandem Computers.

• **Positioning by satellite.** Meanwhile, BN is moving ahead with satellite-based programs in the Iron Range territory of northern Minnesota.

BN's approach, ARES, for Advanced Railroad Electronics System, is a multi-system proposition involving Rockwell International technology. But one problem with satellite positioning has been that while speed can be closely calculated, exact position of a land-based vehicle cannot be.

Late in May, BN began tests that it expected "to improve the accuracy of the track map that will be the base line that ARES will use to provide speed and position information."

BN was working on this with Sercel, a French electronics company represented in the U.S. by Techtrans, on a set of differential global positioning system (GPS) equipment.

BN explained the new tests this way:

"Since GPS provides train position information in terms of longitude, latitude and altitude, determining the exact location—in those terms—of a given segment of rail trackage is essential to establishment of ARES on that trackage.

"The track map for the Iron Range test of ARES was completed using standard GPS techniques. Those techniques are highly accurate but contain inherent satellite position inconsistencies. Differential GPS is expected to measure and correct for those inconsistencies.

"Differential GPS uses the navigation satellites but in addition it uses a GPS receiver at a fixed-location references station of known position and the position information determined from the satellites is measured to arrive at a correction factor.

"Correcting a moving vehicle's position using this correction factor can result in position accuracy within two feet if data are stored and calculations are made later, and four feet if the correction is done continuously on a realtime basis from the moving vehicle."

The overall ARES test in Iron Range country was to involve about 200 miles of track. The differential GPS test was taking place in a triangle northwest of Duluth and was designed "to match accuracy of the mapping results obtained by differential GPS against those obtained by traditional surveying methods at seven checkpoints to determine whether its accuracy meets the stringent requirements of ARES."

• **What UP's tests showed.** Meanwhile, UP had assessed the operational aspects of its pilot tests on the North Platte Sub. in these terms:

—Use of the location system to monitor train movement. A tracking system was developed and implemented on the Tandem central computer which polled the test locomotives at 60-second intervals. A track display subsystem was continuously updated with the location data, and so the position of the trains was dynamically plotted on a track display screen as the trains operated in normal service within the test corridor.

—Provision of operating instructions to the locomotive engineer. Simulated movement authorities were transmitted in the format of freeform messages over the data radio from the central point to a display onboard the locomotive.

—Generation of a route profile. Yet another subsystem in the central computer contained a data base of route-profile information which, on request, downloaded to the engineer's display unit route-profile data for the next five miles.

—Monitoring of fuel consumption. Here, tests laid the groundwork for realtime monitoring of fuel consumption. A special microprocessor was installed on the locomotive to interface to a prototype electronic fuel gauge, and whenever a location message was sent from the locomotive, fuel-level reading was appended onto it. As a result, UP says, it will be possible to monitor the current fuel level and evaluate fuel consumption under varying operating conditions, such as the pacing of trains, in future phases of ATCS testing.

—Use of a transponder as an "electronic torpedo." This is not something that has been widely heralded as a big factor in ATCS. But it was tested, with the fuel gauge interface microprocessor also used to sense unique coding in special transponders used as torpedoes. When one of these transponders was encountered, the fuel gauge interface micro activated a sound alarm in the locomotive cab. That signal, including the train location, also went to the central computer. The tests worked, but there are a few operational questions remaining to be answered. For example, unlike the conventional exploding torpedo, the electronic one is not destroyed when a train passes over it, and so it will remain active to other trains which pass later.

The next phase of tests on UP is under way, and late this year or early in 1988, data from expanded testing should begin to become available. ■

BACKGROUND

ASSOCIATION OF AMERICAN RAILROADS

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REVOLUTIONS IN RESEARCH

WILL BENEFIT RAILROADS AND SHIPPERS

It has been said that if railroads didn't exist, someone would have to invent them. In fact, the railroad industry today is re-inventing itself.

For more than a century, railroads have served America's transportation needs. They have carried coal for energy, grain for food, ores for metal products and much more.

But, in order to meet the competition of the 1980s, the railroad industry has had to become more efficient, more productive. It has had to take advantage of available technology, develop new concepts, and translate those concepts into practical usages.

These new ideas are part of a revolution in the railroad industry that came about because of competitive pressures.

Railroads have had to re-invent themselves.

The leading element of this revolution is an industry-wide effort to re-invent the very basis of railroad operations -- the freight train itself. It's called the High Productivity Integral Train (HPIT); it's a project that involves individual railroads, railroad suppliers and the Association of American Railroads (AAR).

The HPIT could reduce operating costs by as much as 50 percent in piggyback (trailer or container on flatcar) service, and up to 35 percent in bulk commodity (grain, coal, ore) service. Those

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savings add up to greater efficiency and productivity -- which in turn will translate into a brighter future not only for railroads, but for their customers as well.

Deregulation, mergers and unit train operations that avoid yard and classification delays make it possible to design trains to serve designated markets.

How does the HPIT differ from the trains you see today? From a distance, not greatly. But a closer look reveals that the HPIT is, indeed, a re-invention of the freight train -- something created from the ground up, with old ideas discarded and only the latest technologies and ideas utilized.

Instead of coupling a number of individual cars together, the integral train could consist of articulated car units, permanently joined but flexible enough to bend around curves. A simple computerized control cab could be at the front, with power units spaced along the train's length. Because they would not need to meet all operating environments, load-carrying units could be made of lighter-weight, yet strong, materials.

It was April 1984 when the AAR invited railroad manufacturers and suppliers to use these and other criteria to come up with ideas for integral trains -- and they did. In less than 18 months, the AAR had received ten solid, workable, detailed concepts from nine companies or consortiums. Some of the ideas are already being tested; some prototypes could be ready for testing by late 1986.

High productivity trains, using the latest advances in technology, will not only reduce the cost of transporting goods by rail, they will ensure the railroads' ability to increase their share of the changing freight transportation marketplace.

AAR Research Activity

The Research and Test (R&T) Department of the AAR has, for nearly 30 years, served the railroad industry by probing successfully for better ways to move America's freight. And, as times change along with the needs of the industry, R&T not only keeps up, but keeps ahead, by looking to the future.

In 1985, railroads invested more than $17 million in research conducted by R&T. But the actual value of the research in which R&T participated was more than $40 million, through contract work, complimentary funding and cooperative programs.

The department conducts research in nine program areas with projects and objectives spelled out in a five-year plan: energy research, environmental research, employee safety, track and structures, vehicle and track interaction, productivity, train control techniques, freight equipment management, and freight car and train technology.

Research Facilities

In 1982, the AAR took over management and marketing of the U.S. Department of Transportation's Transportation Test Center (TTC) in Pueblo, Colorado.

The Transportation Test Center houses a 4.8-mile loop of track known as FAST (Facility for Accelerated Service Testing). This FAST track enables researchers to simulate actual operating conditions within a concise area, thereby making research accurate and dependable.

The TTC provides the industry and its suppliers with a unique facility capable of conducting proprietary tests on a contract basis for individual railroads and non-railroad companies, as well as general research that benefits the entire rail industry.

Along with the FAST track, the Test Center includes a measurement and maintenance facility for cars; a roster of cars and locomotives donated by AAR members and suppliers; and a network of systems with which to analyze data.

Also, a new test track and laboratory to train railroad crews and emergency workers in handling hazardous material spills were dedicated at the Test Center in mid-1985.

In Chicago, AAR's Technical Center conducts tests in metallurgy, vehicle dynamics and for mechanical certification. The Technical Center, sitting on four-and-a-half acres on the campus of the Illinois Institute of Technology, houses several laboratories and supporting equipment, and focuses on the engineering aspect of research into components of cars, locomotives and track structures.

The Washington, D.C.-based staff consists of professionals working in such areas as freight car management, engineering, economics, energy, safety and environmental research.

The Affiliated Laboratories Program

The academic community is also involved in railroad research. In 1983, the AAR instituted the Affiliated Laboratories program, which is designed to utilize the research capabilities of three institutions to address important problems and issues in freight railroading.

The institutions involved are: Carnegie-Mellon University in Pittsburgh, the University of Illinois in Urbana, and the Massachusetts Institute of Technology in Cambridge. Also, the AAR has formalized its relationship with the Illinois Institute of Technology by establishing a joint laboratory for railroad research.

While the laboratories work on defined problems of mutual interest, they also draw the attention of the railroad industry to new areas of significance identified by the academic community.

The Princeton Rail Network Model

Railroad freight cars run empty for some nine billion miles annually, resulting in an out-of-pocket cost of $3 billion. Even a small reduction in the percentage of empty car miles can represent big savings for the railroads.

To help the railroads reduce empty car miles, R&T has brought to the Association the Princeton Rail Network Model, a package of computer programs and databases that contains a detailed representation of U.S. and Canadian rail systems.

In 1983, the model was at Princeton University, performing a series of studies funded by the AAR analyzing it's empty car return rules. These rules provide methods of sending cars back to their owners by the most efficient routes. By analyzing the economic impact of empty car miles on railroads, it was learned that the rules save the railroads 15 to 30 million empty car miles annually, compared to conventional car service rules.

The model is being used now to simulate the effect of making those rules even more efficient, or developing alternatives.

The model strings together data from more than 300 North American railroads, in the form of 22,000 terminals or connections points and 20,000 "links" between those points, whose attributes include the individual railroads, railroad owners, and distances down to one-tenth of a mile. All this information, from system maps of each railroad to the boundaries of individual counties, is used to simulate various hypothetical situations.

The model keeps up to date on accidents, traffic patterns, car miles, car days and directional flows. It can print out graphs and pie charts, as well as intricate maps containing any category of information useful to improving railroad operations.

Advanced Train Control Systems

With 1.5 million freight cars being pulled by 24,000 locomotives on nearly 260,000 miles of track, management of train speed, location and routes is essential. Computers have already been introduced in the railroad industry to make movement smoother and safer (railroads are one of the largest private users of computers in the nation), and research has led to better ways of keeping track of trains.

But the Advanced Train Control Systems (ATCS) project, now being created by the AAR, the Railway Association of Canada and individual members of both groups, promises a future traffic management system that will greatly enhance safety and efficiency. It will also enable railroads to cut down on their fuel bills and schedule trains in a way that achieves improved productivity.

The ATCS would differ from contemporary train control systems in a number of ways. Contemporary train control is accomplished through the use of signals, operating rules and written instructions. ATCS would accomplish greater train capacity and efficiency by enforcing train speeds at levels computed as the most desirable from a system standpoint. In other words, if a train is to be at a particular location at 4 p.m., ATCS would utilize computer data on traffic levels, track conditions and speed, to see that the train arrives at or just before the appointed time.

In doing so, wasteful waiting time is eliminated. The train, instead of getting to the location an hour early by traveling 60 miles per hour, would travel at a fuel-saving 40 miles per hour -- and arrive in time to unload without waiting. The results would be not only fuel savings, but labor savings.

ATCS would be generic in nature, but capable of accommodating a variety of configurations of hardware and software, depending on the needs of a certain railroad. In researching ATCS and its possibilities, the AAR and others are emphasizing that industry-wide compatibility is a must.

In other words, ATCS will take the form of a modular system that can be put together much like the components of a home stereo system. The units that make up the system will be standardized for compatibility and flexible enough to accommodate simple as well as complex operating needs.

Architecture of ATCS provides for "plug-compatible" modules to accommodate new technologies that would be more flexible than any previous system in their ability to accommodate increasing traffic.

Computers would keep track of all trains -- enforcing speed limits that assure the most efficient fuel use.

Instead of having a number of trains bunching up at a terminal, or at "meets," where one train must stop to let another pass, ATCS would assure that only a manageable number of trains arrives at a given time -- with others still on their way, at fuel-saving speeds that are calculated to get them to the terminal when the terminal is ready for them.

Such a system would prevent delays, high costs and poor performance that result when some trains are out of their best position from the standpoint of the rail system as a whole.

And, much of the technology needed to create advanced train control systems already exists.

As ATCS General Manager Peter Detmold, special consultant to Canadian Pacific, says, "When you bear in mind that when North American railroads say 'fill 'er up,' the annual bill is more than $3 billion, that possibly another $500 million is spent in repairing worn-out wheels and brakes, you will have no difficulty in understanding why we should like to coast up to our equivalent of 'traffic lights' and try to time it so that they turn green just before we get there -- like any good driver on the highway."

Energy-Saving Research

While ATCS promises to help railroads save fuel in the future, research is being done now that could produce tremendous savings in the cost of operating railroad locomotives.

AAR is leading the railroad industry in studying a number of alternatives to the currently used diesel fuel distillate. By mixing that middle distillate diesel with less expensive non-specification fuels, the cost per gallon can be decreased. It's even possible that the days of the coal-fired steam engine could return -- though in an updated form, of course. Studies are looking into the feasibility of a new coal-burning steam engine -- not like the old engines that sprayed soot and cinders through the locomotive's chimney, but one that would use the latest in technology to meet emissions, efficiency and maintenance standards equal to or higher than today's diesel locomotives.

Still other potential sources of energy are being studied. Fuel cells, for example, produce electricity through chemical reaction, and can use alcohol derived from coal as an energy source. Although they are currently too big and heavy for a locomotive, advancing technology could create fuel cells that are suitable for future locomotive use.

Turbines powered by steam and gas have been used by railroads since the 1930s, with varied degrees of success. In fact, gas turbines are more efficient than diesel engines when operating at full throttle. The problem is, locomotives spend much of their time idling or at partial throttle -- for instance, while unit trains are being loaded -- and, at those times, diesel engines are much more efficient. The R&T Department of AAR estimates that turbines will not be competitive with diesel engines for railroad use through the year 2000.

Railroads are also studying how the shape of railroad cars affects the use of energy. Aerodynamic wind tunnel tests conducted on scale models of railroad cars will help determine the optimum characteristics of future railroad cars.

The tests were done on prototype intermodal cars and container designs, and used to develop mathematical models of aerodynamic drag, which will later be verified by full-scale field tests.

Variables in the tests included whether boxcar doors were closed (efficiency is greater if they are), whether cars were loaded or empty, length and height, crosswinds, and construction characteristics.

Lubrication of railroad tracks -- both curved and straight -- has proved to be another energy-saving technique.

At the TTC in Pueblo, AAR researchers applied, via a specially equipped rail car, grease to portions of the 4.8-mile FAST track. A six-car test train traveling across the lubricated rails consumed 34 percent less power than it had before the same track was lubricated.

Robots on the Railroad?

Well, not exactly on the railroad. But robots are becoming increasingly common in the railroad industry, mostly in repair shops where they can be used to free humans to do less routine, more complicated work.

The Association of American Railroads and the Massachusetts Institute of Technology are studying the effectiveness of robots in overhaul shops. Is it profitable to install a robot? Can the feasibility of a robot performing work previously performed by a human be documented? These are questions that research will answer.

Robots are not only adept at replacing humans at mundane chores, but they are more flexible than machines that sometimes are built to handle a particular task.

A robot, which can be relocated and reprogrammed, can become a painter one day, a welder the next and a sand blaster later in the day.

Researchers say that the next five years could see robots getting smarter, more capable and with more potential applications. But they will not suddenly replace people. Rather, they will gradually take the repetitious, routine jobs and free people to do jobs that require, quite simply, the human touch.

Research continues into how effective robots could be under less than optimum conditions -- such as poor light and bad weather. For fueling trains, conducting inspections and other tasks, robots may well prove themselves to be -- along with the High Productivity Integral Train, Advanced Train Control Systems, and many other projects now being researched -- our window into a productive railroad future.

#

AARb - 022686

BACKGROUND

ASSOCIATION OF AMERICAN RAILROADS

Office of Information
and Public Affairs
50 F Street, N.W., Washington, DC 20001
(202) 639-2550

HIGH TECHNOLOGY RIDES THE RAILS

Today's railroads are running more efficiently than ever before, with the aid of high technology.

Technology is playing a major role in the operation of railroads, from computerized freight yards . . . to more versatile radio and communications systems . . . to advanced systems for controlling train movements. Video display terminals have replaced punch cards and reams of paperwork as a means to record and maintain vital waybill information and issue operating orders. And a new generation of "smart" locomotives is being built, with on-board computers that monitor acceleration and braking systems and can even detect and diagnose mechanical problems.

Here's an update on how railroads are using high technology to improve the safety and efficiency of their operations.

Advanced Train Control Systems

An extremely promising use of high technology currently under development is known as Advanced Train Control Systems (ATCS). ATCS will use electronics, computers and telecommunications to control the flow of traffic across an entire railroad system, resulting in increased operating efficiencies.

The development of ATCS is considered by the rail industry to be essential for improving the safety, productivity and energy

31 December 1985 S/N 7/629417 AQ

efficiency of railroads. Efficiencies produced by ATCS are expected to substantially reduce the cost of operations. In addition, ATCS is estimated to generate a potential market of $2 billion for equipment suppliers.

Operating requirements for the concept were initially developed by a consortium of seven railroads under the sponsorship of the Association of American Railroads (AAR) and the Railway Association of Canada (RAC). Representatives from more than 16 railroads, the AAR and the RAC participate on 11 technical task forces which provide direction to the project.

ATCS will take the form of a modular system that can be put together much like stereo components. The units that make up the system will be standardized for compatibility and flexible enough to accommodate simple as well as complex operating needs. ATCS will enable railroads to:

- Know where trains are, where they are going and how fast; receive warnings when there are work crews on the track;
- Be aware of track conditions and identify hazards such as broken rails, snow or mud slides, or out of line switches;
- Identify locomotives by their numbers; receive information on the condition of a locomotive's health -- how it is operating, whether an on-board component is likely to fail -- and warn when a trackside sensor spots a defect in a train;
- Monitor the status of the rail network, including how switches are set at sidings to handle trains moving in opposite directions;
- Monitor the location and movements of all trains in the system and transmit this information to dispatchers;

- Have a management information system capable of communicating with yard systems, a central data system or other dispatcher territories, to achieve maximum productivity, safety and cost savings.

Much of the technology needed to create advanced train control systems already exists. By early 1986, preliminary specifications will be in place and suppliers will develop prototypes. Testing and evaluation of prototypes will follow.

ATCS Could Use Space-Age Technology

One aspect of ATCS being studied is the possibility of using satellite technology to locate the position of trains along a rail system. These high-tech systems would use locomotive on-board computers linked to satellites to show a train's location within 150 feet. While there is divergent opinion within the industry on their application, some railroads are seriously investigating the feasibility of satellite positioning systems.

In addition to improved dispatching control, the eye-in-the-sky locomotive sensing system would contribute to lower fuel consumption, and -- along with ATCS -- better train handling by engineers, safer and faster service, and improved communication between trains and dispatch centers. Suppliers say the systems could be built to meet operating requirements for Advanced Train Control Systems.

Railroads and Computers -- A Productive Partnership

The freight railroad industry is one of the top private-sector users of computers -- and with recent advances in microcircuitry, the industry is making greater use of computers than ever before.

Computer data processing came into widespread use on railroads during the 1950s, first for payroll processing, then spreading to materials and supply, freight and passenger revenue, and car record information. During the 1960s, railroads expanded their use of computers to include freight claims, loss and damage, marketing development, and stockholder accounting. Significant changes occurred in the 1970s as data processing was combined with data communications to expand computational abilities and keep track of train movements within outlying areas of a railroad's territory. The increased use of computers was perhaps the most profound change experienced by the railroad industry during the 1970s.

Today, computers reach into virtually all aspects of railroad operations -- from yard control and dispatching to information on car movements, inventory control, and electronic waybill exchange.

The increased efficiency and productivity that computers bring to railroad operations is essential for the survival of railroads in the highly competitive transportation marketplace. Computers allow a railroad to track cars and locomotives across its system, aiding equipment utilization. Data is instantaneously available, allowing railroads to respond to market changes and customer needs on an hour-to-hour basis rather than in days -- and sometimes weeks -- as in the past.

The advent of microprocessors has meant further increases in cost and space savings for railroads. Microprocessors perform logic functions, automatically relaying feedback on operating status and making adjustments for component failure. Miniaturization of circuitry has been a boon in areas such as communications and signaling controls. Today, very few electronic developments for railroads do <u>not</u> involve microprocessors. A prediction was made at the American Association of Railroad Superintendents' 13th winter meeting in Kansas City last year that, by the year 2000, microprocessors will be the basis for the control of the entire railroad system.

Following is a brief overview of the varied uses of computers by railroads.

<u>Rail Yard Control</u>

Computer control of freight yards began in 1964 at a hump* yard in East St. Louis, IL, where a computer was used to help sort and classify some 2,500 freight cars a day. Today, most major yards on Class I railroads are under computer control.

In an automated rail yard, computer technology is used to control the speed of the cars as they roll down the hump. Computers also control the switches so cars are routed to the proper classifying track for the makeup of outbound trains. In the event the automatic system malfunctions, manual controls are available.

Information on the makeup -- called the "consist" -- of incoming trains is received by the yard computer. Consist information on outbound trains is generated and sent to the railroad's main computer, which updates car movement records on the system and provides an advance consist to the next yard along the way.

---

*A "hump" in a railroad classifying yard is exactly that -- a small hill where freight cars are uncoupled at the crest and then roll down through switches onto classification tracks.

Railroad officials report improved service and cost savings from computer-controlled freight yards, along with reductions in loss and damage and in the number of cars that need repair. Other advantages are shorter yard times and resulting improved transit times. All this means lower rail costs, which are being translated into lower freight rates.

The "Electronic Horse"

New technology has turned the locomotive into a computerized, rolling data center. Locomotives with on-board computers have been in general use by several railroads since early 1984. They boast radically better performance because the on-board microcomputers control propulsion and braking, as well as regulating the flow of power to maximize fuel efficiency. The locomotives have built-in diagnostics and self-correction features, and can communicate with a railroad's central computers.

Communications and Signaling

Computer technology and microprocessors have greatly improved the efficiency of railroad communications and signaling, speeding operations and allowing large amounts of data to be handled with ease.

Computerized telephone systems are widely used by railroads for both voice and data transmission. Computer technology is also used to ease communications between dispatchers, field workers and train crews. An increasing number of mobile radios are being centrally controlled by a dispatcher with computer assistance. New multichannel radios that utilize microprocessors are replacing traditional crystal-controlled radios. The new radios are less expensive and easier to use.

In many rail yards, the yardmaster or manager has several communications facilities at his command. Computer technology enables him to communicate with field workers or train crew members, whether they use radios, telephones or intercom systems.

Railroads have used computers to aid dispatchers since the mid-1970s, but recent developments in microprocessors have spread to other aspects of signaling, such as track circuits and "interlockings." (An "interlocking" is a series of switches and signals within a local area that is locally controlled.) The AAR's Communications and Signal Division recently polled 21 railroads and found that 11 are using or planning to use computer assistance in their signal operations.

Several railroads have installed "solid-state" or microprocessor-based interlocking systems to replace equipment that used electrically operated relays. The microprocessor control systems for interlockings allow faster operating speeds along with improved space savings and data handling capabilities. They also include self-diagnostics for testing, inspection and maintenance.

While the majority of track circuits -- electrical circuits which use the rails as electrical paths for detecting the presence of trains -- use conventional relays, microprocessor track circuits are now being installed by railroads. The microprocessor systems yield space and maintenance savings.

Centralized Traffic Control

A major development in railroad use of computers occurred in 1966 at the Union Railroad in Pittsburgh, where more than 55 miles of track were handled by a single dispatcher in a Centralized Traffic Control (CTC) system. A CTC system enables one operator at a central location to control track switches and signals over a long territory comprising many miles of railroad.

The first system performed only route control and a minimal amount of data recording. CTC systems today automatically solve conflicts by routing trains according to a predetermined set of priorities. Computers aid the handling of increased traffic densities, automatically "clearing" trains, figuring "meets" and "passes" and executing them, including the movement of switches.

Computer-aided train dispatching is also widely used by railroads, primarily in conjunction with CTC. Some computerized dispatch systems have an automatic field-clearing feature that goes into operation if communications fail for any reason. Trains are allowed to line themselves up on a first-come, first-served basis in complete safety, even if the dispatcher cannot control signals and switches on the line.

CTC increases the capacity of a single-track mainline by up to 60 percent. CTC and computerized dispatching cut down on running times, saving on fuel, equipment requirements and maintenance costs. Nearly 56,000 track miles are now equipped with CTC.

Many railroads are combining former divisional CTC offices into regional control centers. Powerful new microprocessor-based CTC systems allow larger territories to be covered while providing a greater degree of control and safety.

Other Applications of Computers

Large-scale, computer-based maintenance-of-way information systems are commonplace on railroads in the 1980s. Computerized maintenance scheduling is also performed on items such as shop and track machinery and communications equipment. Systems to plan basic maintenance work as well as a majority of production work allow for maximum efficiency in the scheduling and allocation of resources.

Microprocessor technology has been used in end-of-train telemetry units that monitor brake-pipe pressure, train speed and direction, allowing cabooseless trains to be operated safely.

Many railroads use computers for sophisticated control of inventories, with systems for storage, stock levels, demand adjustments and automatic reordering. Through such systems, railroads can gain better control over inventories and monitor productivity of shop forces.

Computer programs can be used for many areas of railroad research. The AAR is using computers for accident investigations, analysis of freight car components, cost-benefit analyses of fuel-saving strategies, the evaluation of competitive rail and truck operations, and to determine the most efficient methods for railroad workers to perform their jobs. Railroads use computer modeling to evaluate car performance, to determine optimum car movement patterns and for the long-range forecasting of business.

RAILINC and TRAIN II

Although each railroad has always had communication facilities with which to track the location of its fleet within its own territory, the fact that cars move from railroad to railroad through interchanges requires a system of national identification.

RAILINC Corporation, a subsidiary of the AAR, performs this function by managing a national computer information and communications network called TRAIN II (TeleRail Automated Information Network), as well as providing data processing and data communications services to the railroad industry, its customers and the AAR staff. Information maintained and transmitted by RAILINC includes railcar location and registration data, car hire and billing information, and economic, financial and traffic statistics.

Use of the TRAIN II system has grown significantly, especially in the area of message switching, a function that allows computers to talk to other computers in fractions of a second. A service known as SAM, or Shipper Assist Message, uses RAILINC's telecommunications network to transmit car location messages from more than 20 major railroads to the shippers they serve. SAM reduces shipper costs by eliminating the need for expensive communication connections with each individual railroad. The RAILINC network can also be used as a two-way system to transmit information from shipper to rail carrier.

RAILINC's network can be used to transmit fleet updates, bills of lading and other information between a shipper and a rail carrier. This same concept is used in the growing area of electronic data interchange (EDI) to perform other business functions such as purchase order and invoice transactions between railroads and their suppliers. EDI facilitates freight transportation by streamlining the processing of information transactions between users, resulting in improved productivity and faster communications.

Electronic transmission of waybills, an application of message switching which began in 1978, has grown rapidly -- nearly 90 percent of waybills originated are currently being transmitted electronically.

TRAIN II keeps track of car movement and interchange data for the railroads and maintains the UMLER (Universal Machine Language Equipment Register) data base, which is the official registry of railroad cars.

RAILINC also acts as a clearinghouse for railroads in the exchange of car repair billing information, car hire data, freight loss and damage payments, and interline settlements.

Future Directions for High Technology in Railroading

Individual railroad research and development departments, in conjunction with the AAR, are currently investigating the use of high technology in areas such as: computer programs to aid railroads in track analysis and maintenance, systems for automatic vehicle identification, and voice recognition systems for train and crew dispatching.

These examples are just a few of the many systems now under development and testing by North American railroads. The opportunities for the future application of high technology to railroading are almost limitless.

#

AARb - 120585

Transaction History Date 1991-05-06
Date information retrieved from USPTO Patent Application Information Retrieval (PAIR) system records at www.uspto.gov

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MAY 6 1991 PAT. & TRADEMARK OFF.

DOCKET NO.: UPN-401 PATENT

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re patent application of:

Patrick T. Harker and Dejan Jovanovic

Serial No.: **629,417** Group No.: **234**

Filed: **December 18, 1990** Examiner:

For: **"A METHOD FOR ANALYZING FEASIBILITY IN A SCHEDULE ANALYSIS DECISION SUPPORT SYSTEM"**

RECEIVED
MAY 09 1991
GROUP 230

Commissioner of Patents & Trademarks
Washington, DC 20231

Sir:

PRELIMINARY AMENDMENT TRANSMITTAL LETTER

Transmitted herewith is a preliminary amendment for the above-identified application.

(X) Small entity status of this application under 37 CFR 1.9 and 1.27 has been established by a verified statement previously submitted.

( ) A verified statement claiming small entity status under 37 CFR 1.9 and 1.27 is enclosed.

( ) Statement to Support Filing and Submission of DNA/Amino Acid Sequences in Accordance with 37 CFR §§ 1.821 through 1.825.

( ) No additional fee is required.

The fee for additional claims presented in this amendment has been calculated as follows:

CLAIMS REMAINING AFTER AMENDMENT		HIGHEST # PREVIOUSLY PAID FOR	PRESENT EXTRA	SMALL ENTITY			OTHER THAN A SMALL ENTITY	
				RATE	ADDIT FEE	OR	RATE	ADDIT FEE
TOTAL CLAIMS	28 -	20 = (at least 20)	10	x10 =	$100	OR	x20 =	$
INDEP. CLAIMS	2 -	3 = (at least 3)	0	x30 =	$0	OR	x60 =	$
FIRST PRESENTATION MULTIPLE DEPENDENT CLAIM				+100=	$	OR	+200 =	$
				TOTAL	$100	OR		$
Total fee for added claims								$100.

( ) Please charge my Deposit Account No. 23-3050 in the amount of $____. This sheet is attached in triplicate.

(X) A check in the amount of $100. is attached. Please charge any deficiency or credit any overpayment to Deposit Account No. 23-3050.

(XX) The Commissioner is hereby authorized to charge payment of the following fees associated with this communication or credit any overpayment to Deposit Account No. 23-3050. This sheet is attached in triplicate.

(XX) Any additional filing fees required under 37 CFR 1.16 including fees for presentation of extra claims.

(XX) Any additional patent application processing fees under 37 CFR 1.17 and under 37 CFR 1.20(d).

(XX) The Commissioner is hereby authorized to charge payment of the following fees during the pendency of this application or credit any overpayment to Deposit Account No. 23-3050. This sheet is attached in triplicate.

(XX) Any patent application processing fees under 37 CFR 1.17 and under 37 CFR 1.20(d).

( ) The issue fee set in 37 CFR 1.18 at or before mailing of the Notice of Allowance, pursuant to 37 CFR 1.311(b).

(XX) Any filing fees under 37 CFR 1.16 including fees for presentation of extra claims.

Date: May 2, 1991

Signature
Steven J. Rocci
Registration No. **30,489**

WOODCOCK WASHBURN KURTZ
MACKIEWICZ & NORRIS
One Liberty Place - 46th Floor
Philadelphia, PA 19103
(215) 568-3100

I, STEVEN J. ROCCI REGISTRATION NO. 30,489 CERTIFY THAT THIS CORRESPONDENCE IS BEING DEPOSITED WITH THE U.S. POSTAL SERVICE AS FIRST CLASS MAIL IN AN ENVELOPE ADDRESSED TO THE COMMISSIONER OF PATENTS AND TRADEMARKS, WASHINGTON, D.C. 20231

ON May 2, 1991

STEVEN J. ROCCI

69 3 1991 PAT. & TRADEMARK OFF.

DOCKET NO.: UPN-401 PATENT

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re patent application of:

Patrick T. Harker and Dejan Jovanovic

Serial No.: **629,417** Group No.: **234**

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RECEIVED

MAY 09 1991

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Washington, DC 20231

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INDEP. CLAIMS	2	-	3 = (at least 3)	0	x30 =	$0	OR	x60 =	$
FIRST PRESENTATION MULTIPLE DEPENDENT CLAIM					+100=	$	OR	+200 =	$
					TOTAL	$100	OR		$
Total fee for added claims									$100.

( ) Please charge my Deposit Account No. 23-3050 in the amount of $____. This sheet is attached in triplicate.

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ON May 2, 1991

STEVEN J. ROCCI

7-103 - Gp 234

PATENT

UPN-401

MAIL ROOM MAY 6 1991 PAT. & TRADEMARK OFF.

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

3/a

In re application of:

Patrick T. Harker
and Dejan Jovanovic

5-22-91
M. Cole

Serial No.: 629,417 Group Art Unit: 234

Filed: December 18, 1990 Examiner:

For: "A Method For Analyzing Feasibility In a Schedule Analysis Decision Support System"

RECEIVED
MAY 09 1991
GROUP 230

Honorable Commissioner of
Patents and Trademarks
Washington, D.C. 20231

Dear Sir:

PRELIMINARY AMENDMENT

Preliminary to examination of the above-referenced patent application, please amend the application as follows:

IN THE SPECIFICATION:

Page 11, line 36, after "cross-overs" insert --these points may interchangeably be referred to as meetpoints or delay points--;

a'

Page 13, line 37, after "is measured in", insert --the--;

Page 14, line 10, after "from", delete "the";

Page 14, line 10, after "from", insert --a--;

070 AA 05/08/91 07629417 1 103 100.00 CK

LA10110 05/21/91 07629417 23-3050 010 103 100.00CH

Page 14, line 30, after "updated", insert --a--;

Page 15, line 5, after "The", delete "search";

Page 15, line 5, after "The", insert --algorithm--;

Page 15, line 5, after "designed", delete "as";

Page 15, line 5, after "designed", insert --to provide a--;

Page 15, lines 5 after "depth-first", insert --search--;

Page 17, line 33, after "at least" delete "at";

Page 18, line 2, after "caused", delete "deadly";

Page 18, line 2, after "caused", insert --delay--;

Page 18, line 3, after "additional", insert --delay--;

Page 18, line 18, after "if", delete "none";

Page 18, line 18, after "if", insert --neither--;

Page 18, line 19, after "to", insert --either--;

Page 19, line 26-27 after "at step 200", delete "In this implementation it simply checks";

Page 19, line 26 after "at step 200" insert --Specifically the algorithm determines--;

Page 19, line 31, after "or", delete "with the lower cost than the best previous one";

Page 19, line 31, after "or" insert --one with a cost lower than any previous solution";

Page 23, delete lines 9 through 37.

Page 24, delete lines 1 through 8;

Page 26, line 15, after "at", delete "it";

Page 26, line 15, after "at", insert --its--;

Page 28, line 10, after "and" delete "beings";

Page 28, line 10, after "and", insert --begins--;

Page 28, line ~~25~~ 26, before "and" delete "reduction";

Page 28, line ~~25~~ 26, before "and" insert --decrease--;

Page 28, line 25, after "minimum" delete "cost increase";

Page 28, line 25, after "minimum" insert --additional cost--;

Page 29, line 17, after "distinct" delete ways--;

Page 29, line 18, after "cost" delete "increase;

Page 29, line 18, before "cost" insert --additional--;

Page 29, line 19, after "minimum" insert --additional--;

Page 29, line 20, delete "increase";

Page 29, line 30, after "arriving" delete "to";

Page 29, line 30, after "arriving" insert --at--;

Page 30, line 8, after "minimum" insert --additional--;

Page 30, line 9, delete "increase";

Page 30, line 10, after "meet" ~~insert~~ delete --o--;

Page 30, line 10, after "meet" insert --to--;

Page 30, line 12, after "cost" delete "increase";

Page 30, line 12, after "The general meet-shift minimum, insert --additional--;

Page 30, line 13, after "cost", delete "increase";

Page 30, line 23, after "minimum" insert --additional--;

Page 30, line 24, delete "increase";

Page 30, line 25, after "minimum" insert --additional--;

Page 30, line 25, after "cost" delete "increase";

Page 30, line 34, after "and" delete "in";

Page 31, line 23, after "minimum" insert --additional--;

Page 31, line 23, after "cost" delete "increase";

Page 31, line 26, after "minimum" insert --additional--;

Page 31, line 26, after "cost" delete "increase";

Page 31, line 36, after "reductions", delete "other";

Page 32, line 23, after "of" delete "maximum";

Page 32, line 24, after "meet-shift" insert --maximum--;

BA 9 July 92 N.F. Page 33, line 11, after "Table" delete "110";

Page 33, line 11, after "from" delete "the";

Page 33, line 19, delete "the";

Page 33, line 25, after "from" delete "the";

Page 33, line 34, after "decrease" delete "if";

Page 33, line 34, after "decrease" insert --is--;

Page 34, line 3, delete "minimum";

Page 34, line 3, after "meet-shift" insert --minimum--;

Page 34, line 3, before "cost" insert --additional--;

Page 34, line 3, after "cost" delete "increase";

Page 34, line 5, after "positive" delete "minimum general meet=shift cost increase";

Page 34, line 5, after "positive" insert --general meet-shift minimum additional cost--;

Page 34, lines 13-14, after "minimum" delete "cost increase";

Page 34, line 13, after "minimum" insert --additional cost--;

Page 34, line 14, after "in" insert --a--;

Page 34, line 16, after "minimum" delete "cost increase";

Page 34, line 16, after "minimum" insert --additional cost--;

Page 34, line 28, after "minimum" delete "cost increase";

Page 34, line 28, after "minimum" insert --additional cost";

Page 34, line 31, after "with" delete "zero";

Page 34, line 31, after "with" delete "minimum general meet-shift cost increases";

Page 34, line 31-32, after "with" insert --general meet-shift minimum additional costs of zero--;

N.E. Page 34, lines 34-35, after "non-zero" insert --general meet-shift minimum additional cost--;

3A July 92

Page 35, line 8, after "desired" delete --from the--;

N.E. Page 35, line 9, after "this" delete "to decreases";

3A July 92

Page 36, line 8, after "branch" delete "it and to";

Page 36, line 8, after "branch" insert --the--;

Page 36, line 23, after "including" insert --the--;

Page 36, line 37, after "level" delete "and";

Page 36, line 37, after "level" insert --otherwise--;

Page 37, line 1, after "step" delete --~~250~~ 350--;

Page 37, line 31, after "that" delete "a";

Page 39, line 6, after "potential" insert --'--;

Page 40, line 6, after "positive" delete ")";

Page 40, line 6, after "positive" insert --(--;

3A July 92 N.E. Page 41, line 12-13, after "potential" delete "trains";

Page 41, line 12-13, after "potential" insert --trains--;

Page 43, line 22, after "potential" delete --train--;

Page 43, line 37, after "to" delete "the";

Page 44, line 24, after "nodes" delete "that";

Page 44, line 24, after "nodes" insert --than--;

Page 45, line 5, delete "band";

Page 45, line 5, before "method" insert --bound--.

IN THE DRAWINGS:

Please authorize the proposed amendment to step 550 of Figure 14D shown in red in the attachment hereto.

In particular, it is proposed to substitute the existing text of step 550 with the following language:

"PLAN_LOWER_BOUND [NO_OF_PLANS] = PLAN_LOWER_BOUND [NO_OF_PLANS] - MERGED COST_DECREASE; IF PLAN_LOWER_BOUND [NO_OF_PLANS]> LOWER_BOUND THEN LOWER_BOUND = PLAN_LOWER_BOUND [NO_OF_PLANS];"

Support for this proposed correction can be found in the specification at page 34, lines 33 through 37 and page 35, lines 1 through 6. It is respectfully submitted that this correction does not add new matter.

IN THE CLAIMS:

Please add new claims 2 through 30 as follows.

--2. The method according to claim 1, further comprising the steps of:

A2 B

(d) inputting into the computer system data indicative of: (v) any changes in the routing networks, (vi) any changes in vehicle travel paths within the routing network and, (vii) vehicle traffic status in the routing network;

(e) generating, based upon the data input in steps (a) and (d), a plurality of feasibility plans for avoiding conflicts between vehicles where at least one vehicle is delayed at a delay point so that a second vehicle may pass by without collision; and

(f) determining which of the plurality of feasibility plans is substantially optimal based upon costs resulting from delaying vehicles according to each conflict resolution.

a2

3. The method of claim 2, further comprising the step of initializing at least one of the following:

(i) a first variable indicative of a number of feasibility plans generated, the first variable defining a plan number;

(ii) a second variable indicative of two vehicles having a potential conflict within a single plan, the second variable defining a level;

(iii) a third variable indicative of a cumulative cost due to vehicle delays within a single feasibility plan, the third variable defining a cumulative delay cost;

(iv) a fourth variable indicative of a maximum cost due to vehicle delays within a single plan, the fourth variable defining an upper bound;

(v) a fifth variable indicative of a minimum cost due to vehicle delays for the input data provided in steps (a) and (d), the fifth variable defining a lower bound; and

(vi) a sixth variable indicative of an acceptable level of optimally based on costs due to vehicle delays, the sixth variable defining a tolerance.

4. The method of claim 3, wherein step (e) comprises the steps of:

(i) ordering the vehicles chronologically;

(ii) incrementing the level to a next level and defining the next level as the current level;

a2

(iii) selecting a vehicle pair having a first and second vehicle based upon the order determined in step (i);

(iv) updating arrival and departure times for each vehicle of the vehicle pair at each delay point along the vehicle route based upon the data input at step (d) and physical constraints of vehicle movement;

(v) identifying any vehicle delay as a result of the update of step (iv) of this claim 4;

(vi) subtracting the updated arrival time at the destination from the scheduled arrival time at the destination resulting in a difference for each vehicle and defining the difference in time as the slack time for the respective vehicles;

(vii) calculating a cost of delay based upon the respective vehicle tardiness functions of the first and second vehicles for all identified delays;

(viii) adding the cost of delay, if any, calculated in step (vii) with any pre-existing cumulative delay cost if any, and

a²

identifying the sum as the cumulative delay cost;

(ix) determining, based upon the updated departure and arrival times at each delay point, if a conflict between the first and second vehicle will occur and if so, identifying at least one delay point where the conflict could be resolved by delaying at least one vehicle at a delay point until the other vehicle passed by without collision, the delay points so identified defining conflict resolution points;

(x) estimating at least one delay time indicative of the time at least one of the vehicles of the vehicle pair would be required to wait at each of the conflict resolution points identified in step (ix) for the vehicles to pass without collision therebetween;

(xi) estimating the delay cost resulting from delays, if any, at each of the conflict resolution points;

(xii) selecting one conflict resolution point based upon one of the following:

a²

(a) which of the conflict resolution points results in less delay cost where the delay will result in additional cost, and

(b) which of the conflict resolution points will result in less vehicle delay where the delay will not produce additional delay cost;

(xiii) calculating at least one delay time at least one of the vehicles would be required to wait at the conflict resolution point selected in step (xii) so that the vehicles of the vehicle pair pass without collision therebetween;

(xiv) updating the vehicle arrival, departure and slack times based upon the vehicle delays calculated in step (xiii) at the selected conflict resolution point;

(xv) calculating the delay costs resulting from delays, if any, at the selected conflict resolution point;

(xvi) adding the delay cost, if any, associated with the conflict resolution point selected to the pre-existing cumulative delay cost and

a

identifying the sum as the cumulative delay cost; and

(xvii) repeating steps (ii) of this claim 4 through (xvi) if the cumulative delay cost is less than the upper bound.

5. The method of claim 4, wherein steps (ii) through (xvi) of claim 4 are not repeated in step (xvii) if all vehicles have previously been selected in step (ii) of claim 4, the method further comprising the steps of:

a²

(xviii) setting the upper bound equal to the cumulative delay cost defining a plan cost;

(xix) defining the arrival and departure times for each vehicle at each point along the vehicle route as the current plan;

(xx) storing the current plan for future reporting and output to a user interface; and

(xxi) incrementing the plan counter.

6. The method of claim 5, further comprising

(xxii) decrementing the current level to arrive at a most previous level and identifying the vehicles in the vehicle pair selected in step (ii) of claim 4 and the conflict resolution points selected at step (xii) along with the vehicles' respective arrival and departure times and redefining the most previous level as the current level;

(xxiii) repeating steps (xiii) through (xxii) for at least one conflict resolution point not previously selected in step (xii);

(xxiv) repeating steps (xxii) and (xxiii) if at least one of the following conditions exists:

(a) no conflict resolution points at the current level ~~remain~~ to be selected which were identified in step (ix)

(b) no conflict exists between the vehicles at the current level; and

(c) the cumulative delay cost resulting from delays at the other conflict resolution points is greater than the upper bound.

a

7. The method of claim 6, wherein steps (xxii) through (xxiv) are not repeated if at least one of the following conditions exists;

(a) at least one feasibility plan has been found and a time limit to find a substantially optimal plan has expired;

(b) the current level is equal to zero; and

(c) a difference between the upper bound and the lower bound is not greater than the tolerance.

8. The method of claim 4, wherein the vehicle delayed in step (xiii), if any, is the vehicle arriving at the conflict resolution point first in time, the delayed vehicle defining a first vehicle and the other vehicle in the pair defining a second vehicle.

a^v

9. The method of claim 6, further comprising the steps of:

(xxv) setting a seventh variable indicative of the last vehicle pair selected within a plan equal to the current level and defining the seventh variable as a bottom level;

(xxvi) initializing an eighth variable indicative of levels where selection of an alternate conflict resolution point in step (xii) could produce a plan with a lower plan cost than the upper bound and defining the eighth variable as the potential level set;

(xxvii) selecting at least one conflict resolution point identified in step (ix) at the current level by determining which conflict resolution point is both physically located closest to the conflict resolution point selected in step (xii) and closest to the location of potential conflict, the conflict resolution point defining a meet-shift resolution point.

(xxviii) calculating at least one delay time indicative of the time at least one vehicle is required to wait at the meet-shift resolution point for the other vehicle of the vehicle pair to pass without collision therebetween, thereby reducing the delay time calculated in step (xiii);

(xxix) identifying substantially all delay reductions arising from delaying at least one vehicle at the meet-shift resolution point and thereby reducing the delay cost calculated in step (xv);

(xxx) summing substantially all potential cost reductions of the current plan which are both later in time than the meet-shift resolution point and physically located in the direction of movement of the delayed vehicle, the summed cost reductions defining a meet-shift maximum cost decrease;

(xxxi) calculating the delay cost of the delayed vehicle at the meet-shift resolution point and redefining the delay cost as a meet-shift minimum additional cost;

(xxxii) subtracting the meet-shift minimum additional cost from the meet-shift maximum cost decrease resulting in a difference, the difference defining a meet-shift maximum net benefit;

(xxxiii) adding a level to the potential level set if the meet-shift maximum net benefit calculated for the level is greater than zero;

(xxxiv) repeating steps (xxvii) through (xxxiii) for each level of the current plan;

(xxxv) repeating steps (xiii) through (xxi) based on the meet-shift resolution point selected

a²

in step (xxvii) for each level in the potential level set;

10. The method of claim 9 further comprising the step of:

(xxxvi) repeating steps (xxii) through (xxxv) each time the current level is less than or equal to the bottom level.

11. The method of claim 4, wherein the cumulative delay cost is set equal to the upper bound if no feasible conflict resolution point is identified in step (ix) and steps (ii) through (ix) of claim 4 are repeated.

12. The method of claim 11, further comprising the steps of:

(xxxvii) setting an eighth variable indicative of the current plan equal to the number of feasibility plans plus one and defining the eighth variable as the last plan;

(xxxviii) setting a ninth variable indicative of a new portion of the current plan equal to the number of plans and defining the ninth variable as the branching plan number;

13. The method of claim 12, further comprising the step of initializing at least one of the following;

(a) the bottom level equal to the current level;

(b) a tenth variable indicative of a minimum plan cost set equal to zero, the tenth variable defining a plan lower bound;

(c) the potential level set equal to empty, and;

(d) an eleventh variable indicative of vehicles benefitted by reduced delays resulting from the selection of alternate conflict resolution points in step (xii) set to empty, the eleventh variable defining a potential vehicle set.

14. The method of claim 13, further comprising the steps of;

(xl) repeating steps (xxvii) through (xxxii) for each level of the current plan;

(xli) identifying substantially all vehicles whose delays could be reduced with respect to the current plan by delaying at least one at the meet-shift resolution point, the vehicles so identified defining benefitted vehicles;

a

(xlii) determining a reduced delay time compared to the delay time calculated in step (xxvii) which would result if the vehicles delayed at the meet-shift resolution point incurred no ~~previous delay.~~

(xliii) identifying substantially all further cost reductions of the current plan arising from the reduced delay determined in step (xlii);

(xliv) summing substantially all the additional cost reductions of the current plan arising from delays at conflict resolution points which are both later in time than the meet-shift resolution point and physically located in the direction of movement of the delayed vehicle, the summed delay costs defining a general-meet-shift maximum cost decrease;

(xlv) calculating, based on the reduced delay time determined in step (xlii), the resulting delay cost, and identifying that amount as the general-meet-shift minimum additional cost;

(xlvi) subtracting the general-meet-shift minimum additional cost from the general-meet-shift maximum cost decrease resulting in a difference, the difference defining a general-meet-shift maximum net benefit; and

(xlvii) repeating steps (xli) through (xlvi) for each level within the current plan.

15. The method of claim 14, wherein steps (xl) through (xlvii) are not repeated if at least one of the following conditions exists;

(a) at least one feasibility plan has been found and a time limit to find a substantially optimal plan has expired;

(b) the current level is equal to zero; and

(c) a difference between the upper bound and the lower bound is not greater than the tolerance.

16. The method of claim 14, further comprising the following steps provided the general-meet-shift maximum net benefit is greater than zero:

(xlviii) subtracting the general-meet-shift maximum net benefit from the plan lower bound resulting in a difference and defining the difference as the plan lower bound if the general-meet-shift minimum additional cost is ~~positive;~~

(xlix) merging the delays associated with the benefitted vehicles identified in step (xli), if the general-meet-shift minimum additional cost is non-positive, by computing the absolute delay time attributed to the benefitted vehicles within the current plan based upon the reduced delay resulting from delaying at least one vehicle at the meet-shift resolution point.

(l) adding a level to the potential level set if the meet-shift maximum net benefit calculated for the level is greater than zero;

(li) calculating a cost of the merged delays, based on the vehicles's tardiness functions, and defining the cost as the merged cost ~~decrease~~;

(lii) setting the lower bound equal to the plan lower bound if the plan lower bound is greater than the lower bound;

(liii) subtracting the merged cost decrease from the plan lower bound resulting in a difference, the difference redefining the ~~plan lower bound;~~

(liv) repeating steps (xiii) through (xxi) based on the meet-shift resolution point selected in step (xxvii) for each level in the potential level set;

(lv) repeating steps (xl) through (liv) if the plan cost is less than the upper bound;

(lvi) setting a variable indicative of the last branch from the current plan equal to zero if the current level is the bottom level; and

(lvii) setting the branching plan number equal to the last plan if the current level is the bottom level.

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17. The method of claim 16, wherein the following data is initialized if the cumulative delay cost calculated in step (xvi) is not less than the upper bound:

(a) setting the branching plan number to zero;

(b) setting a twelfth variable indicative of a reduced cumulative delay cost resulting from merging the vehicles' delays to (lx) adding the merged maximum net benefit and the general-meet-shift maximum net benefit if the general-meet-shift maximum net benefit is positive and the general-meet-shift minimum additional cost is positive, the sum defining the merged maximum net benefit;

(lxi) merging the delays associated with the benefitted vehicles identified in step (xli) by computing the absolute delay time of the benefitted vehicles in the path, if any, based upon the reduced delay resulting from delaying at least one vehicle at a meet-shift resolution point if the general-meet-shift maximum net benefit is positive and the general-meet-shift minimum additional cost is non-positive;

(lxii) calculating the merged cost decrease;

(lxiii) adding the merged cost decrease to the merged maximum net benefit and defining the sum as the merged maximum net benefit.

20. The method of claim 19, further comprising the step of:

zero, the twelfth variable defining a merged maximum net benefit;

(c) setting the plan cost equal to the cumulative delay cost; and

(d) setting a thirteenth variable to empty and defining the third variable as a potential vehicle set;

18. The method of claim 17, further comprising the step of:

(lviii) adding vehicles in the vehicle pair of the current level, to the potential vehicle set, if the general meet-shift maximum net benefit at said level is positive and the meet-shift maximum net benefits at levels below the current level are negative.

19. The method of claim 18, further comprising the steps of:

(lvix) repeating steps (xl) through (xlvi) if the current level is not the last branch from the current plan level and the branching plan equals zero;

(lxix) making a positive determination if at least one of the following conditions exists:

(a) at least one conflict resolution point identified in step (ix) has not been selected and the difference between the plan cost and the merged maximum net benefit is less than the upper bound;

(b) at least one vehicle in the potential vehicle set is a benefitted vehicle, and,

(c) the meet-shift maximum net benefit is positive.

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21. The method of claim 20, further comprising the following steps if a positive determination is made in step (lxix);

(lxx) decrementing the current level to arrive at a most previous level and identifying the vehicles in the vehicle pair selected in step (ii) of claim 4 and the conflict resolution points selected in one of steps (xii) and (xxvii) along with the vehicles' respective arrival and departure times and redefining the most previous level as the current level;

(lxxi) setting the last branch from plan level equal to the current level if the branching plan is not equal to zero, and

(lxxii) repeating steps (xii) through (lxix).

22. The method of claim 20, further comprising the following steps if a positive determination is not made in step (lxix):

(lxxiii) retracing to the previous level by decrementing the current level and identifying the vehicles in the vehicle pair selected in step (ii) of claim 4 at the level, the conflict resolution points selected in one of steps (xii) and (xxvii) and the vehicles' respective arrival, departure and slack times, and redefining the most previous level as the current level;

a^2

(lxxiv) repeating steps (lvix) through (lxix) if none of the following conditions exist.

(a) at least one feasible plan has been found and a time limit to find a substantially optimal plan has expired;

(b) the current level is equal to zero; and

(c) a difference between the upper bound and the lower bound is not greater than the ~~tolerance.~~

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23. In a transportation system having a plurality of vehicles, each vehicle having a scheduled departure time from an origin and a scheduled arrival time at a destination, there being a routing network defined by travel paths between the origin and destination, and delay points along each path for permitting one vehicle to wait until a second vehicle passes so as to avoid collision, a method comprising the steps of:

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(a) inputting into a computer system at least one of the following data indicative of:

(i) a description of the routing network;

(ii) speed and mobility characteristics of each vehicle;

(iii) proposed transportation schedules for each vehicle specifying at least scheduled departure and arrival times;

(iv) a vehicle tardiness function for each vehicle indicative of an importance of each vehicle arriving at its destination on time;

(v) any changes in the routing networks,

(vi) any changes in a physical characteristic of any path in the routing network; and,

(vii) vehicle status in the routing network;

(b) initializing at least one of:

(i) a first variable indicative of a maximum cost due to vehicle delays for the proposed transportation schedules input in step (a), the first variable defining an upper bound;

(ii) a second variable indicative of the minimum cost due to vehicle delays for the proposed transportation schedules input in step (a), the second variable defining a lower bound.

(c) grouping the vehicles into vehicle pairs having a first and second vehicle comprising substantially all possible combinations;

(d) determining, based upon the data input in (a), whether a potential conflict exists between the two vehicles of each vehicle pair, and if so, identifying the vehicle pair as a level,

(e) identifying substantially all delay points at a first level where at least one vehicle in

a^2

the vehicle pair could be delayed so that the second vehicle in the pair could pass without collision therebetween, defining the delay points so identified as conflict resolution ~~points.~~

(f) selecting one conflict resolution point identified in step (e) for the first level;

(g) determining an amount of time at least one vehicle in the vehicle pair must be delayed at the selected conflict resolution point so that the vehicles can pass by without collision therebetween, the amount of time a vehicle is delayed defining a delay time;

(h) updating the vehicles' scheduled departure and arrival times based upon the delay times determined in step (g);

(i) repeating steps (e) through (i) for each level identified in step (d);

(j) calculating a delay cost, based upon each delay time determined in step (g) and the respective vehicle tardiness functions input in step (a), for each vehicle delayed in step ~~(g).~~

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(k) calculating a cumulative delay cost by adding together the delay costs calculated in step (j), and defining the cumulative delay cost as the plan cost when the delay costs for substantially all levels have been added ~~together;~~

(l) defining the arrival and departure times for each vehicle at each point along the vehicle's travel path between the origin and destination as the current plan if the plan cost is less than the upper bound, and setting the upper bound equal to the plan ~~cost;~~

(m) selecting an alternative conflict resolution point from the conflict resolution points identified in step (e) but not selected in step (f);

(n) identifying substantially all vehicles whose delays determined in step (g) could be reduced by shifting the selected conflict resolution point to the alternate conflict resolution point selected in step (m), the vehicles so identified defining benefitted ~~vehicles;~~

(o) estimating based on the alternative conflict resolution point, an amount indicative of a potential net cost reduction by computing a difference in potential delay reductions at other levels and any delay increases, where the delay reductions and delay increases result from shifting to the alternate conflict resolution point in step (m), the difference computed defining a first maximum ~~net benefit;~~

a2

(p) repeating step (o), wherein the computation is based on the vehicles arriving at the alternate conflict resolution point on time with respect to their scheduled arrival times, the difference so computed defining a second maximum net benefit;

(q) estimating, based on the alternative conflict resolution point, any cost reduction to the plan cost by merging delays of vehicles which are delayed at different levels over at least partially the same time interval thereby determining each vehicle's actual delay time, the estimated cost reduction defining a merged cost decrease

(r) redefining the lower bound by subtracting at least one of:

(i) the second maximum net benefit; and

(ii) the merged cost decrease

(s) defining the set of conflict resolution points selected in step (f) and (m), the vehicles delayed in step (g) and their respective delay times, and the cumulative delay cost as a fathomed path if any cumulative delay cost is greater than the upper bound, and redefining the cumulative delay cost of said path as the upper bound;

(t) identifying vehicle pairs at levels having both a positive second maximum net benefit and negative first maximum net benefit, and defining the vehicles of said vehicle pairs so identified as potential vehicles;

(u) repeating steps (h) through (l) based on the alternate conflict resolution point selected in step (m) when at least one of the following occurs:

(i) the level for which the alternate conflict resolution point has been selected has a positive first maximum net benefit; and

(ii) at least one benefitted vehicle is a potential vehicle for the level and second maximum net benefits at previous levels are ~~negative.~~

(v) repeat step (u) until one of the following events:

(i) no alternative conflict resolution points are available to be selected in one of steps ~~(f) and (m);~~

(ii) the plan cost is less than a tolerance indicative of an acceptable difference between the upper bound and lower bound, a plan having said plan cost defining a feasible plan; and

(iii) a predetermined time limit has expired and no feasible plans have been identified.

a2

24. The method of claim 23, wherein step (c) further ~~comprises the steps of:~~

(i) ordering the vehicles chronologically;

(ii) incrementing the level to a next level and defining the next level as the current ~~level;~~

(iii) selecting each vehicle pair based upon the order determined in step (i);

25. The method of claim 23, wherein the selection in step (f) is based upon one of the following:

(a) which of the conflict resolution points results in less delay cost where the delay will result in additional cost, and

(b) which of the conflict resolution points will result in less vehicle delay where the delay will not produce additional delay cost;

26. The method of claim 23, wherein the selection in step (m) further comprises the following step:

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(i) selecting at least one conflict resolution point identified in step (e) at the current level by determining which conflict resolution point is both physically located closest to the conflict resolution point selected in step (f) and closest to the location of potential conflict, the conflict resolution point defining a meet-shift resolution point.

13 ~~27~~. The method of claim 12 ~~26~~, wherein step (O) further comprises the following steps:

(ii) calculating at least one delay time indicative of a time at least one vehicle is required to wait at the meet-shift resolution point for the other vehicle of the vehicle pair to pass without collision therebetween, thereby reducing the delay time calculated in ~~step (g)~~;

(iii) identifying substantially all delay reductions arising from delaying at least one vehicle at the meet-shift resolution point and thereby reducing the plan cost calculated ~~in step (k)~~;

(iv) summing substantially all potential cost reductions of the current plan which are both later in time than the meet-shift resolution point and physically located in the direction of movement of the delayed vehicle, the summed cost reductions defining a meet-shift maximum cost decrease;

(v) calculating the delay cost of the delayed vehicle at the meet-shift resolution point and redefining the delay cost as a meet-shift minimum additional cost;

(vi) subtracting the meet-shift minimum additional cost from the meet-shift maximum cost decrease resulting in a difference, the difference being the first maximum net ~~benefit~~.

15 ~~28~~. The method of claim 9 ~~23,~~ wherein step (p) further comprises the following steps:

(i) determining a reduced delay time compared to the delay time calculated in step (g) which would result if the vehicles delayed at the meet-shift resolution point incurred no previous delay.

(ii) identifying substantially all further cost reductions of the current plan arising from the reduced delay determined in step (i) of this claim 26;

(iii) summing substantially all the additional cost reductions of the current plan arising from delays at conflict resolution points which are both later in time than the meet-shift resolution point and physically located in the direction of movement of the delayed

a²

vehicle, the summed delay costs defining a general-meet-shift maximum cost decrease;

(iv) calculating, based on the reduced delay time determined in step (i) of this claim 26, the resulting delay cost and identifying that amount as the general-meet-shift minimum additional cost;

(v) subtracting the general-meet-shift minimum additional cost from the general-meet-shift maximum cost decrease resulting in a difference, the difference being the second maximum net benefit.

a[n]

27. The method of claim 26, wherein step (r) further comprises:

(vi) subtracting the second maximum net benefit from the plan lower bound resulting in a difference, the difference redefining the lower bound if the general-meet-shift minimum additional cost is positive.

29. The method of claim 1, wherein the transportation schedules and the vehicles are trains.

a v Sub B3 > 30. The method of claim 23, wherein the transportation schedules and the vehicles are trains.

REMARKS

The purpose of the amendments to the specification is to correct typographical errors and to enhance the readability of the text. Note, no new matter has been added.

New claims have been added to further define the invention. Again, no new matter has been added.

Respectfully submitted,
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Date: May 2, 1991

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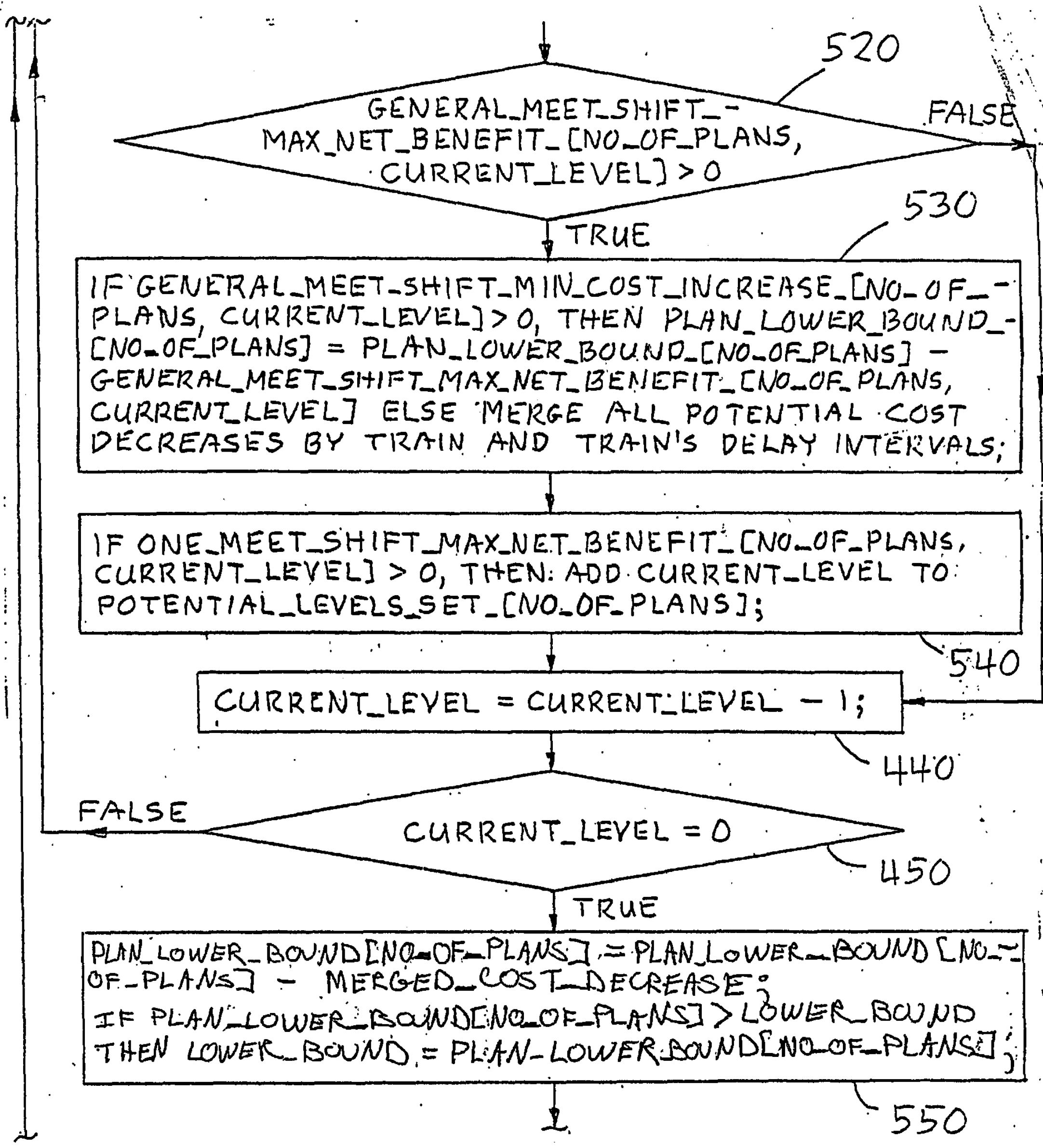
FIG 14D

629,419 #3



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ART UNIT	PAPER NUMBER
2304	4

DATE MAILED: 12/11/91

This is a communication from the examiner in charge of your application.
COMMISSIONER OF PATENTS AND TRADEMARKS

☒ This application has been examined ☐ Responsive to communication filed on __________ ☐ This action is made final.

A shortened statutory period for response to this action is set to expire 3 month(s), ______ days from the date of this letter.
Failure to respond within the period for response will cause the application to become abandoned. 35 U.S.C. 133

Part I THE FOLLOWING ATTACHMENT(S) ARE PART OF THIS ACTION:

1. ☒ Notice of References Cited by Examiner, PTO-892.
2. ☒ Notice re Patent Drawing, PTO-948.
3. ☒ Notice of Art Cited by Applicant, PTO-1449. (Two Sheets)
4. ☐ Notice of Informal Patent Application, Form PTO-152
5. ☐ Information on How to Effect Drawing Changes, PTO-1474.
6. ☐ __________

Part II SUMMARY OF ACTION

1. ☒ Claims 1-30 are pending in the application.

   Of the above, claims __________ are withdrawn from consideration.

2. ☐ Claims __________ have been cancelled.

3. ☐ Claims __________ are allowed.

4. ☒ Claims 1-30 are rejected.

5. ☐ Claims __________ are objected to.

6. ☐ Claims __________ are subject to restriction or election requirement.

7. ☐ This application has been filed with informal drawings under 37 C.F.R. 1.85 which are acceptable for examination purposes.

8. ☐ Formal drawings are required in response to this Office action.

9. ☐ The corrected or substitute drawings have been received on __________. Under 37 C.F.R. 1.84 these drawings are ☐ acceptable; ☐ not acceptable (see explanation or Notice re Patent Drawing, PTO-948).

10. ☒ The proposed ~~additional~~ or substitute sheet(~~s~~) of drawings, filed on 6 MAY 91. has (have) been ☒ approved by the examiner; ☐ disapproved by the examiner (see explanation).

11. ☐ The proposed drawing correction, filed __________, has been ☐ approved; ☐ disapproved (see explanation).

12. ☐ Acknowledgement is made of the claim for priority under U.S.C. 119. The certified copy has ☐ been received ☐ not been received ☐ been filed in parent application, serial no. __________ ; filed on __________.

13. ☐ Since this application apppears to be in condition for allowance except for formal matters, prosecution as to the merits is closed in accordance with the practice under Ex parte Quayle, 1935 C.D. 11; 453 O.G. 213.

14. ☐ Other

EXAMINER'S AC

1) The title is objected to because it does not convey an inventive feature, i.e., that the invention is directed toward vehicular transportation scheduling.

2) The drawings are objected to because Figs. 5, 7-9, 12-13, and 15-17 need descriptive titles. Correction is required. See 37 C.F.R. §§ 1.83(a) & 1.84(g).

3) 35 U.S.C. § 101 reads as follows:

> 3.1) "Whoever invents or discovers any new and useful process, machine, manufacture, or composition of matter or any new and useful improvement thereof, may obtain a patent therefore, subject to the conditions and requirements of this title".

4) Claims 1-30, as best understood, are rejected under 35 U.S.C. § 101 because the claimed invention is directed to non-statutory subject matter.

4.1) One analyzes claims for statutory subject matter by using the two-step, Freeman-Walter-Abele test. In re Freeman, 573 F.2d 1237, 197 USPQ 464 (CCPA 1978), as modified by In re Walter, 618 F.2d 758, 205 USPQ 397 (CCPA 1980), and In re Abele, 684 F.2d, 214 USPQ 682 (CCPA 1982). Taking Claim 1 as exemplary, it is clear that a mathematical algorithm is indirectly recited in the claims.

4.2) The equation is recited in a prose format within Claim 1. Specifically, the step of

> 4.2.1 b) determining based upon at least the data indicative of (i), (ii), and (iv) entered in step (a) whether the proposed transportation schedules may be met by the vehicles without addition of any substantial cost due to delays of the vehicles at the delay points,
>
> > 4.2.1.1 [wherein] the determination of step (b) . . .

> [is] a measure the feasibility of
> the proposed transportation
> schedules,

represents the algorithm in a prose format. Mathematical algorithms in prose form may be expressed as literal translations of the mathematical algorithm (e.g, substituting the expression "division" or "taking the ratio" for a division sign) or may be expressed in words which indicate the mathematical algorithm. See Safeflight v. Sunstrand, 706 F. Supp. 1146, 10 USPQ2d 1733, 1734 (D. Del. 1989) (subtracting); In re Taner, 214 USPQ 678 (CCPA 1978) (summing); In re Johnson, 589 F.2d 1070, 200 USPQ 199 (CCPA 1978) ("computing connotes the execution of one or a sequence of mathematical operations"). Thus, the first step of the two-step test is satisfied.

4.3) Proceeding to the second step of the Freeman-Walter-Abele test, one considers the claim as a whole to determine if the algorithm is applied to physical elements or process steps, in any manner, provided that its application is circumscribed by more than a field of use limitation or non-essential post-solution activity. Continuing to focus upon Claim 1, the step of

> 4.3.1 a) inputting into a computer system data
> indicative of: (i) . . . ; (ii) . . . ; (iii) . . .
> ; (iv) . . . ,

is a mere data gathering step for providing the values for the variables that are inherently required by the mathematical algorithms noted above in section 4.2. In re Gelnovatch, 595 F.2d 32, 201 USPQ 136 (CCPA 1979).

4.4) Aside from the mathematical algorithm and those steps dictated as necessary thereto, if the only limitation is insignificant or non-essential "post-solution activity," the claimed subject matter is nonstatutory. Parker v. Flook, 437 U.S. 584, 590, 198 USPQ 193, 197 (1978). Here, once the solution to the algorithm is obtained, said Claim merely

> 4.4.1 c) provid[es] an output indicative of the determination of step (b).

This is not significant post-solution activity which could transform an otherwise non-statutory claim into a statutory one.

4.5) Further, in respect to the preamble of Claim 1 which recites

> 4.5.1 in a transportation system having a plurality of vehicles, each vehicle having a scheduled departure time from an origin and a scheduled arrival time at a destination, there being a routing network defined by travel paths between the origin and destination, and delay points along each path for permitting one vehicle to wait until a second vehicle passes so as to avoid collision,

the Supreme Court has held: "A mathematical formula does not suddenly become patentable subject matter simply by having the applicant acquiesce to limiting the reach of that formula to a particular technological use." Diamond v. Diehr, 450 U.S. 175, 209 USPQ 1 (1981). Also, a Jepson preamble has not been held to limit the "subject matter as a whole", so as to avoid the 101 rejection. In re Walter, 618 F.2d 758, 205 USPQ 397 (CCPA 1980). (See also MPEP 2110).

4.6) Physical, structural limitations in method claims are usually not entitled to patentable weight. Gottschalk v. Benson, 175 USPQ 673, 677 (1972). This is especially true in claims which recited the structural limitations within the preamble, e.g., Diamond v. Diehr, 450 U.S. 175, 209 USPQ 1 (1981), but still applies if the structure is recited within the body of the claim. Therefore, in claims 29-30, for example, the claimed

> 4.6.1 wherein the transportation schedules and the vehicles are trains

is not entitled to patentable weight per Benson.

4.7) Also, the claim is not presumed to be statutory simply because it is in apparatus form. An apparatus claim that differs from a method claim only in that the term "means for" has been inserted before each process step, to convert the step into the "means" for performing it, does not have separate meaning as an apparatus claim. In re Walter, 618 F.2d 758, 205 USPQ 397, 408 (CCPA 1980).

> [T]he burden must be placed on the applicant to demonstrate that the claims are truly drawn to specific apparatus distinct from other apparatus capable of performing the identical functions.
> If this burden has not been discharged, the apparatus claim will be treated as if it were drawn to the method or process which encompasses all of the claimed means."

In re Walter, 205 USPQ 397, at 408)

4.8) Other claims, not explicitly discussed above, do not possess further limitations which would enable said claims to overcome rejection under 35 USC § 101.

4.9) Applicant is referred to the Patent Office position on the patentability of mathematical algorithms and computer programs. 1106 TMOG 2 (5 September 1989).

5) Only for the purpose of making the following rejections are the claims viewed as statutory.

6) Claims 1-30, as best understood, are rejected under 35 U.S.C. § 112, second paragraph, as being indefinite for failing to particularly point out and distinctly claim the subject matter which applicant regards as the invention.

6.1) For improved claim language clarity, it is recommended, in all references to aforementioned items and/or steps, that the definite article "the" be replaced with the more definite adjective "said."

6.2) Claims 1-30 are rejected because it is unclear whether Applicant is claiming a system, i.e., an apparatus, or a method. Ex parte Lyell, 17 USPQ2d 1548 (BPAI 1990). Physical structure limitations are usually given little patentable weight in method claims, e.g., claims 29-30.

6.3) Claim 27 fails because it is recited twice.

6.4) Those claims not explicitly discussed are rejected for incorporating the errors of their respective base claim by dependency.

7) The following is a quotation of the appropriate paragraphs of 35 U.S.C. § 102 that form the basis for the rejections under this section made in this Office action:

7.1) A person shall be entitled to a patent unless --

7.2) (b) the invention was patented or described in a printed publication in this or a foreign country or in public use or on sale in this country, more than one year prior to the date of application for patent in the United States.

7.3) (e) the invention was described in a patent granted on an application for patent by another filed in the United States before the invention thereof by the applicant for patent, or on an international application by another who has fulfilled the requirements of paragraphs (1), (2), and (4) of section 371(c) of this title before the invention thereof by the applicant for patent.

8) Claims 1 and 30, as best understood, also are rejected under 35 U.S.C. § 102(b) as being anticipated by MORSE ET AL., USPN 4122523. Claim 1, as best understood, is rejected under 35 U.S.C. § 102(e) as being anticipated by MINAMI, USPN 5038290.

8.1) As to Claim 1, the cited references teach the claimed method, applicable to a field of use such as

8.2 a transportation system having a plurality of vehicles, each vehicle having a scheduled departure time from an origin and a scheduled arrival time at a destination, there being a routing network defined by travel paths between the origin and destination, and delay points along each path for permitting one vehicle to wait until a second vehicle passes so as to avoid collision,

comprising the claimed steps of

8.3 a) inputting into a computer system data indicative of:
(i) a description of the routing network (MORSE ET AL. col. 2, ll. 30-34; MINAMI col. 4, ll. 3-5);
(ii) speed and mobility characteristics of each vehicle (MORSE ET AL. col. 6, ll. 17-20; MINAMI col. 2, ll. 6-12);
(iii) proposed transportation schedules for each vehicle specifying at least one scheduled departure and arrival times (MORSE ET AL. col. 4, ll. 30-34; MINAMI col. 4, ll. 13-26);
(iv) a vehicle tardiness function for each vehicle indicative of an importance of each vehicle arriving at its destination on time (MORSE ET AL. col. 10, ll. 42-61; MINAMI col. 5, ll. 25-30);

8.4 b) determining based upon at least the data indicative of (i), (ii), and (iv) entered in step (a) whether the proposed transportation schedules may be met by the vehicles without addition of any substantial cost due to delays of the vehicles at the delay points,
8.4.1 [wherein] the determination of step (b) . . . [is] a measure the feasibility of the proposed transportation schedules (MORSE ET AL. col. 10, ll. 5-14, col. 13, ll. 32-34; MINAMI col. 4, ll. 45-46, feasibility=possible or feasibility=not-possible); and

8.5 c) providing an output indicative of the determination of step (b) (MORSE ET AL. col. 20, ll. 64-65; MINAMI Fig. 2, outputs of decision block #2).

8.6) As to claim 30, MORSE ET AL. teach the claimed invention

8.6.1 wherein the transportation schedules and the vehicles are trains (MORSE ET AL. abstract).

9) The following is a quotation of 35 U.S.C. § 103 which forms the basis for all obviousness rejections set forth in this Office action:

9.1) A patent may not be obtained though the invention is not identically disclosed or described as set forth in section 102 of this title, if the differences between the subject matter sought to be patented and the prior art are such that the subject matter as a whole would have been obvious at the time the invention was made to a person having ordinary skill in the art to which said subject matter pertains. Patentability shall not be negatived by the manner in which the invention was made.

9.2) Subject matter developed by another person, which qualifies as prior art only under subsection (f) or (g) of section 102 of this title, shall not preclude patentability under this section where the subject matter and the claimed invention were, at the time the invention was made, owned by the same person or subject to an obligation of assignment to the same person.

9.3) This application currently names joint inventors. In considering patentability of the claims under 35 U.S.C. § 103, the examiner presumes that the subject matter of the various claims was commonly owned at the time any inventions covered therein were made absent any evidence to the contrary. Applicant is advised of the obligation under 37 C.F.R. § 1.56 to point out the inventor and invention dates of each claim that was not commonly owned at the time a later invention was made in order for the examiner to consider the applicability of potential 35 U.S.C. § 102(f) or (g) prior art under 35 U.S.C. § 103.

10) Claims 2-29, as best understood, also are rejected under 35 U.S.C. § 103 as being unpatentable over MORSE ET AL. in view of TSURUTA ET AL., USPN 4926343.

10.1) As to Claim 2, MORSE ET AL. teach part of the claimed

10.1.1 (d) inputting into the computer system data indicative of:
(vii) vehicle traffic status in the routing network (MORSE ET AL. col. 8, ll. 37-39);

10.1.2 (e) generating, based upon the data input in steps (a) and (d), a plurality of feasibility plans for avoiding conflicts between vehicles where at least one vehicle is delayed at a delay point so that a second vehicle may pass by without collision (MORSE ET AL. col. 20, ll. 37-67); and

10.1.3 (f) determining which of the plurality of feasibility plans is substantially optimal based upon costs resulting from delaying vehicles according to each conflict resolution (MORSE ET AL. col. 20, ll. 37-67).

10.2) The teachings of MORSE ET AL. differ from claim 2 by the feature taught by

10.2.1 (d) inputting into the computer system data indicative of:
(v) any changes in the

routing networks (TSURUTA ET AL. col. 8, ll. 33-44); and

(vi) any changes in vehicle travel paths within the routing network (TSURUTA ET AL. col. 8, ll. 33-44).

Claim 2 would have been obvious; one of ordinary skill in the art, at the time the invention was made, would have been motivated to combine the teachings of TSURUTA ET AL. into those of MORSE ET AL. in order to make adapting old schedules to new schedules more efficient (TSURUTA ET AL. col. 2, ll. 11-18).

10.3) As to Claims 3-30, MORSE ET AL. teach conflict resolution based upon a single conflicting pair (MORSE ET AL. col. 7, l. 45).

11) Claims 1 and 30, as best understood, also are rejected under 35 U.S.C. § 103 as being unpatentable over "Railroad Freight Train Scheduling: A Mathematical Programming Formulation," MORLOK ET AL., The Transportation Ctr. & Technology Instit., Northwestern Univ., May 1970, in view of "Computer Aided Train Dispatching Decision Support Through Optimization," SAUDER ET AL., Interfaces 13, 6 December 1987).

11.1) As to Claims 1 and 30, MORLOK ET AL. teach part of the claimed method, applicable to a field of use such as

11.2 in a transportation system having a plurality of vehicles, each vehicle having a scheduled departure time from an origin and a scheduled arrival time at a destination, there being a routing network defined by travel paths between the origin and destination, and delay points along each path for permitting one vehicle to wait until a second vehicle passes so as to avoid collision,

comprising the claimed steps of

11.2.1 a) inputting into a computer system data indicative of:

(i) a description of the routing network (MORLOK ET AL. p. 6, ll. 1-2);

(ii) speed and mobility characteristics of each vehicle (MORLOK ET AL. p. 6, ll. 2-3); and

(iii) proposed transportation schedules for each vehicle specifying at least one scheduled departure and arrival times (MORLOK ET AL. p. 6, ll. 1-2);

11.2.2 b) determining based upon at least the data indicative of (i), (ii), and (iv) entered in step (a) whether the proposed transportation schedules may be met by the vehicles without addition of any substantial cost due to delays of the vehicles at the delay points,

11.2.2.1 [wherein] the determination of step (b) . . . [is] a measure the feasibility of the proposed transportation schedules (MORLOK ET AL. p. 4, ll. 9-14); and

11.2.3 c) providing an output indicative of the determination of step (b) (MORLOK ET AL. p. 4, ll. 9-14).

In addition, MORLOK ET AL. suggest expanding their teachings to include data indicative of the priority of a vehicle (MORLOK ET AL. p. 53, ll. 3-4) for the motivation that it would add greatly to a model's realism and usefulness (MORLOK ET AL. p. 53, ll. 4-5).

11.3) The teachings of MORLOK ET AL. differ from Claims 1 and 30 by the claimed feature taught by the secondary reference:

11.3.1 a) inputting into a computer system data indicative of:

(iv) a vehicle tardiness function for each vehicle indicative of an importance of each vehicle arriving at its destination on time (SAUDER ET AL. p. 36, 1st col.).

Claims 1 and 30 would have been obvious; given the suggestion and motivation noted above in section 11.2, one of ordinary skill in the art, at the time the invention was made, would have been motivated to combine the teachings of

SAUDER ET AL. into those of MORLOK ET AL. for the additional motivation that adherence to a schedule is promoted (SAUDER ET AL. p. 36, 1st col.).

12) Claims 1 and 30, as best understood, also are rejected under 35 U.S.C. § 103 as being unpatentable over "Tactical Scheduling of Rail Operations: The SCAN I System," HARKER ET AL., The Wharton School - University of Pennsylvania, May 1989, in view of SAUDER ET AL.

12.1) As to Claims 1 and 30, HARKER ET AL. teach part of the claimed method, applicable to a field of use such as

> 12.2 in a transportation system having a plurality of vehicles, each vehicle having a scheduled departure time from an origin and a scheduled arrival time at a destination, there being a routing network defined by travel paths between the origin and destination, and delay points along each path for permitting one vehicle to wait until a second vehicle passes so as to avoid collision,

comprising the claimed steps of

> 12.2.1 a) inputting into a computer system data indicative of:
>
> (i) a description of the routing network (HARKER ET AL. p. 7, l. 11 "track description");
>
> (ii) speed and mobility characteristics of each vehicle (HARKER ET AL. p. 7, l. 12 "train travel times");
>
> (iii) proposed transportation schedules for each vehicle specifying at least one scheduled departure and arrival times (HARKER ET AL. p. 7, l. 12 "proposed train schedules");
>
> 12.2.2 b) determining based upon at least the data indicative of (i), (ii), and (iv) entered in step (a) whether the proposed transportation schedules may be met by the vehicles without addition of any substantial cost due to delays of the vehicles at the delay points,
>
> 12.2.2.1 [wherein] the determination of step (b) . . . [is] a measure the feasibility of the proposed transportation

schedules (HARKER ET AL. pp. 7-9); and

12.2.3 c) providing an output indicative of the determination of step (b) (HARKER ET AL. Figs. 2-9 & p. 35).

HARKER ET AL. explicitly suggest inputting data indicative of a tardiness function for the motivation that it is a measure of "goodness" for a given set of schedules (HARKER ET AL. p. 18, 4 lines from bottom).

12.3) The teachings of HARKER ET AL. differ from Claims 1 and 30 by the claimed feature taught by the secondary reference:

12.3.1 a) inputting into a computer system data indicative of:

(iv) a vehicle tardiness function for each vehicle indicative of an importance of each vehicle arriving at its destination on time (SAUDER ET AL. p. 36, 1st col.).

Claims 1 and 30 would have been obvious; given the suggestion and motivation noted above in section 12.2, one of ordinary skill in the art, at the time the invention was made, would have been motivated to combine the teachings of SAUDER ET AL. into those of HARKER ET AL. for the additional motivation that adherence to a schedule is promoted (SAUDER ET AL. p. 36, 1st col.).

13) Claims 2-29, as best understood, also are rejected under 35 U.S.C. § 103 as being unpatentable over HARKER ET AL. and SAUDER ET AL. as applied to claim 1 above, and further in view of "The Use of ATES in Scheduling and operating Railroads: Models, Algorithms and Applications," HARKER, The Wharton School - University of Pennsylvania, May 1989.

13.1) The teachings of HARKER ET AL. and SAUDER ET AL. differ from Claims 2-29 by the claimed feature taught by HARKER:

13.1.1 (d) inputting into the computer system data indicative of:

(v) any changes in the routing networks (HARKER p. 9);

(vi) any changes in vehicle travel paths within the routing network (HARKER p. 9); and

(vii) vehicle traffic status in the routing network (HARKER p. 10, item 4).

Claims 2-29 would have been obvious; one of ordinary skill in the art, at the time the invention was made, would have been motivated to combine the teachings of HARKER into those of HARKER ET AL. and SAUDER ET AL. in order to achieve a system that is responsive to unexpected vehicle breakdowns and accidents (HARKER p. 10, item 4).

14) The following cited references, although not applied against the claims, have been considered by the examiner as of interest. Applicant is urged to consider the teachings of these references in view of the claimed invention.

14.1) TAKAHASHI ET AL., USPN 4791571, teach a transit schedule control system.

15) In the Preliminary Amendment dated 6 May 1991, the instructions to amend p. 33, l. 11, p. 34, ll. 34-35, p. 35, l. 9, and p. 41, ll. 12-13 were not sufficiently clear to be executed.

16) Any inquiry concerning this communication or earlier communications from the examiner should be directed to Thomas S. Auchterlonie whose telephone number is (703) 308-1663. Any inquiry of a general nature or relating to the status of this application should be directed to the Group receptionist whose telephone number is (703) 308-0754. If necessary, facsimile transmissions may be directed to the PTO Facsimile Center whose telecopy numbers are (703) 308-3719, -3720. It is respectfully requested that Applicant alert the Examiner, via courtesy telephone call to the Examiner, that a facsimile transmission has been made.

THOMAS S. AUCHTERLONIE
PATENT EXAMINER
GROUP 230
TSA

Art Unit 2304
2 December 1991

PSLall
PARSHOTAM S. LALL
SUPERVISORY PATENT EXAMINER
ART UNIT 234

TO SEPARATE, HOLD TOP AND BOTTOM EDGES, SNAP–APART AND DISCARD CARBON

SK

1 of 3

FORM PTO-892 (REV. 3-78)

U.S. DEPARTMENT OF COMMERCE PATENT AND TRADEMARK OFFICE

NOTICE OF REFERENCES CITED

SERIAL NO. 7/629417

GROUP ART UNIT 2304

ATTACHMENT TO PAPER NUMBER 4

APPLICANT(S) Harker et al.

U.S. PATENT DOCUMENTS

*		DOCUMENT NO.	DATE	NAME	CLASS	SUB-CLASS	FILING DATE IF APPROPRIATE
	A	5038290	6 Aug 91	Minami	364	436	31 Aug 89
	B	4926343	15 MAY 90	Tsuruta et al.	364	513	11 Oct 88
	C	4791571	13 Dec 88	Takahashi et al.	364	436	
	D	4122523	24 Oct 78	Morse et al.	364	436	
	E						
	F						
	G						
	H						
	I						
	J						
	K						

FOREIGN PATENT DOCUMENTS

*		DOCUMENT NO.	DATE	COUNTRY	NAME	CLASS	SUB-CLASS	PERTINENT SHTS. DWG	PP. SPEC.
	L								
	M								
	N								
	O								
	P								
	Q								

OTHER REFERENCES (Including Author, Title, Date, Pertinent Pages, Etc.)

R	
S	
T	
U	

EXAMINER Thomas S. Auchterlonie

DATE 2 Dec 91

* A copy of this reference is not being furnished with this office action.
(See Manual of Patent Examining Procedure, section 707.05 (a).)

PTO FORM 948
(REV. 5-90)

U.S. DEPARTMENT OF COMMERCE
Patent and Trademark Office

ATTACHMENT TO PAPER NUMBER	4
APPLICATION NUMBER	629417.

NOTICE OF DRAFTSMAN'S PATENT DRAWING REVIEW

THE PTO DRAFTSMEN REVIEW ALL ORIGINALLY FILED DRAWINGS REGARDLESS OF WHETHER THEY WERE DESIGNATED AS INFORMAL OR FORMAL.

The drawings filed 12/18/90

A. ☐ are approved.

B. ☒ are objected to under 37 CFR 1.84 for the reason(s) checked below. The examiner will require submission of new, corrected drawings at the appropriate time. Corrected drawings must be submitted according to the instructions listed on the back of this Notice.

1. Paper and ink. 37 CFR 1.84(a), copy machine marks obj.
   ☒ Sheet(s) 28 Poor.

2. Size of Sheet and Margins. 37 CFR 1.84(b)
   Acceptable Paper Sizes and Margins

	Paper Size		
Margin	8 1/2 by 14 inches	8 1/2 by 13 inches	DIN size A4 21 by 29.7 cm.
Top	2 inches	1 inch	2.5 cm.
Left	1/4 inch	1/4 inch	2.5 cm.
Right	1/4 inch	1/4 inch	1.5 cm.
Bottom	1/4 inch	1/4 inch	1.0 cm.

   ☒ Proper Size Paper Required. All Sheets Must be Same Size.
   Sheet(s) 28.

   ☐ Proper Margins Required.
   Sheet(s)

   ☐ TOP ☐ RIGHT
   ☐ LEFT ☐ BOTTOM

3. Character of Lines. 37 CFR 1.84(c)
   ☒ Lines ~~Pale or~~ Rough and Blurred.
   Fig(s) 1 – 18

   ☐ Solid Black Shading Not Allowed.
   Fig(s)

4. Hatching and Shading. 37 CFR 1.84(d)
   ☐ Shade Lines are Required.
   Fig(s)

   ☐ Criss-Cross Hatching Not Allowed.
   Fig(s)

   ☐ Double Line Hatching Not Allowed.
   Fig(s)

   ☐ Parts in Section Must be Hatched.
   Fig(s)

5. Reference Characters. 37 CFR 1.84(f)
   ☒ Reference {lines / Characters} Poor ~~or~~ rough, blurred Incorrectly Sized. (in part)
   Fig(s) 1 – 18

   ☐ Reference Characters Placed Incorrectly.
   Fig(s)

6. Views. 37 CFR 1.84(i) & (j)
   ☐ Figures Must be Numbered Properly.

   ☐ Figures Must Not be Connected.
   Fig(s)

7. ☐ Photographs Not Approved.

8. ☒ Other. – All fig. legends poor

Telephone inquires concerning this review should be directed to the Chief Draftsman at telephone number (703) 557-6404.

Tang
Reviewing Draftsman

1/16/91.
Date

Transaction History Date 1992-04-08
Date information retrieved from USPTO Patent
Application Information Retrieval (PAIR)
system records at www.uspto.gov

5500-215-98234

DOCKET NO.: UPN-0401 PATENT #5

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

RECEIVED
APR 15 1992
GROUP 230

In re patent application of:

Patrick T. Harker et al.

Serial No.: **629,417** Group No.: **2304**

Filed: **December 18, 1990** Examiner: **T. Auchterlonie**

For: **A METHOD FOR ANALYZING FEASIBILITY IN A SCHEDULE ANALYSIS DECISION SUPPORT SYSTEM**

I, Steven J. Rocci, Registration No. 30,489 certify that this correspondence is being deposited with the U.S. Postal Service as First Class mail in an envelope addressed to the Commissioner of Patents and Trademarks, Washington, D.C. 20231.

On April 6, 1992

Steven J. Rocci, Registration No. 30,489

Commissioner of Patents & Trademarks
Washington, DC 20231

Sir:

AMENDMENT TRANSMITTAL LETTER
AND REQUEST FOR EXTENSION OF TIME

Transmitted herewith is an amendment in the above-identified application.

(XX) Small entity status of this application under 37 CFR 1.9 and 37 CFR 1.27 has been established by a verified statement previously submitted.

( ) A verified statement claiming small entity status under 37 CFR 1.9 and 37 CFR 1.27 is enclosed.

( ) Statement to Support Filing and Submission of DNA/Amino Acid Sequences in Accordance with 37 CFR §§ 1.821 through 1.825.

060 MC 04/13/92 07629417 1 215 55.00 CK

The fee for additional claims presented in this amendment has been calculated as follows:

				SMALL ENTITY			OTHER THAN SMALL ENTITY	
	Claims Remaining After Amendment	Highest Number Previously Paid for	No. Extra	Rate	Fee	OR	Rate	Fee
Total Claims	17 -	28 = (at least 20)	0	x$10=	$0	OR	x$20=	$
Indep. Claims	2 -	3 = (at least 3)	0	x$36=	$0	OR	x$72=	$
First Presentation Multiple Dependent Claims			+	$110=	$	OR	$220=	$
Total fee for added claims:					$0			$

(XX) Request is hereby made under 37 CFR 1.136(a) to extend the time for response to the Office Action of December 11, 1991 to and through April 11, 1992, comprising an extension of the shortened period of one (1) month:

	SMALL ENTITY		OTHER THAN SMALL ENTITY	
One Month	xxxx	$ 55		$ 110
Two Months		$175		$ 350
Three Months		$405		$ 810
Four Months		$640		$1,280
Additional fee for extended response:			$55.00	

Applicant(s) has/have not been notified that the requested extension will not be permitted. The present application is not involved in an interference declared pursuant to 37 CFR 1.207.

Total fee required $55.00

( ) Please charge my Deposit Account No. 23-3050 in the amount of $_____. This sheet is attached in triplicate.

(XX) A check in the amount of $55.00 is attached. Please charge any deficiency or credit any overpayment to Deposit Account No. 23-3050.

(XX) The Commissioner is hereby authorized to charge payment of the following fees associated with this communication or credit any overpayment to Deposit Account No. 23-3050. This sheet is attached in triplicate.

(XX) Any additional filing fees required under 37 CFR 1.16 including fees for presentation of extra claims.

(XX) Any additional patent application processing fees under 37 CFR 1.17 and under 37 CFR 1.20(d).

(XX) The Commissioner is hereby authorized to charge payment of the following fees during the pendency of this application or credit any overpayment to Deposit Account No. 23-3050. This sheet is attached in triplicate.

(XX) Any patent application processing fees under 37 CFR 1.17 and under 37 CFR 1.20(d).

( ) The issue fee set in 37 CFR 1.18 at or before mailing of the Notice of Allowance, pursuant to 37 CFR 1.311(b).

(XX) Any filing fees under 37 CFR 1.16 including fees for presentation of extra claims.

Date: April 6, 1992

Signature
Steven J. Rocci
(Name of Attorney of Record)
Registration No. **30,489**

WOODCOCK WASHBURN KURTZ
MACKIEWICZ & NORRIS
One Liberty Place - 46th Floor
Philadelphia, PA 19103
(215) 568-3100

MAIL ROOM APR 8 1992 PAT. & TRADEMARK OFFICE

DOCKET NO.: UPN-0401 PATENT

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re patent application of:

Patrick T. Harker et al.

RECEIVED APR 15 1992 GROUP 230

Serial No.: 629,417 Group No.: 2304

Filed: December 18, 1990 Examiner: T. Auchterlonie

For: A METHOD FOR ANALYZING FEASIBILITY IN A SCHEDULE ANALYSIS DECISION SUPPORT SYSTEM

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On April 6, 1992

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Steven J. Rocci, Registration No. 30,489

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AND REQUEST FOR EXTENSION OF TIME

Transmitted herewith is an amendment in the above-identified application.

(XX) Small entity status of this application under 37 CFR 1.9 and 37 CFR 1.27 has been established by a verified statement previously submitted.

( ) A verified statement claiming small entity status under 37 CFR 1.9 and 37 CFR 1.27 is enclosed.

( ) Statement to Support Filing and Submission of DNA/Amino Acid Sequences in Accordance with 37 CFR §§ 1.821 through 1.825.

The fee for additional claims presented in this amendment has been calculated as follows:

				SMALL ENTITY			OTHER THAN SMALL ENTITY	
	Claims Remaining After Amendment	Highest Number Previously Paid for	No. Extra	Rate	Fee	OR	Rate	Fee
Total Claims	17 -	28 = (at least 20)	0	x$10=	$0	OR	x$20=	$
Indep. Claims	2 -	3 = (at least 3)	0	x$36=	$0	OR	x$72=	$
First Presentation Multiple Dependent Claims			+	$110=	$	OR	$220=	$
Total fee for added claims:					$0			$

(XX) Request is hereby made under 37 CFR 1.136(a) to extend the time for response to the Office Action of <u>December 11, 1991</u> to and through <u>April 11, 1992</u>, comprising an extension of the shortened period of <u>one (1)</u> month:

	SMALL ENTITY		OTHER THAN SMALL ENTITY	
One Month	xxxx	$ 55		$ 110
Two Months		$175		$ 350
Three Months		$405		$ 810
Four Months		$640		$1,280
Additional fee for extended response:			$55.00	

Applicant(s) has/have not been notified that the requested extension will not be permitted. The present application is not involved in an interference declared pursuant to 37 CFR 1.207.

Total fee required <u>$55.00</u>

( ) Please charge my Deposit Account No. 23-3050 in the amount of $_____. This sheet is attached in triplicate.

(XX) A check in the amount of $55.00 is attached. Please charge any deficiency or credit any overpayment to Deposit Account No. 23-3050.

(XX) The Commissioner is hereby authorized to charge payment of the following fees associated with this communication or credit any overpayment to Deposit Account No. 23-3050. This sheet is attached in triplicate.

(XX) Any additional filing fees required under 37 CFR 1.16 including fees for presentation of extra claims.

(XX) Any additional patent application processing fees under 37 CFR 1.17 and under 37 CFR 1.20(d).

(XX) The Commissioner is hereby authorized to charge payment of the following fees during the pendency of this application or credit any overpayment to Deposit Account No. 23-3050. This sheet is attached in triplicate.

(XX) Any patent application processing fees under 37 CFR 1.17 and under 37 CFR 1.20(d).

( ) The issue fee set in 37 CFR 1.18 at or before mailing of the Notice of Allowance, pursuant to 37 CFR 1.311(b).

(XX) Any filing fees under 37 CFR 1.16 including fees for presentation of extra claims.

Date: April 6, 1992

Steven Rocci

Signature

Steven J. Rocci
(Name of Attorney of Record)
Registration No. **30,489**

WOODCOCK WASHBURN KURTZ
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Philadelphia, PA 19103
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DOCKET NO.: UPN-0401 PATENT

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

RECEIVED
APR 15 1992
GROUP 230

In re patent application of:

Patrick T. Harker et al.

Serial No.: 629,417 Group No.: 2304

Filed: December 18, 1990 Examiner: T. Auchterlonie

For: A METHOD FOR ANALYZING FEASIBILITY IN A SCHEDULE ANALYSIS DECISION SUPPORT SYSTEM

I, Steven J. Rocci, Registration No. 30,489 certify that this correspondence is being deposited with the U.S. Postal Service as First Class mail in an envelope addressed to the Commissioner of Patents and Trademarks, Washington, D.C. 20231.

On April 6, 1992

Steven J. Rocci

Steven J. Rocci, Registration No. 30,489

Commissioner of Patents & Trademarks
Washington, DC 20231

Sir:

AMENDMENT TRANSMITTAL LETTER
AND REQUEST FOR EXTENSION OF TIME

Transmitted herewith is an amendment in the above-identified application.

(XX) Small entity status of this application under 37 CFR 1.9 and 37 CFR 1.27 has been established by a verified statement previously submitted.

( ) A verified statement claiming small entity status under 37 CFR 1.9 and 37 CFR 1.27 is enclosed.

( ) Statement to Support Filing and Submission of DNA/Amino Acid Sequences in Accordance with 37 CFR §§ 1.821 through 1.825.

The fee for additional claims presented in this amendment has been calculated as follows:

				SMALL ENTITY			OTHER THAN SMALL ENTITY	
	Claims Remaining After Amendment	Highest Number Previously Paid for	No. Extra	Rate	Fee	OR	Rate	Fee
Total Claims	17 -	28 = (at least 20)	0	x$10=	$0	OR	x$20=	$
Indep. Claims	2 -	3 = (at least 3)	0	x$36=	$0	OR	x$72=	$
First Presentation Multiple Dependent Claims			+	$110=	$	OR	$220=	$
Total fee for added claims:					$0			$

(XX) Request is hereby made under 37 CFR 1.136(a) to extend the time for response to the Office Action of December 11, 1991 to and through April 11, 1992, comprising an extension of the shortened period of one (1) month:

	SMALL ENTITY		OTHER THAN SMALL ENTITY	
One Month	xxxx	$ 55		$ 110
Two Months		$175		$ 350
Three Months		$405		$ 810
Four Months		$640		$1,280
Additional fee for extended response:			$55.00	

Applicant(s) has/have not been notified that the requested extension will not be permitted. The present application is not involved in an interference declared pursuant to 37 CFR 1.207.

Total fee required $55.00

K:\U\FORMS\AM-EXT.TNS

( ) Please charge my Deposit Account No. 23-3050 in the amount of $_____. This sheet is attached in triplicate.

(XX) A check in the amount of $55.00 is attached. Please charge any deficiency or credit any overpayment to Deposit Account No. 23-3050.

(XX) The Commissioner is hereby authorized to charge payment of the following fees associated with this communication or credit any overpayment to Deposit Account No. 23-3050. This sheet is attached in triplicate.

(XX) Any additional filing fees required under 37 CFR 1.16 including fees for presentation of extra claims.

(XX) Any additional patent application processing fees under 37 CFR 1.17 and under 37 CFR 1.20(d).

(XX) The Commissioner is hereby authorized to charge payment of the following fees during the pendency of this application or credit any overpayment to Deposit Account No. 23-3050. This sheet is attached in triplicate.

(XX) Any patent application processing fees under 37 CFR 1.17 and under 37 CFR 1.20(d).

( ) The issue fee set in 37 CFR 1.18 at or before mailing of the Notice of Allowance, pursuant to 37 CFR 1.311(b).

(XX) Any filing fees under 37 CFR 1.16 including fees for presentation of extra claims.

Date: April 6, 1992

Steven J. Rocci
Signature
Steven J. Rocci
(Name of Attorney of Record)
Registration No. **30,489**

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6/L

DOCKET NO.: UPN-401 PATENT

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

RECEIVED
APR 15 1992
GROUP 230

MAIL ROOM
APR 8 1992
PAT. & TRADEMARK OFFICE

In re application of:

PATRICK T. HARKER, et al.

Serial No.: **629,417** Group Art Unit: **2304**

Filed: **December 18, 1990** Examiner: **T. Auchterlonie**

For: **A METHOD FOR ANALYZING FEASIBILITY IN A SCHEDULE ANALYSIS DECISION SUPPORT SYSTEM**

I, Steven J. Rocci, Registration No. 30,489 certify that this correspondence is being deposited with the U.S. Postal Service as First Class mail in an envelope addressed to the Commissioner of Patents and Trademarks, Washington, D.C. 20231.

On April 6, 1992

Steven J. Rocci

Steven J. Rocci, Registration No. 30,489

Honorable Commissioner of
Patents and Trademarks
Washington, D.C. 20231

Dear Sir:

AMENDMENT

In response to the Office Action dated December 11, 1991, having a shortened statutory period of response up to and including March 11, 1992, extended herewith up to and including April 11, 1992 please amend the above-identified application as follows.

In The Title:

Please change the title to --METHOD FOR ANALYZING AND GENERATING OPTIMAL TRANSPORTATION SCHEDULES FOR VEHICLES SUCH AS TRAINS AND CONTROLLING THE MOVEMENT OF VEHICLES IN RESPONSE THERETO--.

B1

DOCKET NO.: UPN-401 PATENT

In the Drawings:

Authorization is hereby requested to amend Figures 5, 7-9, 12-13 and 15-18 to insert descriptive titles as shown in red on the attached copies of those Figures.

In the Specification:

Page 33, line 11, after "Table", delete "0.4" and substitute therefor --4--.

Page 35, line 9, after "thus", delete "to decrease" and substitute therefor -- decreases --.

In the Claims:

Please cancel claims 1-22, 27 (second occurrence) and 29.

Please amend claims 23-26 and claim 30 as follows.

9 ~~23~~. (Amended) In a transportation system having a plurality of vehicles, each vehicle having a scheduled departure time from an origin and a scheduled arrival time at a destination, there being a routing network defined by travel paths between the origin and destination, and delay points along each path for permitting one vehicle to wait until a second vehicle passes so as to avoid collision, a method comprising the steps of:

(a) inputting into a computer system at least one of the following data indicative of:

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(i) a description of [the] <u>said</u> routing network;

(ii) speed and mobility characteristics of each vehicle;

(iii) proposed transportation schedules for each vehicle specifying at least scheduled departure and arrival times;

(iv) a vehicle tardiness function for each vehicle indicative of an importance of each vehicle arriving at its destination on time;

(v) any changes in [the] <u>said</u> routing network,

B2

(vi) any changes in a physical characteristic of any path in [the] <u>said</u> routing network; and,

(vii) vehicle status in [the] <u>said</u> routing network;

(b) initializing at least one of:

(i) a first variable indicative of a maximum cost due to vehicle delays for [the] <u>said</u> proposed transportation schedules input in step (a), [the] <u>said</u> first variable defining an upper bound;

(ii) a second variable indicative of the minimum cost due to vehicle delays for [the] said proposed transportation schedules input in step (a), [the] said second variable defining a lower bound [.] ;

(c) grouping [the] said vehicles into vehicle pairs having a first and second vehicle comprising substantially all possible combinations;

(d) determining, based upon the data input in (a), whether a potential conflict exists between [the] said two vehicles of each vehicle pair, and if so, identifying [the] said vehicle pair as a level,

B2

(e) identifying substantially all delay points at a first level where at least one vehicle in [the] said vehicle pair could be delayed so that the second vehicle in [the] said pair could pass without collision therebetween, defining [the] said delay points so identified as conflict resolution points.

(f) selecting one conflict resolution point identified in step (e) for [the] said first level;

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P' (g) determining an amount of time at least one vehicle in [the] said vehicle pair must be delayed at [the] said selected conflict resolution point so that the [vehicles] second vehicle can pass by without collision therebetween, [the] said amount of time [a] said vehicle is delayed defining a delay time;

P' (h) updating [the] said vehicles' scheduled departure and arrival times based upon [the] said delay times determined in step (g);

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P' (i) repeating steps (e) through (i) for each level identified in step (d);

P' (j) calculating a delay cost, based upon each delay time determined in step (g) and [the] said respective vehicle tardiness functions input in step (a), for each vehicle delayed in step (g);

P' (k) calculating a cumulative delay cost by adding together [the] said delay costs calculated in step (j), and defining [the] said cumulative delay cost as [the] a plan cost when [the] said delay costs for substantially all levels have been added together;

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(l) defining the arrival and departure times for each vehicle at each point along the vehicle's travel path between [the] <u>said</u> origin and destination as [the] <u>a</u> current plan if [the] <u>said</u> plan cost is less than [the] <u>said</u> upper bound, and setting [the] <u>said</u> upper bound equal to [the] <u>said</u> plan cost;

(m) selecting an alternative conflict resolution point from [the] <u>said</u> conflict resolution points identified in step (e) but not selected in step (f);

B2

(n) identifying substantially all vehicles whose delays determined in step (g) could be reduced by shifting [the] <u>said</u> selected conflict resolution point to [the] <u>said</u> alternate conflict resolution point selected in step (m), the vehicles so identified defining benefitted vehicles;

(o) estimating, based on [the] <u>said</u> alternative conflict resolution point, an amount indicative of a potential net cost reduction by computing a difference in potential delay reductions at other levels and any delay

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increases, where [the] said delay reductions and delay increases result from shifting to [the] said alternate conflict resolution point in step (m), [the] said difference computed defining a first maximum net benefit;

(p) repeating step (o), wherein the computation is based on [the] said vehicles arriving at [the] said alternate conflict resolution point on time with respect to their scheduled arrival times, [the] said difference so computed defining a second maximum net benefit;

(q) estimating, based on [the] said alternative conflict resolution point, any cost reduction to [the] said plan cost by merging delays of vehicles which are delayed at different levels over at least partially the same time interval thereby determining each vehicle's actual delay time, [the] said estimated cost reduction defining a merged cost decrease;

(r) redefining [the] said lower bound by subtracting at least one of:

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(i) [the] said second maximum net benefit; and

(ii) [the] said merged cost decrease

(s) defining [the] said set of conflict resolution points selected in step (f) and (m), the vehicles delayed in step (g) and their respective delay times, and [the] said cumulative delay cost as a fathomed path if any cumulative delay cost is greater than [the] said upper bound, and redefining the cumulative delay cost of said path as [the] said upper bound;

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(t) identifying vehicle pairs at levels having both a positive second maximum net benefit and negative first maximum net benefit, and defining the vehicles of said vehicle pairs so identified as potential vehicles;

(u) repeating steps (h) through (l) based on [the] said alternate conflict resolution point selected in step (m) when at least one of the following occurs:

(i) [the] said level for which [the] said alternate conflict resolution point has been

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selected has a positive first maximum net benefit; and

(ii) at least one benefitted vehicle is a potential vehicle for [the] <u>said</u> level and second maximum net benefits at previous levels are negative.

(v) [repeat] <u>repeating</u> step (u) until one of the following events:

(i) no alternative conflict resolution points are available to be selected in one of steps (f) and (m);

(ii) [the] <u>said</u> plan cost is less than a tolerance indicative of an acceptable difference between [the] <u>said</u> upper bound and <u>said</u> lower bound, a plan having said plan cost defining a feasible plan; and

(iii) a predetermined time limit has expired and no feasible plans have been identified[;] <u>the step further comprising identifying said current plan as an optimal plan when one of said events has occurred; and</u>

<u>(w) controlling the movement of said vehicles so that the arrival and departure times for each vehicle at each point along the vehicle's</u>

respective travel path between said origin and said destination is controlled according to said optimal plan.

~~24~~ 10. (Amended) The method of claim ~~23~~ 9, wherein step (c) further comprises the steps of:

(i) ordering [the] said vehicles chronologically;

(ii) incrementing [the] said level to a next level and defining [the] said next level as [the] said current level;

(iii) selecting each vehicle pair based upon [the] said order determined in step (i);

B2

~~25~~ 11. (Amended) The method of claim ~~23~~ 9, wherein [the] said selection in step (f) is based upon one of the following:

(a) which of [the] said conflict resolution points results in less delay cost where [the] said delay will result in additional cost, and

(b) which of [the] said conflict resolution points will result in less vehicle delay where [the] said delay will not produce additional delay cost[;].

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~~26~~. (Amended) The method of claim ~~23~~ 9, wherein [the] said selection in step (m) further comprises the following step:

(i) selecting at least one conflict resolution point identified in step (e) at [the] said current level by determining which conflict resolution point is both physically located closest to [the] said conflict resolution point selected in step (f) and closest to [the] said location of potential conflict, [the] said conflict resolution point defining a meet-shift resolution point.

B2

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~~27~~. (First occurrence) (Amended) The method of claim ~~26~~ 12, wherein step (O) further comprises the following steps:

[(ii)] (i) calculating at least one delay time indicative of a time at least one vehicle is required to wait at [the] said meet-shift resolution point for [the] said other vehicle of [the] said vehicle pair to pass without collision therebetween, thereby reducing [the] said delay time calculated in step (g);

[(iii)] (ii) identifying substantially all delay reductions arising from delaying at least one vehicle at [the] said meet-shift resolution point and thereby reducing [the] said plan cost calculated in step (k);

[(iv)] (iii) summing substantially all potential cost reductions of [the] said current plan which are both later in time than [the] said meet-shift resolution point and physically located in the direction of movement of [the] said delayed vehicle, [the] said summed cost reductions defining a meet-shift maximum cost decrease;

[(v)] (iv) calculating [the] said delay cost of [the] said delayed vehicle at [the] said meet-shift resolution point and redefining [the] said delay cost as a meet-shift minimum additional cost;

B2

[(vi)] (v) subtracting [the] said meet-shift minimum additional cost from [the] said meet-shift maximum cost decrease resulting in a difference, [the] said difference being the first maximum net benefit.

15 ~~28~~. (Amended) The method of claim 9 ~~23~~, wherein step (p) further comprises the following steps:

(i) determining a reduced delay time compared to [the] said delay time calculated in step (g)

Cl. 14-15

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which would result if [the] said vehicles delayed at [the] said meet-shift resolution point incurred no previous delay.

(ii) identifying substantially all further cost reductions of [the] said current plan arising from [the] said reduced delay determined in step (i) of this claim 28;

(iii) summing substantially all the additional cost reductions of [the] said current plan arising from delays at conflict resolution points which are both later in time than [the] said meet-shift resolution point and physically located in the direction of movement of [the] said delayed vehicle, [the] said summed delay costs defining a general-meet-shift maximum cost decrease;

(iv) calculating, based on the reduced delay time determined in step (i) of this claim 26, [the] said resulting delay cost and identifying that amount as [the] said general-meet-shift minimum additional cost;

(v) subtracting [the] said general-meet-shift minimum additional cost from the general-meet-shift maximum cost decrease resulting in

B2

a difference, [the] said difference being [the] said second maximum net benefit.

B3

16 ~~30~~. (Amended) The method of claim 9 ~~23~~, wherein [the] said transportation schedules are train schedules and [the] said vehicles are trains.

Please add new claims 31-39.

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14 ~~31~~. The method of claim 12 ~~26~~, wherein step (r) further comprises:

1.

(vi) subtracting [the] said second maximum net benefit from [the] said plan lower bound resulting in a difference, [the] said difference redefining [the] said lower bound if [the] said general-meet-shift minimum additional cost is positive.--

B4

1 ~~32~~. A method for controlling the movement of vehicles traveling in a transportation system, comprising the steps of:

(a) inputting data into a processor indicative of at least i) a physical description of a routing network on which said vehicles travel, and ii) a proposed transportation schedule for each vehicle traveling in said

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transportation system, each proposed schedule having at least a time of departure from a specified origin and a time of arrival at a specified destination;

(b) identifying potential conflicts between two vehicles based on said proposed schedules, and a set of conflict resolution points based upon said routing network and said potential conflicts, each conflict resolution point being a meetpoint at which one of said two vehicles can be delayed to permit the other of said two vehicles to pass thereby avoiding a collision between said two vehicles, said potential conflicts being chronologically sequenced based on said proposed schedules and said conflict resolution points being identified according to said chronological sequence and taking into consideration a possible delay of said one vehicle in each identified potential conflict;

(c) generating an initial meet-pass plan using a depth-first search bounded by delay costs arising from delaying said one vehicle at one

B4

C7

of said identified conflict resolution points for each potential conflict for an amount of time such that each potential conflict is resolved without a collision, said initial plan having a delay cost substantially equal to an accumulation of all delay costs resulting from said one vehicle being delayed in each potential conflict, said delay cost defining an upper bound;

(d) estimating a maximum cost benefit arising from shifting from said one conflict resolution point used to resolve each respective potential conflict in said initial meet-pass plan to another conflict resolution point, said shifting resulting in a potential alternative plan;

(e) generating alternative meet-pass plans using the depth-first search bounded by delay costs from said other conflict resolution point in each potential alternative plan where said estimated maximum cost benefit is positive, said alternative meet-pass plan having a delay cost substantially equal to an accumulation of all delay costs resulting from said one vehicle being delayed in each potential conflict, and if said delay cost of said alternative meet-pass plan so generated is lower than said upper bound, the step further comprising replacing said upper bound with said delay cost of said alternative meet-pass plan;

P1 (f) identifying one meet-pass having a substantially minimal delay cost among said initial and alternative meet-pass plans so generated by comparing each alternative meet-pass plan generated to said upper bound; and

B24

P1 (g) controlling the movement of said vehicles according to said identified meet-pass plan, said vehicles being delayed at said identified conflict resolution points for the amount of time specified by said identified meet-pass plan.

2 ~~33~~. The method of claim 1 ~~32~~, wherein a substantially minimal delay cost is determined according to at least one of the following conditions:

P1 i) said upper bound is zero;

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ii) said upper bound is less than or equal to a predetermined value indicative of an acceptable delay cost;

iii) a predetermined time has expired for generating said one identified meet-pass plan and at least said initial meet-pass plan has been generated; and

iv) substantially all alternative meet-pass plans according to step (e) have been generated.

3 ~~34~~. The method of claim 1 ~~32~~, further comprising the step of:

B24

(h) providing an output indicative of a measure of feasibility of said proposed transportation schedules.

4 ~~35~~. The method of claim 1 ~~32~~, wherein the step of estimating a maximum cost benefit further comprises the step of:

determining a one meet shift maximum net benefit for each potential conflict by shifting said conflict resolution point at which said one vehicle is delayed in said initial meet-pass plan to a conflict resolution point at which said other vehicle of said two vehicles is delayed defining an alternate conflict resolution point;

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said step of generating said alternative meet-pass plan being initiated from each alternate conflict resolution point if said one meet shift maximum net benefit so determined is positive.

5 ~~36~~. The method of claim 1 ~~32~~, wherein the step of estimating delay costs, further comprises the step of:

determining a general meet shift maximum net benefit for each potential conflict by shifting from the conflict resolution at which the one vehicle is delayed in the initial meet-pass plan to a conflict resolution point at which the other vehicle of the two vehicles is delayed defining an alternate conflict resolution point;

B4

generating a lower bound indicative of a lowest delay cost arising from any possible meet-pass plan, said lower bound being further indicative of said delay cost of said initial meet-pass plan minus a sum of one or more of said general meet shift maximum net benefits;

said identified meet-pass plan being determined based on a difference of said upper bound and said lower bound being less than a predetermined tolerance.

6 ~~37~~. The method of claim 5 ~~36~~, wherein said lower bound is generated after merging said delay costs of each vehicle

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having at least one of i) a lower delay cost at said identified conflict resolution point and ii) a lesser amount of time delayed at said alternate conflict resolution point as compared to the amount of time delayed at said identified conflict resolution point.

B4

7 ~~38~~. The method of claim 1 ~~32~~, wherein said vehicles are trains.

8 ~~39~~. The method of claim 1 ~~32~~, wherein said proposed schedules are revised based upon said identified meet-pass plan.

REMARKS

Claims 23-28, and 30-39 are pending in this application. Claims 1-22, 27 (second occurrence) and 29 have been cancelled and claims 23-28 (including claims 27, first occurrence) and 30 have been amended. Claims 31-39 are new. The Examiner's attention is directed to the fact that the second occurrence of claim 27 has been cancelled and rewritten as claim 31. No new matter has been added. The specification has been amended to correct for minor typographical and grammatical errors.

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The Examiner has objected to the drawings because Figures 5, 7-9, 12-13, and 15-18 require descriptive titles. Authorization has therefore been requested to amend Figures 5, 7-9, 12-13, and 15-18 as shown in red on the attached copies of those Figures. Upon approval by the Examiner, the indicated changes will be made in accordance with the current Patent Office procedures.

Claims 1-30 have been rejected under 35 U.S.C. §§ 101, 102(b), 103 and 112, second paragraph. However, the Examiner has not cited any reasons for the rejections of claims 23, 24-28 and 30. Therefore, it is submitted that it would be improper for the Examiner to make any next rejection final. 37 CFR §1.104(b); MPEP §707. The Examiner's detailed reasons in support of the rejection of these claims is requested.

Turning now to merits of the instant Office Action, reconsideration is respectfully requested in view of the foregoing amendments and following remarks.

THE INVENTION

The present invention is directed to a method of controlling the movement of vehicles in a transportation system. In general terms, the method of the present invention simulates characteristics of a transportation system such as a railroad system in real time. Then using this simulation as a model, proposed transportation schedules are evaluated to determine when the vehicles should move from one point to the next in the transportation system so that the vehicles arrive at their scheduled destinations on-time according to the proposed schedules.

Assuming for exemplary purposes that the vehicles are trains, conflicts may arise among the various trains traveling in a particular railroad system, i.e., between trains traveling in opposite directions on the same track at the same time or alternatively trains traveling on the same track at different speeds. To avoid such conflicts, one train must be delayed at a point between its origin and destination to allow a conflicting train to pass by to avoid a collision between the trains. These points are referred to as "meet-points" and may include side tracks or railway stations for example.[1]

Most transportation scheduling allows for some vehicle delay which is known as "slack time". Delaying a train may result in a delay cost if the delayed train does not reach its destination on time, i.e., if the delay time is greater than the train's scheduled slack time. A "tardiness function" based in part on the importance of a train's on-time arrival can be determined for each train. Using a train's tardiness function, a

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1 Terms of art used in the specification and claims have been quoted.

"delay cost" can be calculated for any delay of that train resulting from the resolution of a conflict with another train.

The method of the present invention, generates what is referred to as a "meet-pass" plan or a "conflict resolution plan" which specify which trains should be delayed at which points along their respective travel path and for how long the train should be delayed so that all of the trains traveling in the railroad system arrive at their destinations according to the proposed schedules. A meet-pass plan which can provide on-time performance is referred to as a "feasible plan." However, it is not unusual in complex transportation systems such as the railroad system, that there are no feasible plans. Thus the present invention evaluates other possible plans to identify a meet-pass plan having a substantially "minimal delay cost."

As described in detail in the background section of the instant application, numerous schedule analysis methods, as well as techniques for optimizing schedules have been developed and are known in the art. However, none of these prior art techniques can effectively process a set of transportation schedules in real-time for a complex transportation network such as a railroad system. See page 4, lines 4-5, 15-18, page 6, lines 23-26.

It is known to generate a meet-pass plan using a "branch-and-bound method." Branching includes determining which vehicles have conflicting schedules in terms of potential collisions as described above. Then each conflict is evaluated by determining the delay costs and/or the delay time required to resolve each conflict. Typically conflicts are evaluated in terms of delay cost/delay time at two different meet-points for each potential conflict. The two meet-points are selected by first determining the location where the conflict would occur if it was not otherwise resolved. The meet-points are then selected by choosing one meet-point on each side of that location. In this way one of the trains can be delayed at one meet-point to allow the other train to pass by and alternatively the other train can be delayed at the second meet-point to allow the former train to pass by. These meet-points are referred to as "conflict resolution points." The resolution having a lower delay cost/delay time forms what is known as a "node." "Bounding" refers to forming a node based on the resolution determined to have a lower delay cost/delay time.

These steps of the branching method are repeated for each conflict. The result is a sequence of nodes which specify which train is delayed at which meet-point and its corresponding delay cost/delay time. This sequence of nodes forms an "initial meet-pass plan." The delay cost for the plan is calculated. If it is zero, the proposed schedules are feasible by controlling the movement of the trains according to the plan.

When the proposed schedules are not feasible, according to the initial plan, other plans can be evaluated to identify and generate one that is feasible. It is known to retrace up the sequence of nodes and branch from those conflict resolution points which did not form nodes in the initial plan. Typically this secondary branching will be limited to those resolutions which will not result in a delay cost which exceeds that of the plan it is branching from (the plan delay cost is called the "upper band"). However, to branch from every one of these conflict resolution points in a complex transportation system cannot be accomplished in a computationally practical time. Therefore, the present invention provides a method for generating a meet-pass plan having a substantially minimal delay cost in a computationally practical time.

This feature of the present invention is accomplished by estimating maximum cost benefits which could be achieved from branching from a resolution that did not form a node. Then only those resolutions possibly leading to a plan with a lower delay cost (i.e., positive maximum cost benefit) form nodes from which further branching is performed.

One method of estimating a maximum cost benefit provided by the present invention is called a "one meet-shift local improvement." According to this method, a "one meet-shift maximum net benefit" is determined at each conflict resolution point which was not a node in the initial branch. By shifting the resolution to these conflict resolution points, one of the trains that was delayed according to the resolution represented by each node will no longer be delayed. Thus, a reduction in delay time to these trains will have a ripple effect on other conflicts the same train would be involved in occurring later in time. To determine the one meet-shift maximum net benefit, a maximum potential cost reduction is estimated based on an accumulation of all the delay costs which could be eliminated by shifting to these conflict resolution points. Of course, there is also a cost increase corresponding to delaying the other train at the conflict resolution point that was not previously delayed in the resolution resulting in a node in a former plan. Therefore, the maximum net benefit represents the difference in the maximum potential cost reduction and the cost increase after shifting from a node in a former plan to the other conflict resolution point for resolving each conflict.

Additionally, the present invention provides a method to further decrease the time for generating a plan having a minimal delay cost by generating a "lower bound." The lower bound is an indication of the least possible cost of any plan based on the proposed schedules (i.e., if this value is greater than zero there are no feasible plans so it is desired to find one with the least delay cost in the shortest amount of time).

One method of generating a lower bound is by determining a "general meet-shift maximum net benefit." The primary difference between the general meet shift maximum net benefit and the one meet shift maximum net benefit is that the maximum cost reduction for the general meet shift maximum net benefit includes all delay costs prior to the resolution being evaluated, i.e., cost savings which would be obtained if the train that is not delayed at the shifted resolution had not incurred any previous delay. Each positive general meet shift maximum net benefit is then subtracted from the delay cost of the initial plan thereby forming the lower bound.

Since, the cost savings from the same train over the same time intervals may be duplicated in more than one of the maximum cost reductions used in determining each general meet shift maximum net benefit, the present invention also provides a method of merging these cost reductions so that there is no duplication in generating the lower bound, i.e., increases the value of the lower bound. As the lower bound approaches the delay cost of a former plan, or the upper bound, it indicates that the former plan is substantially optimal in terms of delay costs.

Since not every plan is evaluated by the present invention, the plan generated is not necessarily the absolute optimal plan in terms of delay cost/delay time, but represents an optimal compromise between generating a plan having a substantially minimal delay cost/delay time and generating that plan in a computationally feasible time period.

The plan generated by the method of the present invention is used by a dispatcher (or a real time controller, if desired) for controlling the movement of the trains. For instance the dispatcher or controller may set the track switches and signals to implement the plan or they may be automatically set according to the generated plan. In addition, the proposed schedules may be revised in accordance with the meet-pass plan generated.

NO NEW MATTER HAS BEEN ADDED BY CLAIMS 32-39

New claims 32-39 provide no new matter and each element of these new claims is described in detail in the present specification. In particular, the subject matter of new claim 32, is directed to a "method for controlling the movement of vehicles traveling in a transportation system". See Figure 1, block 7 and page 11, lines 15-16; Figure 3, block 80 and page 12, lines 23-30; and Figure 4, block 120, and page 13, lines 18-21.

Similarly the present specification and drawings provide support for each step of claim 32. Step (a) of claim 32 provides:

> (a) inputting data into a processor indicative of ...
> i) a physical description of a routing network ... and
> ii) a proposed transportation schedule for each vehicle
> ... having at least a time of departure from a

> specified origin and a time of arrival at a specified destination;

Figure 1 depicts a user interface 3 for facilitating the input of data into a processor designated as CPU 4. The input data includes a description of the routing network and the transportation schedules as shown in Figure 2, block 12, and described on page 11, lines 29-32. Additionally, the routing network includes stations, rail yards, side tracks, etc. described on page 11, line 32 to page 12, line 2, as points where vehicles can enter or leave the network, and pass or overtake each other. Each vehicle traveling in the transportation system has one of these points as its origin, one as its destination and perhaps some points in between designating its travel path. See table 1 as an example.

Step (b) of claim 32 provides:

> b) identifying potential conflicts between two vehicles ... and a set of conflict resolution points...

This step is described by way of example on page 15, line 31 to page 18, line 22. Likewise, step (c) which provides:

> c) generating an initial meet-pass plan using a depth-first search bounded by delay costs arising from delaying said one vehicle at one of said identified conflict resolution points for each potential conflict ....

is also described in detail in the instant specification and drawings. In particular, see page 13, line 22 to page 14, line 34, and page 18, line 23 to page 19, line 36, and Figures 7 and

10A. For an example see page 21, line 8 to page 22, line 30, and Figure 8.

The subject matter of steps (d) and (e) are supported in the present specification using the one meet shift local improvement algorithm, the lower bound based pruning algorithms and the accelerated heuristic lower bound-based algorithm as examples of methods to estimate and generate meet-pass plans having a lower delay cost than the initial plan. Specifically, these steps provide:

> d) estimating a maximum cost benefit arising from shifting from said one conflict resolution point used to resolve each respective potential conflict in said initial meet-pass plan to another conflict resolution point, ... [and]
>
> e) generating alternative meet-pass plans using the depth-first search bounded by delay costs from said other conflict resolution point in each potential alternative plan where said estimated maximum cost benefit is positive, ...

The one meet shift local improvement method is described in detail on page 23, line 9 to page 28, line 11 and flow charted in Figures 11A and 11B. The subject matter of dependent claim 35 is particularly directed to the one meet shift local improvement method. The lower bound based methods for estimating and generating alternative plans having a lower delay cost than the initial plan is described in detail on page 28, line 12 to page 42, line 11 and flow charted in Figures 14A through 14H. Dependent claim 36 is directed to an exact lower bound method and dependent claim 37 is directed to the use of a global lower bound pruning method specifically described on page 31, line 28 to page 35, line 10. Additionally, steps (d) and (e) may also comprise the accelerated heuristic lower bound method described on page 42, line 12 to page 44, line 36. See also Figure 18.

Step (f) provides for "identifying one meet-pass plan having a substantially minimal delay cost among the initial and alternative meet-pass plans so generated ...". The local improvement and lower bound methods provide practical solutions to finding a plan with a minimal cost in terms of processing time and processing capability. In other words, to minimize the processing requirements, the optimal or identified plan in step (f) may not be one having the lowest delay cost of any possible plan. Identifying an optimal plan in terms of minimal delay cost is described in the specification of the instant application with reference to the drawings. For instance see page 20, lines 13-25 for a description of criteria which can be used to identify an optimal plan and Figures 10C, step 330, and 14F, step 330. Claim 33 more particularly points out the criteria for identifying the optimal plan having a substantially minimal delay cost.

Step (g), which provides "controlling the movement of said vehicles according to said identified meet-pass plan" is supported by the specification and drawings as described herein above. In particular, see Figure 1, block 7 and page 11, lines 15-16; Figure 3, block 80 and page 12, lines 23-30; and Figure 4, block 120, and page 13, lines 18-21.

Claim 34 is directed to the method of analyzing the proposed schedules in terms of feasibility. Page 11, lines 2-11 describes how an output is provided to a dispatcher representing how the proposed schedules can be achieved or why the proposed schedules cannot be achieved. Thus, claim 34 which states:

> h) providing an output indicative of a measure of feasibility of said proposed transportation schedules.

is fully supported by the specification.

Similarly, claim 39 is directed to revising the schedules according to an optimal plan generated by a method of the present invention. In this respect, the optimal plan is provided as an output is provided to the dispatcher who can set the track signals and switches to implement the plan (page 13, lines 28-31) or as an output to a scheduler to revise the proposed schedules (see page 10, lines 23-25).

New claim 38 incorporates the limitation of cancelled claim 29.

Therefore, new claims 32-39 provide no new matter and Applicant respectfully requests that the Examiner consider these claims accordingly.

THE SECTION 101 REJECTION

The Examiner has rejected claims 1-30 under 35 U.S.C. §101 as being directed to non-statutory subject matter. For the reasons that follow, Applicant submits that all of the pending claims clearly recite statutory subject matter under the law.

The Examiner has correctly noted that the appropriate test for patentability under §101 involves a two-step analysis. The first step requires a determination as to whether the claim directly or indirectly recites a mathematical algorithm. The second step requires a determination as to whether the claim, **read as a whole**, wholly preempts that mathematical algorithm. However, the second step of the test is reached only if the first determination is affirmative. Ex parte Logan, 20 USPQ 2d 1465,1469 (Bd.P.App & Int. 1991).

The Examiner's basis for rejection of claim 1 is exemplary of the reasons for the §101 rejection:

> [I]t is clear that a mathematical algorithm is indirectly recited in the claims. ... The equation is cited in prose format within claim 1. Specifically, the step of [setting forth step (b) of claim 1] represents the algorithm in a prose format.

Office Action at pages 2-3. Although the Examiner has stated the proper test for determining statutory subject matter, Applicant respectfully submits that the Examiner's analysis under this test was improper.

A mathematical algorithm has been defined by the U.S. Supreme Court as a "procedure for solving a given type of mathematical problem." Gottschalk v. Benson, 409 U.S. 63, 175 USPQ 673, 674 (1972); Diamond v. Diehr, 450 U.S. 175, 209 USPQ 1, 8 (1981). Thus, a claim meeting the first part of the test must have two identifiable aspects: 1) a mathematical problem, and 2) a procedure to solve that problem. A claim which directly or indirectly recites a mathematical computation, formula, equation, etc. cannot be a "mathematical algorithm" unless the claim is drawn to a procedure to solve a mathematical problem. Mere recitation of a mathematical expression within a claim is not sufficient to establish that the claim recites a mathematical algorithm under the Supreme Courts's definition of that term in Benson and Diehr. In re Grams, 12 USPQ 2d 1824, 1827 (Fed. Cir. 1989). Applicant submits that there is simply no mathematical problem in claim 1 for which a procedure to solve that problem is claimed.

Applicant directs the Examiner's attention to a recent case decided by the Board of Patent Appeals and Interferences, Ex parte Logan, 20 USPQ 2d 1465 (Bd.P.App & Int. 1991). In that case the Board stated:

> [W]e believe a claim should be considered as reciting a mathematical algorithm **only if** it **essentially** recites directly or indirectly, a method of computing one or more numbers from a different set of numbers by performing a series of mathematical computations.

> **Consequently, a claim which essentially recites another type of method does not recite a mathematical algorithm, even though it incidently recites, directly or indirectly, the performance of some mathematical computation.**

(emphasis added) Id. at 1468.

Claim 32 is directed to a method of "controlling the movement of vehicles traveling in a transportation system, comprising the steps of:

> a) inputting data ....
>
> b) identifying potential conflicts ... and a set of conflict resolution points ...
>
> c) generating an initial meet-pass plan...
>
> d) estimating a maximum cost benefit ...
>
> e) generating alternate meet-pass plans ...
>
> f) identifying one meet-pass plan having a substantially minimal delay cost ....; and
>
> g) controlling the movement of the vehicles according to the identified meet-pass plan..."

New claim 32, therefore, recites a method of controlling the movement of vehicles in a routing network according to a meet-pass plan generated by the method which specifies the movement of the vehicles such that the vehicles avoid collision therebetween and substantially minimizes delay costs. It does not recite a method of computing one or more numbers from a different set of numbers by performing a series of mathematical computations. Therefore, Applicant respectfully submits that even if some of the steps of new claim 32 directly or indirectly recite mathematical computations, the claim does not recite a mathematical algorithm according to the Supreme Courts's and Federal Circuit's definition of that term.

Likewise, claim 23 as amended does not recite a mathematical algorithm. In particular, steps (v) and (w) provide:

> (v) repeating step (u) until one of the following events:
>
> . . . .
>
> the step further comprising identifying said current plan as an optimal plan when one of said events has occurred; and
>
> w) controlling the movement of said vehicles so that the arrival and departure times for each vehicle at each point along the vehicle's respective travel path between said origin and said destination is controlled according to said optimal plan.

Thus the method of claim 23 as amended also is directed to controlling the movement of vehicles in a transportation system based on an optimal plan generated by the method and is not a method of computing numbers.

In Ex parte Logan, The Board of Patent Appeals and Interferences held that the correct approach "places the emphasis on **what** the claimed method steps do rather than **how** the steps are performed." (emphasis original) Id. Specifically the Board determined that even though the steps of "establishing a baseline level, establishing a trigger level, and generating inspiration trigger signals," were disclosed as involving a series of mathematical computations, **these computations "were merely ancillary to a more encompassing process"** directed to detecting the occurrence of events (emphasis added). Id. Therefore, claim 23 must be analyzed for what the claimed steps do rather than how the steps are performed. The steps of claim 23 input and initialize data (see step (a) and (b)), identify potential conflicts (steps (c) and (d)), generate an initial meet-pass plan (steps (e) through (l)), estimate a maximum cost benefit (steps (m) through (r)), generate alternate meet-pass plans (steps (s) through (u)), identify one meet-pass plan having a substantially minimal delay cost (step (v)); and *control the movement of the vehicles according to the identified plan* (step (w)). The steps recited by the instant claims are merely ancillary to that of controlling the vehicle's movement. Accordingly, Applicant is not claiming merely a method for generating numbers. In view of the foregoing, any steps directly or indirectly reciting a mathematical computation in claim 23 are merely ancillary to the method of controlling the vehicles in a transportation system to avoid collisions therebetween while minimizing delay costs.

Since, Applicant respectfully submits that a mathematical algorithm is not directly or indirectly recited by either claim 23 as amended or new claim 32, the first step of the two-part test is not satisfied. Accordingly, it is unnecessary to consider whether these claims pass muster under the second step as set forth above. However, in the interest of advancing prosecution, Applicant proposes the following analysis of claims 23 and 32 under part two of the test.

The Examiner has stated that the only steps not indirectly reciting a mathematical algorithm in canceled claim 1 are directed to either non-essential post-solution activity or data gathering, neither of which would render the canceled claim statutory. Office Action at pages 3-4. Additionally, the Examiner stated that limiting the technological use of a mathematical formula in a preamble would not avoid a Section 101 rejection. Office Action at page 4.

The Examiner, citing In re Walter, correctly states that a Jepson preamble will not limit the subject matter as a whole to avoid a section 101 rejection. However, claim 23 as amended provides:

> w) controlling the movement of said vehicles so that the arrival and departure times for each vehicle at each point along the vehicle's respective travel path between said origin and said destination is controlled according to said optimal plan.

This step, not the preamble, affirmatively limits the use of any mathematical computations indirectly recited by claim 23 to applications directed to controlling the movement of vehicles in a transportation system.

Furthermore, In re Walter held:

> In order to determine whether a mathematical algorithm is 'preempted' by a claim under Freeman, the claim is analyzed to establish the relationship between the algorithm and the physical steps or elements of the claim.

209 USPQ 397,407 (C.C.P.A. 1980). All of the intervening steps of claim 23 likewise affirmatively limit the uses of any mathematical computations indirectly recited by the claim. For example, see step (e):

> identifying substantially all delay points at a first level where at least one vehicle in said vehicle pair could be delayed so that the second vehicle in said pair could pass without collision therebetween, defining said delay points so identified as conflict resolution points.

In other words, although some mathematical computations may be required to identify the delay points as described in the instant specification, clearly their use is limited by the language of the claim to the physical process step and elements contained therein. Therefore, Applicant respectfully submits that claim 23 as amended provides statutory subject matter. It is not an attempt to patent a mathematical algorithm under the guise of a preamble limiting the technological use of the mathematical algorithm. Stated differently, Applicant has invented and claimed a method of controlling the movement vehicles (which is clearly statutory) rather than a mathematical algorithm.

Similarly, new claim 32 provides affirmative steps which limit the technological use to controlling the movement of vehicles based on any computations that may be indirectly recited by the claim. In particular step (g) provides:

> (g) controlling the movement of said vehicles according to said identified meet-pass plan, said vehicles being delayed at said identified conflict resolution points for the amount of time specified by said identified meet-pass plan.

For the same reasons set forth above, Applicant respectfully submits that new claim 32 also provides statutory subject matter.

Regarding the Examiner's contention that claim 1 (now canceled) did not provide significant post-solution activity transforming an otherwise non-statutory claim into a statutory one, Applicant respectfully submits that the Examiner has overlooked critical features of the claimed invention. The C.C.P.A. in <u>In re Walter</u> provided some guidelines for determining whether post-solution activity was significant or non-essential.

> For instance if the end product of a claimed invention is a **pure number**, as in <u>Benson</u> and <u>Flook</u>, the invention is nonstatutory regardless of any post-solution activity which makes it available for use by a person or machine for other purposes. If, however, the claimed invention produces a physical thing such as the noiseless seismic trace in <u>In re Johnson</u>, the fact that it is represented in numeric form does not render the claim nonstatutory.

(emphasis original) <u>In re Walter</u>, 205 USPQ at 407. Not only does the step of "controlling the movement of the vehicles" in step

(w) of claim 23 and step (g) in claim 32 provide significant post solution activity, but the steps of generating meet-pass plans provide statutory subject matter as well. The meet-pass plans generated according to steps (l), (u), and (v) of claim 23 as amended and steps (c) and (e) of new claim 32, are not just pure numbers which are made available for other purposes. Rather they are "physical things" in the Walter sense of that term. The fact that the meet-pass plans generated might be represented in numeric form will not render these claims non-statutory. Id.

The Federal Circuit has recently affirmed this position concerning analogous claims in Arrhythmia Research Technology, Inc., v. Corazonix Corp., No. 91-1091, 1992 U.S.App. LEXIS 4202 (Fed. Cir. March 12, 1992). The claim at issue in Arrhythmia was as follows:

> 1. A method for analyzing electrocardiograph signals to determine the presence or absence of a predetermined level of high frequency energy in the late QRS signal, comprising the steps of:
> converting a series of QRS signals to time segments, ...
> applying a portion of said time segments in reverse time order to high pass filter means;
> determining an arithmetic value of the amplitude of the output of said filter; and
> comparing said value with said predetermined level.

The defendant in this case asserted that the end product of the claim was a pure number which could not be saved by any limitation to its use. The Federal Circuit rejected this argument stating:

> [T]he number obtained is not a mathematical abstraction; it is a measure in microvolts of a specified heart activity, an indicator of the risk of ventricular tachycardia. That the product is numerical is not a criterion of whether the claim is directed to statutory subject matter.

Id. at 43. Similarly, it would be improper to conclude that the meet-pass plans generated by the claimed invention for controlling the movement of vehicles is directed to non-statutory subject matter simply because the meet-pass plans are numerical in nature.

In sum, claim 23 as amended and new claim 32 provide statutory subject matter because neither directly or indirectly recites a mathematical algorithm as defined by the Supreme Court. Therefore, it is unnecessary to determine whether these claims would wholly preempt the use of a mathematical algorithm. However, even upon further analysis, any mathematical computation indirectly recited by the steps of the claims are explicitly related to the physical steps and elements of the claims. Furthermore, claims 23 and 32 provide significant post solution activity with respect to any mathematical computation indirectly recited by the claims so that the end-product of the claimed invention is not a pure number subject to other uses. For these reasons, Applicant submits that claim 23 as amended and new claim 32 provide statutory subject matter under Section 101.

THE SECTION 112 REJECTION

The Examiner has rejected claims 1-30 under 35 U.S.C. §112, second paragraph, as being indefinite for failing to particularly point out and distinctly claim the subject matter which the Applicant regards as the invention. In particular the Examiner has recommended that "the definite article 'the' be replaced with the more definite adjective 'said'". Office Action at page 6. Claims 23-28 and 30 have been amended to overcome the Section 112 rejections by deleting the definite article 'the' and replacing it with the more definite adjective 'said' throughout these claims.

Additionally the Examiner has stated that "it is unclear whether Applicant is claiming a system, i.e., an apparatus or a method." Office Action at 6. Applicants respectfully points out that claim 23 is expressly directed to a method.

> In a transportation system ... **a method comprising the steps of:**

(emphasis added).

THE SECTION 102 REJECTIONS

The Examiner has rejected claims 1-30 under 35 U.S.C. §102(b) as being anticipated by U.S. Patent No. 4,122,523 issued to Morse, et al. The Examiner has additionally rejected claims 1-30 under 35 U.S.C. §102(e) as being anticipated by U.S. Patent No. 5,038,290 issued to Minami. The Examiner has set forth reasons for these rejections only as pertaining to claims 1 and claim 29[2], both of which have now been cancelled. Applicant submits that none of the pending claims are anticipated by either reference.

The Morse patent teaches generating a depth-first search bounded by delay costs, but in contradistinction to the claimed invention, it does not teach or disclose any method or step for identifying an optimal plan based on substantially minimal delay costs. The claimed invention expressly provides in claim 23 as amended:

> (v) ...identifying said current plan as an optimal plan when one of said events has occurred; and

and similarly claim 32 provides:

> f) identifying one meet-pass plan having a substantially minimal delay cost among the initial and alternative meet-pass plans so generated ...

Specifically, Morse teaches only manual adjustments or selection of possible plans. See Col. 20, lines 50-59 which state:

> If ... no feasible solution was found, ... The operator will be informed of the unsuccessful search and he may manually determine the sequencing or he may simply expand some time windows and allow the system to try again.

---

[2] Claims 29 and 30 are identical except that claim 29 depends from claim 1 and claim 30 depends from claim 23. Since the Examiner stated the rejection in respect to claim 30 but has made no reference to claim 23, Applicant has regarded the rejection as pertaining to claim 29.

In fact, Morse teaches away from the claimed invention in many respects. For instance, if a feasible plan is not found after the depth-first search, Morse teaches examining every conflict. Col. 17, lines 48-53. In contradistinction, the present invention evaluates potential plans and examines only those potential plans which evidence a possibly lower delay cost than any plan generated up to that point. Steps (m) through (u) of claim 23 as amended and steps (d) and (e) of claim 32 recite this advantage over the prior art techniques such as Morse. For example, Step (d) of claim 32 recites:

> d) estimating a maximum cost benefit arising from shifting from said one conflict resolution point used to resolve each respective potential conflict in said initial meet-pass plan to another conflict resolution point,

and Step (e) provides;

> e) generating alternative meet-pass plans using the depth-first search bounded by delay costs **from a point in each potential alternative plan where said estimated maximum cost benefit is positive,...**

(Emphasis added). Applicant has found no teaching, direct or indirect, in Morse disclosing either step (d) or (e) as provided by claim 32 or steps (m) through (u) of claim 23. Therefore, Applicant respectfully submits that claims 23-28 and 30-31 and claims 32-39 would not be anticipated by Morse.

Similarly, Minami does not anticipate claims 23-28 and 30-31 or new claims 32-39. In contradistinction to the claimed invention, Minami does not teach generating any plans for the movement of vehicles using the depth-first search technique claimed by the present invention. Minami is directed to a problem different than the present invention, i.e., finding a plan for determining the shortest routes based on the fewest number of diversions from origin to destination. See Col. 5, lines 48-59. Therefore, Minami does not teach any of the following steps of the claimed invention; 1) generating an initial plan using the depth-first search technique, (steps (f) through (l) of claim 23 and step (c) of claim 32), 2) estimating benefits of potential plans possibly having a lower delay cost than other plans generated (steps (m) through (r) of claim 23 and step (d) of claim 32), 3) generating alternate plans based on the potential plans having estimated cost benefits over other plans generated (steps (s) through (u) of claim 23 and step (e) of claim 32), and 4) identifying a plan having a substantially minimal delay cost (step (v) of claim 23 and step (f) of claim 32).

THE SECTION 103 REJECTIONS

Claims 2-29 have been rejected under 35 U.S.C. § 103 as being unpatentable over Morse et al. in view of U.S. patent No. 4,926,343 issued to Tsuruta et al. The Examiner has further rejected claims 1-30 under 35 U.S.C. § 103 as being unpatentable over the article *Railroad Freight Train Scheduling: A mathematical Programming Formulation,* by Morlock et al, (hereinafter "Morlock") in view of *Computer Aided Train Dispatching Decision Support Through Optimization,* by Sauder et al. (hereinafter "Sauder"). Additionally, claims 1-30 have been rejected under 35 U.S.C. § 103 as being unpatentable over *Tactical Scheduling of Rail Operations: The SCAN I System,* by Harker et al. (hereinafter "SCAN I"), in view of Sauder. Claims 2-29 have been further rejected under 35 U.S.C. § 103 as being unpatentable over SCAN I and Sauder as applied to claim 1 and further in view of *The ATES in Scheduling and Operating Railroads: Models, Algorithms, and Applications,* by Harker (hereinafter "Harker").

Claim 23 as amended and new claim 32 patentably define over the prior art of record because none of the prior art cited by the Examiner teach or suggest the steps of searching for a plan having a substantially minimal delay cost by searching **only** those potential plans having an estimated maximum cost benefit (indicating that the potential plan may possibly provide a lesser delay cost than any other plan generated). The Applicant has combed the references of record and has not found even an inference of using either (i) a one meet shift local improvement method or (ii) a lower bound based pruning method for searching potential plans, and identifying a plan having a substantially minimal delay cost.

As described in the instant specification all meets are screened but not tested. Thus only those meets which indicate some potential for improvement are tested for optimality. See page 24 of the instant specification. This advantage of the claimed invention eliminates those problems associated with the prior art (e.g., computational time, limited size and complexity of the routing network, etc.). See page 3, line 10 to page 7, line 32.

Although one or more of the prior art references may be modified to arrive at the claimed invention, there must be some suggestion in the prior art as a whole to do so. Applicant has found no suggestion or inference in any of the prior references which would lead one skilled in the art to combine or modify the prior art to arrive at the claimed invention. Therefore, claims 23-28, 30, 31 and 32-39 patentably define over the prior art of record.

DOCKET NO.: UPN-401 **PATENT**

For the foregoing reasons, reconsideration of the present Office Action and an early Notice of Allowance are respectfully requested.

Respectfully submitted,

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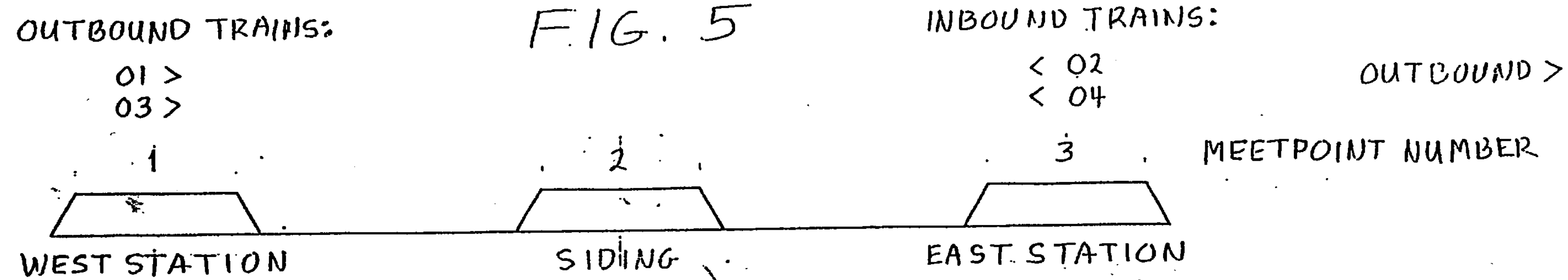
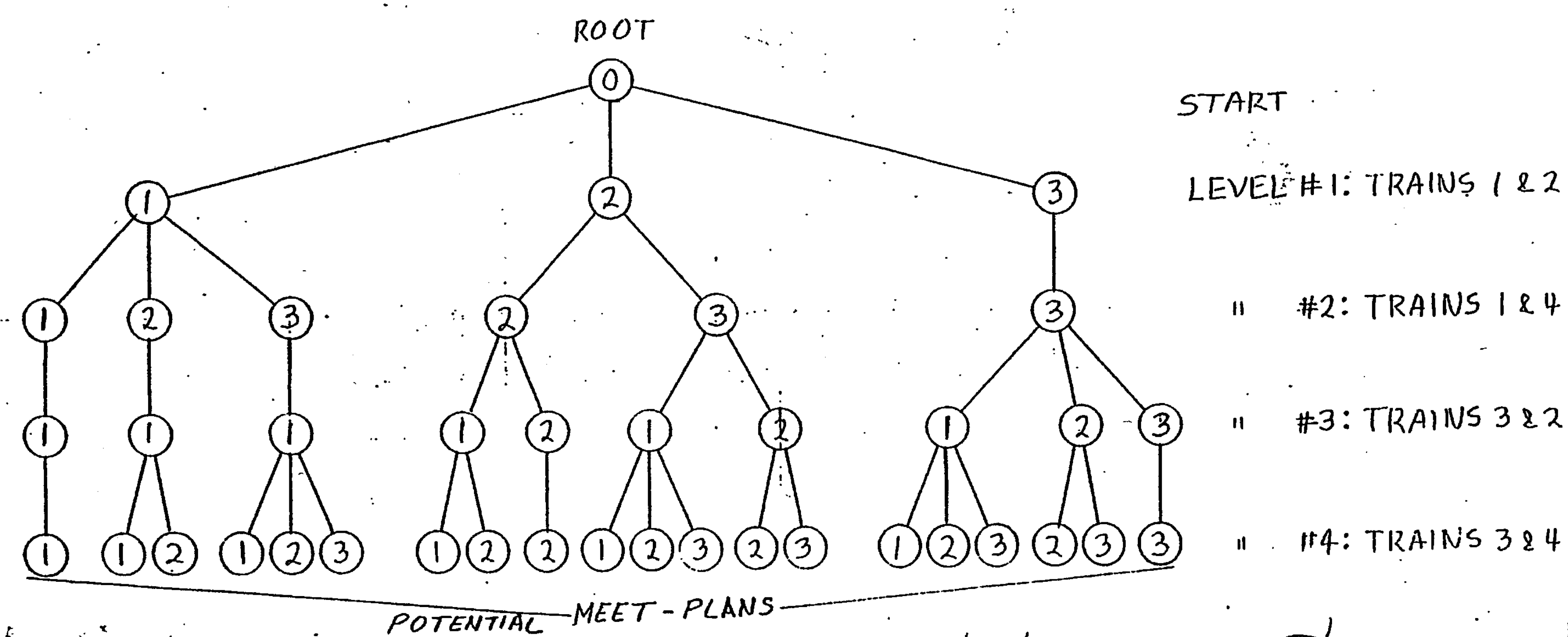
#6 pl 4-23

FIG. 5



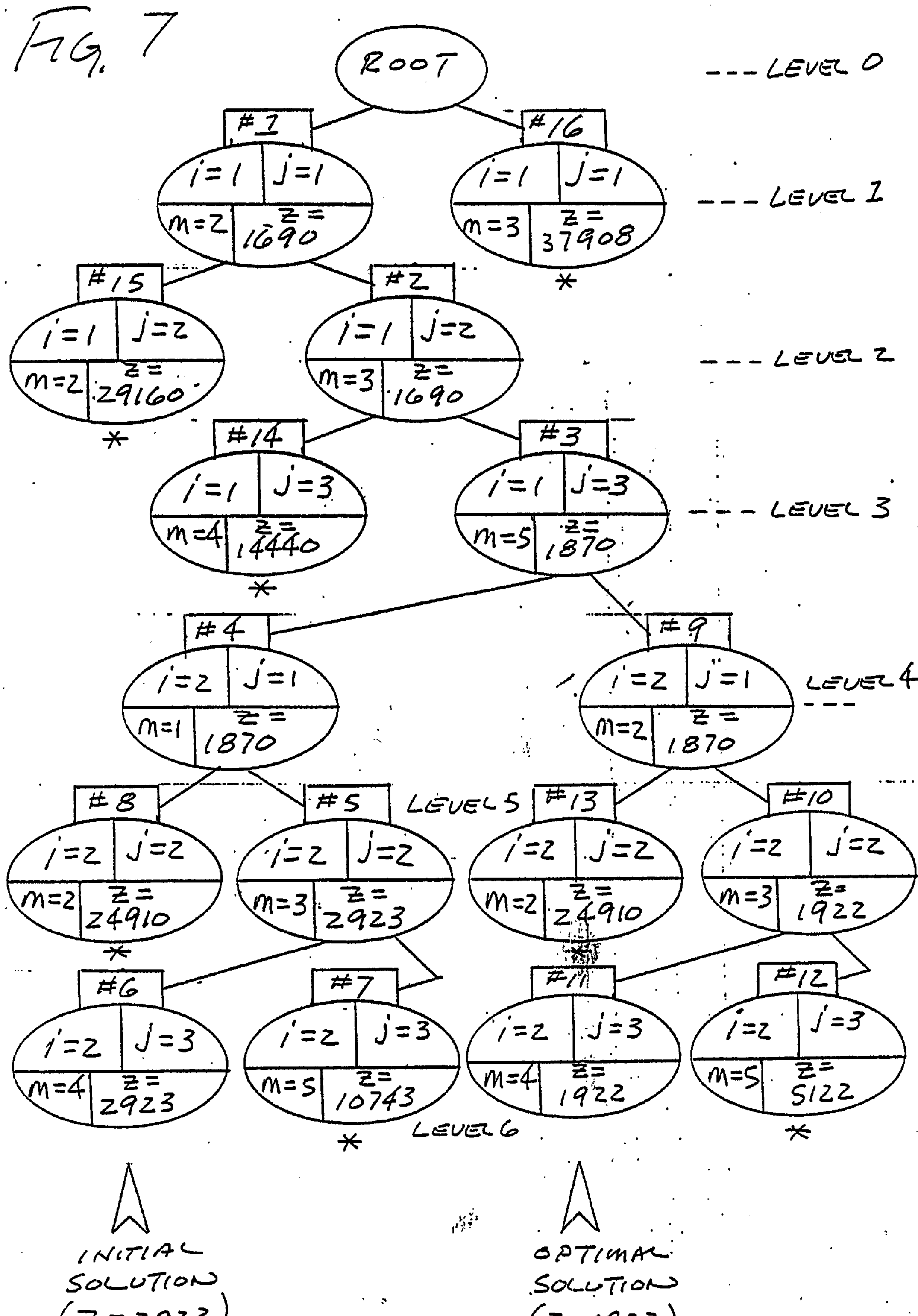
Travel Path Having 3 Meetpoints



Search Tree Representation of Travel Path Having 3 Meetpoints

Approved [illegible] 9 July 92

FIG. 7



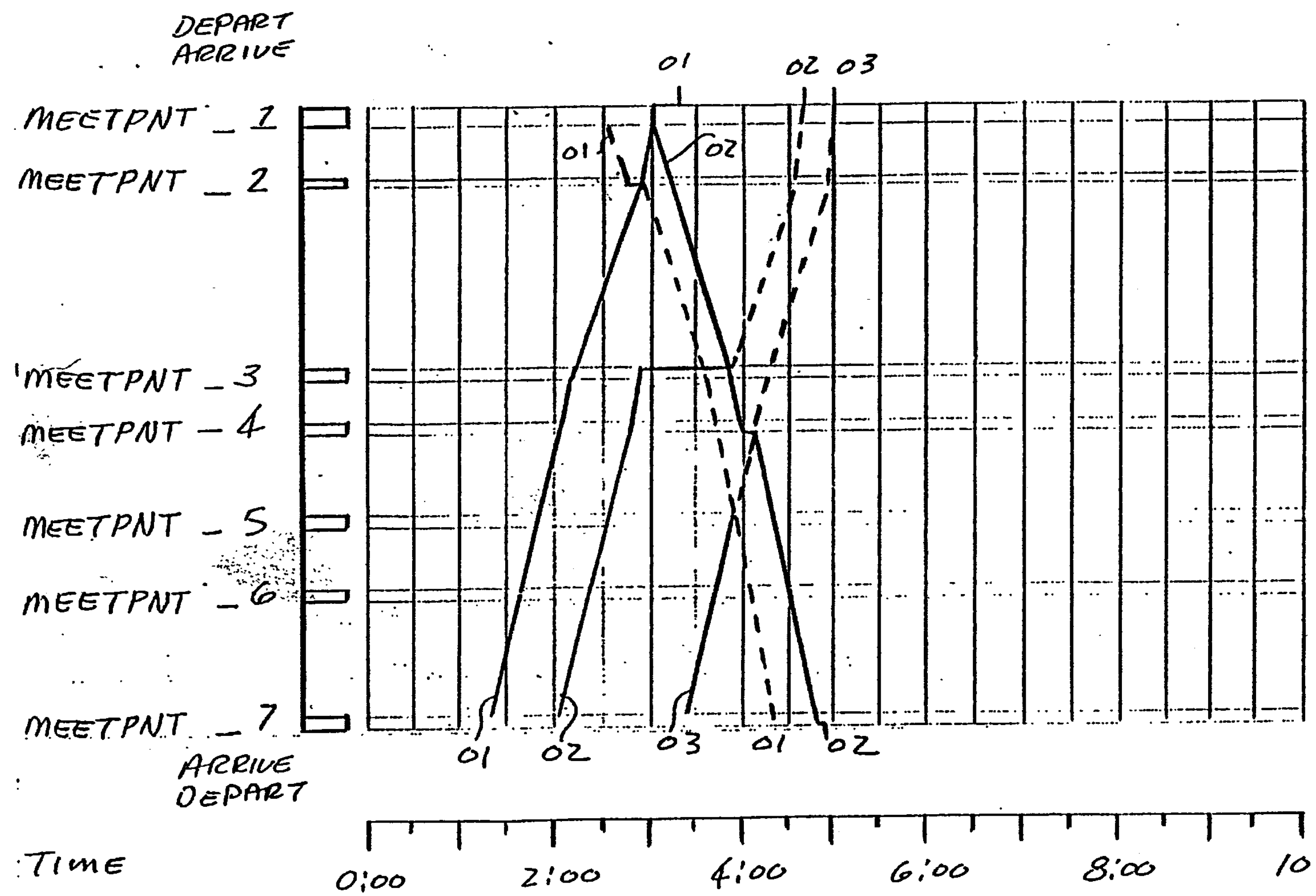
Nodes Enumerated Using Branch-and-Bound method Of Implicit Enumeration Algorithm

Approved
BA
9 July 92

Approved
TSA
9 July 92

Time-Distance Diagram of
Initial Feasibility Plan

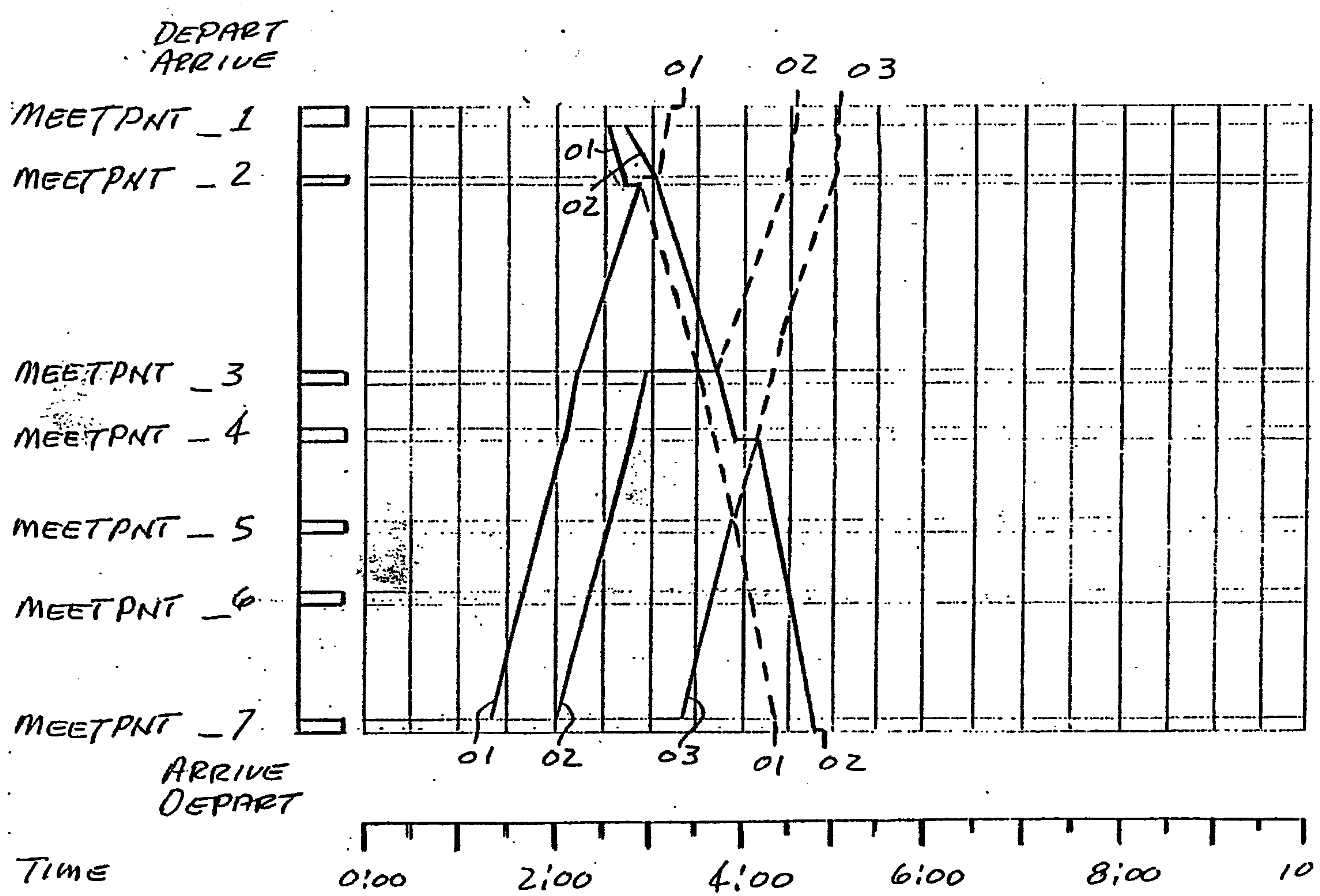
FIG. 8



Approved
3
7 Jul 92

Time-Distance Diagram of Optimal Feasibility Plan

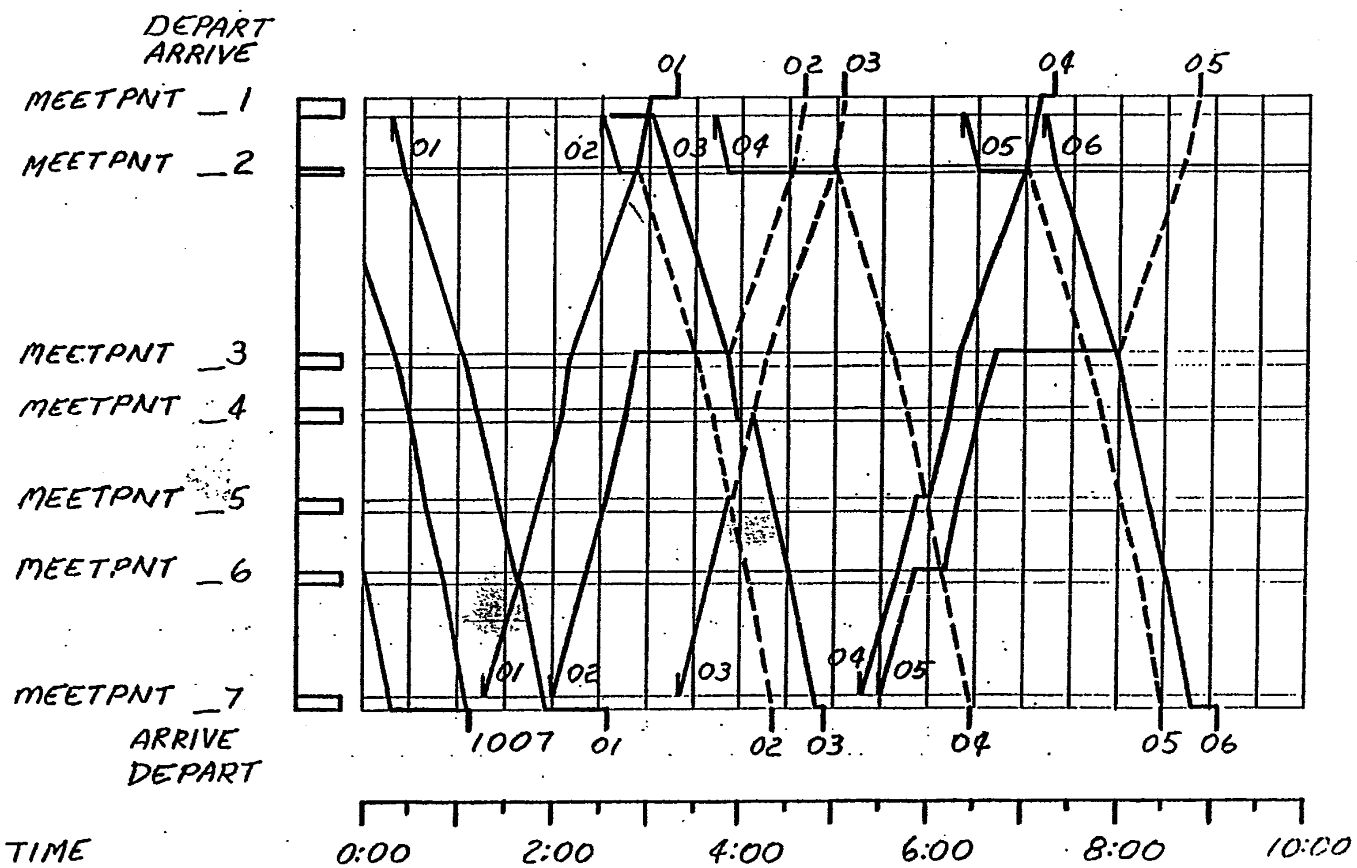
FIG. 9



Approved TJA 7 July 92

Time-Distance Diagram Of Initial Meet-Pass Plan

Fig. 12



Approved
3A
7 Jul 92

Time-Distance Diagram
Of Optimal Meet-Pass Plan
Using One-Meet-shift
Local Improvement

FIG. 13

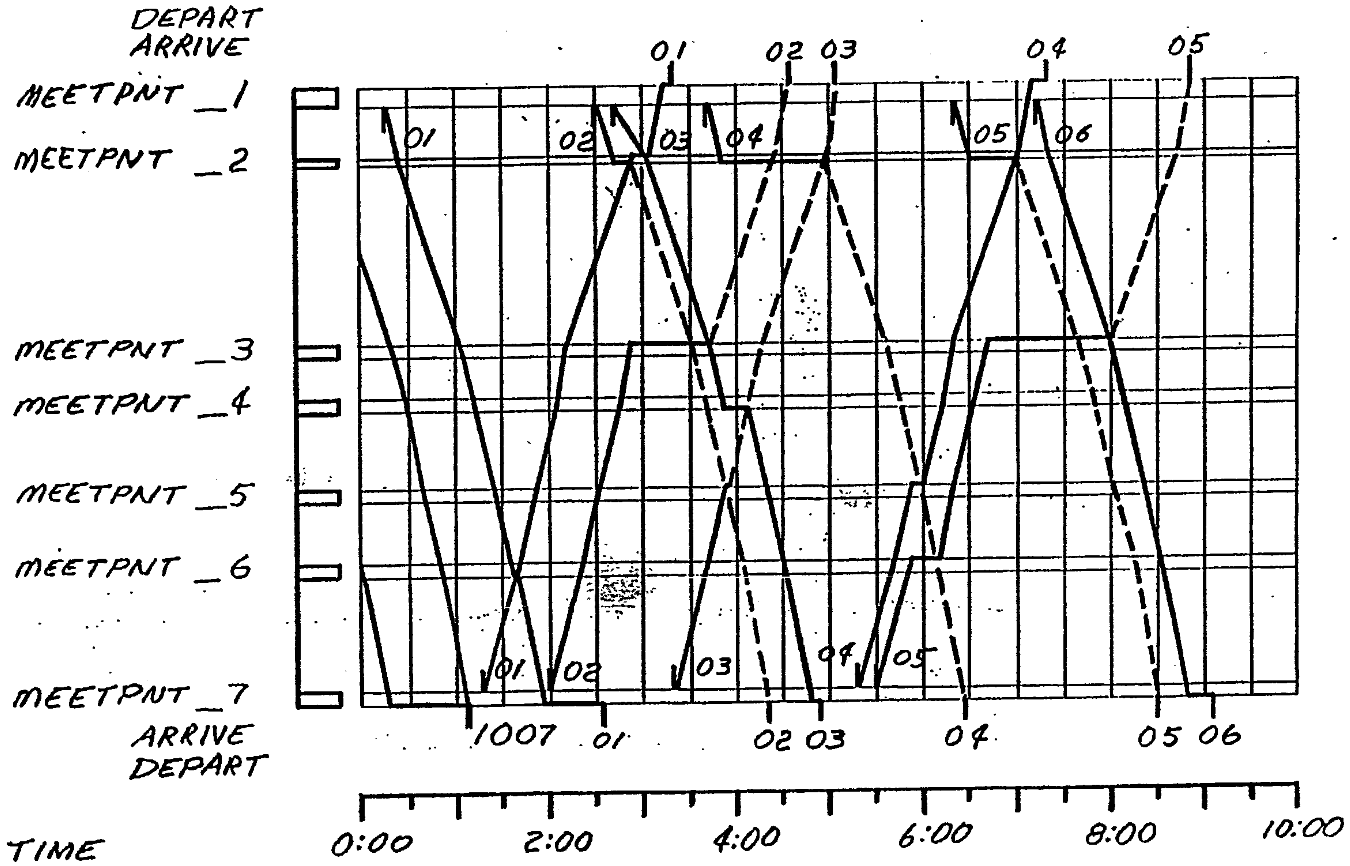
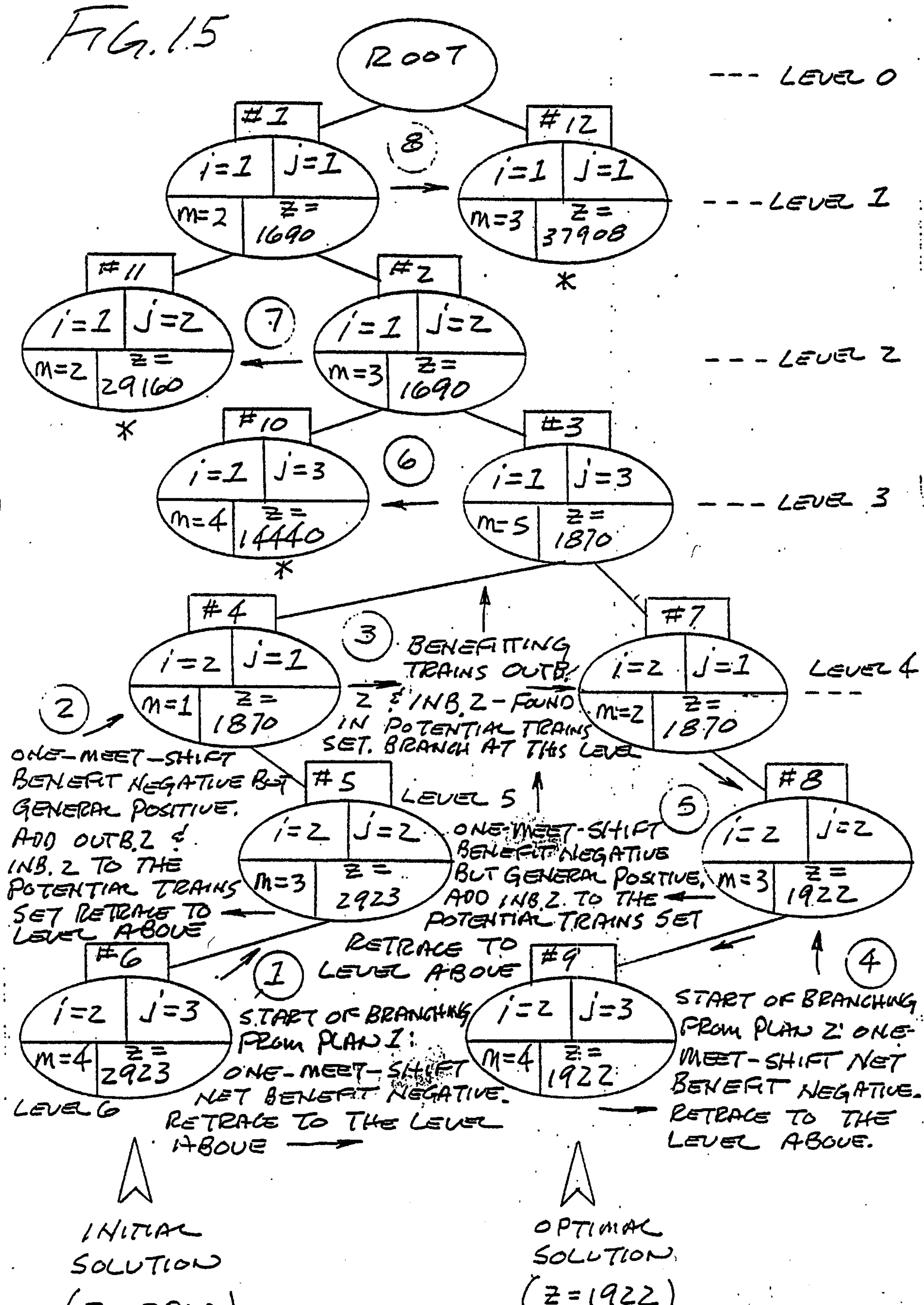


FIG. 15



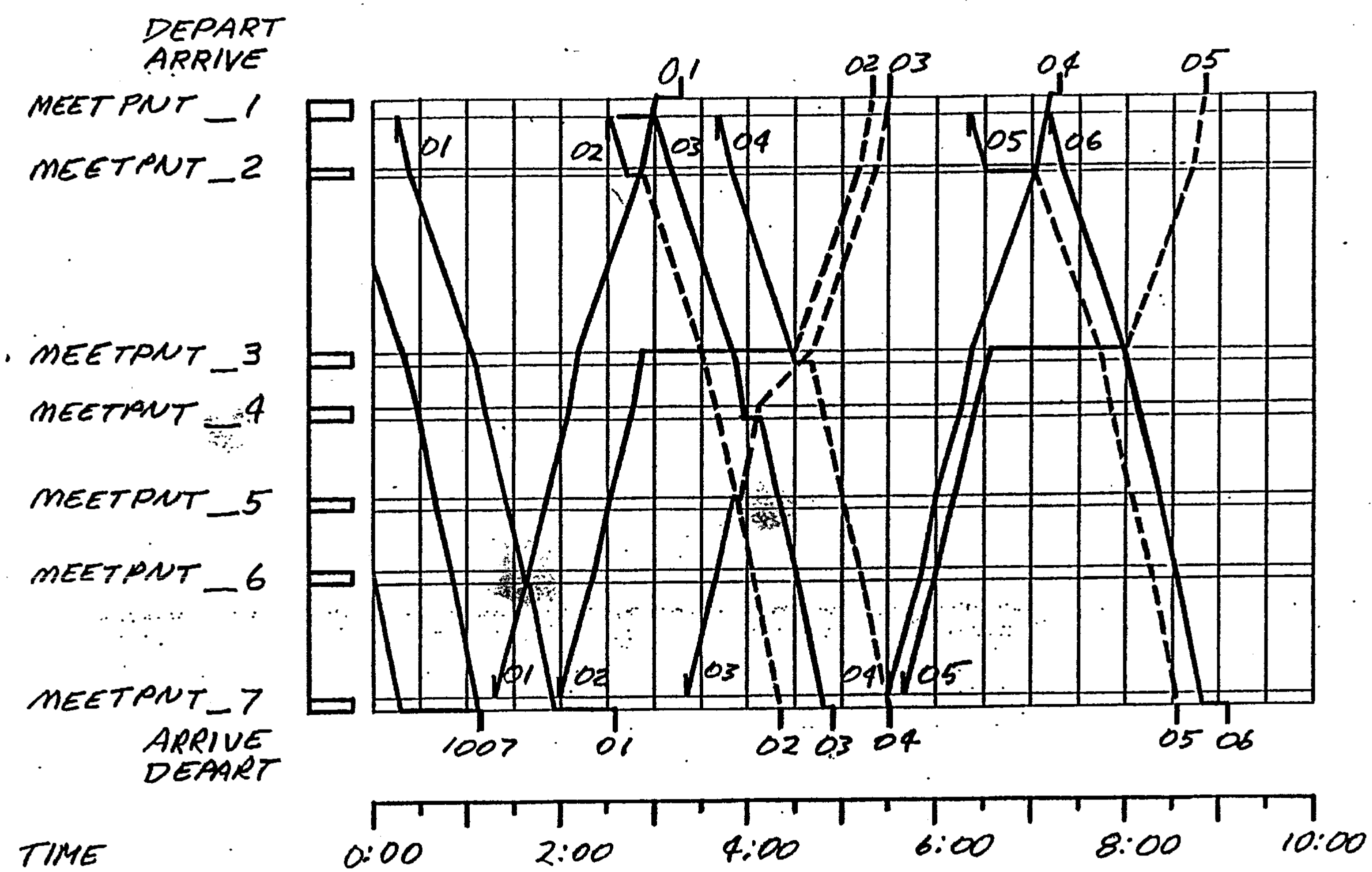
Nodes Enumerated Using the Branch-and-Band Method of the Lower-Band Exact Pruning Algorithm

Approved TSA 1 Jul 92

Approved TSA 7 Jul 92

Time - Distance Diagram
Of an Initial Meet-Pass Plan

FIG. 16



Approved
JSA
9 Jul 92

FIG. 17

Time—Distance Diagram
of an Optimal Meet-Pass Plan
Using Lower-Bound Based
Pruning Algorithm

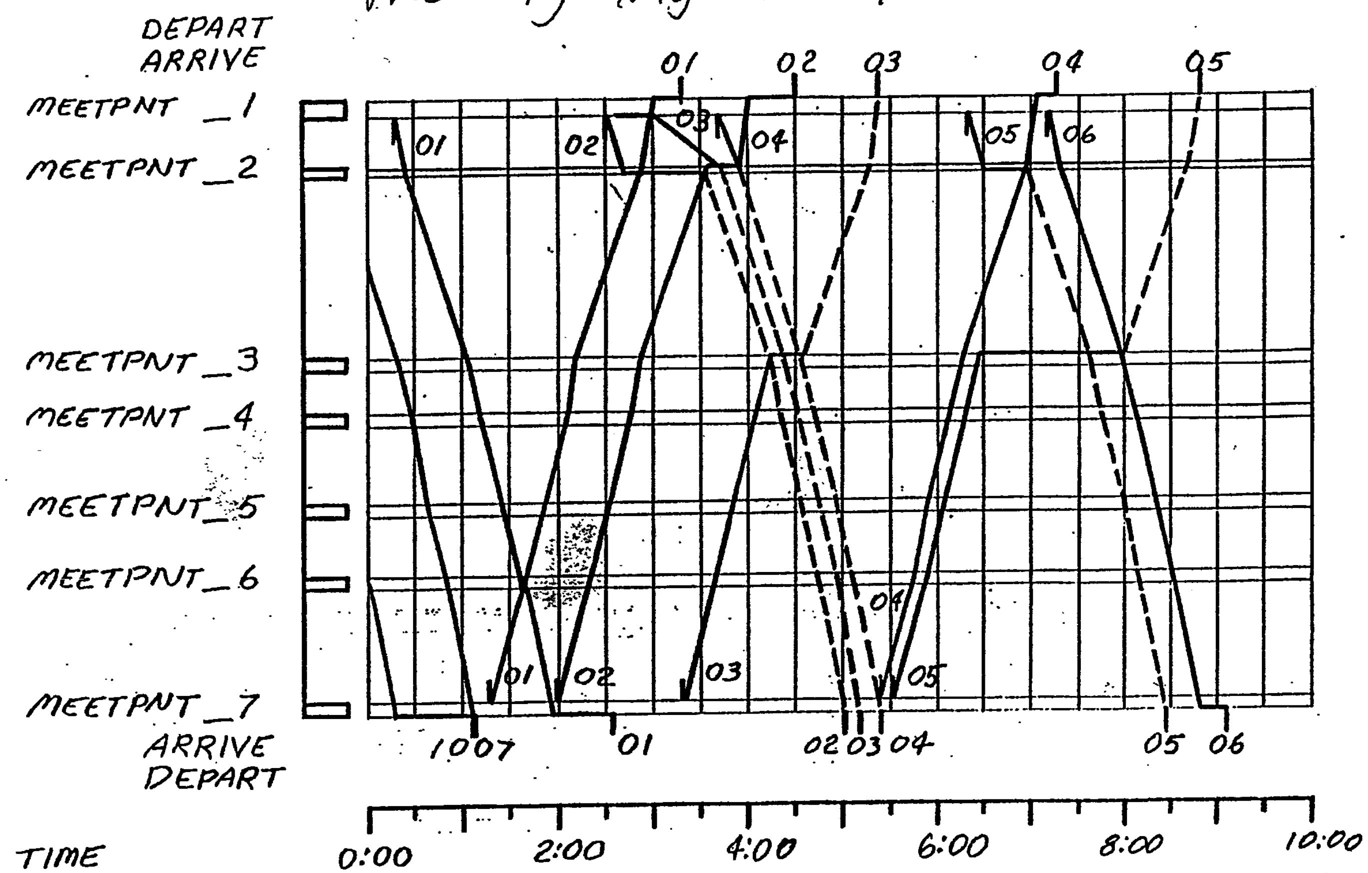
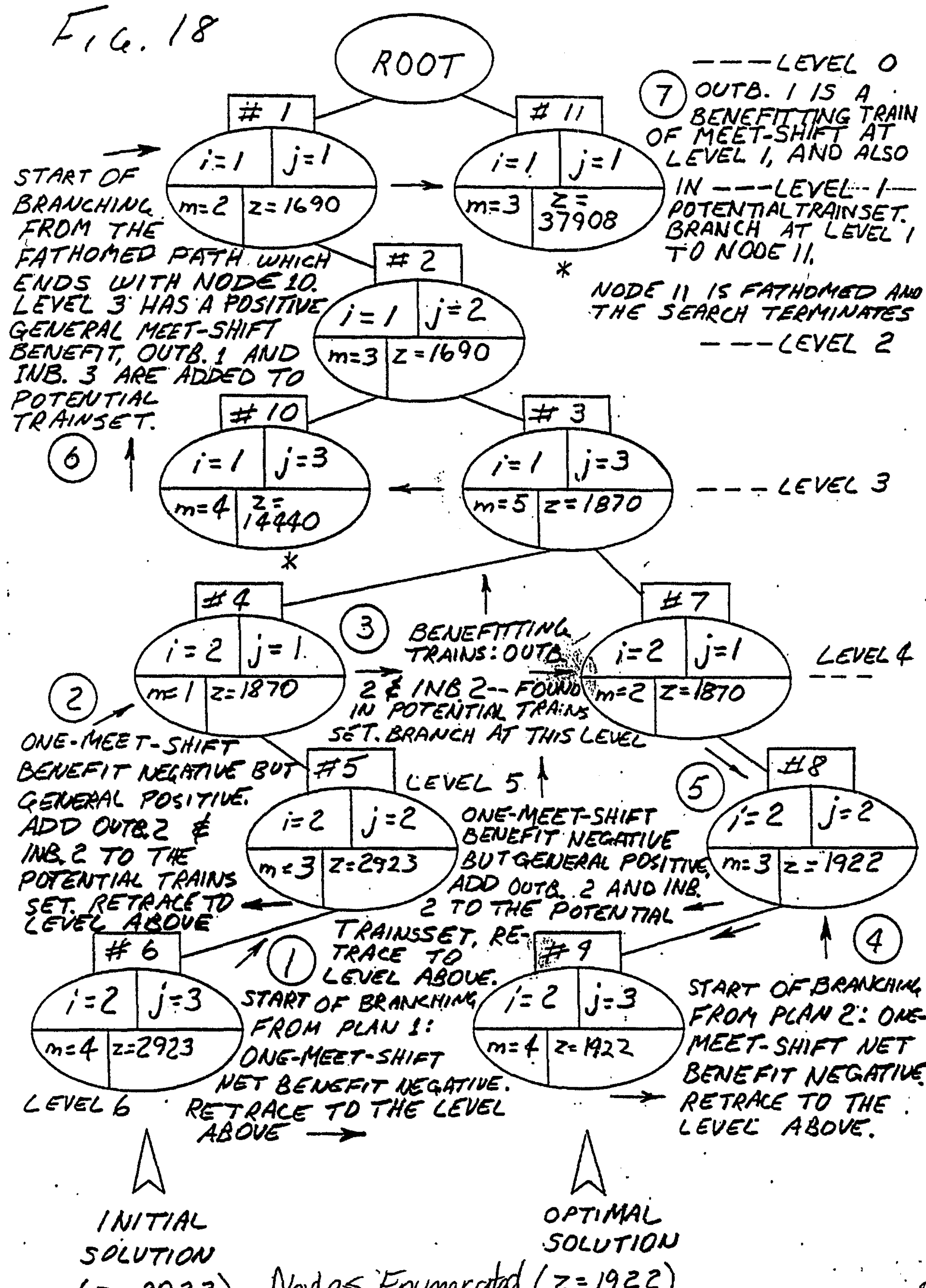


Fig. 18



(z=2923) Nodes Enumerated (z=1922)
Using the Branch-and-Bound Method
of the Accelerated Heuristic Lower-Bound
Based Algorithm

Approved TSA 9 Jul 92

Transaction History Date 1992-04-08
Date information retrieved from USPTO Patent Application Information Retrieval (PAIR) system records at www.uspto.gov

#6

ARRHYTHMIA RESEARCH TECHNOLOGY, INC., Plaintiff-Appellant, v. CORAZONIX CORPORATION, Defendant-Appellee.

91-1091

UNITED STATES COURT OF APPEALS FOR THE FEDERAL CIRCUIT

1992 U.S. App. LEXIS 4202

March 12, 1992, Decided

PRIOR HISTORY: [*1] Appealed from: U.S. District Court for the Northern District of Texas. Judge Tolle. Judge Fish

DISPOSITION: REVERSED AND REMANDED

COUNSEL: John F. Flannery, Fitch, Even, Tabin & Flannery, of Chicago, Illinois, argued for plaintiff-appellant. With him on the brief was Robert J. Fox.
Robert W. Turner, Jones, Day, Reavis & Pogue, of Dallas, Texas, argued for defendant-appellee. With him on the brief was John E. Vick, Jr., Hubbard, Thurman, Tucker & Harris, of Dallas, Texas.

JUDGES: Before NEWMAN, LOURIE, and RADER, Circuit Judges.

OPINIONBY: NEWMAN

OPINION: NEWMAN, Circuit Judge.

Arrhythmia Research Technology, Inc. appeals the grant of summary judgment by the United States District Court for the Northern District of Texas n1 declaring United States Patent No. 4,422,459 to Michael B. Simson (the '459 or Simson patent) invalid for failure to claim statutory subject matter under 35 U.S.C. @ 101. The court did not decide the question of infringement.

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n1 Arrhythmia Research Technology, Inc. v. Corazonix Corp., No. CA 3-88-1745-AJ (N.D. Tex. October 3, 1990), reconsid. denied (November 8, 1990) (Order); appeal authorized (November 9, 1990) (Order).

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We conclude that the claimed subject matter is statutory in terms of section 101. The judgment of invalidity on this ground is reversed.

The Simson Invention

The invention claimed in the '459 patent is directed to the analysis of electrocardiographic signals in order to determine certain characteristics of the heart function. In the hours immediately after a heart attack (myocardial infarction) the victim is particularly vulnerable to an acute type of heart arrhythmia known as ventricular tachycardia. Ventricular tachycardia leads

quickly to ventricular fibrillation, in which the heart ceases effectively to pump blood through the body. Arrhythmia Research states that 15-25% of heart attack victims are at high risk for ventricular tachycardia. It can be treated or prevented with certain drugs, but these drugs have undesirable and sometimes dangerous side effects. Dr. Simson, a cardiologist, sought a solution to the problem of determining which heart attack victims are at high risk for ventricular tachycardia, so that these persons can be carefully monitored and appropriately treated.

Heart activity is monitored by means of an electrocardiograph device, whereby electrodes attached [*3] to the patient's body detect the heart's electrical signals in accordance with the various phases of heart activity. The signals can be displayed in wave form on a monitor and/or recorded on a chart. It was known that in patients subject to ventricular tachycardia certain anomalous waves having very low amplitude and high frequency, known as "late potentials," appear toward the end of the QRS n2 segment of the electrocardiographic signal, that is, late in the ventricular contraction cycle. Dr. Simson's method of detecting and measuring these late potentials in the QRS complex, and associated apparatus, are the subject of the '459 patent.

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n2 According to Arrhythmia Research, the QRS complex lasts about one tenth of a second and arises from the depolarization of the ventricles prior to contraction.

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The '459 patent specification describes these procedures. Certain of the heart attack patient's electrocardiographic signals, those obtained from electrodes designated as X, Y, and Z leads, are converted from analog to digital [*4] values, and a composite digital representation of the QRS segment is obtained by selecting and averaging a large number of the patient's QRS waveforms. The anterior portion of the composite QRS waveform is first isolated, and then processed by a digital high pass filter in reverse time order; that is, backwards. This step of reverse time order filtering is described as the critical feature of the

Simson invention, in that it enables detection of the late potentials by eliminating certain perturbations that obscure these signals. The root mean square of the reverse time filtered output is then calculated, as described in the specification, to determine the average magnitude of the anterior portion of the QRS complex. Comparison of the output, which is measured in microvolts, with a predetermined level of high frequency energy, indicates whether the patient is subject to ventricular tachycardia. That is, if the root mean square magnitude is less than the predetermined level, then low amplitude, high frequency late potentials have been shown to be present, indicating a higher risk of ventricular tachycardia. If the root mean square value is greater than the predetermined level, high [*5] risk for ventricular tachycardia is not indicated.

Certain steps of the invention are described as conducted with the aid of a digital computer, and the patent specification sets forth the mathematical formulae that are used to configure (program) the computer. The specification states that dedicated, specific purpose equipment or hard wired logic circuitry can also be used.

The district court held that the method and apparatus claims of the Simson patent are directed to a mathematical algorithm, and thus do not define statutory subject matter. Claim 1 is the broadest method claim:

1. A method for analyzing electrocardiograph signals to determine the presence or absence of a predetermined level of high frequency energy in the late QRS signal, comprising the steps of:

converting a series of QRS signals to time segments, each segment having a digital value equivalent to the analog value of said signals at said time;

applying a portion of said time segments in reverse time order to high pass filter means;

determining an arithmetic value of the amplitude of the output of said filter; and

comparing said value with said predetermined level.

Claim 7 is a representative apparatus claim: [*6]

7. Apparatus for analyzing electrocardiograph signals to determine the level of high frequency energy in the late QRS signal comprising:

means for converting X, Y, and Z lead electrocardiographic input signals to digital valued time segments;

means for examining said X, Y, and Z digital valued time segments and selecting therefrom the QRS waveform portions thereof;

means for signal averaging a multiplicity of said selected QRS waveforms for each of said X, Y, and Z inputs and providing composite, digital X, Y, and Z QRS wave forms;

high pass filter means;

means for applying to said filter means, in reverse time order, the anterior portion of each said digital X, Y, and Z waveform; and

means for comparing the output of said filter means with a predetermined level to obtain an indication of the presence of a high frequency, low level, energy component in the filter output of said anterior portions.
The Patent and Trademark Office had granted the patent without questioning that its claims were directed to statutory subject matter under @ 101.

35 U.S.C. @ 101

Whether a claim is directed to statutory subject matter is a question of law. Although determination of this question may [*7] require findings of underlying facts specific to the particular subject matter and its mode of claiming, in this case there were no disputed facts material to the issue. Thus we give plenary review to the question, with appropriate recognition of the burdens on the challenger of a duly issued United States patent. See 35 U.S.C. @ 282 (duly issued patent is presumed valid); Interconnect Planning Corp. v.

Feil, 774 F.2d 1132, 1139, 227 USPQ 543, 548, (Fed. Cir. 1985) (statutory presumption of validity is based in part on recognition of the expertise of patent examiners).

A new and useful process or apparatus is patentable subject matter, as defined in 35 U.S.C. @ 101:

Whoever invents or discovers any new and useful process, machine, manufacture, or composition of matter, or any new and useful improvement thereof, may obtain a patent therefor, subject to the conditions and requirements of this title.
The Supreme Court has observed that Congress intended section 101 to include "anything under the sun that is made by man." Diamond v. Chakrabarty, 447 U.S. 303, 309, 206 USPQ 193, 197 (1980),

Funk Bros. Seed Co. v. Kalo Inoculant Co., 333 U.S. 127, 134-35 (1948) (Frankfurter, J., concurring). When attempting to enforce a legal standard embodied in broad, vague, nonstatutory terms, the courts have floundered.

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n1 See, e.g., In re Christensen, 478 F.2d 1392, 1396, 178 USPQ 35 (CCPA 1973) (Rich, J., concurring) ("The Supreme Court in Benson appears to have held that claims drafted in such terms are not patentable -- for what reason remaining a mystery."), overruled in part by In re Taner, 681 F.2d 787, 214 USPQ 678 (1982); In re Johnston, 502 F.2d 765, 773, 183 USPQ 172, 179 (CCPA 1974) (Rich, J, dissenting) ("I am probably as much -- if not more -- confused by the wording of the Benson opinion as many others."); rev'd, Dann v. Johnston, 425 U.S. 219 (1976); In re Chatfield, 545 F.2d 152, 157, 191 USPQ 730, 735 (CCPA 1976) (Nonstatutory claims are "drawn to mathematical problem-solving algorithms or to purely mental steps."), cert. denied, Dann v. Noll, 434 U.S. 875 (1977). [*31]

n2 The Court in Diamond v. Diehr, 450 U.S. 175 (1981), expressly recognized that the term algorithm "is subject to a variety of definitions." 450 U.S. at 186 n.9. Even Benson's definition for "algorithm" creates legal problems. For instance, the Benson-Tabbot algorithm worked with numbers, but "solved" a "mathematical problem" only in a very loose sense. Rather the Benson-Tabbot algorithm translated symbols from one numerical system to another. Cf. In re Toma, 575 F.2d 872, 197 USPQ 852 (CCPA 1978) (Using a digital computer to translate technical languages was not an algorithm.); In re Freeman, 573 F.2d 1237, 197 USPQ 464 (CCPA 1978) (Using computer to transcribe alphanumeric characters was not an algorithm.).

Moreover some problems, even if expressed in mathematical terms, are not mathematical problems. Mathematics, like a language, is a form of expression. The operation of a machine, the generation of electricity, the reaction of two chemicals, a baseball batter's swing, a satellite's orbit -- all are within the descriptive power of mathematics. The Court of Customs and Patent Appeals recognized this axiomatic point:

However, some mathematical algorithms . . . represent ideas or mental processes and are simply logical vehicles for communicating possible solutions to complex problems.

In re Meyer, 688 F.2d 789, 794, 215 USPQ 193, 197 (CCPA 1982). No wonder the Benson rule is confusing when electrical, chemical, or mechanical processes escape scrutiny when expressed in written language, but become suspect when expressed in the mathematical language. In In re Grams, 888 F.2d 835, 12 USPQ2d 1824 (Fed. Cir. 1989), for instance, a medical diagnostic process was considered an unpatentable "mathematical algorithm" even though it did not present, or propose a solution to, a mathematical problem at all.

By strictly limiting Benson, the Supreme Court signalled a change in the focus for patentability from the algorithm rule to the statutory standards of the Patent Act. The Supreme Court confined Benson to a narrow proposition which certainly does not preclude patentability of the [*41] '459 patent's heart attack risk detection process.

The '459 Patent

The '459 patent discloses an apparatus and a method for analyzing electrocardiograph signals to detect heart attack risks. The apparatus is a machine and is covered by the Iwahashi rule. The method converts an analog signal to a digital signal which passes, in reverse time order, through the mathematical equivalent of a filter. The filtered signal's amplitude is then measured and compared with a predetermined value.

The '459 invention manipulates electrocardiogram readings to render a useful result. While many steps in the '459 process involve the mathematical manipulation of data, the claims do not describe a law of nature or a natural phenomenon. Furthermore, the claims do not disclose mere abstract ideas, but a practical and potentially life-saving process. Regardless of whether performed by a computer, these steps comprise a "process" within the meaning of section 101.

The district court granted summary judgment in favor of Corazonix because "the claims of the '459 patent are drawn to a non-statutory mathematical algorithm and, as such, are unpatentable pursuant to the provisions of 35 U.S.C. @ 101." This erroneous [*42] conclusion illustrates the confusion caused by Benson and its progeny.

This conclusion is erroneous for several reasons. First, even if mathematical algorithms are barred from patentability, n3 the '459 patent as a whole does not present a mathematical algorithm. The '459 patent is a method for detecting the risk of a heart attack, not the presentation and proposed solution of a mathematical problem. In Diehr, the Supreme Court viewed the claims as "an industrial process for molding of rubber products," not a mathematical algorithm. 450 U.S. at 186. The '459 patent's claims as a whole disclose a patentable process.

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n3 The Court in Diehr stated: "we concluded that such an algorithm, or mathematical formula, is like a law of nature, which cannot be the subject of a patent." 450 U.S. at 186 (emphasis added). In fact, a mathematical algorithm does not appear in nature at all, but only in human numerical processes.

A law of nature is indeed not patentable, but for reasons unrelated to the meaning of "process." A law of nature, even if a process, is not "new" within the meaning of @ 101. Moreover, in no patentable invention." Flook, 437 U.S. at 594, 198 USPQ at 199.

In accordance with Flook, the claims were analyzed to determine whether the process itself was new and useful, assuming the mathematical algorithm was "well known". Id. at 592, 198 USPQ at 198. As the jurisprudence developed, inventions that were implemented by the mathematically-directed performance of computers were viewed in the context of the practical application to which the computer-generated data were put. The Court of Customs and Patent Appeals observed in In re Bradley, 600 F.2d 807, 811-112, 202 USPQ 480, 485 (CCPA 1979), aff'd by [*11] an equally divided court, sub nom. Diamond v. Bradley, 450 U.S. 381 (1981):

It is of course true that a modern digital computer manipulates data, usually in binary form, by performing mathematical operations, such as addition, subtraction, multiplication, division, or bit shifting, on the data. But this is only how the computer does what it does. Of importance is the significance of the data and their manipulation in the real world, i.e., what the computer is doing. [Emphases in original]

Thus computers came to be generally recognized as devices capable of performing or implementing process steps, or serving as components of an apparatus, without negating patentability of the process or the apparatus. In Diamond v. Diehr the Court explained that non-statutory status under section 101 derives from the "abstract", rather than the "sweeping", nature of a claim that contains a mathematical algorithm. The Court stated:

"While a scientific truth, or the mathematical expression of it, is not a patentable invention, a novel and useful structure created with the aid of knowledge of scientific truth may be."

Diehr, 450 U.S. at 188, 209 USPQ at 8-9, [*12] quoting Mackay Radio & Telegraph Co. v. Radio Corp. of America, 306 U.S. 86, 94, 40 USPQ 199, 202 (1939). The mathematical algorithm in Diehr was the known Arrhenius equation, and the Court held that when the algorithm was incorporated in a useful process, the subject matter was statutory. The Court confirmed the rule that process steps or apparatus functions that entail computer-performed calculations, whether the calculations are described in mathematical symbols or in words, do not of themselves render a claim nonstatutory. Diehr, 450 U.S. at 187, 209 USPQ at 8. The Court clarified its earlier holdings, n4 stating that "it is inappropriate to dissect the claims into old and new elements and then to ignore the presence of the old elements in the [section 101] analysis." Id. at 188, 209 USPQ at 9.

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n4 Although commentators have differed in their interpretations of Benson, Flook, and Diehr, it appears to be quoting S. Rep. No. [*8] 1979, 82d Cong., 2d Sess., 5 (1952); H.R. Rep. No. 1923, 82d Cong., 2d Sess., 6 (1952). There are, however, qualifications to the apparent sweep of this statement. Excluded from patentability is subject matter in the categories of "laws of nature, physical phenomena, and abstract ideas". Diamond v. Diehr, 450 U.S. 175, 185, 209 USPQ 1, 7 (1981). A mathematical formula may describe a law of nature, a scientific truth, or an abstract idea. As courts have recognized, mathematics may also be used to describe steps of a statutory method or elements of a statutory apparatus. The exceptions to patentable subject matter derive from a lengthy jurisprudence, but their meaning was probed anew with the advent of computer-related inventions.

In Gottschalk v. Benson, 409 U.S. 63, 72, 175 USPQ 673, 676 (1972) the Court held that a patent claim that "wholly pre-empts" a mathematical formula used in a general purpose digital computer is directed solely to a mathematical algorithm, n3 and therefore does not define statutory subject matter under section 101. The Court described the mathematical process claimed in Benson as "so abstract [*9] and sweeping as to cover both known and unknown uses of the BCD [binary coded decimal] to pure binary conversion", 409 U.S. at 68, 175 USPQ at 675, citing O'Reilly v. Morse, 56 U.S. (15 How.) 62, 113 (1852) for its holding that the patentee may not claim more than he has actually invented.

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n3 A mathematical algorithm was defined in Benson as a procedure or formula for solving a particular mathematical problem. 409 U.S. at 65, 175 USPQ at 674. As discussed in In re Iwahashi, 888 F.2d 1370, 1374, 12 USPQ2d 1908, 1911 (Fed. Cir. 1989), however, any step-by-step process, whether mechanical, electrical, biological or chemical, involves an "algorithm" in the broader sense of the term.

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In Parker v. Flook, 437 U.S. 584, 591, 198 USPQ 193, 198 (1978) the Court explained that the criterion for patentability of a claim that requires the use of mathematical procedures is not simply whether [*10] the claim "wholly pre-empts" a mathematical algorithm, but whether the claim is directed to a new and useful process, independent of whether the mathematical algorithm required for its performance is novel. Applying these criteria the Court held nonstatutory a method claim for computer-calculating "alarm limits" for use in a catalytic conversion process, on the basis that "once that algorithm is assumed to be within the prior art, the application, considered as a whole, contains generally agreed that these decisions represent evolving views of the Court, and that the reasoning in Diehr not only elaborated on, but in part superseded, that of Benson and Flook. See, e.g., R.L. Gable & J.B. Leaheey, The Strength of Patent Protection for Computer Products, 17 Rutgers Computer & Tech. L.J. 87 (1991); D. Chisum, The Patentability of Algorithms, 47 U. Pitt. L. Rev. 959 (1986).

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The Court thus placed the patentability of computer-aided inventions in the mainstream of the law. The ensuing mode of analysis of such inventions was summarized in In re Meyer, 688 F.2d 789, 795, 215 USPQ 193, 198 (CCPA 1982):
In considering a claim for compliance with 35 U.S.C. 101, it must be determined whether a scientific principle, law of nature, idea, or mental process, which may be represented by a mathematical algorithm, is included in the subject matter of the claim. If it is, it must then be determined whether such principle, law, idea, or mental process is applied in an invention of a type set forth in 35 U.S.C. 101.

The law crystallized about the principle that claims directed solely to an abstract mathematical formula or equation, including the mathematical expression of scientific truth or a law of nature, whether directly or indirectly stated, are nonstatutory under section 101; whereas claims to a specific process or apparatus that is implemented in accordance with a mathematical algorithm will generally satisfy section 101.

In applying this principle to an invention whose process steps or apparatus elements are described at least [*14] in part in terms of mathematical procedures, the mathematical procedures are considered in the context of the claimed invention as a whole. Diehr, 450 U.S. at 188, 209 USPQ at 9. Determination of statutory subject matter has been conveniently conducted in two stages, following a protocol initiated by the Court of Customs and Patent Appeals in In re Freeman, 573 F.2d 1237, 197 USPQ 464 (CCPA 1978); modified after the Court's Flook decision by In re Walter, 618 F.2d 758, 205 USPQ 397 (CCPA 1980); and again after the Court's Diehr decision by In re Abele, 684 F.2d 902, 214 USPQ 682 (CCPA 1982).

This analysis has been designated the Freeman-Walter-Abele test for statutory subject matter. It is first determined whether a mathematical algorithm is recited directly or indirectly in the claim. If so, it is next determined whether the claimed invention as a whole is no more than the algorithm itself; that is, whether the claim is directed to a mathematical algorithm that is not applied to or limited by physical elements or process steps. Such claims are [*15] nonstatutory. However, when the mathematical algorithm is applied in one or more steps of an otherwise statutory process claim, or one or more elements of an otherwise statutory apparatus claim, the requirements of section 101 are met. The court explained in Abele, 684 F.2d at 907, 214 USPQ at 686:

Patentable subject matter [is not limited] to claims in which structural relationships or process steps are defined, limited or refined by the application of the algorithm.

Rather, Walter should be read as requiring no more than that the algorithm be "applied in any manner to physical elements or process steps," provided that its application is circumscribed by more than a field of use limitation or non-essential post-solution activity.

As summarized by the PTO in Ex Parte Logan, 20 USPQ2d 1465, 1468 (PTO Bd. Pat. App. and Interf. 1991), the emphasis is "on what the claimed method steps do rather than how the steps are performed". (Emphases in original)

Although the Freeman-Walter-Abele analysis is not the only test for statutory subject matter, Meyer, 688 F.2d at 796, 215 USPQ at 198, [*16] and this

court has stated that failure to meet that test may not always defeat the claim, In re Grams, 888 F.2d 835, 839, 12 USPQ2d 1824, 1827 (Fed. Cir. 1989), this analytic procedure is conveniently applied to the Simson invention.

Analysis

Arrhythmia Research states that the district court erred in law, and that the combination of physical, mechanical, and electrical steps that are described and claimed in the '459 patent constitutes statutory subject matter. Arrhythmia Research stresses that the claims are directed to a process and apparatus for detecting and analyzing a specific heart activity signal, and do not preempt the mathematical algorithms used in any of the procedures. Arrhythmia Research states that the patentability of such claims is now well established by law, precedent, and practice.

Corazonix states that the claims define no more than a mathematical algorithm that calculates a number. Corazonix states that in Simson's process and apparatus claims mathematical algorithms are merely presented and solved, and that Simson's designation of a field of use and post-solution activity are not essential to the claims and thus do not cure [*17] this defect. Thus, Corazonix states that the claims are not directed to statutory subject matter, and that the district court's judgment was correct.

A. The Process Claims

Although mathematical calculations are involved in carrying out the claimed process, Arrhythmia Research argues that the claims are directed to a method of detection of a certain heart condition by a novel method of analyzing a portion of the electrocardiographically measured heart cycle. This is accomplished by procedures conducted by means of electronic equipment programmed to perform mathematical computation.

Applying the Freeman-Walter-Abele protocol, we accept for the purposes of this analysis the proposition that a mathematical algorithm is included in the subject matter of the process claims in that some claimed steps are described in the specification by mathematical formulae. See In re Johnson, 589 F.2d 1070, 1078, 200 USPQ 199, 208 (CCPA 1979) ("Reference to the specification must be made to determine whether [claimed] terms indirectly recite mathematical calculations, formulae, or equations.") We thus proceed to the second stage of the analysis, to determine whether [*18] the claimed process is otherwise statutory; that is, we determine what the claimed steps do, independent of how they are implemented.

Simson's process is claimed as a "method for analyzing electrocardiograph signals to determine the presence or absence of a predetermined level of high-frequency energy in the late QRS signal". This claim limitation is not ignored in determining whether the subject matter as a whole is statutory, for all of the claim steps are in implementation of this method. The electrocardiograph signals are first transformed from analog form, in which they are obtained, to the corresponding digital signal. These input signals are not abstractions; they are related to the patient's heart function. The anterior portion of the QRS signal is then processed, as the next step, by the procedure known as reverse time order filtration. The digital filter design selected by Dr. Simson for this purpose, known as the Butterworth filter, is one of several known procedures for frequency filtering of digital waveforms. The filtered

signal is further analyzed to determine its average magnitude, as described in the specification, by the root mean square technique. Comparison of [*19] the resulting output to a predetermined level determines whether late potentials reside in the anterior portion of the QRS segment, thus indicating whether the patient is at high risk for ventricular tachycardia. The resultant output is not an abstract number, but is a signal related to the patient's heart activity.

These claimed steps of "converting", "applying", "determining", and "comparing" are physical process steps that transform one physical, electrical signal into another. The view that "there is nothing necessarily physical about 'signals'" is incorrect. In re Taner, 681 F.2d 787, 790, 214 USPQ 678, 681 (CCPA 1982) (holding statutory claims to a method of seismic exploration including the mathematically described steps of "summing" and "simulating from"). The Freeman-Walter-Abele standard is met, for the steps of Simson's claimed method comprise an otherwise statutory process whose mathematical procedures are applied to physical process steps.

It was undisputed that the individual mathematical procedures that describe these steps are all known in the abstract. The method claims do not wholly preempt these procedures, but limit their application [*20] to the defined process steps. In answering the question "What did the applicant invent?", Grams, 888 F.2d at 839, 12 USPQ2d at 1827, the Simson method is properly viewed as a method of analyzing electrocardiograph signals in order to determine a specified heart activity. Like the court in Abele, which was "faced simply with an improved CAT-scan process", 684 F.2d at 909, 214 USPQ at 688, the Simson invention is properly viewed as an electrocardiograph analysis process. The claims do not encompass subject matter transcending what Dr. Simson invented, as in O'Reilly v. Morse, 56 U.S. (15 How.) at 113 (claims covered any use of electric current to transmit characters at a distance); or in Benson, 409 U.S. at 68, 175 USPQ at 675 (use of claimed process could "vary from the operation of a train to verification of driver's licenses to researching the law books for precedents"); or in Grams, 888 F.2d at 840, 12 USPQ2d at 1828 (invention had application to "any complex system, whether it be electrical, mechanical, chemical or biological, or combinations [*21] thereof.")

The Simson claims are analogous to those upheld in Diehr, wherein the Court remarked that the applicants "do not seek to patent a mathematical formula. . . . they seek only to foreclose from others the use of that equation in conjunction with all of the other steps in their claimed process". 450 U.S. at 187, 209 USPQ at 8. Simson's claimed method is similarly limited. The process claims comprise statutory subject matter.

B. The Apparatus Claims

The Simson apparatus for analyzing electrocardiographic signals is claimed in the style of 35 U.S.C. @ 112, paragraph 6, whereby functionally described claim elements are "construed to cover the corresponding structure, material, or acts described in the specification and equivalents thereof". Thus the statutory nature vel non of Simson's apparatus claims is determined with reference to the description in the '459 patent specification. In re Iwahashi, 888 F.2d 1370, 1375, 12 USPQ2d 1908, 1911-12 (Fed. Cir. 1989).

The apparatus claims require a means for converting the electrocardiograph signals from the analog form in which they are generated into digital form. [*22] This means is described in the specification as a specific electronic

device, a conventional analog-to-digital converter. A minicomputer, configured as described in the specification, is the means of calculating composite digital time segments of the QRS waveform. The product is stored, as stated in the specification, in the form of electrical signals. The high pass filter means is described in the specification as the minicomputer configured to perform the function of reverse time order filtration of the anterior portion of the QRS waveform. The specification and drawings show a disc memory unit to store the composite QRS signals, and associated connecting leads to the computer's processing unit. The comparing means is the processing unit configured to perform the specified function of root mean square averaging of the anterior portion of the QRS complex, and comparison of the resulting output with a predetermined level to provide an indication of the presence of late potentials in the electrocardiograph signal.

The Simson apparatus claims thus define "a combination of interrelated means" for performing specified functions. Iwahashi, 888 F.2d at 1375, 12 USPQ2d at 1911. [*23] The computer-performed operations transform a particular input signal to a different output signal, in accordance with the internal structure of the computer as configured by electronic instructions. "The claimed invention . . . converts one physical thing into another physical thing just as any other electrical circuitry would do". In re Sherwood, 613 F.2d 809, 819, 204 USPQ 537, 546 (CCPA 1980), cert. denied, 450 U.S. 994 (1981) (holding statutory claims to an apparatus for analyzing seismic signals including mathematically described means for "sonogramming", "dividing", and "plotting").

The use of mathematical formulae or relationships to describe the electronic structure and operation of an apparatus does not make it nonstatutory. Iwahashi, 888 F.2d at 1375, 12 USPQ2d at 1911. When mathematical formulae are the standard way of expressing certain functions or apparatus, it is appropriate that mathematical terms be used. See W.L. Gore & Assoc., Inc. v. Garlock, Inc., 721 F.2d 1540, 1556, 220 USPQ 303, 315 (Fed. Cir. 1983), cert. denied, 469 U.S. 851 (1984) [*24] (patents are directed to those of skill in the art). See also In re Bernhart, 417 F.2d 1395, 1399, 163 USPQ 611, 616 (CCPA 1969) ("all machines function according to the laws of physics which can be mathematically set forth if known.") That Simson's claimed functions could not have been performed effectively without the speed and capability of electronic devices and components does not determine whether the claims are statutory.

Corazonix argues that the final output of the claimed apparatus (and process) is simply a number, and that Benson and Flook support the position that when the end product is a number, the claim is nonstatutory and can not be saved by claim limitations of the use to which this number is put. However, the number obtained is not a mathematical abstraction; it is a measure in microvolts of a specified heart activity, an indicator of the risk of ventricular tachycardia. That the product is numerical is not a criterion of whether the claim is directed to statutory subject matter. See Meyer, 688 F.2d at 796 n.4, 215 USPQ at 198 n.4 (explaining that so-called "negative rules" of patentability [*25] "were not intended to be separate tests for determining whether a claim positively recites statutory subject matter.")

The Simson apparatus claims satisfy the criteria for statutory subject matter. They are directed to a specific apparatus of practical utility and specified application, and meet the requirements of 35 U.S.C. @ 101.

Conclusion

The judgment of invalidity on the ground that the claimed method and apparatus do not define statutory subject matter is reversed. The cause is remanded for resolution of remaining issues.

Taxable costs in favor of Arrhythmia Research.

REVERSED AND REMANDED

CONCURBY: RADER

CONCUR: RADER, Circuit Judge, concurring.

Nearly twenty years ago, in Gottschalk v. Benson, 409 U.S. 63 (1972), the Supreme Court dealt with a computer process for conversion of binary coded decimals into pure binary numbers was not patentable subject matter. Benson held this mathematical algorithm ineligible for patent protection. 409 U.S. at 65, 71-72. Because computer programs rely heavily on mathematical algorithms, commentators saw dire implications in the Supreme Court's opinion for patent protection of computer [*26] software. For instance, one treatise, citing Benson, stated:

[A] recent Supreme Court decision seemingly eliminated patent protection for computer software.

Donald S. Chisum, Patents @ 1.01 (1991); see also id. at @ 1.03[6].

The court upholds the '459 patent by applying a permutation of the Benson algorithm rule. In reaching this result, the court adds another cord to the twisted knot of precedent encircling and confining the Benson rule. While fully concurring in the court's result and commending its ability to trace legal strands through the tangle of post-Benson caselaw, I read later Supreme Court opinions to have cut the Gordian knot. The Supreme Court cut the knot by strictly limiting Benson.

Relying on the language of the patent statute, the Supreme Court in Diamond v. Diehr, 450 U.S. 175 (1981), turned away from the Benson algorithm rule. Thus, I too conclude that the '459 patent claims patentable subject matter -- not on the basis of a two-step post-Benson test, but on the basis of the patentable subject matter standards in title 35. Rather than perpetuate a non-statutory standard, I would find that the [*27] subject matter of the '459 patent satisfies the statutory standards of the Patent Act.

I.

The questions presented by this case are whether the '459 patent claims a process and apparatus within the meaning of 35 U.S.C. @ 101 (1988). Section 101 states:

Whoever invents or discovers any new and useful process, machine, manufacture, or composition of matter, or any new and useful improvement thereof, may obtain a patent therefor, subject to the conditions and requirements of this title.

According to this language, "any" invention or discovery within the four broad

categories of "process, machine, manufacture, or composition of matter" is eligible for patent protection. "Any" is an expansive modifier which broadens the sweep of the categories. See Diamond v. Chakrabarty, 447 U.S. 303, 308-09 (1980). The language of section 101 conveys no implication that the Act extends patent protection to some subcategories of machines or processes and not to others.

The limits on patentable subject matter within section 101 focus not on subcategories of machines or processes, but on characteristics, such as newness and usefulness. Section 101 also specifies that, [*28] in addition to newness and usefulness, an invention or discovery must satisfy other "conditions and requirements." These other "conditions and requirements" encompass characteristics like nonobviousness under 35 U.S.C. @ 103 (1988), or requirements like those in 35 U.S.C. @ 112 (1988). In other words, the language of the Patent Act does not suggest that the words "machine" or "process" carry limitations outside their ordinary meaning. See Diehr, 450 U.S. at 182 ("Unless otherwise defined, 'words will be interpreted as taking their ordinary, contemporary, common meaning.'"). Rather the Act, by its terms, extends patent protection to "any" machine or process which satisfies the other conditions of patentability.

II.

In Benson, the Supreme Court encountered the question of whether a method for converting binary-coded decimals, which was useful in programming digital computers, was a patentable "process" under section 101. 409 U.S. at 64. The Court, by reading a limitation not found in the statute into the term "process," determined the method of conversion did not satisfy section 101.

In Parker v. Flook, 437 U.S. 584 (1978), [*29] the Court followed Benson. Flook claimed a method for updating alarm limits during catalytic conversion of hydrocarbons. The Court found Flook's method involving mathematical calculations -- though applied to a post-solution use -- unpatentable. Flook, 437 U.S. at 590. Flook clearly limited the Benson rule to mathematical formulae and mathematical algorithms. Id. at 585, 587, 589, 590, 591, 592, 594, 595. By mixing the terms "formula" and "algorithm," 437 U.S. at 585-86, however, Flook further confused the meaning of "mathematical algorithm." As used by Benson, that term meant "a procedure for solving a given type of mathematical problem." 409 U.S. at 65. Thus, an "algorithm" required both a mathematical problem and a solution procedure. A "formula" does not present or solve a mathematical problem, but merely expresses a relationship in mathematical terms. A "formula," even under Benson's definition, is not an algorithm.

In the wake of Benson, the Court of Customs and Patent Appeals struggled to implement the algorithm rule. n1 Much of [*30] the difficulty sprang from the obscurity of the terms invoked to preclude patentability -- terms like "law of nature," "natural phenomena," "formulae," or "algorithm." n2 Benson, 409 U.S. at 65, 67; Flook, 437 U.S. at 593. In the context of a product's subject matter patentability, Justice Frankfurter discussed this analytical difficulty:

It only confuses the issue, however, to introduce such terms as "the work of nature" and the "laws of nature." For these are vague and malleable terms infected with too much ambiguity and equivocation. Everything that happens may be deemed "the work of nature," and any patentable composite exemplifies in its properties "the laws of nature." Arguments drawn from such terms for

ascertaining patentability could fairly be employed to challenge almost every patent.

- - - - - - - - - - - - - - - - - - -End Footnotes- - - - - - - - - - - - - - - - -[*32]

At length, in In re Freeman, 573 F.2d 1237, 197 USPQ 464 (CCPA 1978) as modified by In re Walter, 618 F.2d 758, 205 USPQ 397 (CCPA 1980), the Court of Customs and Patent Appeals settled on a two-step test to detect unpatentable algorithms under the Benson rule:

First, the claim is analyzed to determine whether a mathematical algorithm is directly or indirectly recited. Next, if a mathematical algorithm is found, the claim as a whole is further analyzed to determine whether the algorithm is "applied in any manner to physical elements or process steps," and, if it is, it "passes muster under @ 101."

In re Pardo, 684 F.2d 912, 915, 214 USPQ 673, 675-76 (CCPA 1982) (citing In re Abele, 684 F.2d 902, 214 USPQ 682 (CCPA 1982)). Walter adopted Flook's implicit limitation of the Benson rule to "mathematical algorithms." 618 F.2d at 764-65 n.4. Like Flook, however, Walter confused "mathematical algorithms" with calculations, formulas, and mathematical procedures generally. Id.

Although downstream from Benson, [*33] this Freeman-Walter fork hid some of the same unnavigable cross-currents. In the first place, the term "mathematical algorithm" remained vague. Without a statutory anchor, this term was buffeted by every judicial wind until its course was indiscernible. The obscurity of the term "mathematical algorithm" is evident in two cases. In Pardo, 684 F.2d 912, the court narrowly limited "mathematical algorithm" to the execution of formulas with given data. In the same year, the court in In re Meyer, 688 F.2d 789, 215 USPQ 193 (CCPA 1982), sweepingly interpreted the same term to include any mental process that can be represented by a mathematical algorithm.

The second part of the test had similar uncertainties. The test did not suggest how many physical steps a claim must take to escape the fatal "mathematical algorithm" category. In Abele, 684 F.2d 902, the court upheld claims applying "a mathematical formula within the context of a process which encompasses significantly more than the algorithm alone." Id. at 909. Thus, the court apparently made compliance with [*34] the two-part test a function of the "significance" of additions to the algorithm -- hardly a predictable standard.

The Court of Customs and Patent Appeals later clarified that the two-part algorithm is not the exclusive test for detecting unpatentable subject matter. Meyer, 688 F.2d at 796. Indeed, the court abandoned the two-step test in In re Taner, 681 F.2d 787, 214 USPQ 678 (CCPA 1982).

With the advent of the Court of Appeals for the Federal Circuit, this court continued to grapple with the inherent vagueness of the two-part test for unpatentable algorithms. See In re Grams, 888 F.2d 835, 12 USPQ2d 1824 (Fed. Cir. 1989); In re Iwahashi, 888 F.2d 1370, 12 USPQ2d 1980 (Fed. Cir. 1989). At one point, this court clarified that failure to satisfy the second prong of the two-part test "does not necessarily doom the claim." Grams, 888 F.2d at 839. Instead this court recommended asking the broader question of "What did applicants invent?" in the context of the claim and its supporting disclosure. Id. At another point in the [*35] same opinion, this court put the central question in terms of whether "the claim in essence covers only the algorithm." Id. at 837.

Recognizing the obscurity of "algorithm," this court in Iwahashi attempted to "take the mystery out of the term":

We point out once again that every step-by-step process, be it electronic or chemical or mechanical, involves an algorithm in the broad sense of the term. Since @ 101 expressly includes processes as a category of inventions which may be patented and @ 100(b) further defines the word "process" as meaning "process, art or method, and includes a new use of a known process, machine, manufacture, composition of matter, or material," it follows that it is no ground for holding a claim is directed to nonstatutory subject matter to say it includes or is directed to an algorithm. This is why the proscription against patenting has been limited to mathematical algorithms . . . .

888 F.2d at 1374 (emphasis in original). Because the Iwahashi claims as a whole described a machine or a manufacture (which fit within section 101 without regard to the meaning of "process"), this court in [*36] Iwahashi did not have occasion to resolve conflicts over the legal bounds of "mathematical algorithm."

In sum, the two-part test was cast in the crucible of confusion created by Benson. If the Benson algorithm rule was the last and binding word on the meaning of "process" under section 101, this court would be obligated to follow -- regardless of any imprecision or ambiguity. The Supreme Court, however, has already shown another reading of the Patent Act.

III.

In Diehr, the Supreme Court adopted a very useful algorithm for determining patentable subject matter, namely, following the Patent Act itself. Diehr upheld claims to a process for curing synthetic rubber which included use of a mathematical computer process. After setting forth the procedural history of the case, the Supreme Court stated:

In cases of statutory construction, we begin with the language of the statute.

Diehr, 450 U.S. at 182. Perhaps with an eye to the attempts to apply the Benson rule, the Court then noted:

In dealing with the patent laws, we have more than once cautioned that "courts 'should not read into the patent laws limitations and conditions [*37] which the legislature has not expressed.'"

Id. (citations omitted). Indeed Congress has never stated that section 101's term "process" excludes certain types of algorithms. Therefore, as Diehr commands, this court should refrain from employing judicially-created tests to limit section 101.

With that introduction, the Court proceeded to interpret the word "process" from section 101. In doing so, the Court briefly examined the history of patent laws back to 1793. See also Chakrabarty, 447 U.S. at 308-09. The Court summed up the legislative intent of the patent laws with this broad admonition:

The Committee Reports accompanying the 1952 Act . . . inform us that Congress intended statutory subject matter to "include anything under the sun that is made by man." S. Rep. No. 1979, 82d Cong., 2d Sess., 5 (1952); H.R. Rep. No.

1923, 82d Cong., 2d Sess., 6 (1952).

Diehr, 450 U.S. at 182. This passage underscores the fallacy of creating artificial limits for the words of the 1952 Act.

Courts should give "process" its literal and predictable meaning, without conjecturing about the policy implications of that literal [*38] reading. Cf. Chakrabarty, 447 U.S. at 316-18. If Congress wishes to remove some processes from patent protection, it can enact such an exclusion. Again, in the absence of legislated limits on the meaning of the Act, courts should not presume to construct limits. The Supreme Court directed this court to follow the Act.

With that preface, the Supreme Court in Diehr specifically limited Benson. In the first place, the Court acknowledged the narrow definition of "mathematical algorithm" set forth by Benson. 450 U.S. 186 n.9. Moreover, the Court expressly stated:

Our previous decisions regarding the patentability of "algorithms" are necessarily limited to the more narrow definition employed by the Court . . . .
Id. Thus, after Diehr, only a mathematical procedure for solution of a specified mathematical problem is suspect subject matter.

The Supreme Court in Diehr also limited Benson to a further narrow proposition. That narrow proposition supports reliance on the statutory language of the 1952 Act, rather than a nonstatutory algorithm rule.

Citing Benson, the Court in Diehr stated:

This Court has [*39] undoubtedly recognized limits to @ 101 and every discovery is not embraced within the statutory terms. Excluded from such patent protection are laws of nature, natural phenomena, and abstract ideas.

Our recent holdings in Gottschalk v. Benson, supra, and Parker v. Flook, supra, both of which are computer-related, stand for no more than these long-established principles.

450 U.S. at 185. In Taner, 681 F.2d at 791, this court's predecessor said:
In Diehr, the Supreme Court made clear that Benson stands for no more than the long-established principle that laws of nature, natural phenomena, and abstract ideas are excluded from patent protection and that "a claim drawn to subject matter otherwise statutory does not become nonstatutory because it uses a mathematical formula, computer program, or digital computer." [Citations omitted.]

Thus, Diehr limited Benson and its progeny to three classes of unpatentable subject matter -- laws of nature, natural phenomena, and abstract ideas. Indeed, in Chakrabarty, the Court also cited Benson for [*40] the proposition that these three categories are unpatentable. 447 U.S. at 309; see also Flook, 437 U.S. at 593.

Because the Supreme Court cited Benson, 450 U.S. at 185-86, this court has doubted whether Diehr limited the algorithm rule. Grams, 888 F.2d at 838. However, In re Taner, clearly interprets Diehr as strictly limiting Benson.

681 F.2d at 789, 791. More importantly, the Supreme Court instructed this court to apply the language of the 1952 Act without reading unexpressed limitations into the statute. Diehr, 450 U.S. at 182. Finally, to the extent that the Benson rule applies to mathematical algorithms in the wake of Diehr, the Supreme Court defined "mathematical algorithm" very narrowly.

Sarker, this court's predecessor gave another reason a law of nature cannot satisfy section 101. In re Sarker, 588 F.2d

1330, 1333, 200 USPQ 132, 137 (CCPA 1978). In sum, the Patent Act excludes laws of nature from patent protection even without a strained explanation excluding laws of nature from the meaning of "process." It is difficult to determine how or why mathematical algorithms are "like" laws of nature.

- - - - - - - - - - - - - - - - - -End Footnotes- - - - - - - - - - - - - - - - -[*43]

Second, the '459 patent does not claim a natural law, abstract idea, or natural phenomenon. Diehr limited the Benson rule to these three categories, none of which encompass the '459 patent.

Finally, and most important, Diehr refocused the patentability inquiry on the terms of the Patent Act rather than on non-statutory, vague classifications. Under the terms of the Act, a "process" deserves patent protection if it satisfies the Act's requirements. The '459 patent claims a "process" within the broad meaning of section 101. Therefore, this court must reverse and remand.

CONCLUSION

When determining whether claims disclosing computer art or any other art describe patentable subject matter, this court must follow the terms of the statute. The Supreme Court has focused this court's inquiry on the statute, not on special rules for computer art or mathematical art or any other art.

The claims of the '459 patent define an apparatus and a process. Both are patentable subject matter within the language of section 101. To me, the Supreme Court's most recent message is clear: when all else fails (and the algorithm rule clearly has), consult the statute. On this basis, I, too, would [*44] reverse and remand.

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S/N 7/629417

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E.O.

SERIAL NUMBER	FILING DATE	FIRST NAMED APPLICANT	ATTORNEY DOCKET NO.
07/629,417	12/18/90	HARKER	P URN-401

EXAMINER
AUCHTERLONIE, T

ART UNIT	PAPER NUMBER
2304	7

STEVEN J. ROCCI
WOODCOCK, WASHBUR, KURTZ, MACKIEWICZ
& NORRIS
ONE LIBERTY PLACE - 46TH FLOOR
PHILADELPHIA, PA 19103

DATE MAILED:
07/13/92

NOTICE OF ALLOWABILITY

PART I.

1. ☒ This communication is responsive to 8 April 92 Communication from Applicant.
2. ☒ All the claims being allowable, PROSECUTION ON THE MERITS IS ~~(OR REMAINS)~~ CLOSED in this application. If not included herewith (or previously mailed), a Notice Of Allowance And Issue Fee Due or other appropriate communication will be sent in due course.
3. ☒ The allowed claims are 23-28, 30-39 (now renumber as 9-13, 15, 16, 14, 1-8, respectively)
4. ☐ The drawings filed on ______ are acceptable.
5. ☐ Acknowledgment is made of the claim for priority under 35 U.S.C. 119. The certified copy has [_] been received. [_] not been received. [_] been filed in parent application Serial No. ______, filed on ______.
6. ☐ Note the attached Examiner's Amendment.
7. ☐ Note the attached Examiner Interview Summary Record, PTOL-413.
8. ☐ Note the attached Examiner's Statement of Reasons for Allowance.
9. ☒ Note the attached NOTICE OF REFERENCES CITED, PTO-892.
10. ☐ Note the attached INFORMATION DISCLOSURE CITATION, PTO-1449.

PART II.

A SHORTENED STATUTORY PERIOD FOR RESPONSE to comply with the requirements noted below is set to EXPIRE THREE MONTHS FROM THE "DATE MAILED" indicated on this form. Failure to timely comply will result in the ABANDONMENT of this application. Extensions of time may be obtained under the provisions of 37 CFR 1.136(a).

1. ☐ Note the attached EXAMINER'S AMENDMENT or NOTICE OF INFORMAL APPLICATION, PTO-152, which discloses that the oath or declaration is deficient. A SUBSTITUTE OATH OR DECLARATION IS REQUIRED.
2. ☒ APPLICANT MUST MAKE THE DRAWING CHANGES INDICATED BELOW IN THE MANNER SET FORTH ON THE REVERSE SIDE OF THIS PAPER.
   a. ☒ Drawing informalities are indicated on the NOTICE RE PATENT DRAWINGS, PTO-948, attached hereto or to Paper No. 4. CORRECTION IS REQUIRED.
   b. ☒ The proposed drawing correction filed on 6May91 & 8April92 has been approved by the examiner. CORRECTION IS REQUIRED.
   c. ☐ Approved drawing corrections are described by the examiner in the attached EXAMINER'S AMENDMENT. CORRECTION IS REQUIRED.
   d. ☒ Formal drawings are now REQUIRED.

Any response to this letter should include in the upper right hand corner, the following information from the NOTICE OF ALLOWANCE AND ISSUE FEE DUE: ISSUE BATCH NUMBER, DATE OF THE NOTICE OF ALLOWANCE, AND SERIAL NUMBER.

Attachments:

_ Examiner's Amendment
_ Examiner Interview Summary Record, PTOL-413
_ Reasons for Allowance
X Notice of References Cited, PTO-892
_ Information Disclosure Citation, PTO-1449
_ Notice of Informal Application, PTO-152
_ Notice re Patent Drawings, PTO-948
_ Listing of Bonded Draftsmen
_ Other

TSA

PTOL-37 (REV. 4-89) *

USCOMM-DC 89-3789

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& NORRIS
ONE LIBERTY PLACE - 46TH FLOOR
PHILADELPHIA, PA 19103

NOTICE OF ALLOWANCE AND ISSUE FEE DUE

☐ Note attached communication from the Examiner
☐ This notice is issued in view of applicant's communication filed ____________

SERIES CODE/SERIAL NO.	FILING DATE	TOTAL CLAIMS	EXAMINER AND GROUP ART UNIT		DATE MAILED
07/629,417	12/18/90	016	AUCHTERLONIE, T	2304	07/13/92

First Named Applicant: HARKER, PATRICK T.

TITLE OF INVENTION: METHOD FOR ANALYZING AND GENERATING OPTIMAL TRANSPORTATION SCHEDULES FOR VEHICLES SUCH AS TRAINS AND CONTROLLING THE MOVEMENT OF VEHICLES IN RESPONSE THERETO (AS AMENDED)

	ATTY'S DOCKET NO.	CLASS-SUBCLASS	BATCH NO.	APPLN. TYPE	SMALL ENTITY	FEE DUE	DATE DUE
2	UPN-401	364-436.000	E45	UTILITY	YES	$565.00	10/13/92

THE APPLICATION IDENTIFIED ABOVE HAS BEEN EXAMINED AND IS ALLOWED FOR ISSUANCE AS A PATENT. PROSECUTION ON THE MERITS IS CLOSED.

THE ISSUE FEE MUST BE PAID WITHIN THREE MONTHS FROM THE MAILING DATE OF THIS NOTICE OR THIS APPLICATION SHALL BE REGARDED AS ABANDONED. THIS STATUTORY PERIOD CANNOT BE EXTENDED.

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12-88)(OMB Clearance is pending)

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SERIES CODE/SERIAL NO.	FILING DATE	TOTAL CLAIMS	EXAMINER AND GROUP ART UNIT		DATE MAILED
07/629,417	12/18/90	016	AUCHTERLONIE, T	2304	07/13/92

First Named Applicant HARKER, PATRICK T.

TITLE OF INVENTION METHOD FOR ANALYZING AND GENERATING OPTIMAL TRANSPORTATION SCHEDULES FOR VEHICLES SUCH AS TRAINS AND CONTROLLING THE MOVEMENT OF VEHICLES IN RESPONSE THERETO (AS AMENDED)

	ATTY'S DOCKET NO.	CLASS-SUBCLASS	BATCH NO.	APPLN. TYPE	SMALL ENTITY	FEE DUE	DATE DUE
2	UPN-401	364-436.000	E45	UTILITY	NO	$1130.00	10/13/92

THE APPLICATION IDENTIFIED ABOVE HAS BEEN EXAMINED AND IS ALLOWED FOR ISSUANCE AS A PATENT. PROSECUTION ON THE MERITS IS CLOSED.

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PTOL-85 (REV 12-88)(OMB Clearance is pending)

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SERIAL NUMBER	FILING DATE	FIRST NAMED APPLICANT	ATTORNEY DOCKET NO.
07/629,417	12/18/90	HARKER	P UNR-401

EXAMINER
AUCHTERLONIE, T

ART UNIT	PAPER NUMBER
2304	8

STEVEN J. ROCCI
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PHILADELPHIA, PA 19103

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07/16/92

NOTICE OF ALLOWABILITY

PART I.

1. ☒ This communication is responsive to 8 April 92 Communication from Applicant *.
2. ☒ All the claims being allowable, PROSECUTION ON THE MERITS IS (OR REMAINS) CLOSED in this application. If not included herewith (or previously mailed), a Notice Of Allowance And Issue Fee Due or other appropriate communication will be sent in due course.
3. ☒ The allowed claims are 23-28, 30-39 (now renumbered as 9-13, 15, 16, 14, 1-8, respectively).
4. ☐ The drawings filed on ________ are acceptable.
5. ☐ Acknowledgment is made of the claim for priority under 35 U.S.C. 119. The certified copy has [_] been received. [_] not been received. [_] been filed in parent application Serial No. ________, filed on ________.
6. ☐ Note the attached Examiner's Amendment.
7. ☐ Note the attached Examiner Interview Summary Record, PTOL-413.
8. ☐ Note the attached Examiner's Statement of Reasons for Allowance.
9. ☒ Note the attached NOTICE OF REFERENCES CITED, PTO-892.
10. ☐ Note the attached INFORMATION DISCLOSURE CITATION, PTO-1449.

PART II.

A SHORTENED STATUTORY PERIOD FOR RESPONSE to comply with the requirements noted below is set to EXPIRE THREE MONTHS FROM THE "DATE MAILED" indicated on this form. Failure to timely comply will result in the ABANDONMENT of this application. Extensions of time may be obtained under the provisions of 37 CFR 1.136(a).

1. ☐ Note the attached EXAMINER'S AMENDMENT or NOTICE OF INFORMAL APPLICATION, PTO-152, which discloses that the oath or declaration is deficient. A SUBSTITUTE OATH OR DECLARATION IS REQUIRED.
2. ☒ APPLICANT MUST MAKE THE DRAWING CHANGES INDICATED BELOW IN THE MANNER SET FORTH ON THE REVERSE SIDE OF THIS PAPER.
   a. ☒ Drawing informalities are indicated on the NOTICE RE PATENT DRAWINGS, PTO-948, attached hereto or to Paper No. 4. CORRECTION IS REQUIRED.
   b. ☒ The proposed drawing correction filed on 6 MAY 91 & 8 April 92 has been approved by the examiner. CORRECTION IS REQUIRED.
   c. ☐ Approved drawing corrections are described by the examiner in the attached EXAMINER'S AMENDMENT. CORRECTION IS REQUIRED.
   d. ☒ Formal drawings are now REQUIRED.

Any response to this letter should include in the upper right hand corner, the following information from the NOTICE OF ALLOWANCE AND ISSUE FEE DUE: ISSUE BATCH NUMBER, DATE OF THE NOTICE OF ALLOWANCE, AND SERIAL NUMBER.

Attachments:

- _ Examiner's Amendment
- _ Examiner Interview Summary Record, PTOL-413
- _ Reasons for Allowance
- X Notice of References Cited, PTO-892
- _ Information Disclosure Citation, PTO-1449
- _ Notice of Informal Application, PTO-152
- _ Notice re Patent Drawings, PTO-948
- _ Listing of Bonded Draftsmen
- _ Other

* This Notice of Allowability supercedes and replaces the previous Notice of Allowability which was inadvertently mailed in error without the Primary Examiner's stamp and signature.

TGA

Thomas G. Black
THOMAS G. BLACK
PRIMARY EXAMINER
ART UNIT 234

PTOL-37 (REV. 4-89) ★

USCOMM-DC 89-3789

TO SEPARATE, HOLD TOP AND BOTTOM EDGES, SNAP–APART AND DISCARD CARBON

FORM PTO-892 (REV. 3-78) U.S. DEPARTMENT OF COMMERCE PATENT AND TRADEMARK OFFICE	SERIAL NO.	GROUP ART UNIT	ATTACHMENT TO PAPER NUMBER
NOTICE OF REFERENCES CITED	7/629417	2304	8
	APPLICANT(S) Harker et al.		

U.S. PATENT DOCUMENTS

*		DOCUMENT NO.	DATE	NAME	CLASS	SUB-CLASS	FILING DATE IF APPROPRIATE
*	A	5101340	3/31/92	Nanaka et al.	395	650	7 April 89
*	B	5093794	3MAR92	Howie et al.	364	468	8/22/89
*	C	4924386	8MAY90	Freedman et al.	364	402	7/13/87
	D						
	E						
	F						
	G						
	H						
	I						
	J						
	K						

FOREIGN PATENT DOCUMENTS

*		DOCUMENT NO.	DATE	COUNTRY	NAME	CLASS	SUB-CLASS	PERTINENT SHTS. DWG	PERTINENT PP. SPEC.
	L								
	M								
	N								
	O								
	P								
	Q								

OTHER REFERENCES (Including Author, Title, Date, Pertinent Pages, Etc.)

R	
S	
T	
U	

EXAMINER	DATE
Thomas S. Auchterlonie	7/15/92

* A copy of this reference is not being furnished with this office action.
(See Manual of Patent Examining Procedure, section 707.05(a).)

Transaction History Date 1992-08-10
Date information retrieved from USPTO Patent Application Information Retrieval (PAIR) system records at www.uspto.gov

#9
KP
8-20-92
B

DOCKET NO.: UPN

PATENT

MAIL ROOM
AUG 10 1992

Issue Batch No.: E45
Date of Notice of Allowance : 07/13/92
Serial No. : 629,417

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re patent application of:

Patrick T. Harker et al.

Serial No.: **629,417** Group No.: **2304**

Filed: **December 18, 1990** Examiner: **T. Auchterlonie**

For: **METHOD FOR ANALYZING AND GENERATING OPTIMAL TRANSPORTATION SCHEDULES FOR VEHICLES SUCH AS TRAINS AND CONTROLLING THE MOVEMENT OF VEHICLES IN RESPONSE THERETO**

I, Michele K. Herman, Registration No. P35,893 certify that this correspondence is being deposited with the U.S. Postal Service as First Class mail in an envelope addressed to the Commissioner of Patents and Trademarks, Washington, D.C. 20231.

On 8/7/1992
Michele K. Herman
Michele K. Herman Reg. No. P35,893

Box Issue Fee
Commissioner of Patents & Trademarks
Washington, DC 20231

ATTN: Official Draftsman

Sir:

TRANSMITTAL LETTER TO OFFICIAL DRAFTSMAN

Please find enclosed **28** sheet(s) of formal drawings relating to the above-identified patent application.

This Letter, and the enclosed drawings, each bear the Issue Batch No., the date of the Notice of Allowance and Serial No. of the application on the front of the respective document. Please charge any comparison fees to our Deposit Account No. 23-3050.

DOCKET NO.: UPN-0401 PATENT

In view of the above, the present application is believed to be in a condition ready for issuance.

Date: August 7, 1992

Signature
Michele K. Herman
Registration No. **P35,893**

WOODCOCK WASHBURN KURTZ
MACKIEWICZ & NORRIS
One Liberty Place - 46th Floor
Philadelphia, PA 19103
(215) 568-3100

DOCKET NO.: UPN-0401 PATENT

Issue Batch No.: E45
Date of Notice
of Allowance : 07/13/92
Serial No. : 629,417

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re patent application of:

Patrick T. Harker et al.

Serial No.: 629,417 Group No.: 2304

Filed: December 18, 1990 Examiner: T. Auchterlonie

For: METHOD FOR ANALYZING AND GENERATING OPTIMAL TRANSPORTATION SCHEDULES FOR VEHICLES SUCH AS TRAINS AND CONTROLLING THE MOVEMENT OF VEHICLES IN RESPONSE THERETO

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WOODCOCK WASHBURN KURTZ
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Philadelphia, PA 19103
(215) 568-3100

DOCKET NO.: UPN-0401 **PATENT**

MAIL ROOM AUG 10 1992 PAT. & T.M. OFFICE

Issue Batch No.: E45
Date of Notice of Allowance : 07/13/92
Serial No. : 629,417

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re patent application of:

Patrick T. Harker et al.

Serial No.: 629,417 Group No.: 2304

Filed: December 18, 1990 Examiner: T. Auchterlonie

For: METHOD FOR ANALYZING AND GENERATING OPTIMAL TRANSPORTATION SCHEDULES FOR VEHICLES SUCH AS TRAINS AND CONTROLLING THE MOVEMENT OF VEHICLES IN RESPONSE THERETO

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In view of the above, the present application is believed to be in a condition ready for issuance.

Date: August 7, 1992

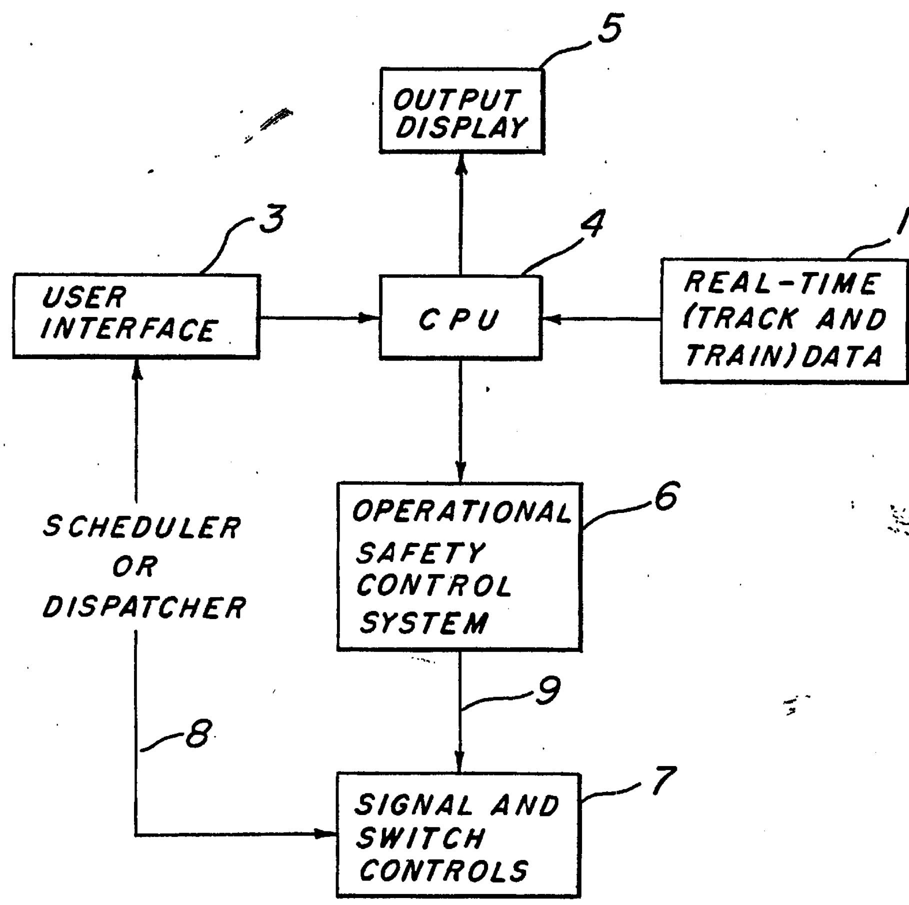
Michele K. Herman

Signature
Michele K. Herman
Registration No. **P35,893**

WOODCOCK WASHBURN KURTZ
MACKIEWICZ & NORRIS
One Liberty Place - 46th Floor
Philadelphia, PA 19103
(215) 568-3100

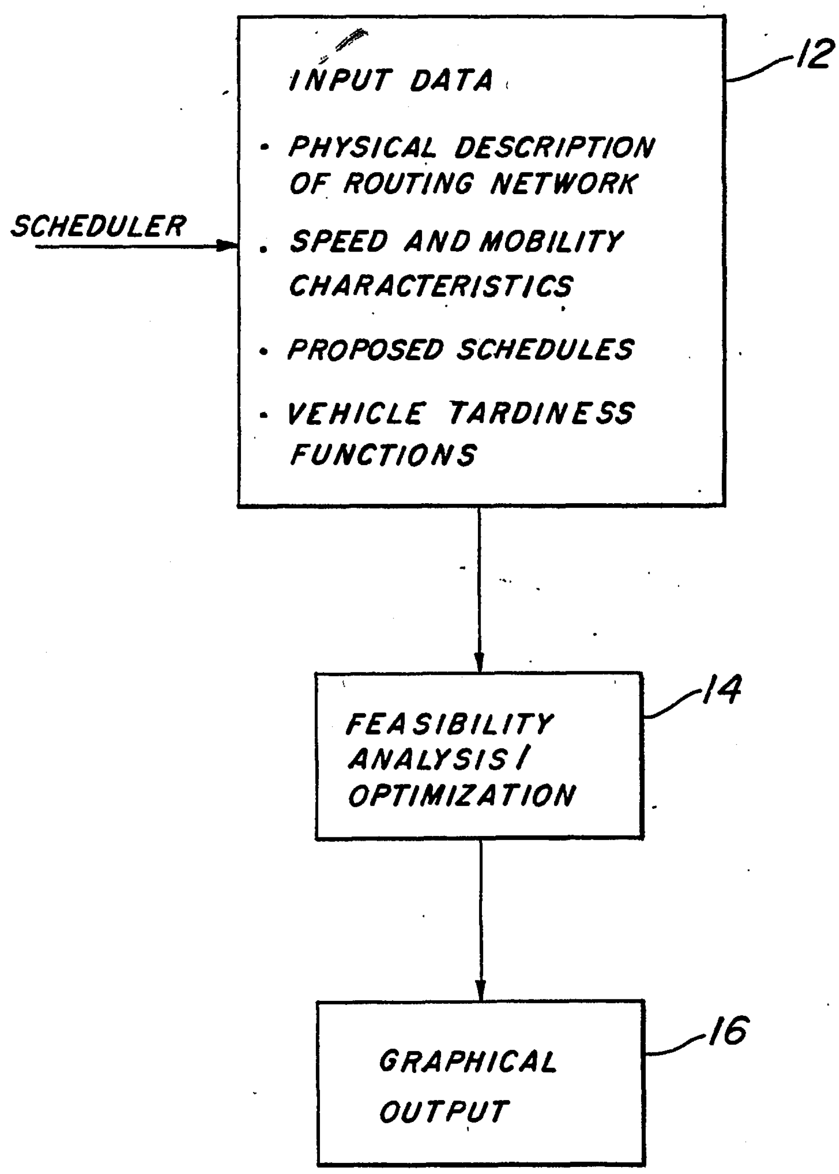
Docket No. UPN-0401 Ser. No.: 629,417 Filed December 18, 1990 Art Unit: 2304 Inventor: Harker et al. Notice of Allowance: 7/13/92 Batch No.: E45 Sheet 1 of 28

FIG. 1



Docket No. UPN-0401 Ser. No.: 629,417 Filed: December 18, 1990 Art Unit: 2304 Inventor: Harker et al. Notice of Allowance: 7/13/92 Bat. No.: E45 Sheet 2 of 28

FIG. 2



Docket No. UPN-0401 Ser. No.: 629,417 Filed: December 18, 1990 Art Unit: 2304 Inventor: Harker et al. Notice of Allowance: 7/13/92 Batc No.: E45 Sheet 3 of 28

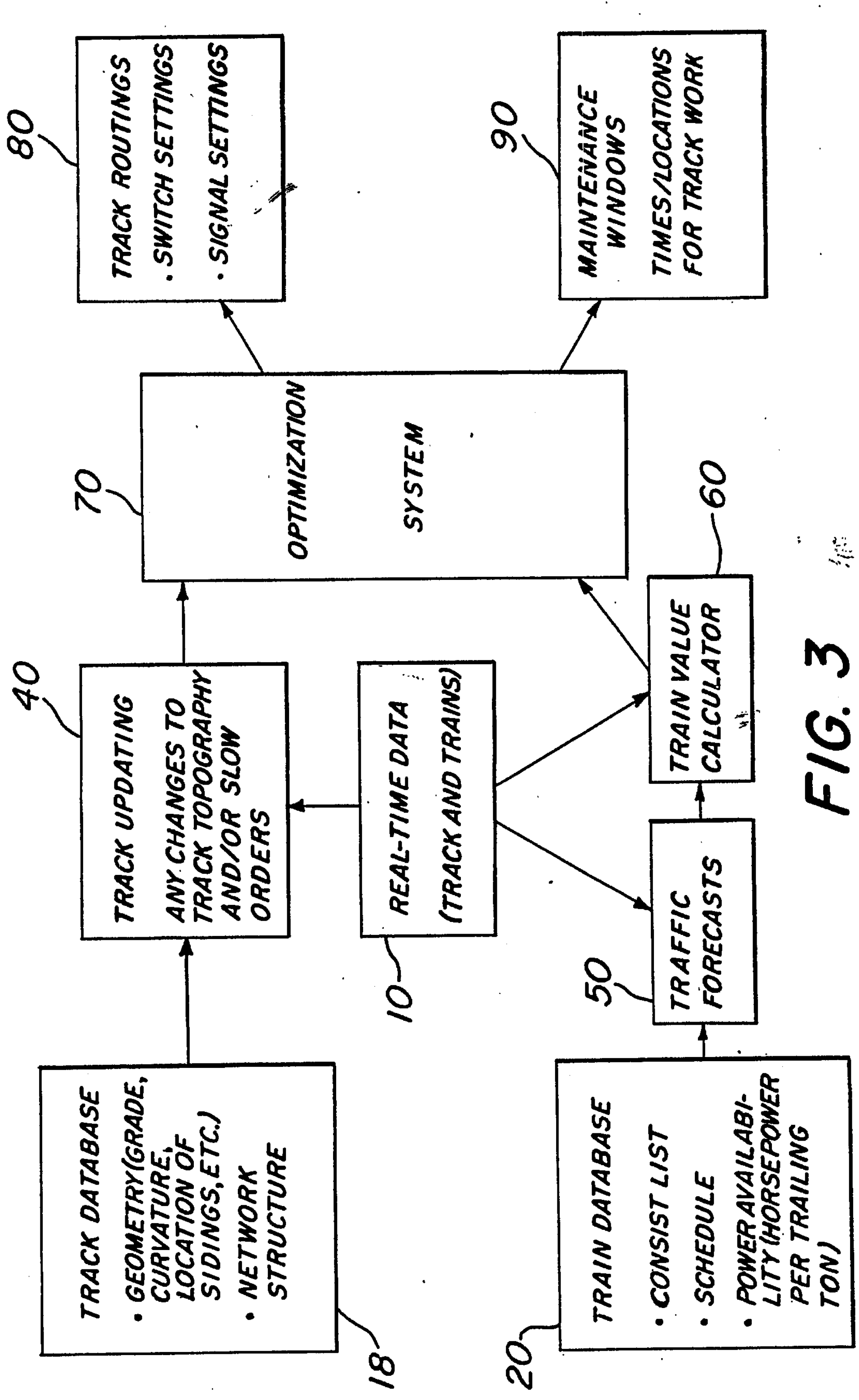
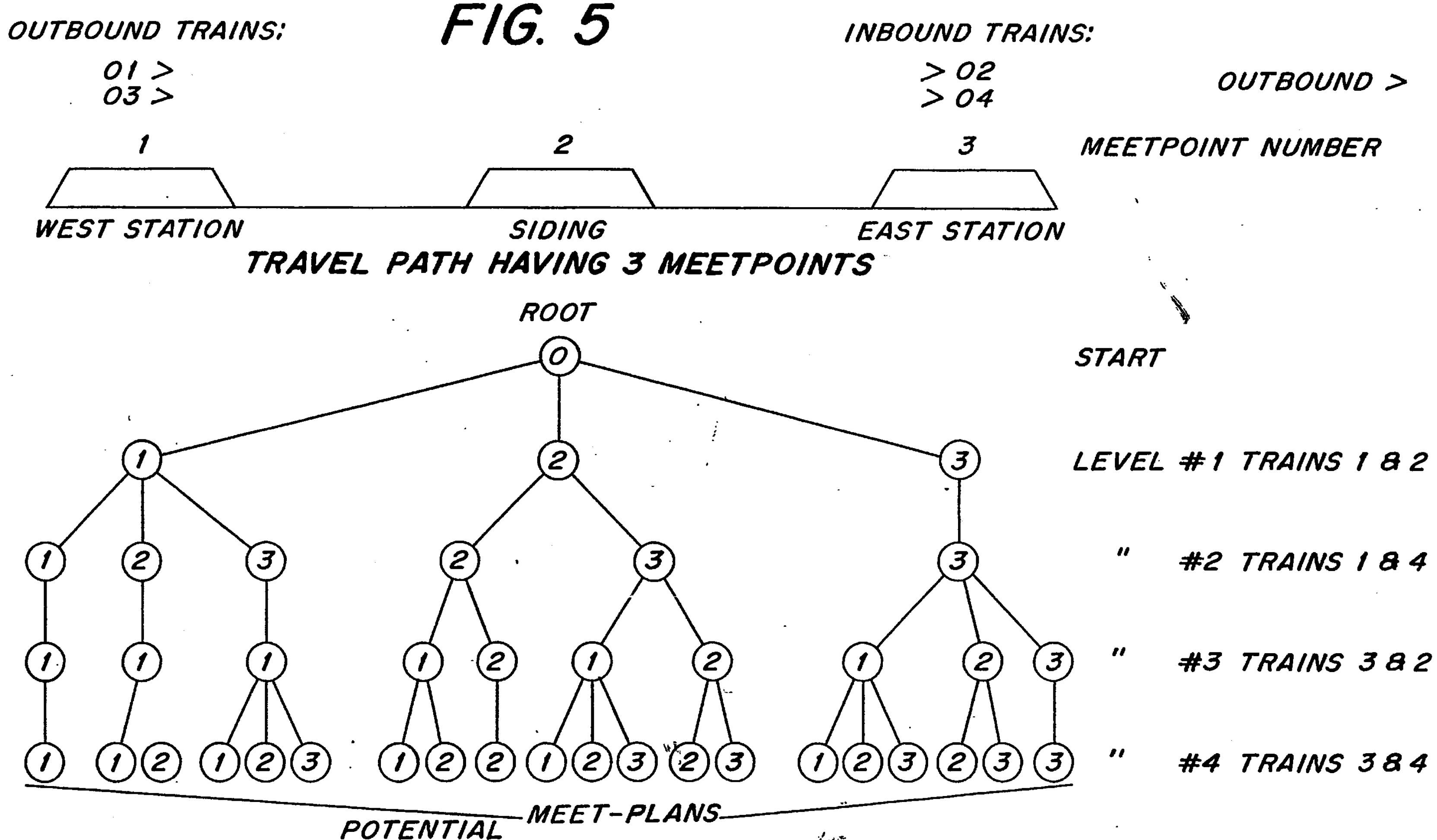


FIG. 3

FIG. 5



SEARCH TREE REPRESENTATION OF TRAVEL PATH HAVING 3 MEETPOINTS

Docket No. UPN-0401 Ser. No.: 629,417 Filed: December 18, 1990 Art Unit: 2304 Inventor: Harker et al. Notice of Allowance: 7/13/92 Batt No.: E45 Sheet 4 of 28

Docket No. UPN-0401 Ser. No.: 629,417 Filed: December 18, 1990 Art Unit: 2304 Inventor: Harker et al. Notice of Allowance: 7/13/92 Batch No.: E45 Sheet 5 of 28

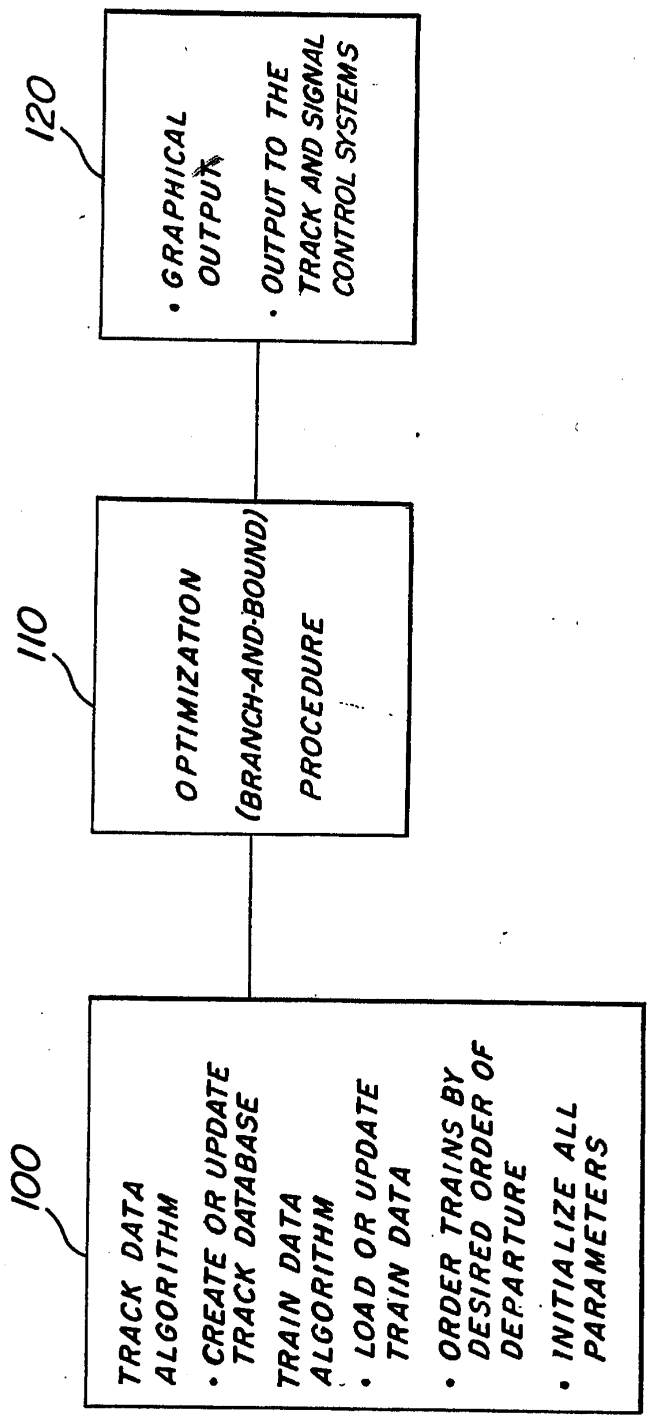


FIG. 4

Docket No. UPN-0401 Ser. No.: 629,417 Filed: December 18, 1990 Art Unit: 2304 Inventor: Harker et al. Notice of Allowance: 7/13/92 Batch No.: E45 Sheet 6 of 28

FIG. 6

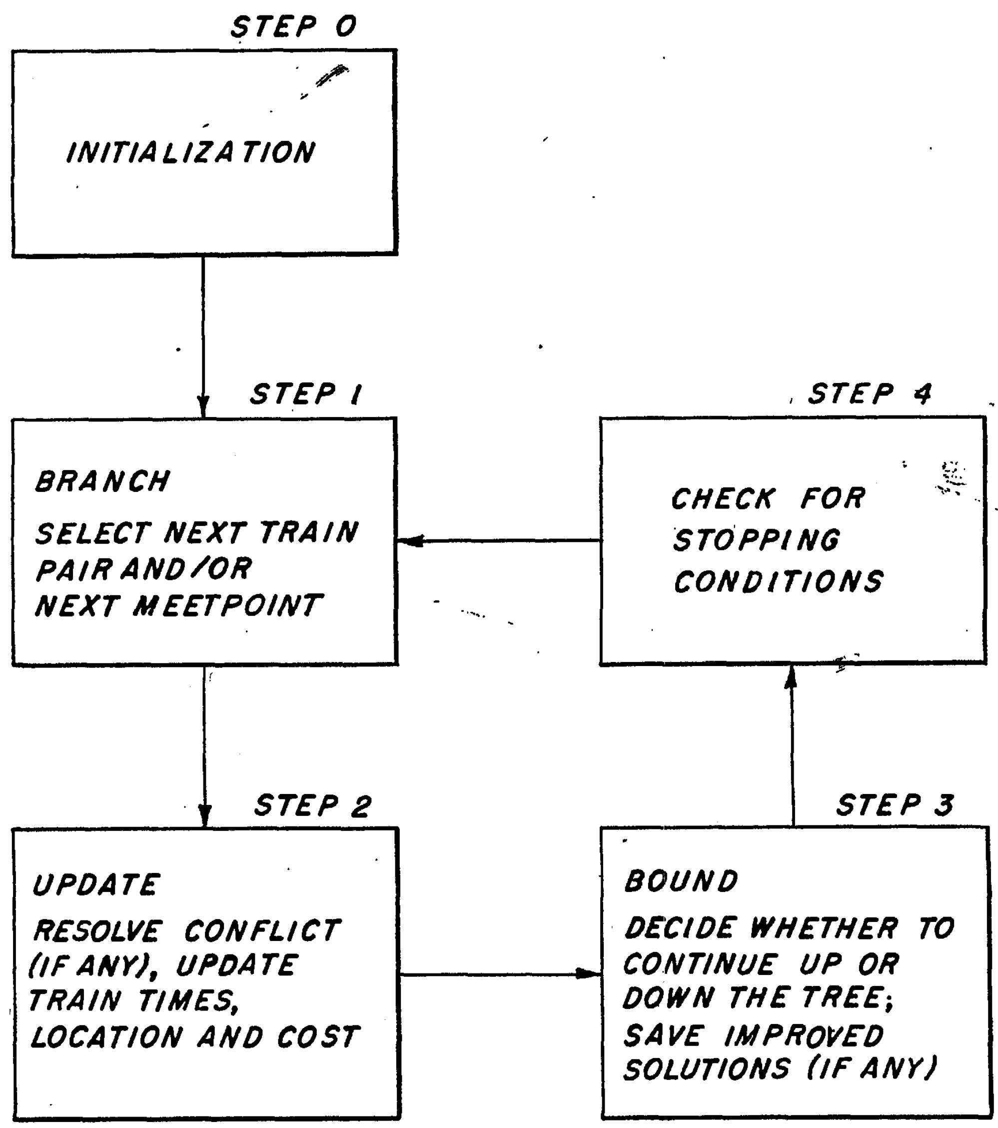
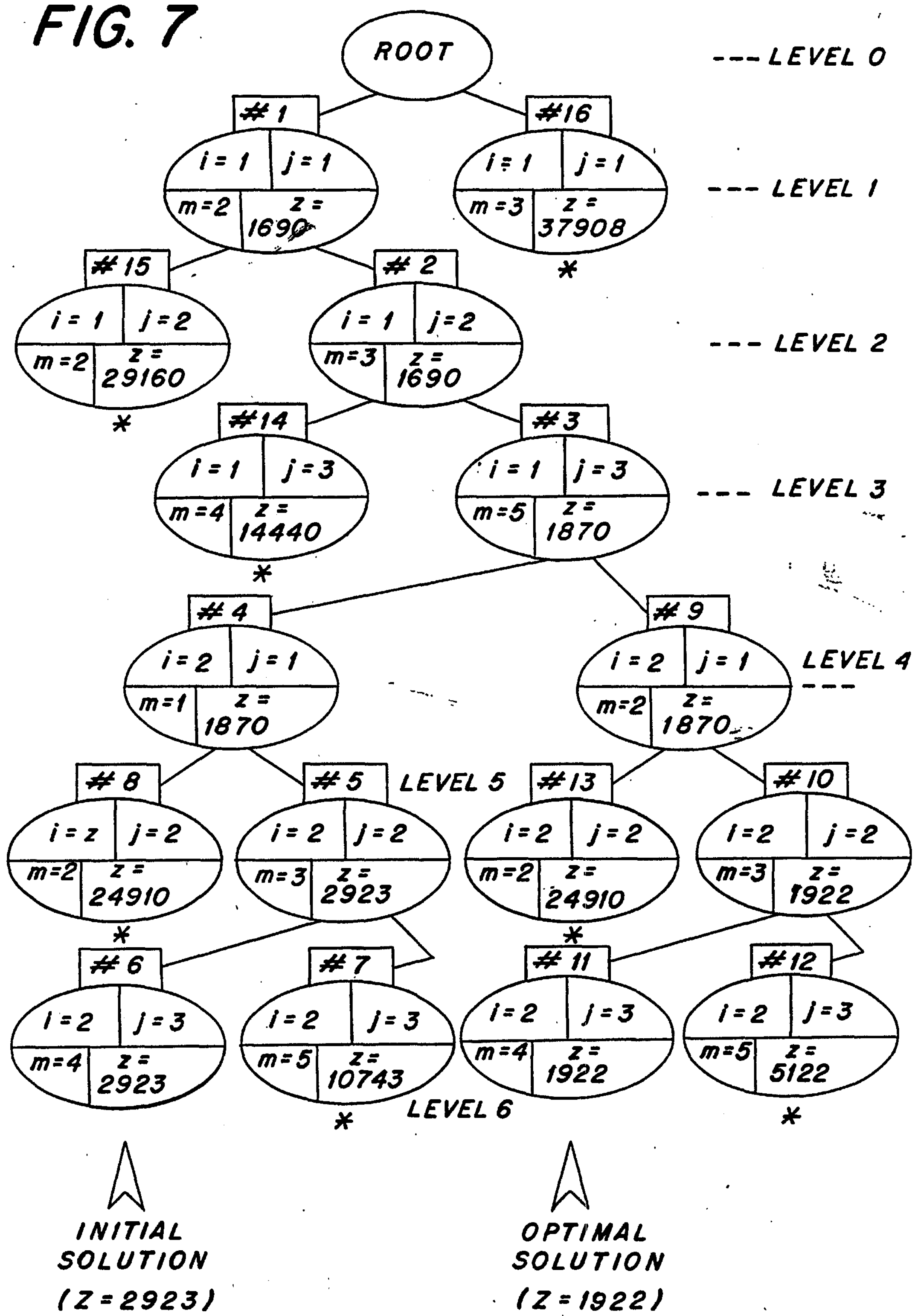


FIG. 7



NODES ENUMERATED USING BRANCH-AND-BOUND METHOD OF IMPLICIT ENUMERATION ALGORITHM

Docket No. UPN-0401 Ser. No.: 629,417 Filed: December 18, 1990 Art Unit: 2304 Inventor: Harker et al. Notice of Allowance: 7/13/92 Batch No.: E45 Sheet 8 of 28

FIG. 8

TIME-DISTANCE DIAGRAM OF
INITIAL FEASIBILITY PLAN

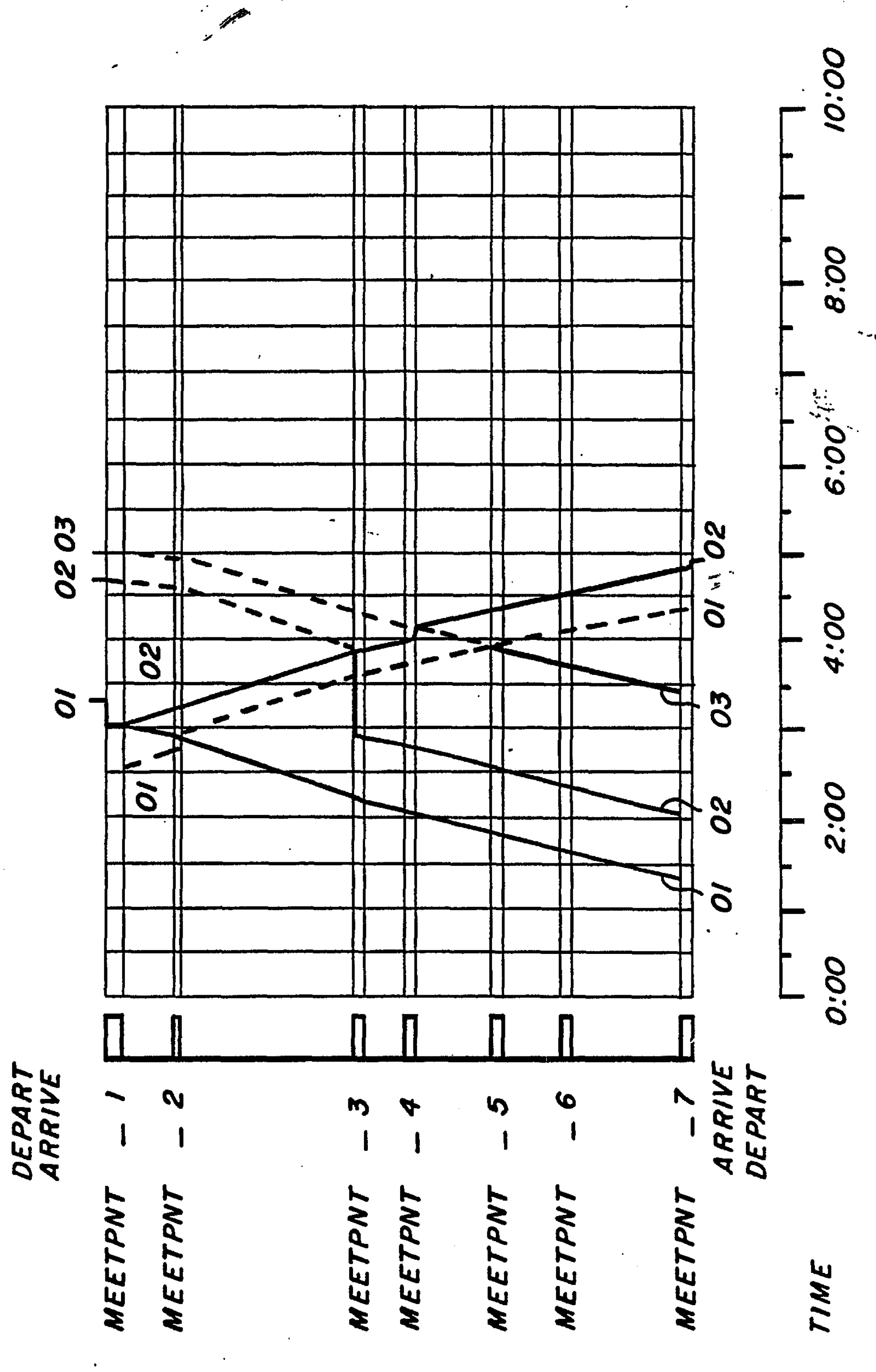
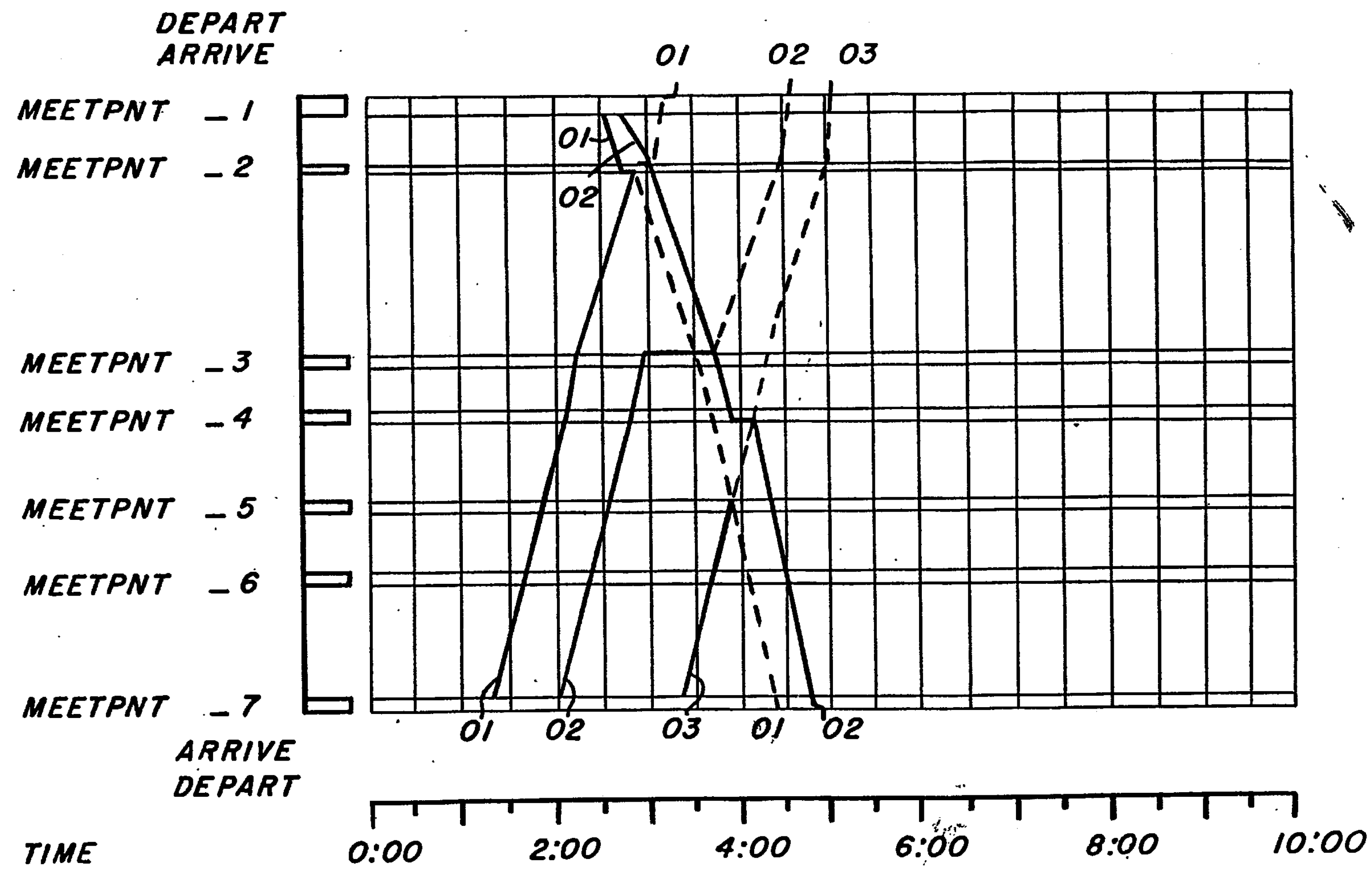


FIG. 9

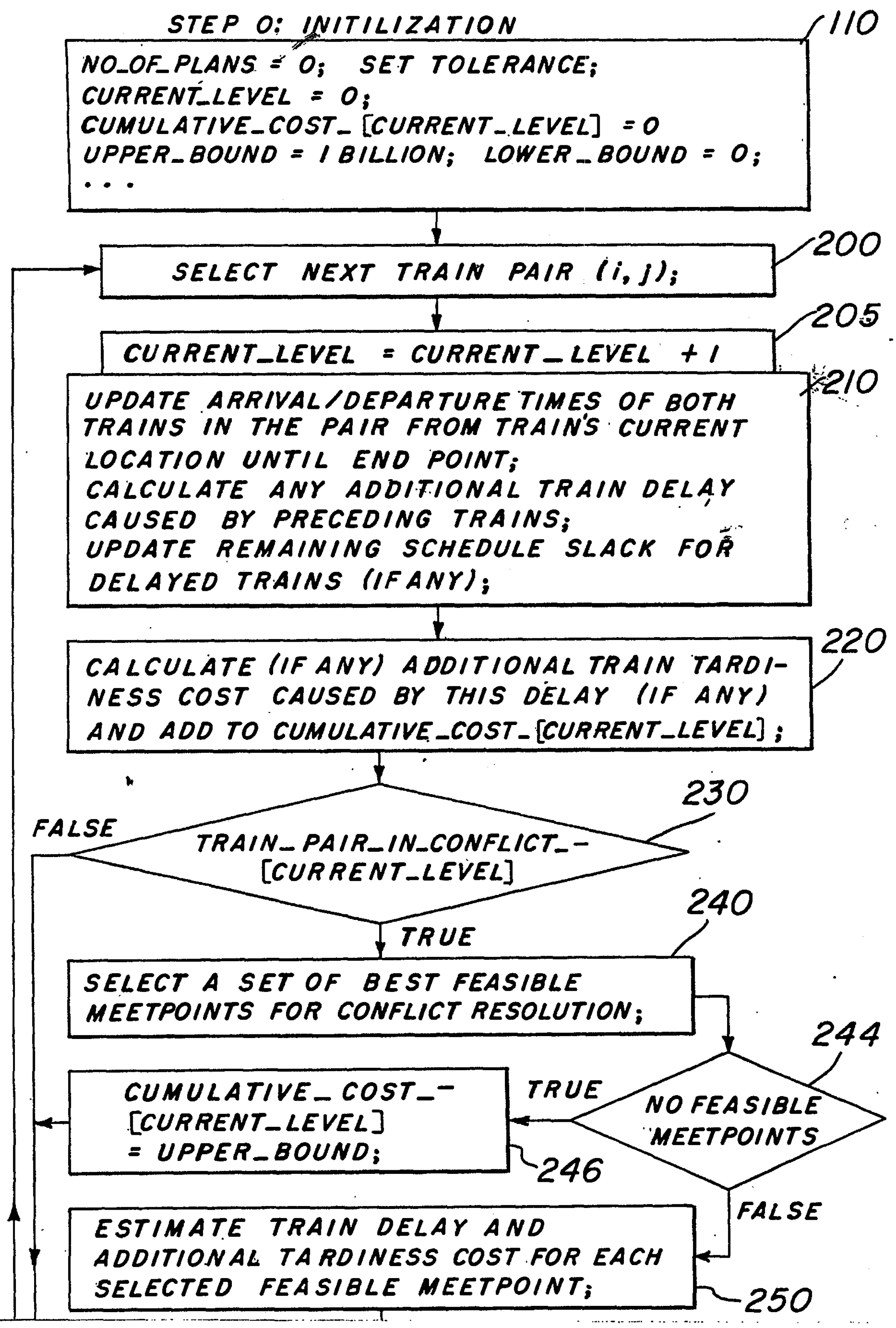
TIME-DISTANCE DIAGRAM OF OPTIMAL FEASIBILITY PLAN



Docket No. UPN-0401 Ser. No.: 629,417 Filed: December 18, 1990 Art Unit: 2304 Inventor: Harker et al. Notice of Allowance: 7/13/92 Batch No.: E45 Sheet 9 of 28

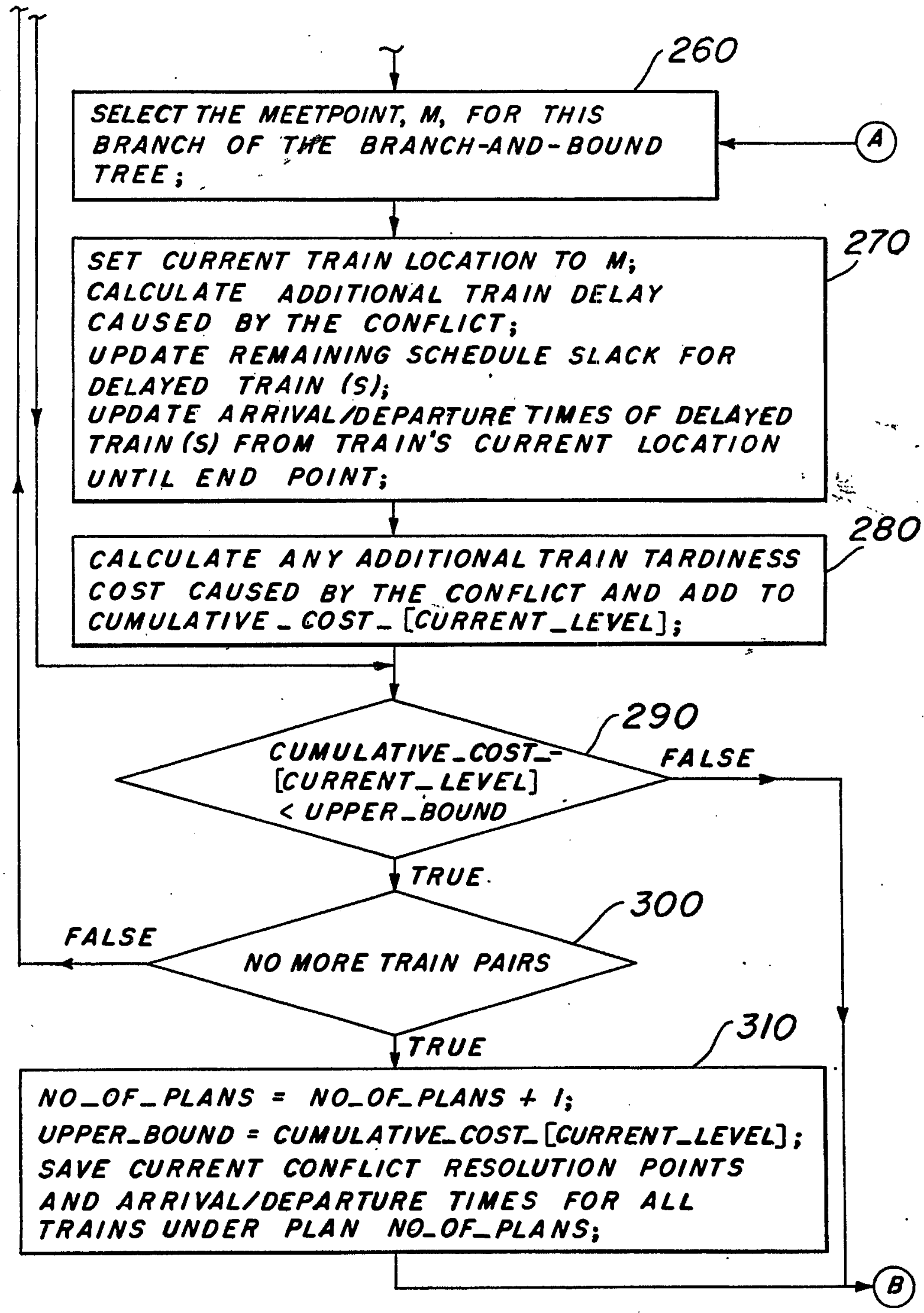
Docket No. UPN-0401 Ser. No.: 629,417 Filed: December 18, 1990 Art Unit: 2304 Inventor: Harker et al. Notice of Allowance: 7/13/92 Batch No.: E45 Sheet 10 of 28

FIG. 10A



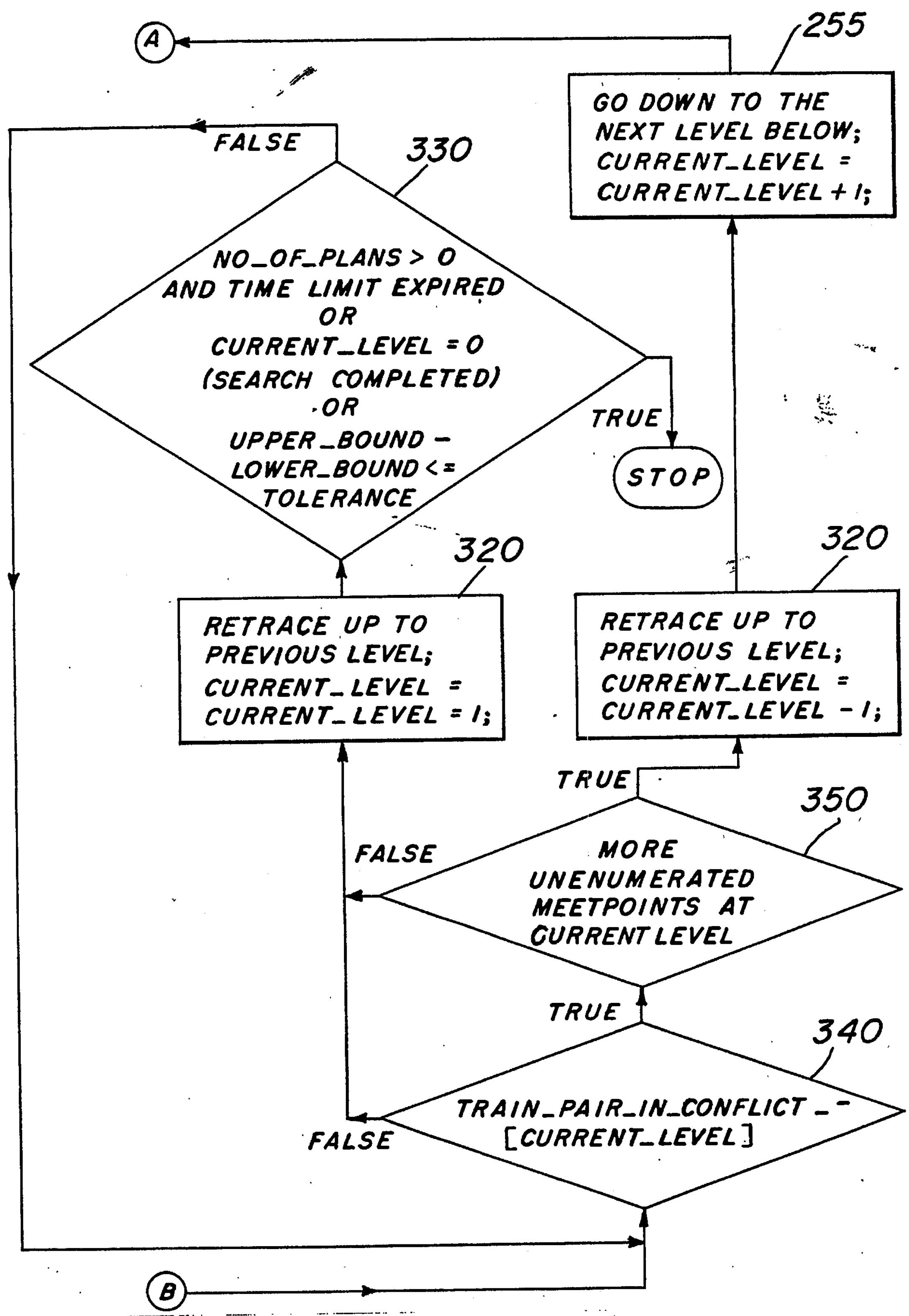
Docket No. UPN-0401 Ser. No.: 629,417 Filed: December 18, 1990 Art Unit: 2304 Inventor: Harker et al. Notice of Allowance: 7/13/92 Batch No.: E45 Sheet 11 of 28

FIG. 10B



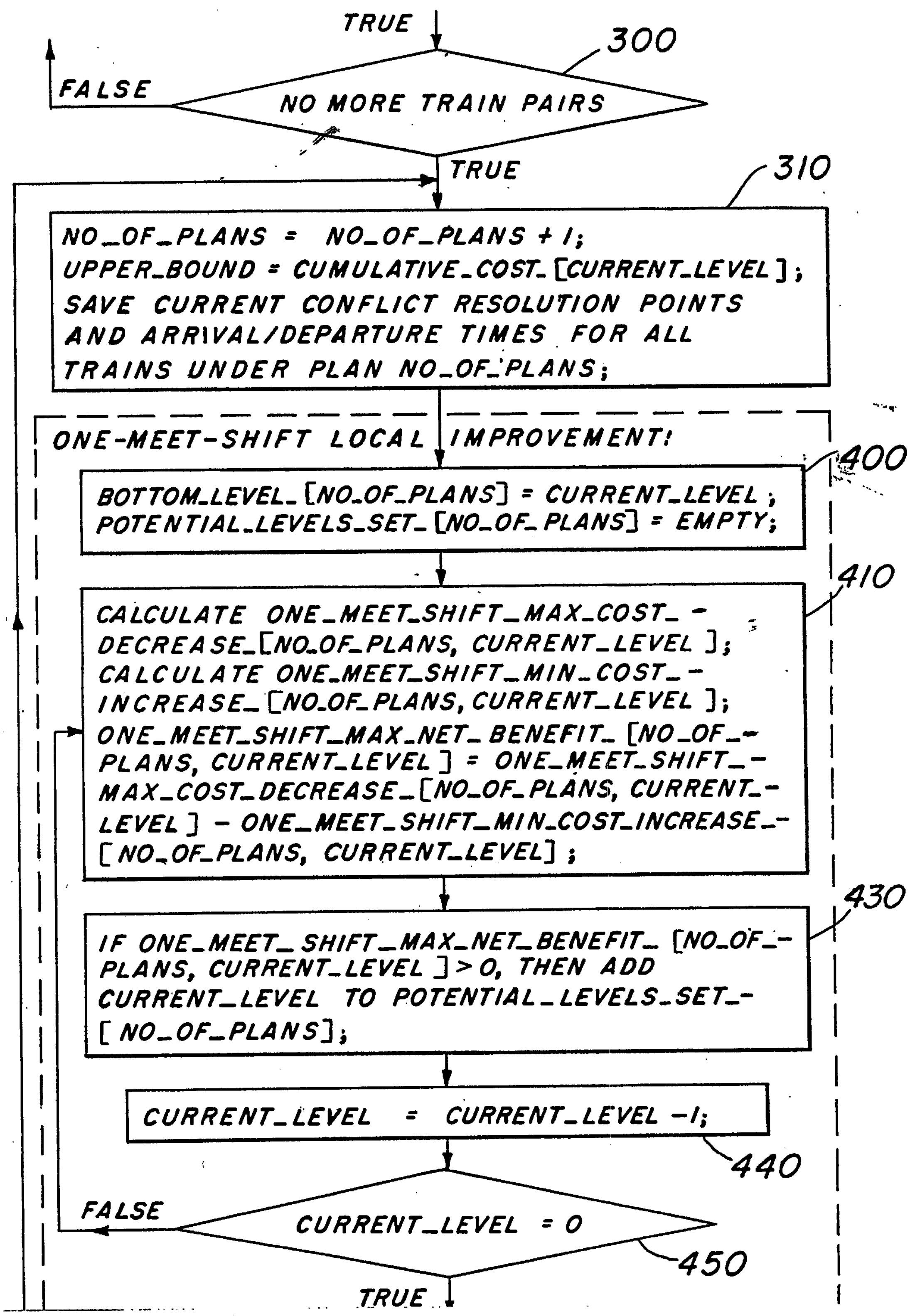
Docket No. UPN-0401 Ser. No.: 629,417 Filed: December 18, 1990 Art Unit: 2304 Inventor: Harker et al. Notice of Allowance: 7/13/92 Batch No.: E45 Sheet 12 of 28

FIG. 10C



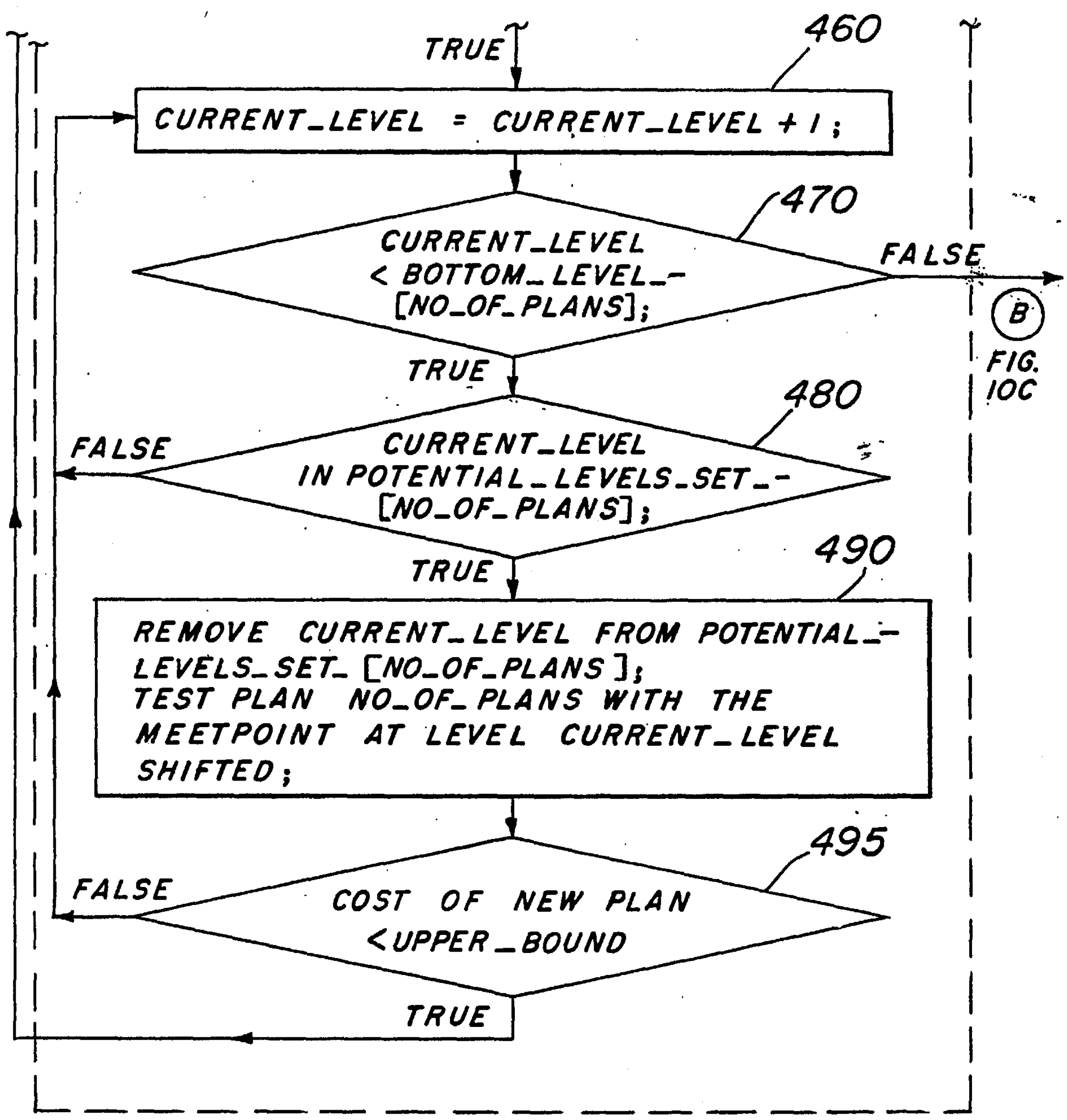
Docket No. UPN-0401 Ser. No.: 629,417 Filed: December 18, 1990 Art Unit: 2304 Inventor: Harker et al. Notice of Allowance: 7/13/92 Batch No.: E45 Sheet 13 of 28

FIG. 11A



Docket No. UPN-0401 Ser. No.: 629,417 Filed: December 18, 1990 Art Unit: 2304 Inventor: Harker et al. Notice of Allowance: 7/13/92 Batch No.: E45 Sheet 14 of 28

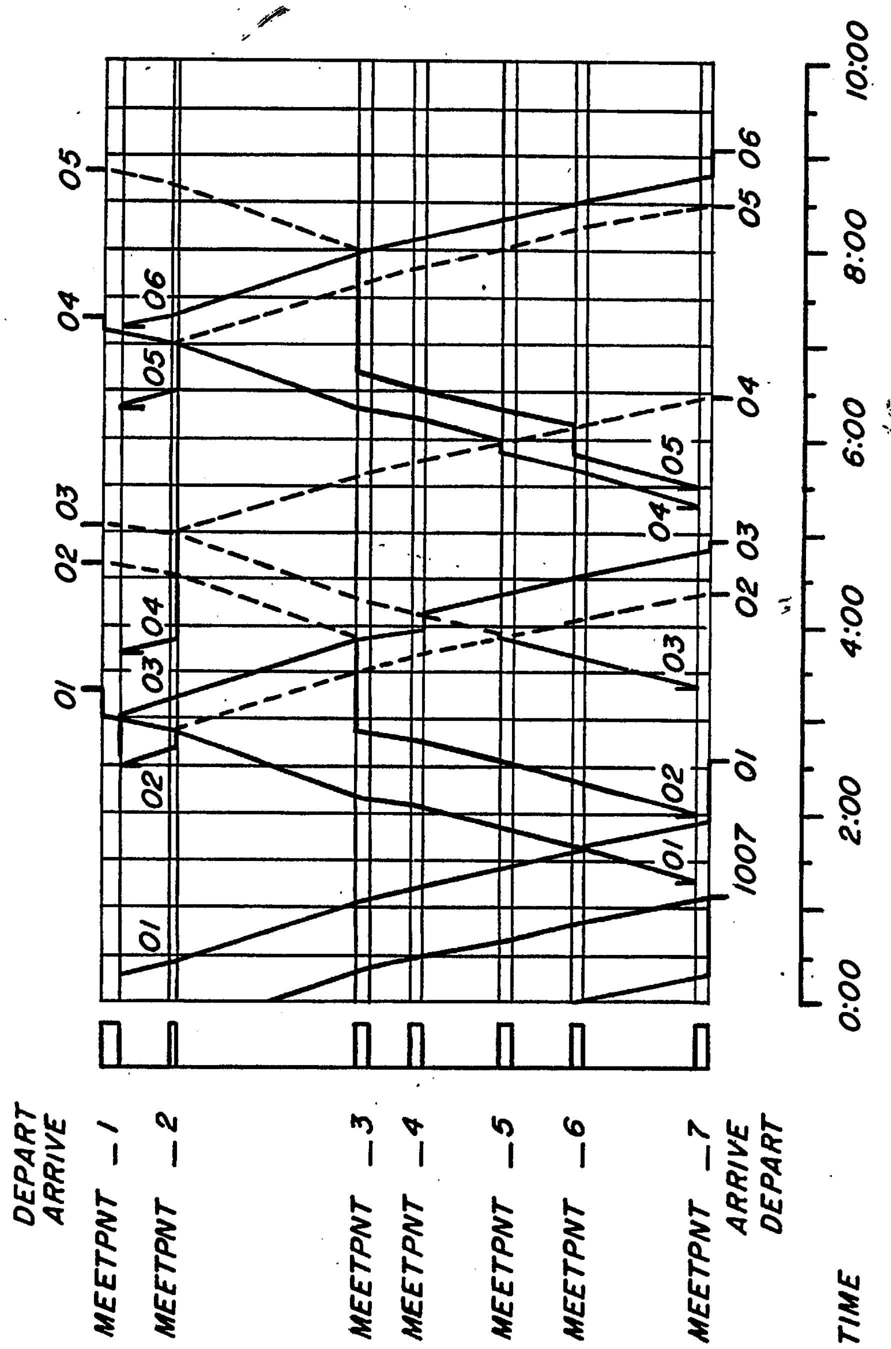
FIG. 11B



Docket No. UPN-0401 Ser. No.: 629,417 Filed: December 18, 1990 Art Unit: 2304 Inventor: Harker et al. Notice of Allowance: 7/13/92 Batch No.: E45 Sheet 15 of 28

FIG. 12

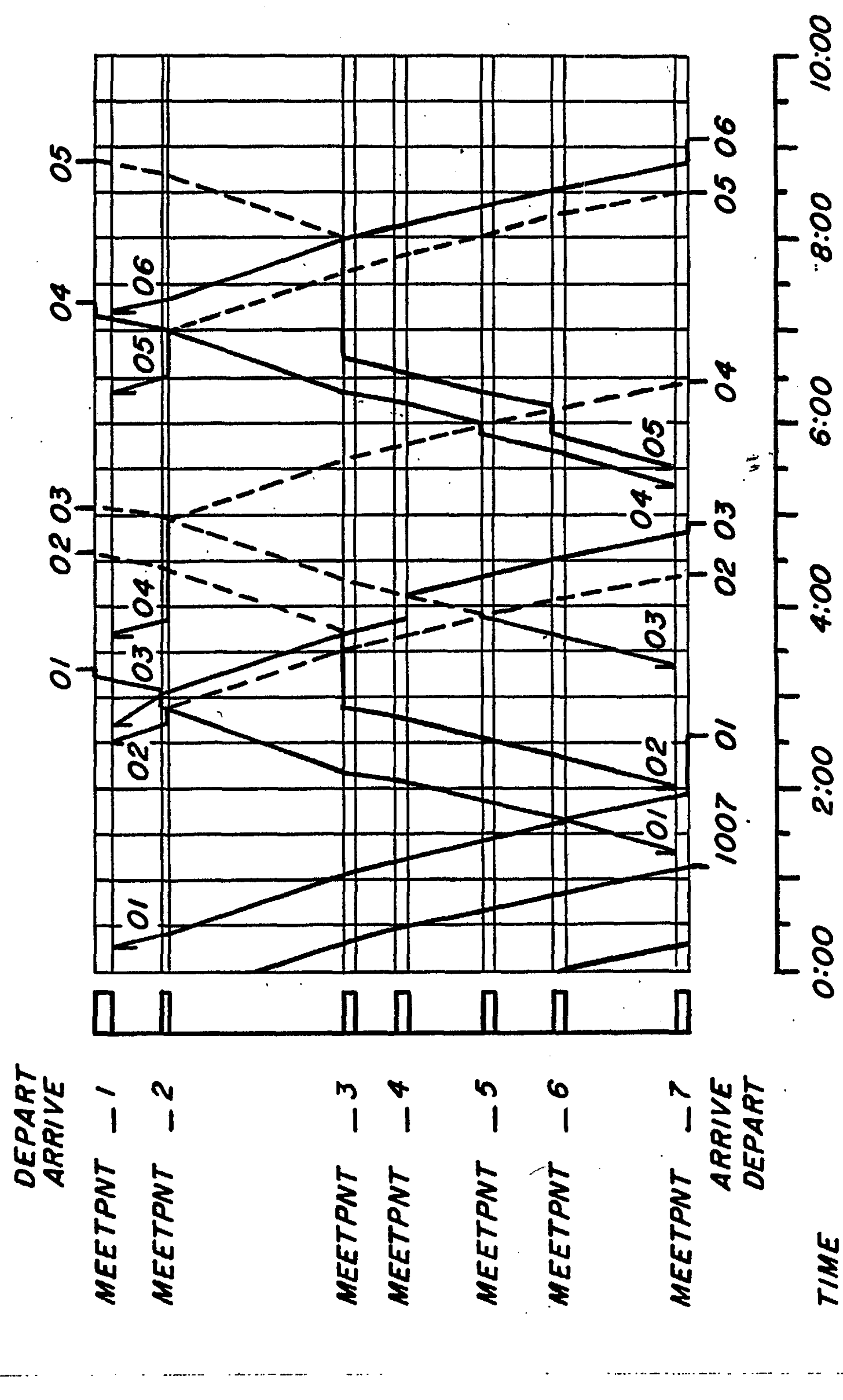
TIME-DISTANCE DIAGRAM OF
INITIAL MEET-PASS PLAN



Docket No. UPN-0401 Ser. No.: 629,417 Filed: December 18, 1990 Art Unit: 2304 Inventor: Harker et al. Notice of Allowance: 7/13/92 Batch No.: E45 Sheet 16 of 28

FIG. 13

TIME-DISTANCE DIAGRAM OF OPTIMAL MEET-PASS PLAN USING ONE-MEET-SHIFT LOCAL IMPROVEMENT



Docket No. UPN-0401 Ser. No.: 629,417 Filed: December 18, 1990 Art Unit: 2304 Inventor: Harker et al. Notice of Allowance: 7/13/92 Batch No.: E45 Sheet 17 of 28

FIG. 14A

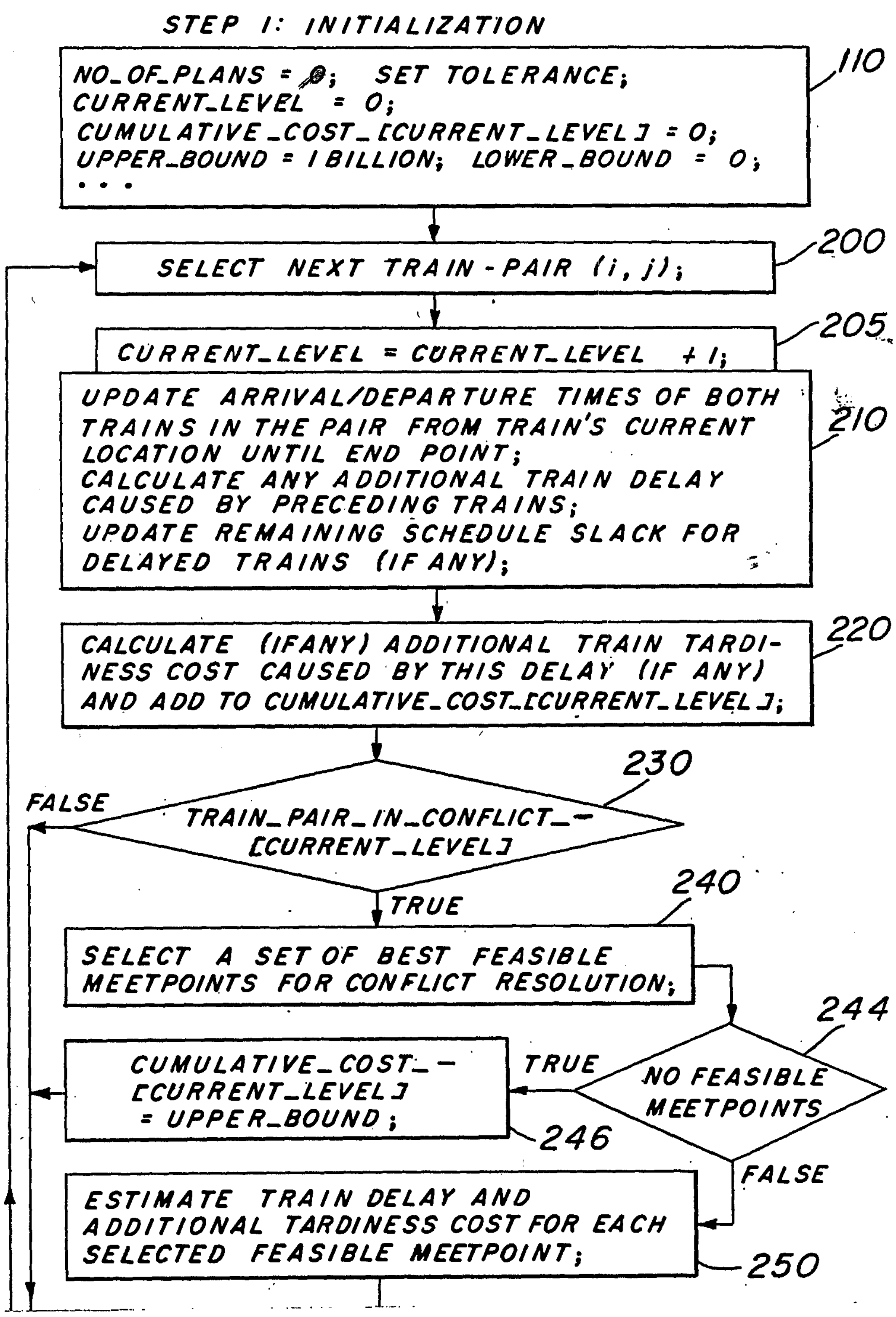
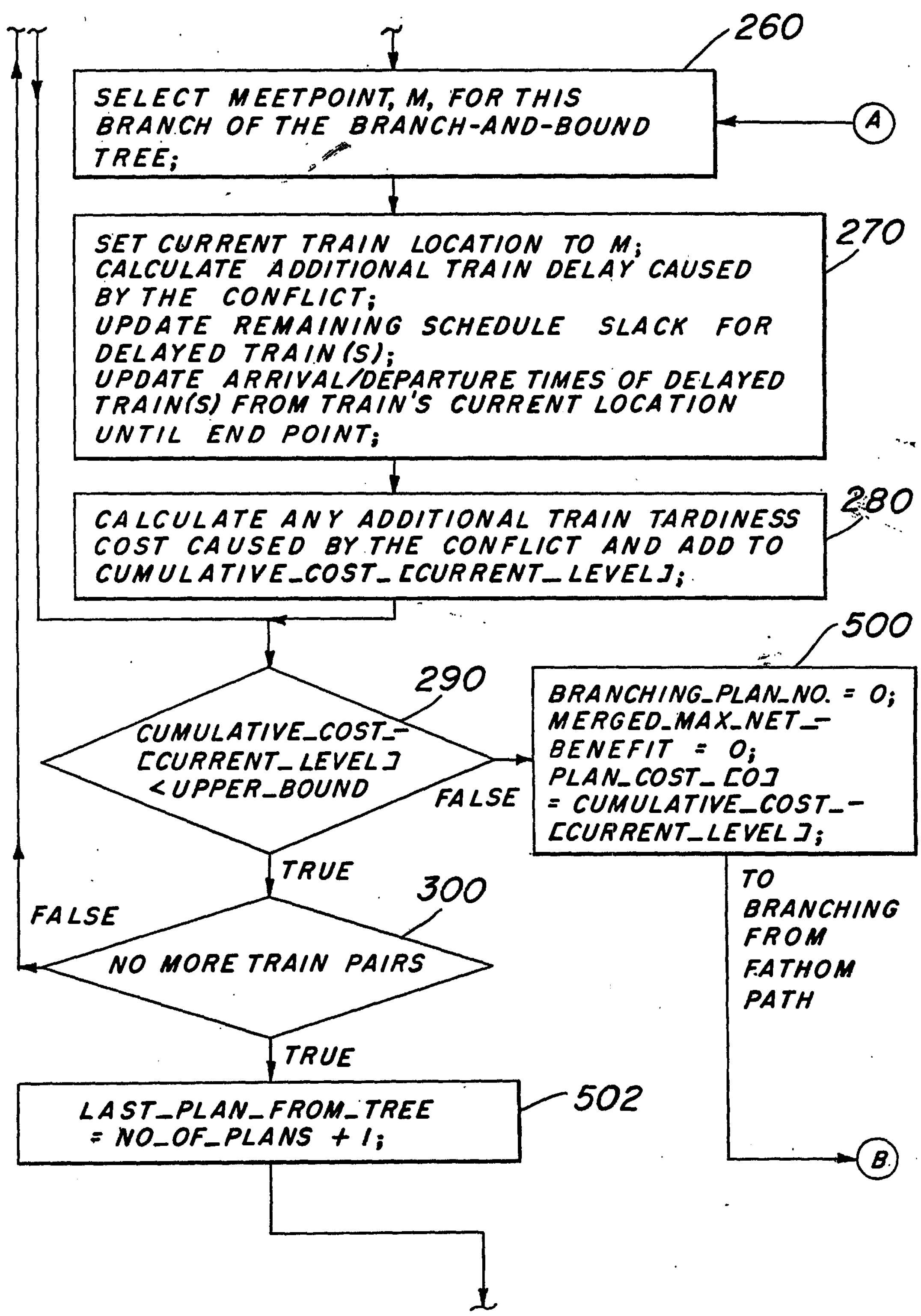
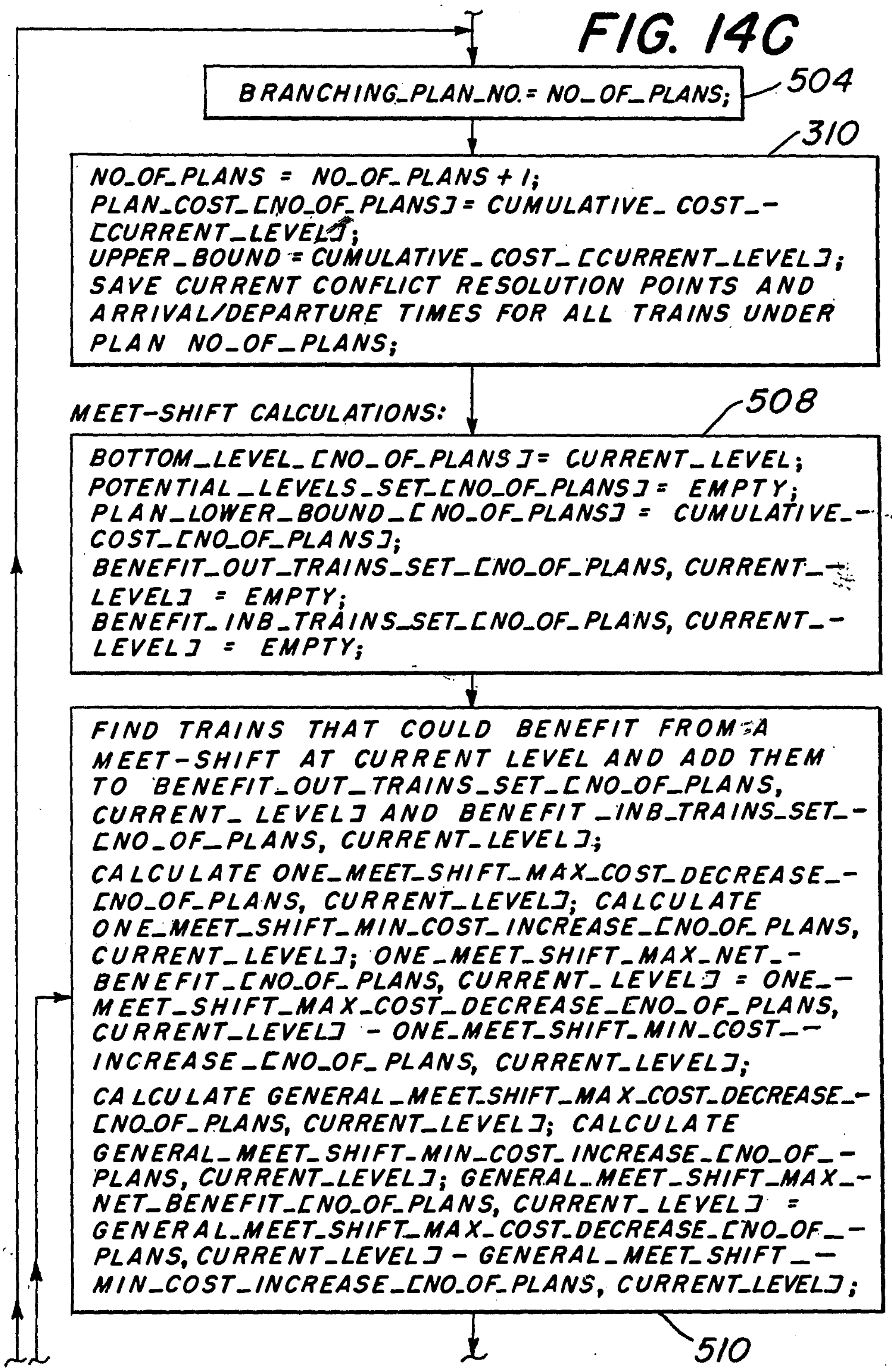


FIG. 14B


260
SELECT MEETPOINT, M, FOR THIS BRANCH OF THE BRANCH-AND-BOUND TREE;
A
270
SET CURRENT TRAIN LOCATION TO M;
CALCULATE ADDITIONAL TRAIN DELAY CAUSED BY THE CONFLICT;
UPDATE REMAINING SCHEDULE SLACK FOR DELAYED TRAIN(S);
UPDATE ARRIVAL/DEPARTURE TIMES OF DELAYED TRAIN(S) FROM TRAIN'S CURRENT LOCATION UNTIL END POINT;
280
CALCULATE ANY ADDITIONAL TRAIN TARDINESS COST CAUSED BY THE CONFLICT AND ADD TO CUMULATIVE_COST_[CURRENT_LEVEL];
290
CUMULATIVE_COST_[CURRENT_LEVEL] < UPPER_BOUND
FALSE
500
BRANCHING_PLAN_NO. = 0;
MERGED_MAX_NET_BENEFIT = 0;
PLAN_COST_[0] = CUMULATIVE_COST_[CURRENT_LEVEL];
TRUE
300
FALSE
NO MORE TRAIN PAIRS
TO BRANCHING FROM FATHOM PATH
TRUE
502
LAST_PLAN_FROM_TREE = NO_OF_PLANS + 1;
B

Docket No. UPN-0401 Ser. No.: 629,417 Filed: December 18, 1990 Art Unit: 2304 Inventor: Harker et al. Notice of Allowance: 7/13/92 Batch No.: E45 Sheet 19 of 28

FIG. 14C



Docket No. UPN-0401 Ser. No.: 629,417 Filed: December 18, 1990 Art Unit: 2304 Inventor: Harker et al. Notice of Allowance: 7/13/92 Batch No.: E45 Sheet 20 of 28

FIG. 14D

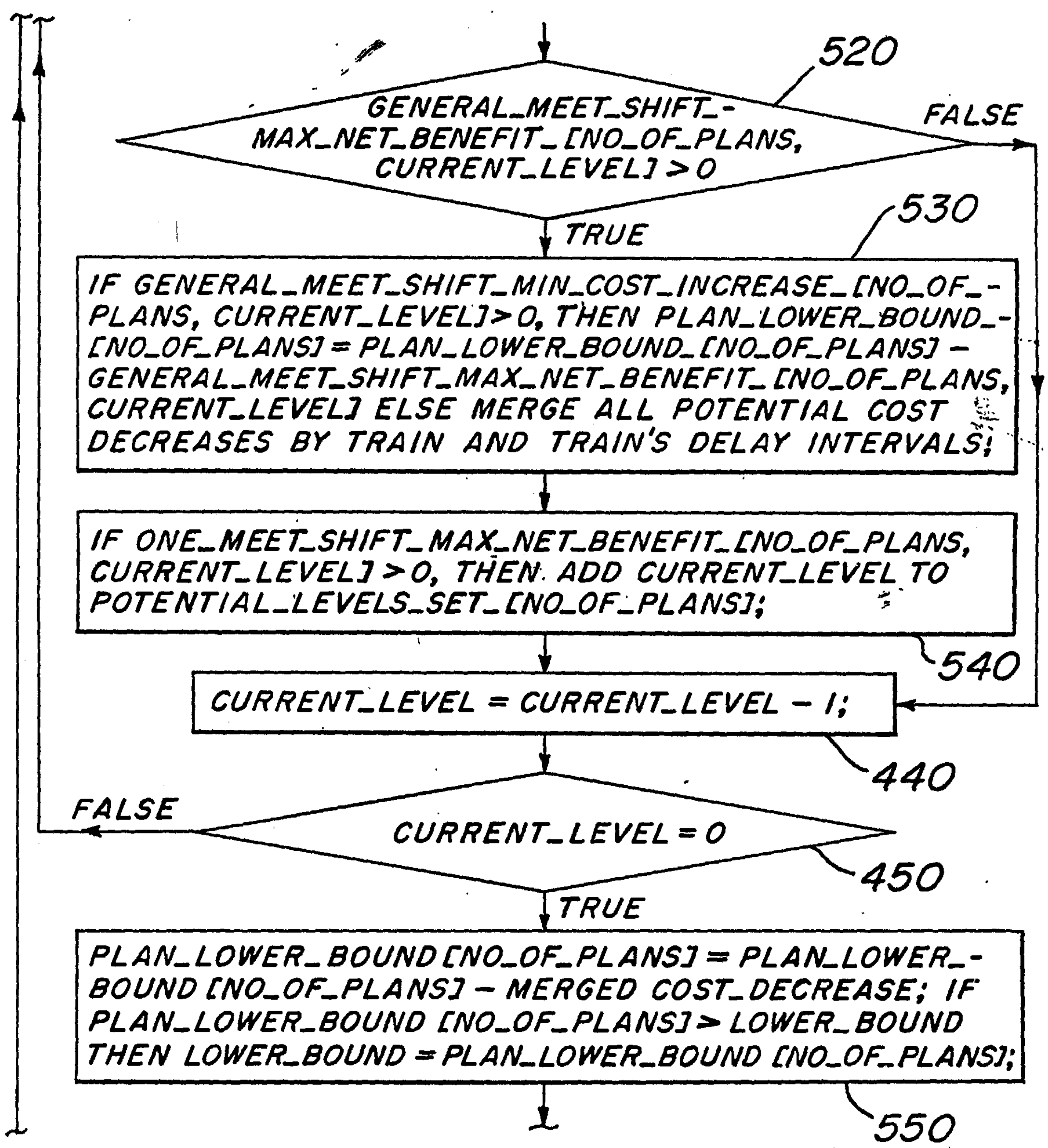
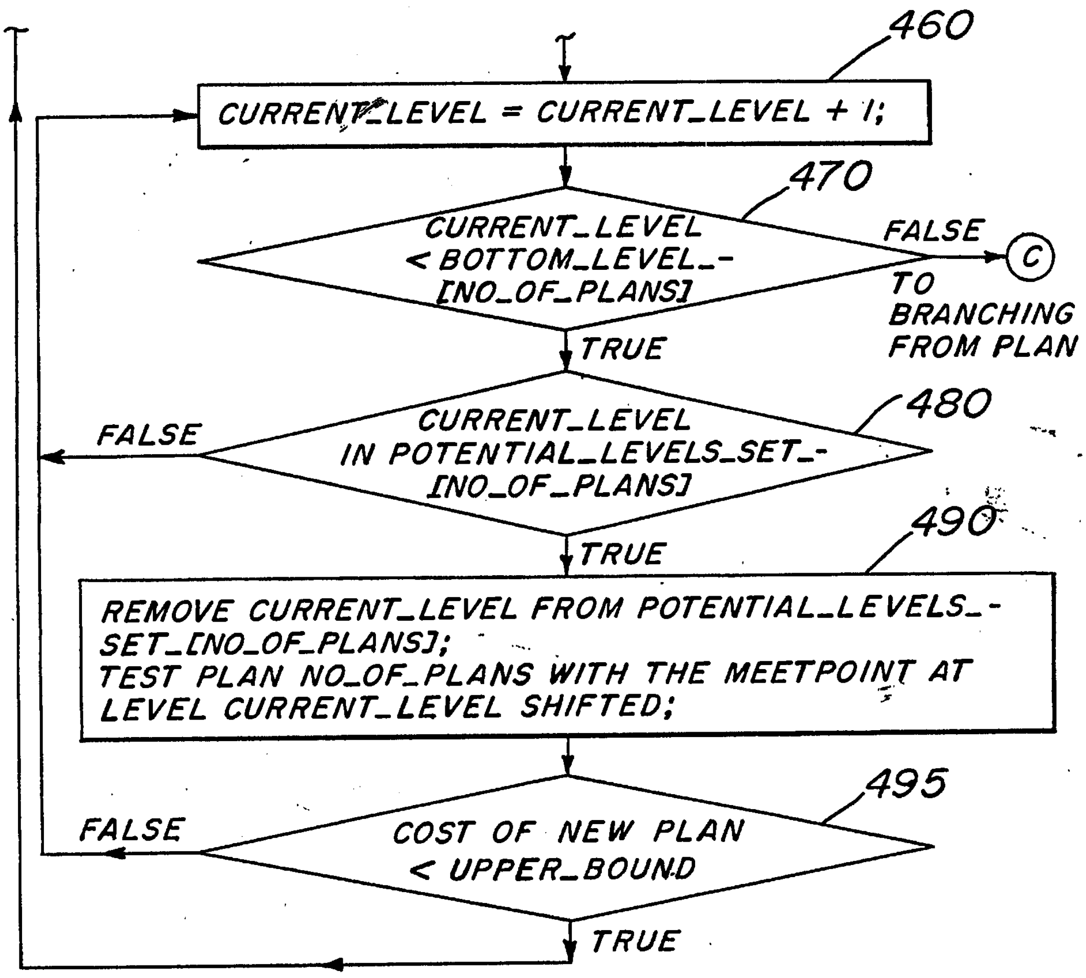
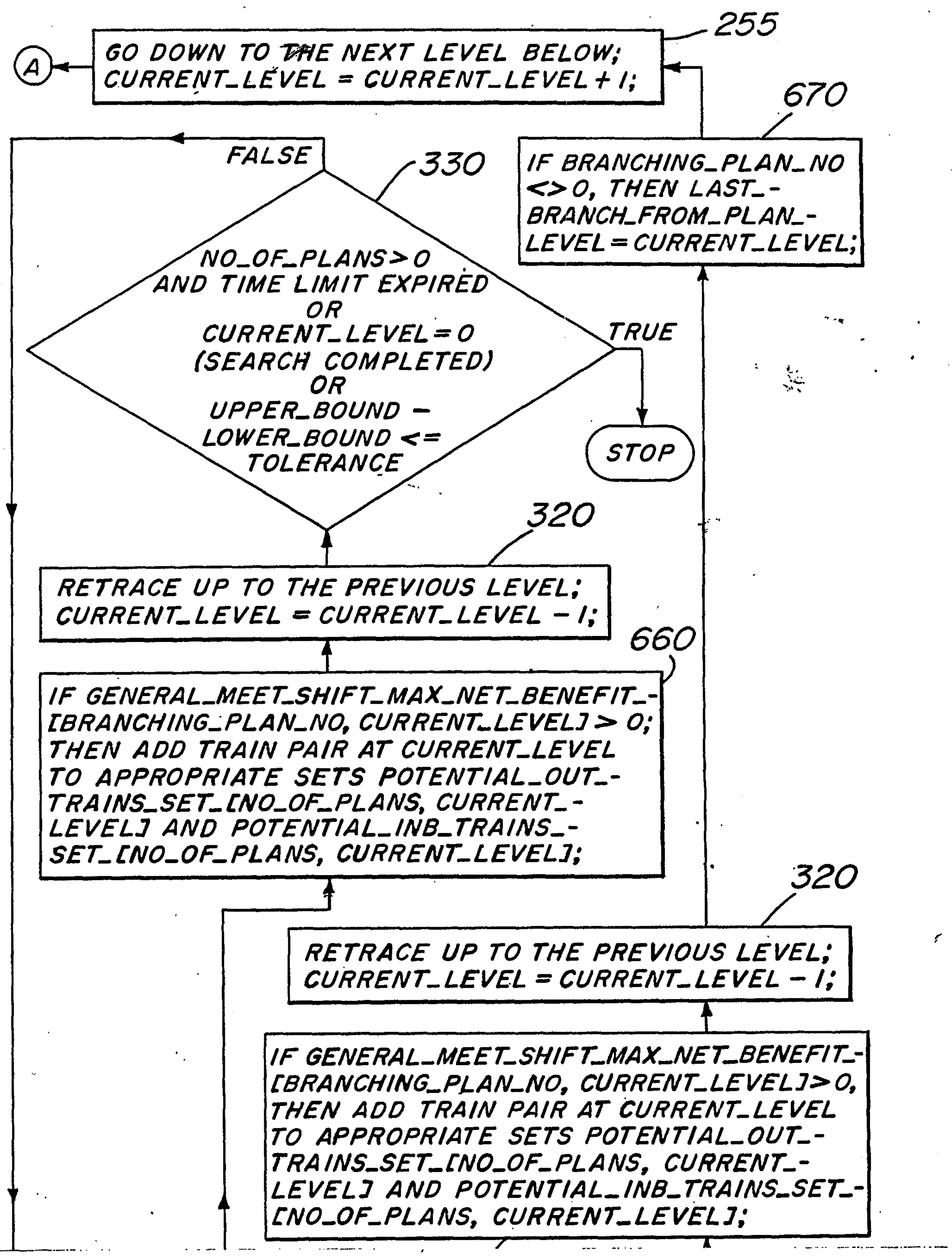


FIG. 14E


460
CURRENT_LEVEL = CURRENT_LEVEL + 1;
470
CURRENT_LEVEL < BOTTOM_LEVEL_[NO_OF_PLANS]
FALSE
C
TO BRANCHING FROM PLAN
TRUE
480
CURRENT_LEVEL IN POTENTIAL_LEVELS_SET_[NO_OF_PLANS]
FALSE
TRUE
490
REMOVE CURRENT_LEVEL FROM POTENTIAL_LEVELS_SET_[NO_OF_PLANS];
TEST PLAN NO_OF_PLANS WITH THE MEETPOINT AT LEVEL CURRENT_LEVEL SHIFTED;
495
COST OF NEW PLAN < UPPER_BOUND
FALSE
TRUE

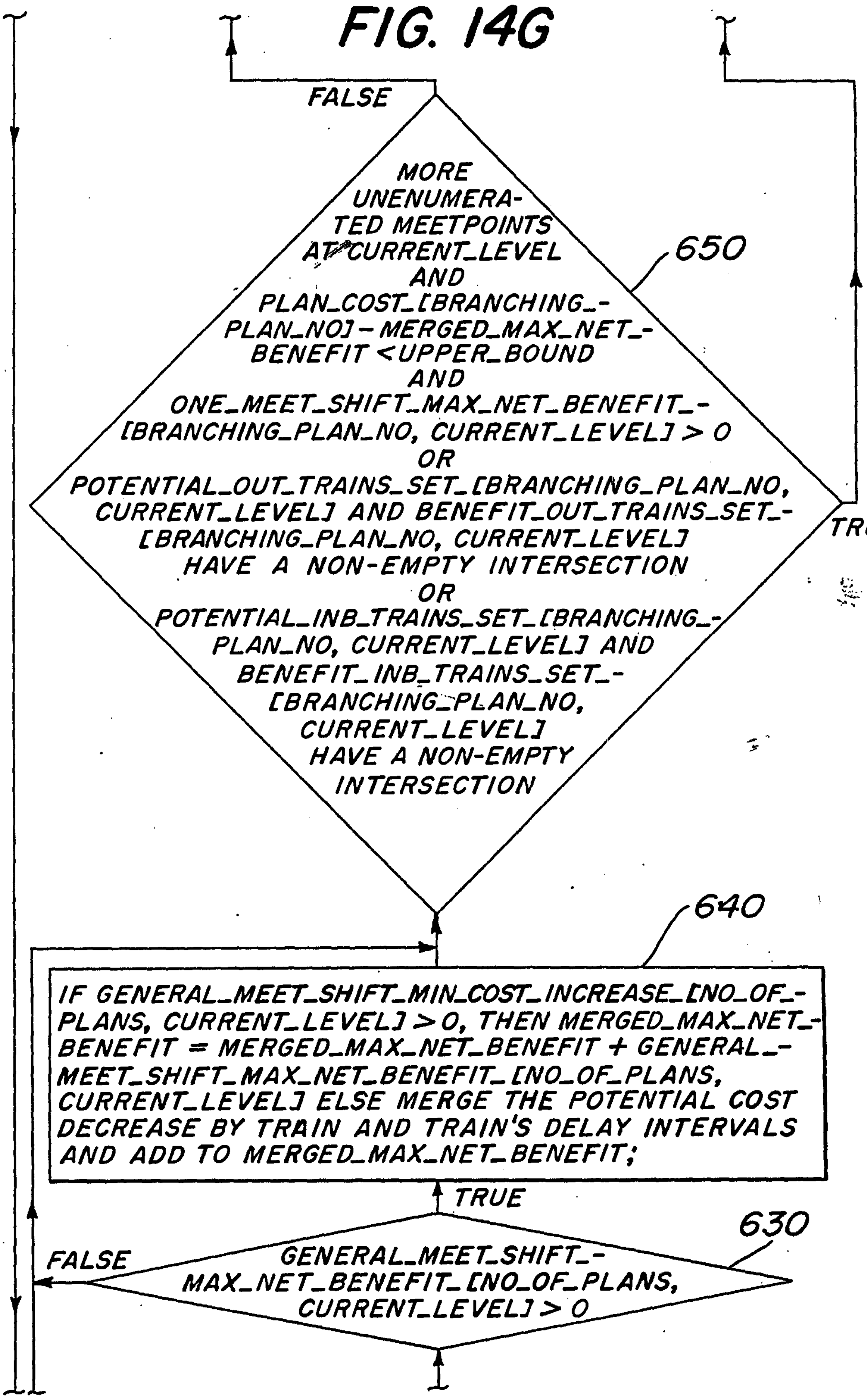
Docket No. UPN-0401 Ser. No.: 629,417 Filed: December 18, 1990 Art Unit: 2304 Inventor: Harker et al. Notice of Allowance: 7/13/92 Batch No.: E45 Sheet 22 of 28

FIG. 14F



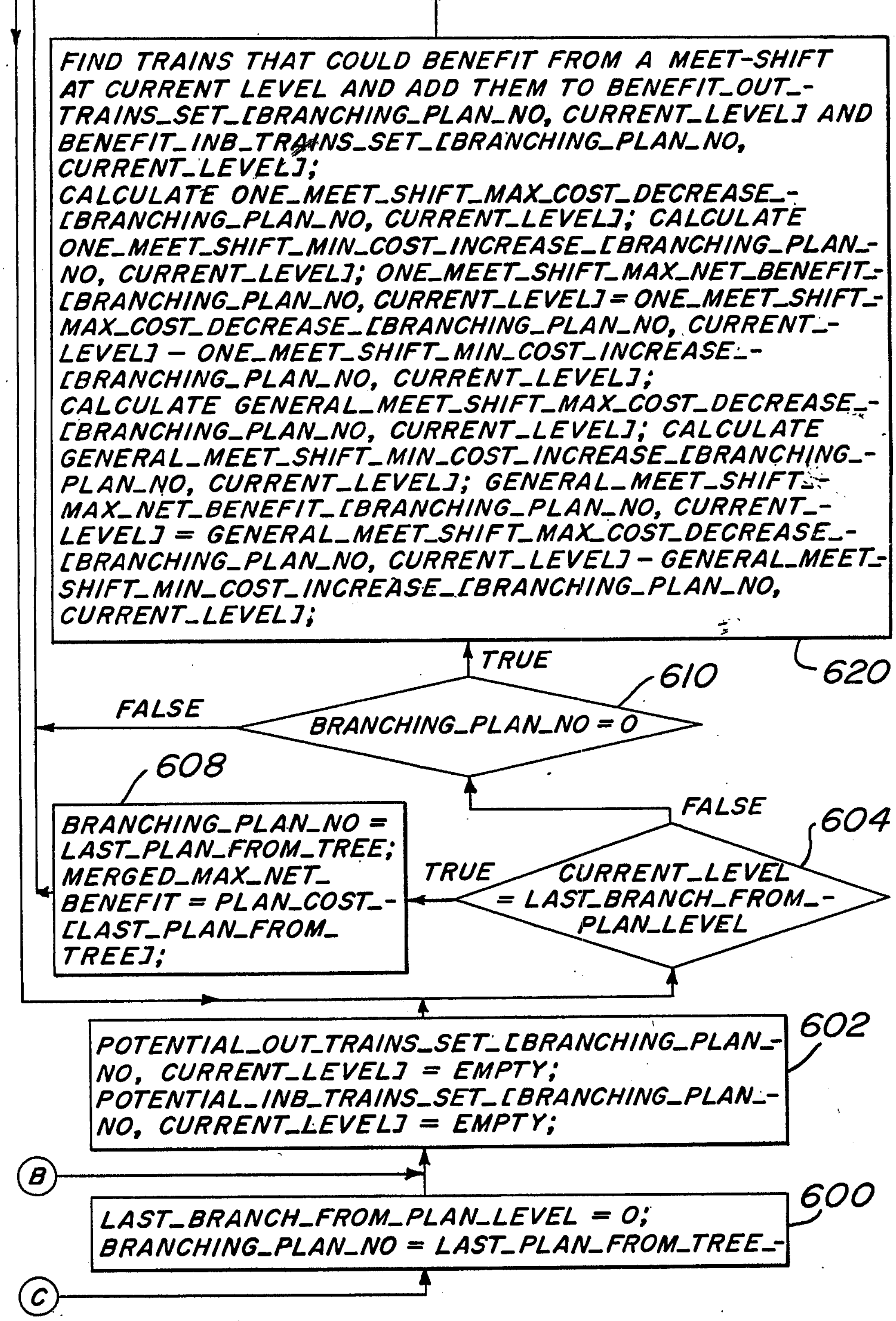
Docket No. UPN-0401 Ser. No.: 629,417 Filed: December 18, 1990 Art Unit: 2304 Inventor Harker et al. Notice of Allowance: 7/13/92 No.: E45 Sheet 23 of 28

FIG. 14G



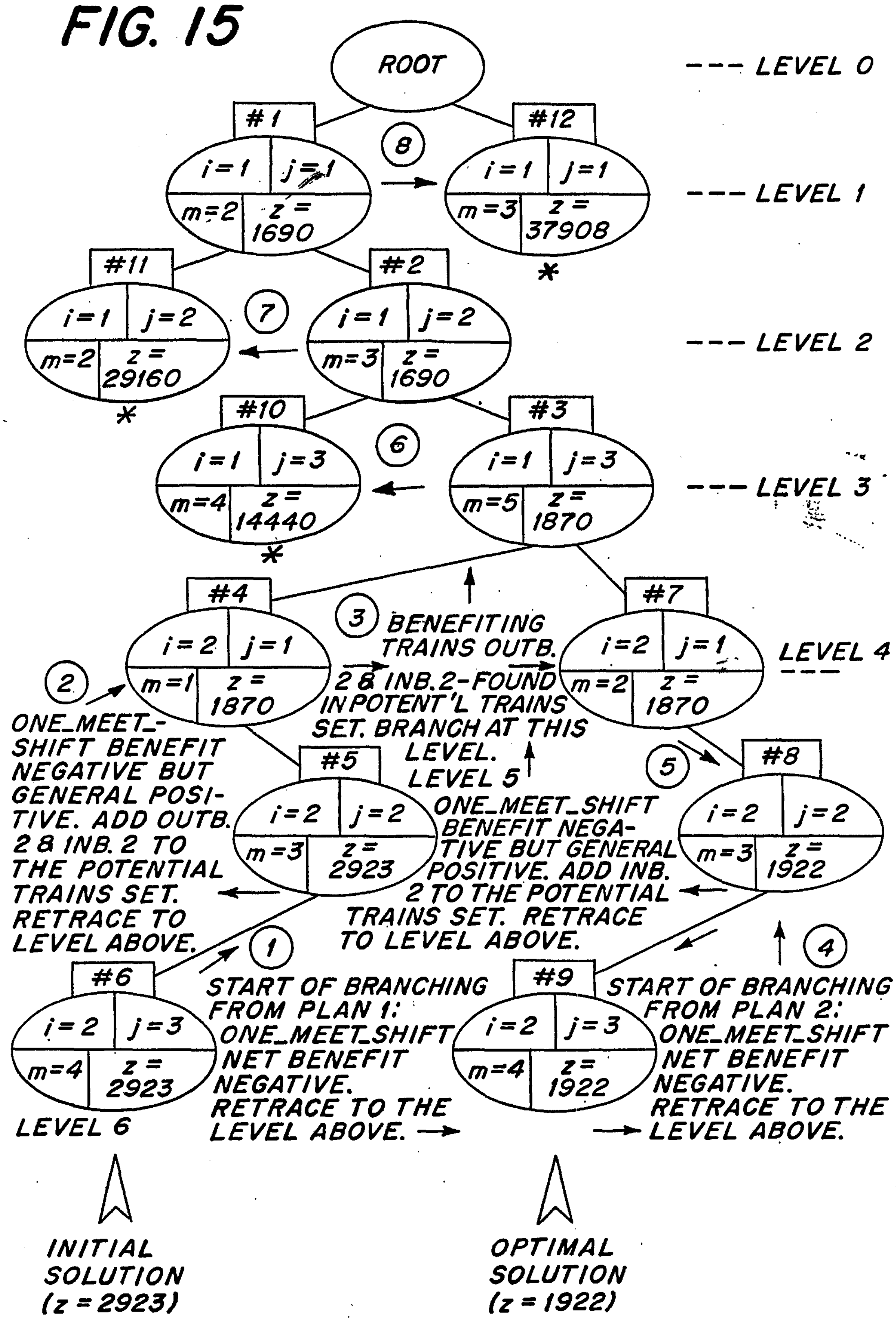
Docket No. UPN-0401 Ser. No.: 629,417 Filed: December 18, 1990 Art Unit: 2304 Inventor: Harker et al. Notice of Allowance: 7/13/92 Batch No.: E45 Sheet 24 of 28

FIG. 14H



Docket No. UPN-0401 Ser. No.: 629,417 Filed: Dece 18, 1990 Art Unit: 2304 Inventor: Harke. et al. Notice of Allowance: 7/13/92 Batch No.: E45 Sheet 25 of 28

FIG. 15

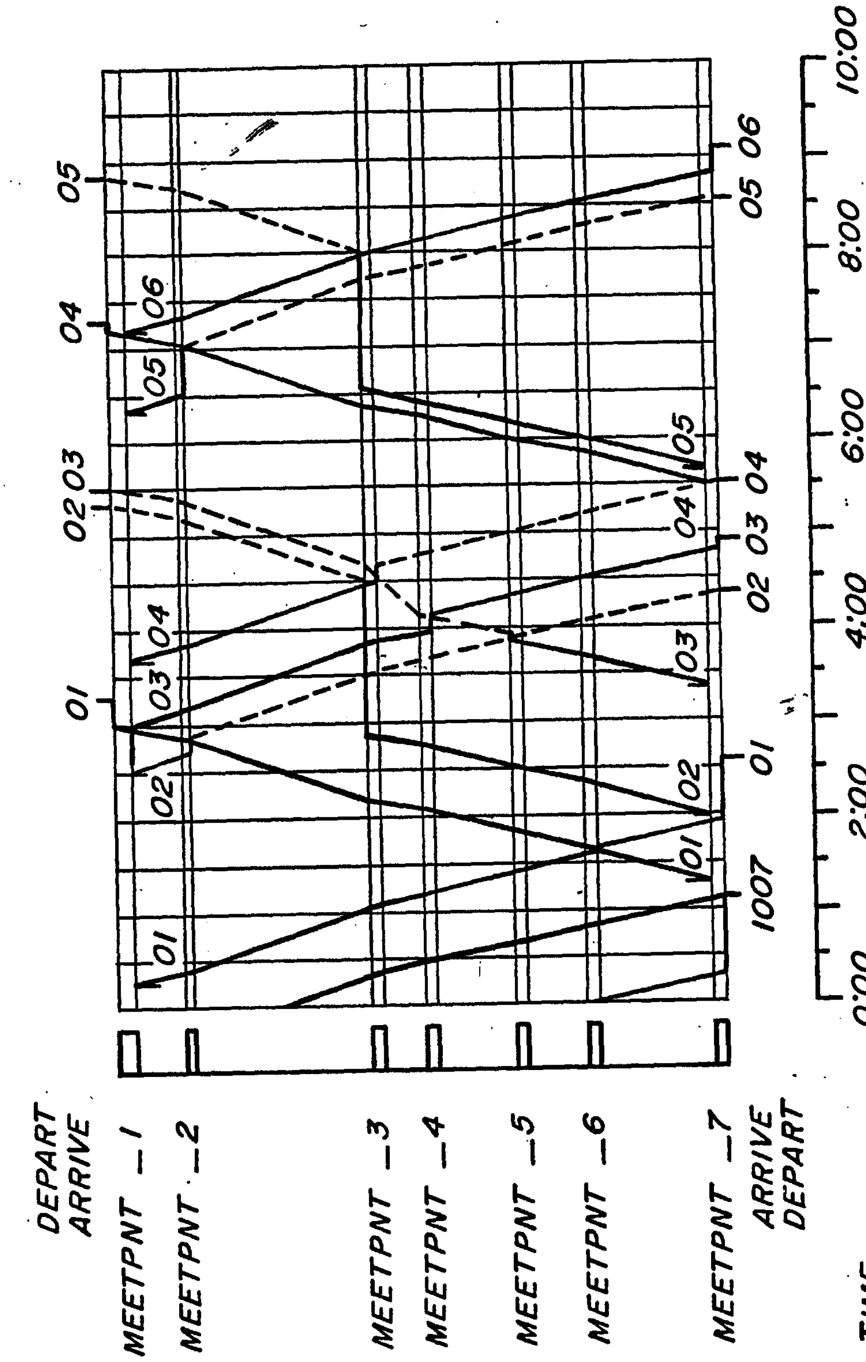


NODES ENUMERATED USING THE BRANCH-AND-BOUND METHOD OF THE LOWER-BOUND EXACT PRUNING ALGORITHM

Docket No. UPN-0401 Ser. No.: 629,417 Filed: De[illegible]ber 18, 1990 Art Unit: 2304 Inventor: Ha[illegible] et al. Notice of Allowance: 7/13/92 Batch No.: E45 Sheet 26 of 28

FIG. 16

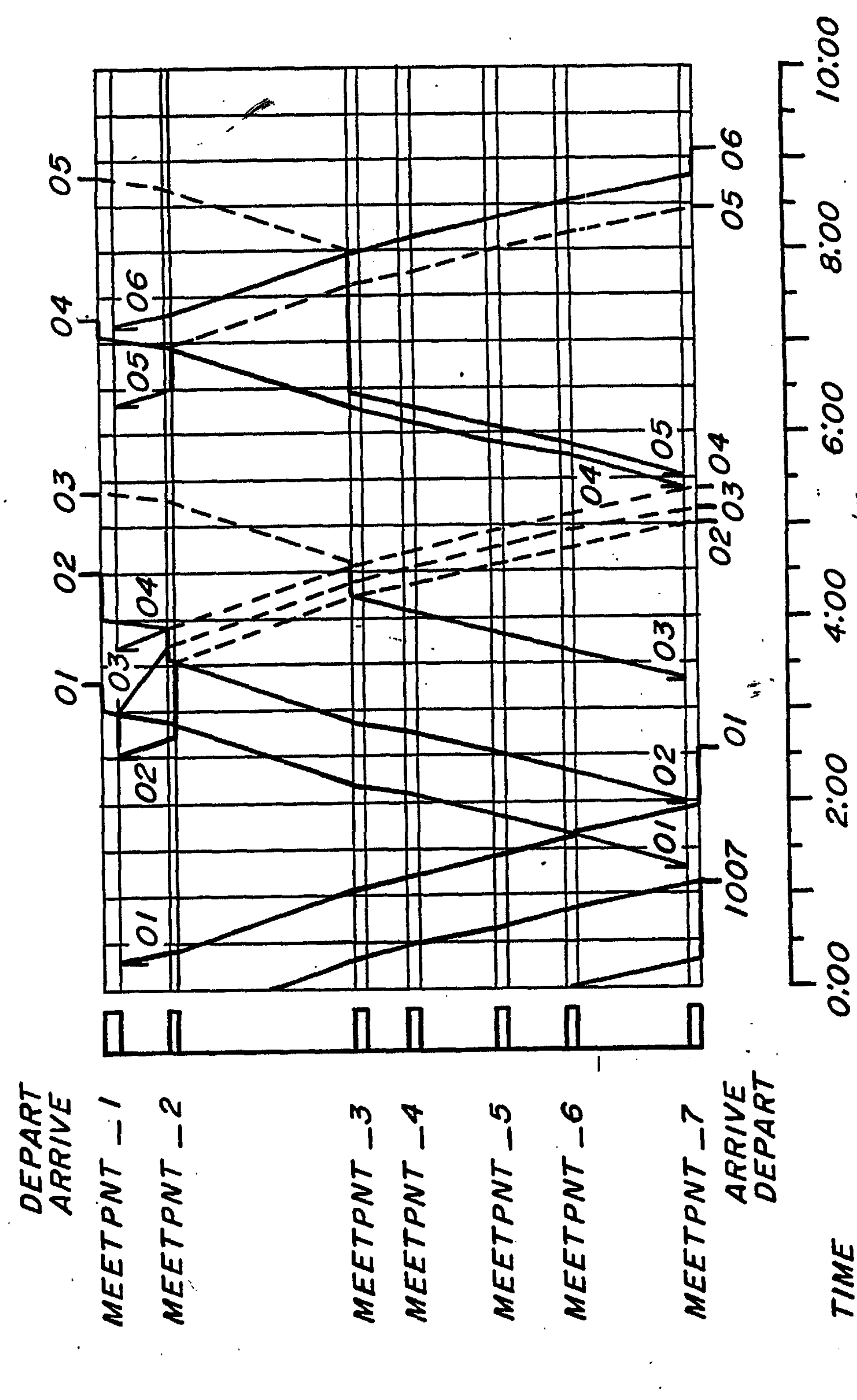
TIME-DISTANCE DIAGRAM OF AN INITIAL MEET-PASS PLAN



Docket No. UPN-0401 Ser. No.: 629,417 Filed: ...mber 18, 1990 Art Unit: 2304 Inventor: Harker et al. Notice of Allowance: 7/13/92 Batch No.: E45 Sheet 27 of 28

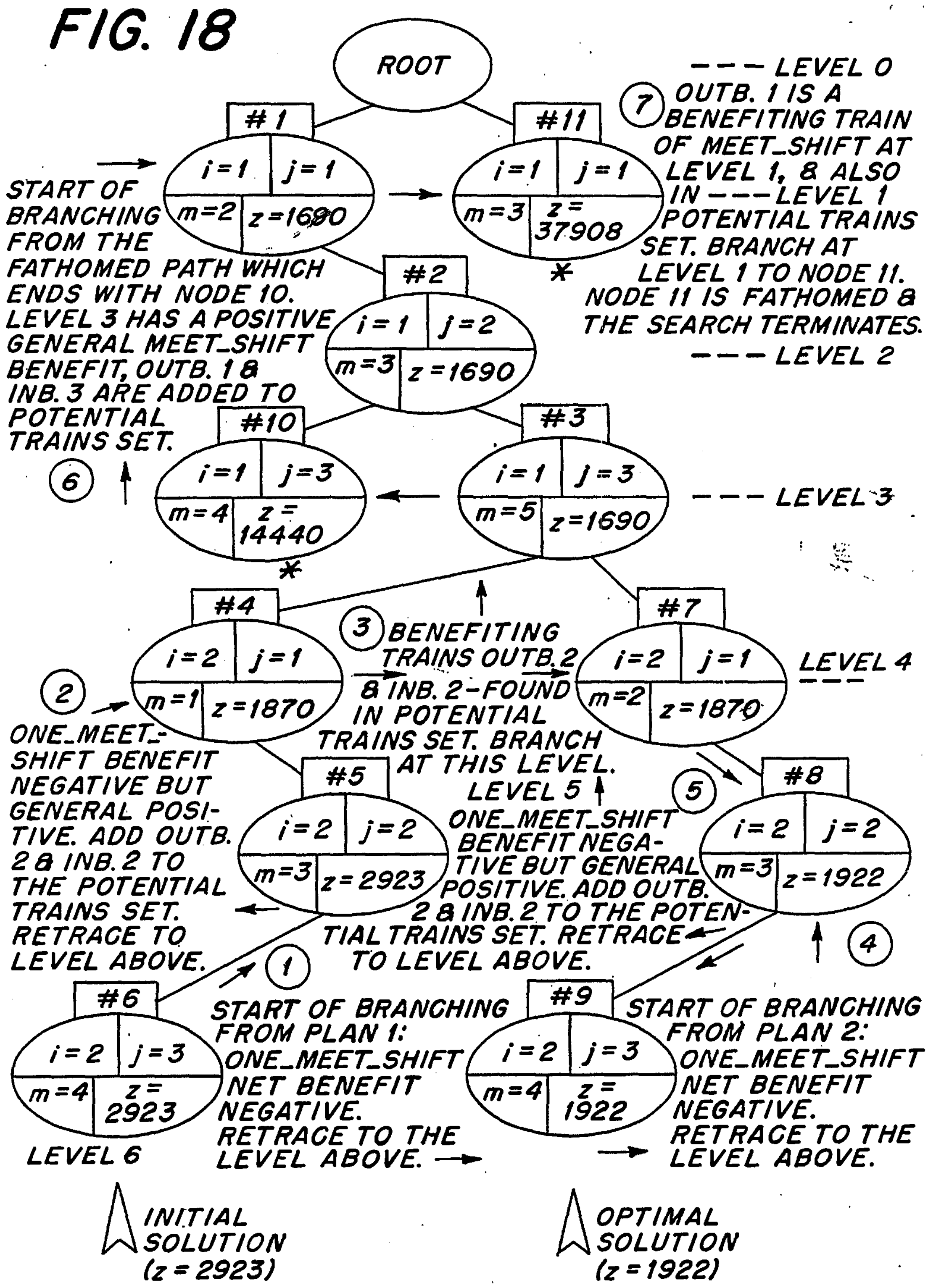
FIG. 17

TIME-DISTANCE DIAGRAM OF AN OPTIMAL MEET-PASS PLAN USING LOWER-BOUND BASED PRUNING ALGORITHM



Docket No. UPN-0401 Ser. No.: 629,417 Filed: D[illegible]mber 18, 1990 Art Unit: 2304 Inventor: [illegible]r et al. Notice of Allowance: 7/13/92 Batch No.: E45 Sheet 28 of 28

FIG. 18



NODES ENUMERATED USING THE BRANCH-AND-BOUND METHOD OF THE ACCELERATED HEURISTIC LOWER-BOUND BASED ALGORITHM

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Transaction History Date 1992-09-09.
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UNITED STATES DEPARTMENT OF COMMERCE
Patent and Trademark Office
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Washington, D.C. 20231

SERIAL NUMBER	FILING DATE	FIRST NAMED APPLICANT	ATTORNEY DOCKET NO.
		MARKER	UPN-401

EXAMINER	
AUCHTERLONIE, T	
ART UNIT	PAPER NUMBER
	10

DATE MAILED: 09/09/92

KURTZ, MACKIEWICZ
46TH FLOOR
10103

NOTICE OF DRAWING REQUIREMENTS

☐ The PTO delayed in providing a commercial bonded draftsman with drawings from the above-identified application. The delay prevented the draftsman from filing corrected drawings within the response period set in the Notice of Allowability mailed ________. Hence, said response period is hereby vacated. THE SHORTENED STATUTORY PERIOD FOR RESPONSE to comply with the requirement for drawing corrections is set to EXPIRE ONE MONTH FROM THE DATE OF THIS LETTER. Failure to comply will result in the ABANDONMENT of this application. Extensions of time may be obtained under the provisions of 37 CFR 1.136(a) by filing the appropriate request and fee before the end of the six month statutory period for response.

☒ Corrected/substituted drawings for the above-identified application, received in the PTO on 8-10-92 are still considered informal for the reason(s) identified on the attached Form PTO-948.

☒ Applicant has the time remaining in the response period set in the Notice of Allowability or Notice of Drawing Requirements mailed 10-13-92 to overcome the objections raised in the attached Form PTO-948. This response period may be extended under the provisions of 37 CFR 1.136(a) by filing the appropriate request and fee before the end of the six month statutory period for response.

☐ The PTO delayed in reviewing the corrected drawings. Applicant is given ONE month time limit from the date of this letter to provide corrected drawings. NO EXTENSION OF THIS TIME LIMIT MAY BE GRANTED UNDER EITHER 37 CFR 1.136(a) or (b). See MPEP 714.03. However, the response period set in the Notice of Allowability or Notice of Drawing Requirements mailed ________ may be extended under the provisions of 37 CFR 1.136(a) by filing the appropriate request and fee before the end of the six month statutory period for response.

☐ Corrected/substituted drawings for the above-identified application received in the PTO on ________ were submitted outside of the period for response set in the Notice of Allowability or Notice of Drawing Requirements mailed ________. This application will become abandoned unless applicant obtains an extension of time under the provisions of 37 CFR 1.136(a) by filing the appropriate request and fee before the end of the six month statutory period for response.

☐ ATTACHMENT: PTO-948

Joe Davis — PATENT AND TRADEMARK OFFICE
8-27-92 — DATE

FORM PTOL-455 (5-86)

PTO FORM 948
(Rev 5-91)

U.S. DEPARTMENT OF COMMERCE
Patent and Trademark Office

ATTACHMENT TO PAPER NUMBER

GROUP

APPLICATION NUMBER 629417

NOTICE OF DRAFTSMAN'S PATENT DRAWING REVIEW

The PTO Draftsmen review all originally filed drawings regardless of whether they were designated as informal or formal.

The drawings filed 8-10-92

A. ☐ are approved.

B. ☑ are objected to under 37 CFR 1.84 for reason(s) checked below. The examiner will require submission of new, corrected drawings at the appropriate time. Corrected drawings must be submitted according to the instructions listed on the back of this Notice.

1. Paper and Ink. 37 CFR 1.84(a)
   ☐ Poor Quality Paper. Must Be White. Transparent Paper Not Allowed. Sheet(s) ______

2. Size of Sheet and Margins. 37 CFR 1.84(b)
   Acceptable Paper Sizes and Margins

Paper Size

Margin	8 1/2 by 14 inches	8 1/2 by 13 inches	DIN size A4 21 by 29.7 cm.
Top	2 inches	1 inch	2.5 cm.
Left	1/4 inch	1/4 inch	2.5 cm.
Right	1/4 inch	1/4 inch	1.5 cm.
Bottom	1/4 inch	1/4 inch	1.0 cm.

   ☐ Proper Size Paper Required. All Sheets Must be Same Size. Sheet(s) ______

   ☑ Proper Margins Required. ~~Sheet(s)~~ Fg 10A, 10C, 11A, Fg 12, 13, 14A, 14F, 15,
   ☐ Top ☐ Right
   ☐ Left ☑ Bottom

3. Character of Lines. 37 CFR 1.84(c)
   ☐ Lines Pale, Rough and Blurred, or Jagged. Fig(s) ______
   ☐ Solid Black Shading Not Allowed. Fig(s) ______

4. ☐ Photographs Not Approved.

5. Hatching and Shading. 37 CFR 1.84(d)
   ☑ ~~Shade Lines are Required.~~ ~~Fig(s)~~ Remove all descriptive matter, Fg 15, Fg 18
   ☐ Cross-Cross Hatching Not Allowed. Fig(s) ______
   ☐ Double Line Hatching Not Allowed. Fig(s) ______
   ☐ Parts in Section Must be Hatched Properly. Fig(s) ______

6. Reference Characters. 37 CFR 1.84(f)
   ☐ Reference Characters Poor or Rough and Blurred. Fig(s) ______
   ☐ Minimum 1/8 inch (3.2 mm.) in height is required. Fig(s) ______
   ☐ Figure Legends Poor or Placed Incorrectly. Fig(s) ______

7. Views. 37 CFR 1.84(i) & (j)
   ☑ Figures Must be Numbered Separately. 5
   ☐ Figures Must Not be Connected Fig(s) ______

8. Identification of Drawings. 37 CFR 1.84(l)
   ☑ ~~Extraneous Matter or~~ Copy Machine Marks Not Allowed. Fig(s) ______

9. ☐ Changes Not Completed from Prior PTO-948 dated ______

☑ Comments: — Remove extra matter at top of all sheets.
— Remove titles, Fig 5, 7, 8, 9, 10A, 12, 13, 15, 16, 17, 18

Telephone inquires concerning this review should be directed to the Chief Draftsman at telephone number (703) 557-6404.

Joe Salas
Reviewing Draftsman

8-27-92
Date

MAIL ROOM
SEP 23 1992
52 PAT. & TRADEMARK OFF.

DOCKET NO: UPN-0401

PATENT

Issue Batch No.: E45
Date of Notice
of Allowance : 07/13/92
Serial No. : 629,417

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re patent application of:

Patrick T. Harker et al.

Serial No.: **629,417** Group No.: **2304**

Filed: **December 18, 1990** Examiner: **T. Auchterlonie**

For: **METHOD FOR ANALYZING AND GENERATING OPTIMAL TRANSPORTATION SCHEDULES FOR VEHICLES SUCH AS TRAINS AND CONTROLLING THE MOVEMENT OF VEHICLES IN RESPONSE THERETO**

I, STEVEN J. ROCCI REGISTRATION NO. 30,489 CERTIFY THAT THIS CORRESPONDENCE IS BEING DEPOSITED WITH THE U.S. POSTAL SERVICE AS FIRST CLASS MAIL IN AN ENVELOPE ADDRESSED TO THE COMMISSIONER OF PATENTS AND TRADEMARKS, WASHINGTON, D.C. 20231
ON September 21, 1992
STEVEN J. ROCCI

Box Issue Fee
Commissioner of Patents & Trademarks
Washington, DC 20231

ATTN: Official Draftsman

Sir:

TRANSMITTAL LETTER TO OFFICIAL DRAFTSMAN

This is in response to the Notice of Drawing Requirement and accompanying Notice of Draftsman's Patent Drawing Review (PTO Form 948) bearing a "date mailed" stamp of September 9, 1992.

Further to the telephone conference with the Reviewing Draftsman whose signature appears on the above papers (Joe Harris) on September 18, 1992, applicant has enclosed herewith 28 sheets of replacement formal drawings relating to the above identified patent application.

Please note as follows.

In response to item no. 2 of PTO Form 948, the enclosed sheets of drawing are believed to have the proper margins.

In response to item no. 5 and the second comment at the bottom of PTO Form 948, applicant notes that the Examiner required the descriptive titles to be placed on the various ones of the sheets of drawings. See Paragraph no. 2 of the Office Action dated December 11, 1991. The drawings originally submitted with this application did not bear such descriptive titles, and it was only in response to the Examiner's requirement that they were placed in this application. The Examiner subsequently approved the proposed drawings bearing such descriptive titles. See the Notice of Allowability dated July 13, 1992.

Regarding first comment at the bottom of PTO Form 948, it is submitted that the new sheets of drawing comply with 37 CFR § 1.84(l).

In view of the above, the present application is believed to be in a condition ready for issuance.

Respectfully submitted,

Date: September 21, 1992

Steven J. Rocci
Registration No. 30,489

WOODCOCK WASHBURN KURTZ
MACKIEWICZ & NORRIS
One Liberty Place - 46th Floor
Philadelphia, PA 19103
(215) 568-3100

DOCKET NO: UPN-0401 PATENT

Issue Batch No.: E45
Date of Notice
of Allowance : 07/13/92
Serial No. : 629,417

MAIL ROOM
SEP 23 1992
52 PAT. & TRADEMARK OFC.

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

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One Liberty Place - 46th Floor
Philadelphia, PA 19103
(215) 568-3100

DOCKET NO: UPN-0401

PATENT

#11 B

Issue Batch No.: E45
Date of Notice
of Allowance : 07/13/92
Serial No. : 629,417

MAIL ROOM SEP 23 1992 52 PAT. & TRADEMARK OFF.

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re patent application of:

Patrick T. Harker et al.

Serial No.: **629,417** Group No.: **2304**

Filed: **December 18, 1990** Examiner: **T. Auchterlonie**

For: **METHOD FOR ANALYZING AND GENERATING OPTIMAL TRANSPORTATION SCHEDULES FOR VEHICLES SUCH AS TRAINS AND CONTROLLING THE MOVEMENT OF VEHICLES IN RESPONSE THERETO**

Box Issue Fee
Commissioner of Patents & Trademarks
Washington, DC 20231

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DOCKET NO: UPN-0401 **PATENT**

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Docket No. UPN-0401 Ser.No.: 629,417 Filed: December 18, 1990 Art Unit: 2304 Inventor: Harker et al. Notice of Allowance: 7/13/93 Batch No.: E45 Sheet 1 of 28

446

364 436

5177684

FIG. 1

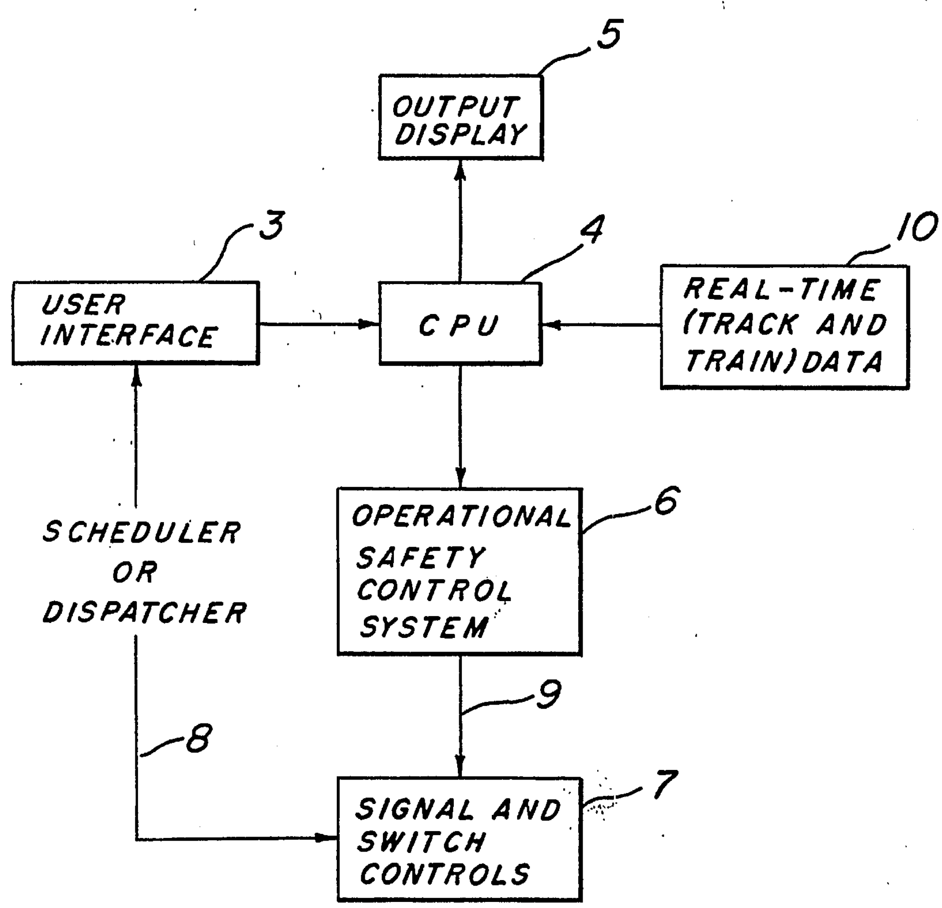
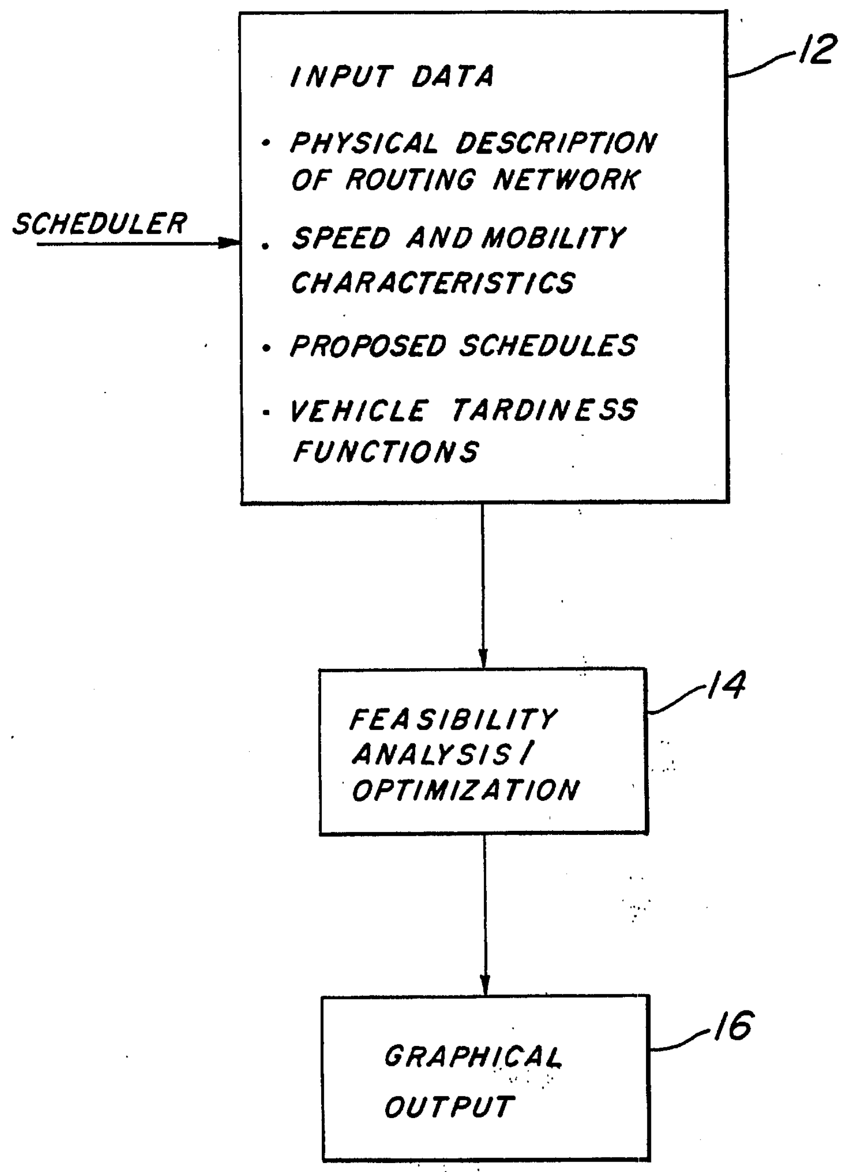


FIG. 2


INPUT DATA
• PHYSICAL DESCRIPTION OF ROUTING NETWORK
• SPEED AND MOBILITY CHARACTERISTICS
• PROPOSED SCHEDULES
• VEHICLE TARDINESS FUNCTIONS
12
SCHEDULER
FEASIBILITY ANALYSIS / OPTIMIZATION
14
GRAPHICAL OUTPUT
16

Docket No. UPN-0401 Ser.No.: 629,417 Filed: December 18, 1990 Art Unit: 2304 Inventor: Harker et al. Notice of Allowance: 7/13/93 Batch No.: E45 Sheet 3 of 28

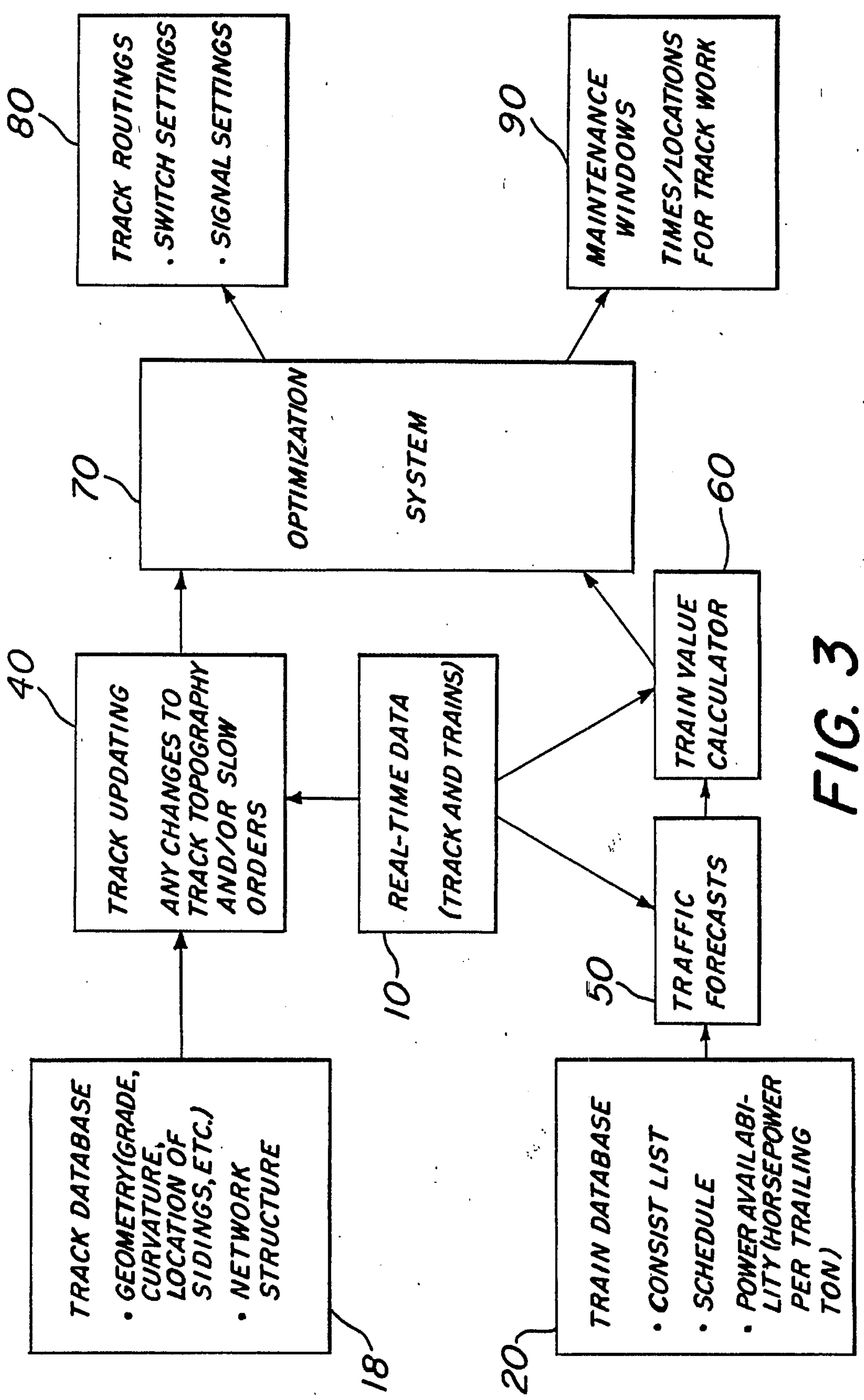


FIG. 3

446

364 436

Docket No. UPN-0401 Ser.No.: 629,417 Filed:
December 18, 1990 Art Unit: 2304 Inventor:
Harker et al. Notice of Allowance: 7/13/93
h No.: E45 Sheet 5 of 28

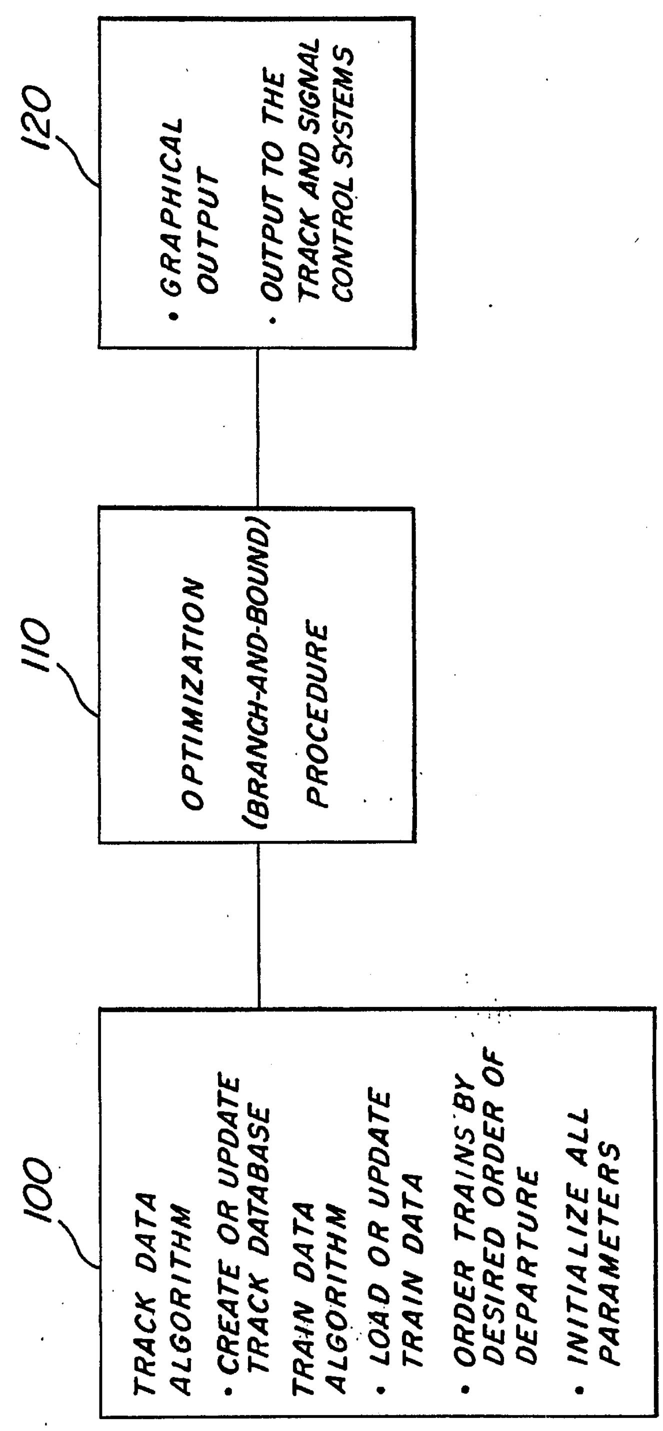
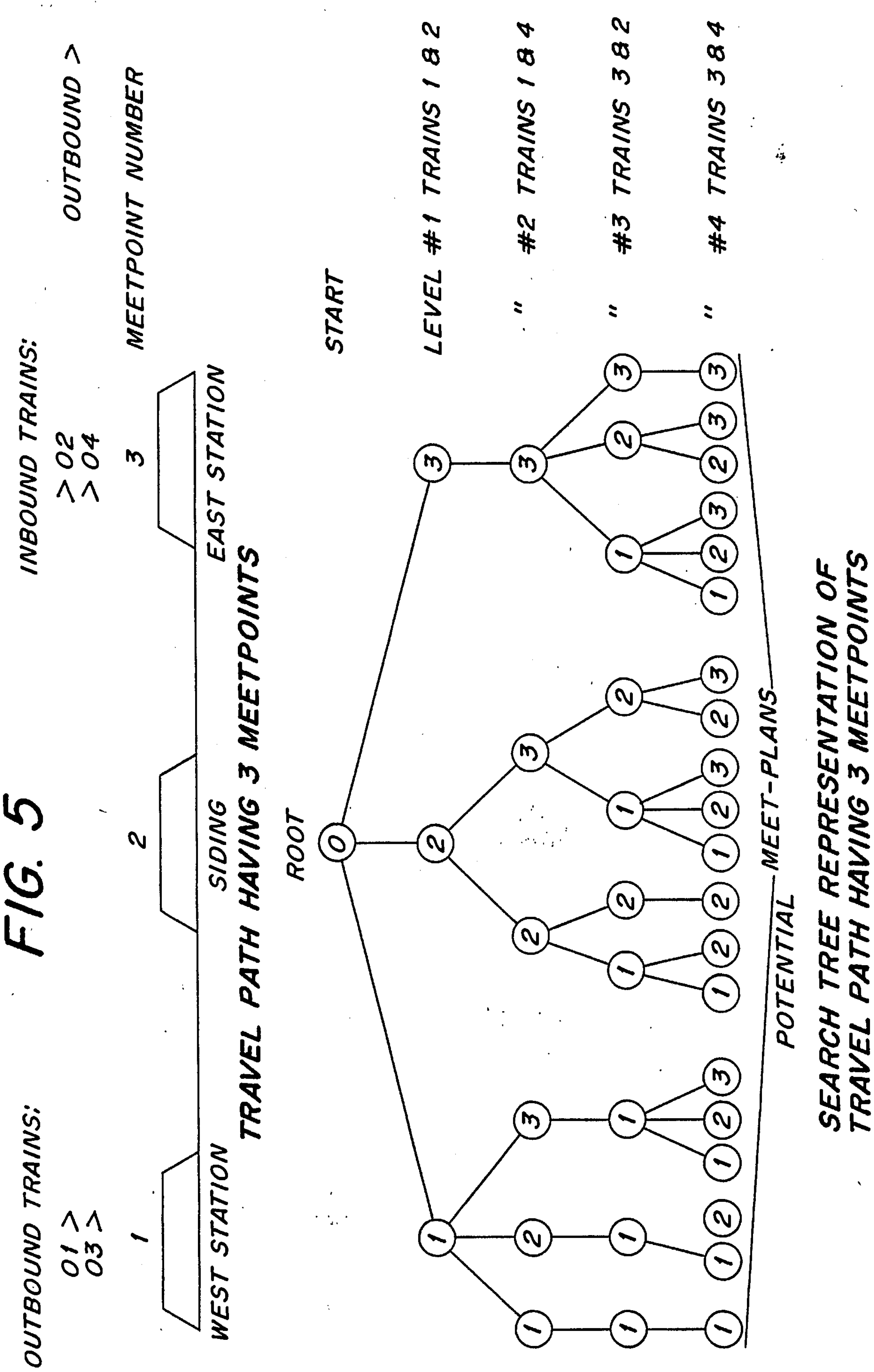


FIG. 4

Docket No. UPN-0401 Ser.No.: 629,417 Filed: December 18, 1990 Art Unit: 2304 Inventor: Harker et al. Notice of Allowance: 7/13/93 Batch No.: E45 Sheet 4 of 28

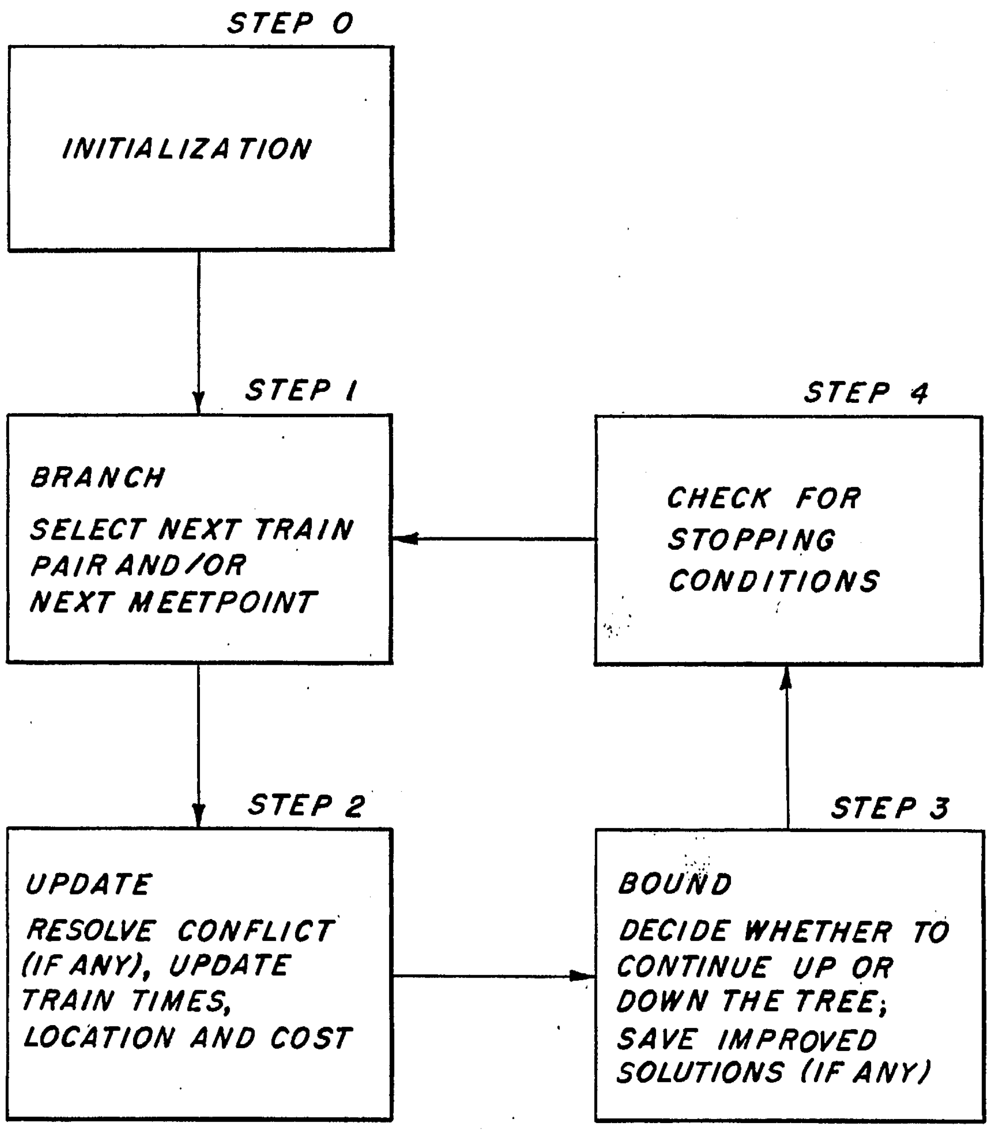
FIG. 5



Docket No. UPN-0401 Ser.No.: 629,417 Filed: December 18, 1990 Art Unit: 2304 Inventor: Harker et al. Notice of Allowance: 7/13/93 Batch No.: E45 Sheet 6 of 28

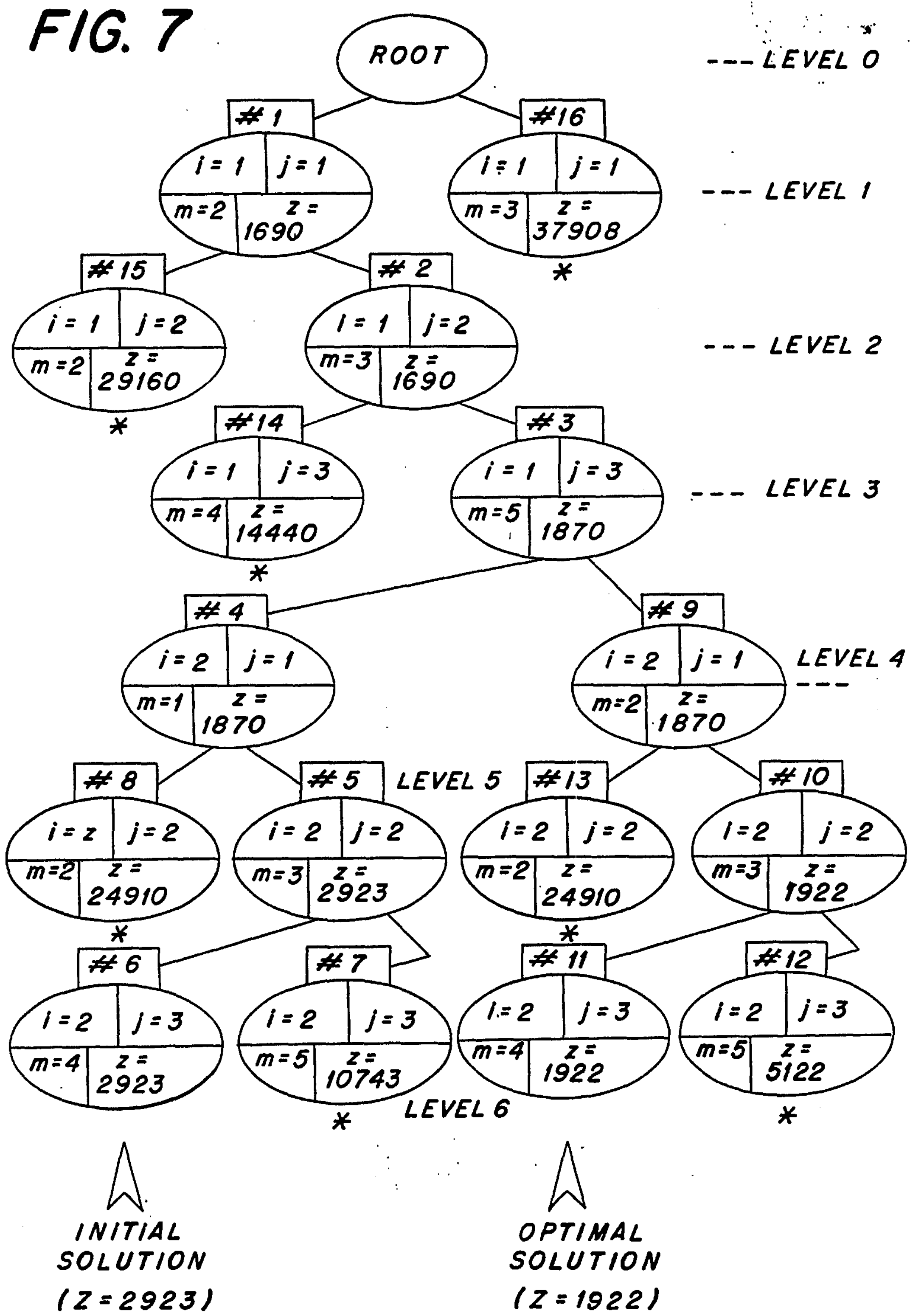
446
364 436

FIG. 6



Docket No. UPN-0401 Ser.No.: 629,417 Filed: December 18, 1990 Art Unit: 2304 Inventor: Harker et al. Notice of Allowance: 7/13/93 Batch No.: E45 Sheet 7 of 28

FIG. 7

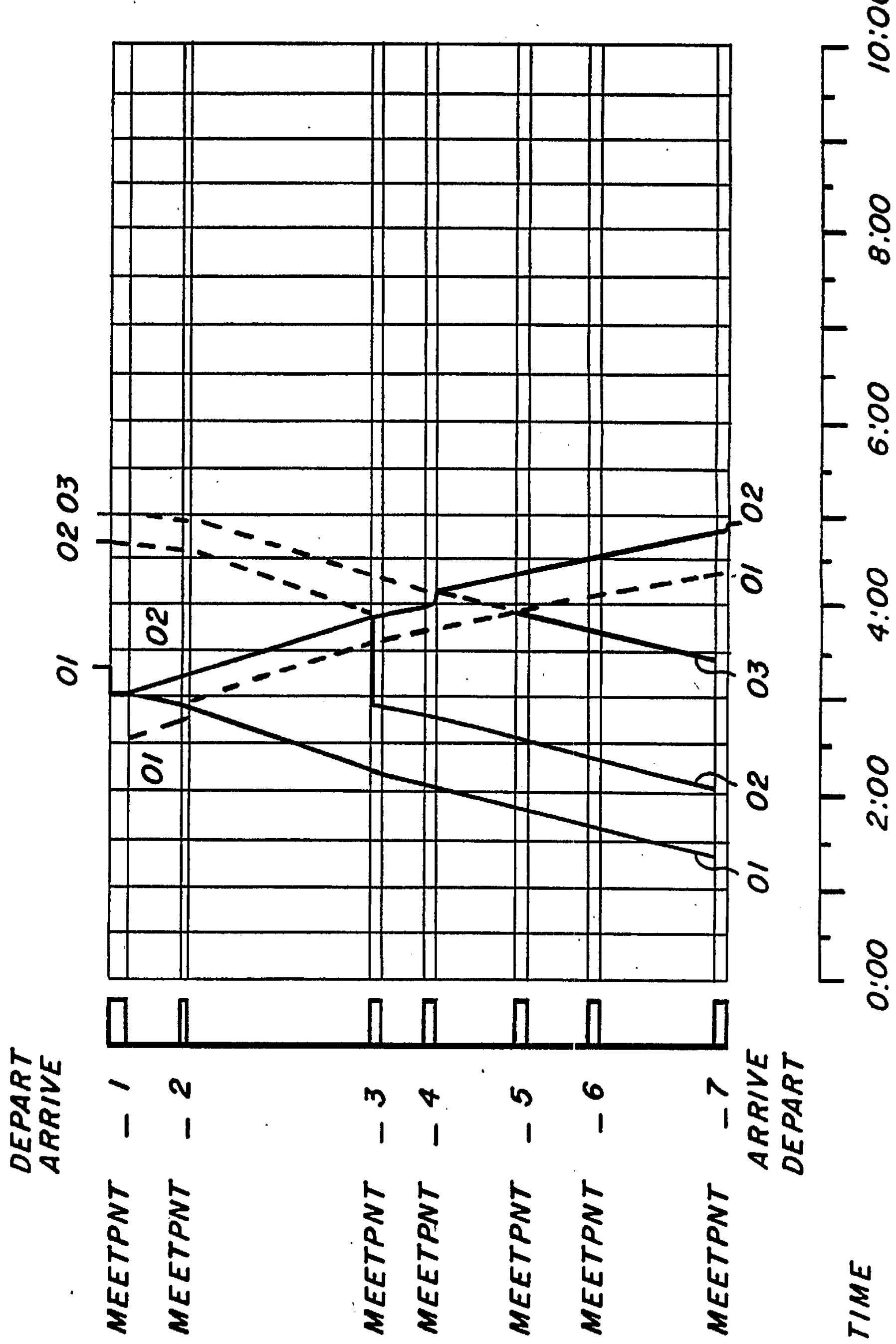


NODES ENUMERATED USING BRANCH-AND-BOUND METHOD OF IMPLICIT ENUMERATION ALGORITHM

Docket No. UPN-0401 Ser.No.: 629,417 Filed:
December 18, 1990 Art Unit: 2304 Inventor:
Harker et al. Notice of Allowance: 7/13/93
Batch No.: E45 Sheet 8 of 28

FIG. 8

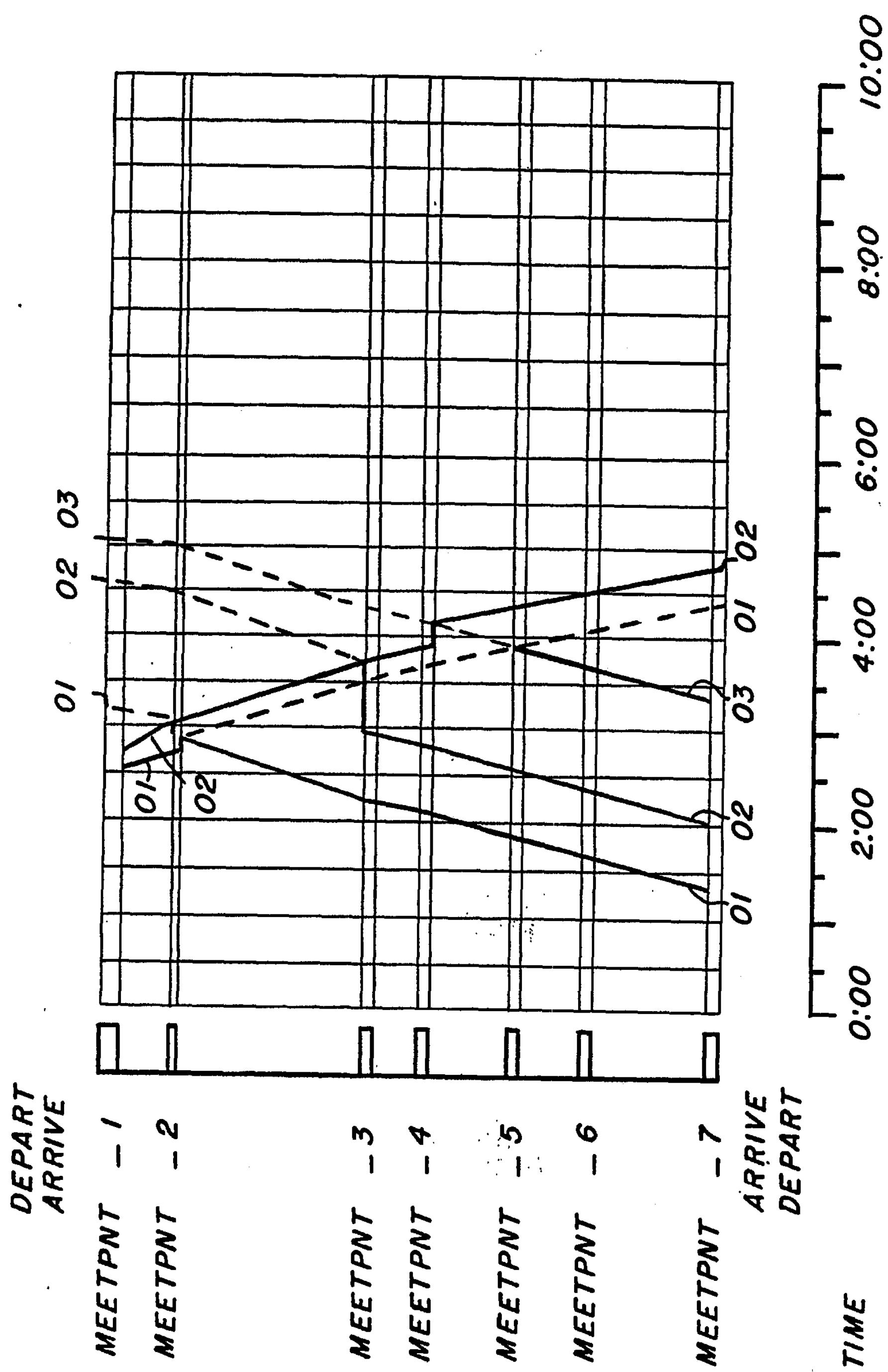
TIME-DISTANCE DIAGRAM OF INITIAL FEASIBILITY PLAN



Docket No. UPN-0401 Ser.No.: 629,417 Filed: December 18, 1990 Art Unit: 2304 Inventor: Harker et al. Notice of Allowance: 7/13/93 Batch No.: E45 Sheet 9 of 28

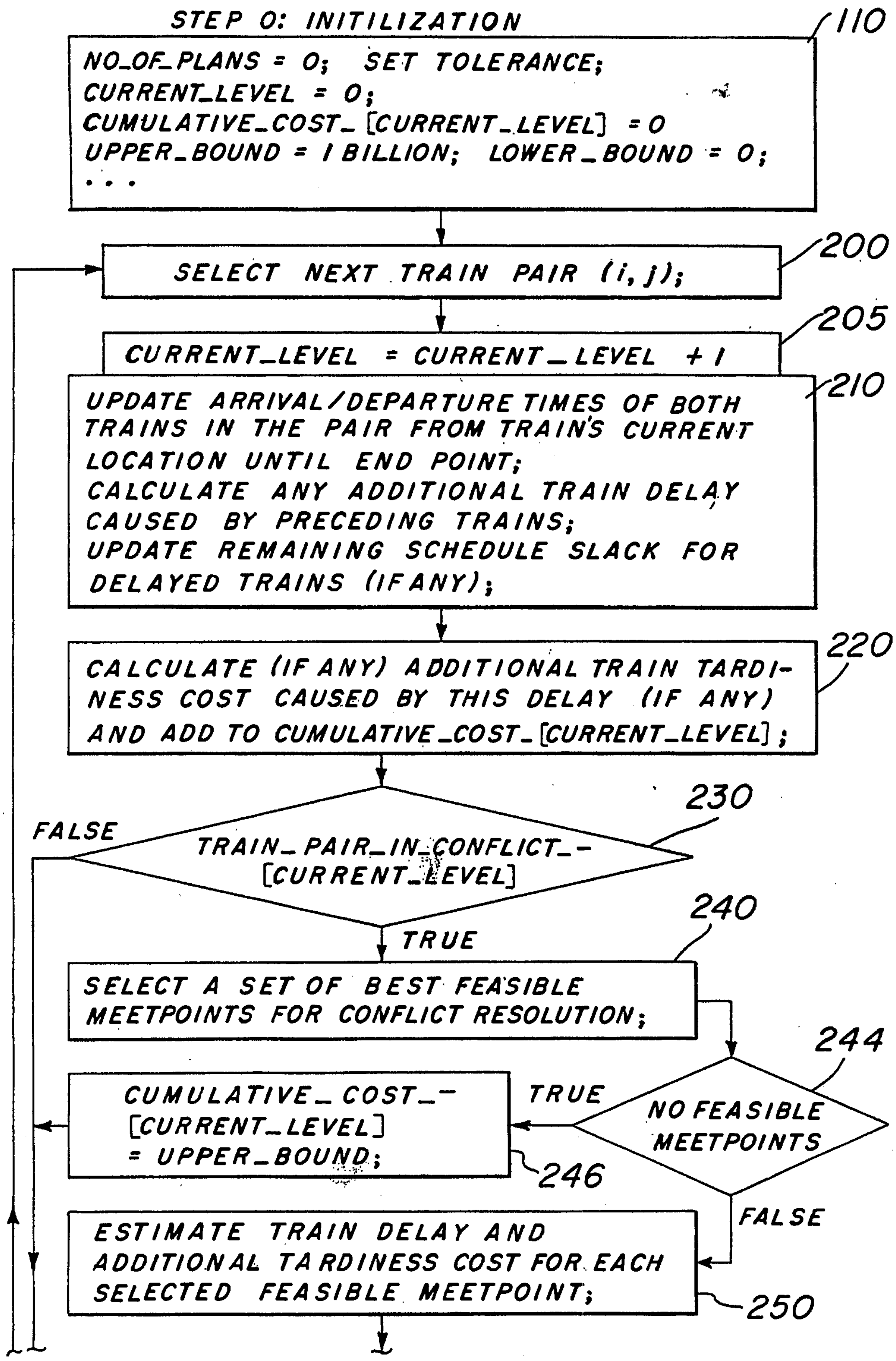
FIG. 9

TIME-DISTANCE DIAGRAM OF OPTIMAL FEASIBILITY PLAN



Docket No. UPN-0401 Ser.No.: 629,417 Filed: December 18, 1990 Art Unit: 2304 Inventor: Harker et al. Notice of Allowance: 7/13/93 Batch No.: E45 Sheet 10 of 28

FIG. 10A



10

Docket No. UPN-0401 Ser.No.: 629,417 Filed: December 18, 1990 Art Unit: 2304 Inventor: Harker et al. Notice of Allowance: 7/13/93 Batch No.: E45 Sheet 11 of 28

FIG. 10B

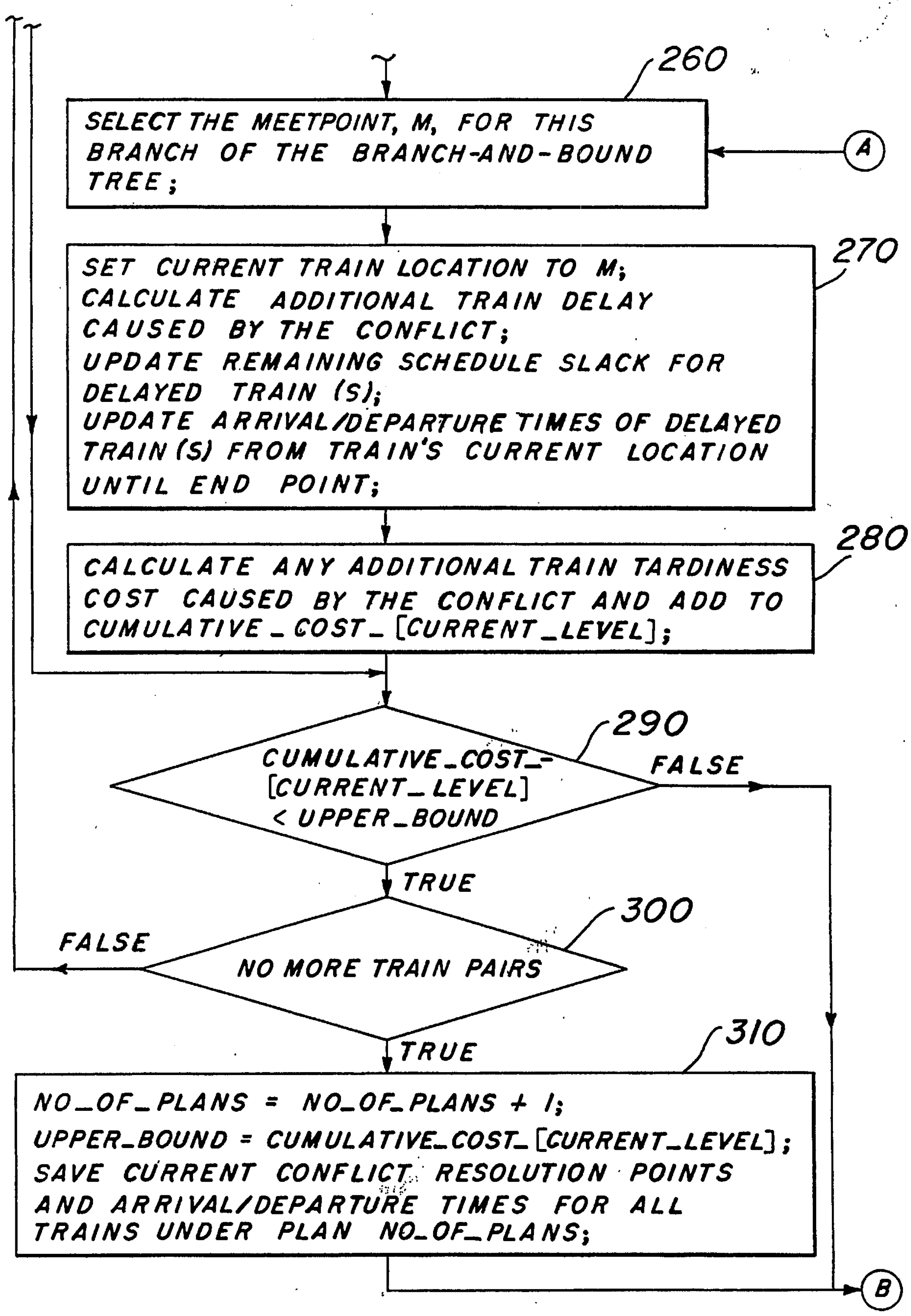


FIG. 10C

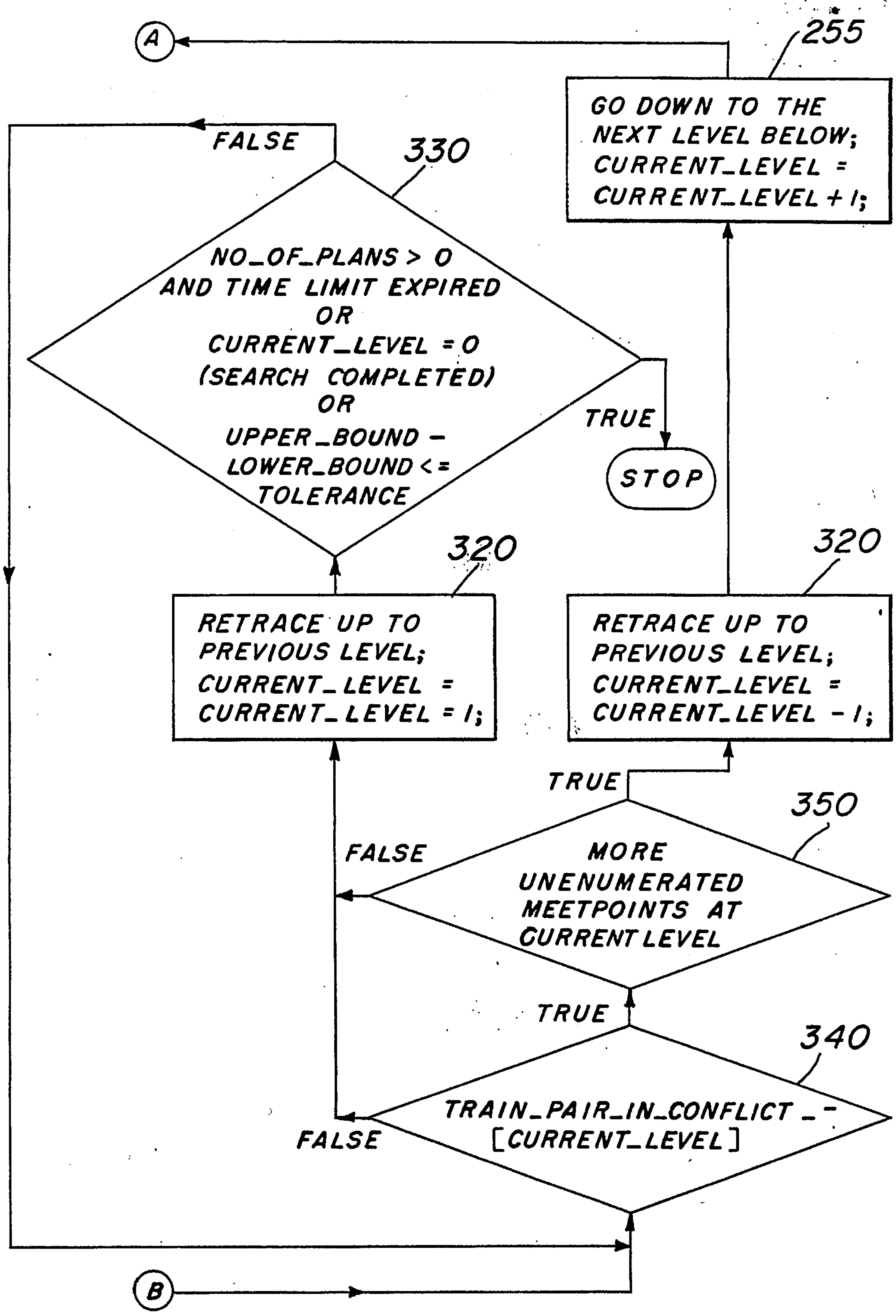

A
255
GO DOWN TO THE NEXT LEVEL BELOW; CURRENT_LEVEL = CURRENT_LEVEL + 1;
FALSE
330
NO_OF_PLANS > 0 AND TIME LIMIT EXPIRED OR CURRENT_LEVEL = 0 (SEARCH COMPLETED) OR UPPER_BOUND - LOWER_BOUND <= TOLERANCE
TRUE
STOP
320
RETRACE UP TO PREVIOUS LEVEL; CURRENT_LEVEL = CURRENT_LEVEL = 1;
320
RETRACE UP TO PREVIOUS LEVEL; CURRENT_LEVEL = CURRENT_LEVEL - 1;
TRUE
350
FALSE
MORE UNENUMERATED MEETPOINTS AT CURRENT LEVEL
TRUE
340
TRAIN_PAIR_IN_CONFLICT _ [CURRENT_LEVEL]
FALSE
B

FIG. 11A

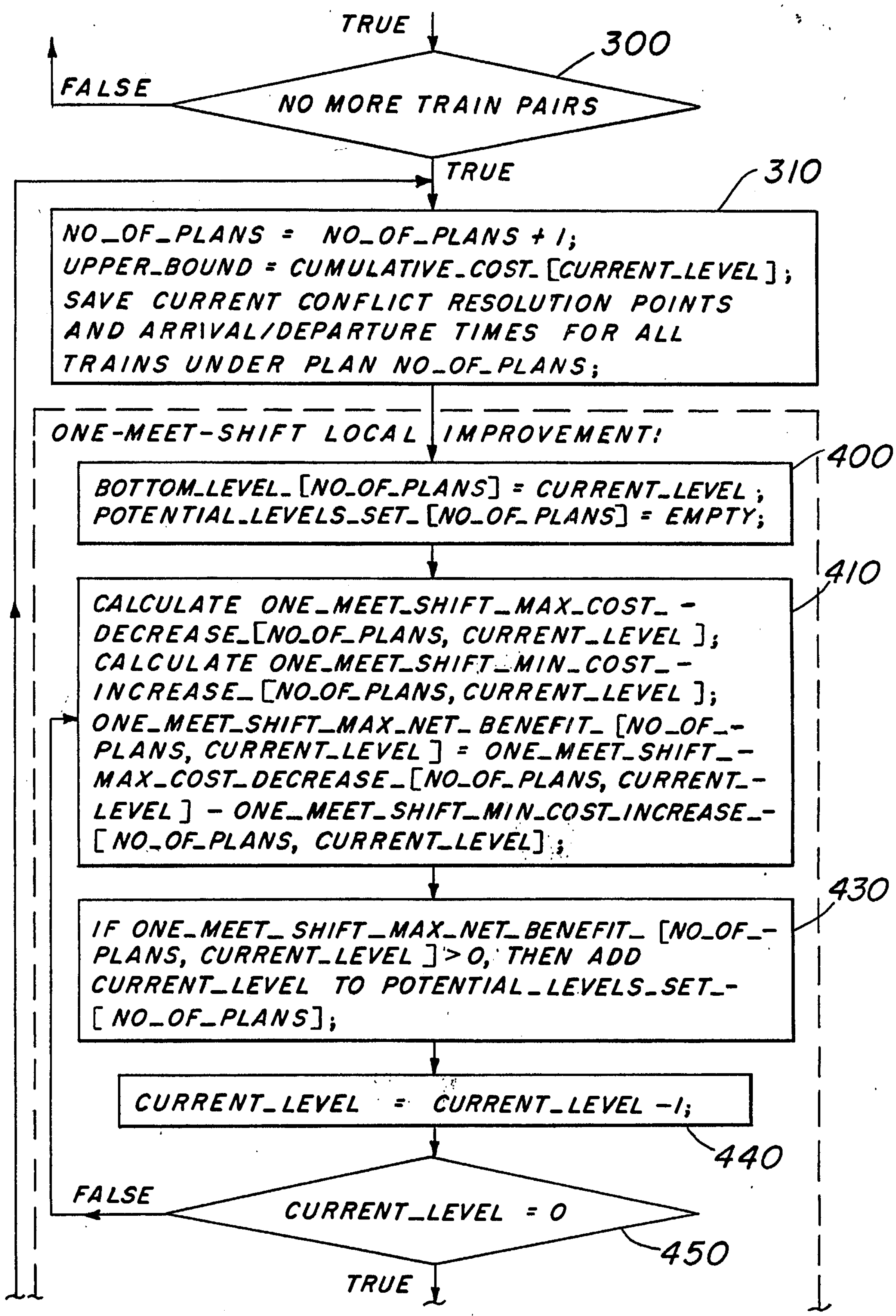

TRUE
300
FALSE
NO MORE TRAIN PAIRS
TRUE
310
NO_OF_PLANS = NO_OF_PLANS + 1;
UPPER_BOUND = CUMULATIVE_COST_[CURRENT_LEVEL];
SAVE CURRENT CONFLICT RESOLUTION POINTS
AND ARRIVAL/DEPARTURE TIMES FOR ALL
TRAINS UNDER PLAN NO_OF_PLANS;
ONE-MEET-SHIFT LOCAL IMPROVEMENT:
400
BOTTOM_LEVEL_[NO_OF_PLANS] = CURRENT_LEVEL;
POTENTIAL_LEVELS_SET_[NO_OF_PLANS] = EMPTY;
410
CALCULATE ONE_MEET_SHIFT_MAX_COST_-
DECREASE_[NO_OF_PLANS, CURRENT_LEVEL];
CALCULATE ONE_MEET_SHIFT_MIN_COST_-
INCREASE_[NO_OF_PLANS, CURRENT_LEVEL];
ONE_MEET_SHIFT_MAX_NET_BENEFIT_[NO_OF_-
PLANS, CURRENT_LEVEL] = ONE_MEET_SHIFT_-
MAX_COST_DECREASE_[NO_OF_PLANS, CURRENT_-
LEVEL] - ONE_MEET_SHIFT_MIN_COST_INCREASE_-
[NO_OF_PLANS, CURRENT_LEVEL];
430
IF ONE_MEET_SHIFT_MAX_NET_BENEFIT_[NO_OF_-
PLANS, CURRENT_LEVEL] > 0, THEN ADD
CURRENT_LEVEL TO POTENTIAL_LEVELS_SET_-
[NO_OF_PLANS];
CURRENT_LEVEL = CURRENT_LEVEL -1;
440
FALSE
CURRENT_LEVEL = 0
450
TRUE

FIG. 11B

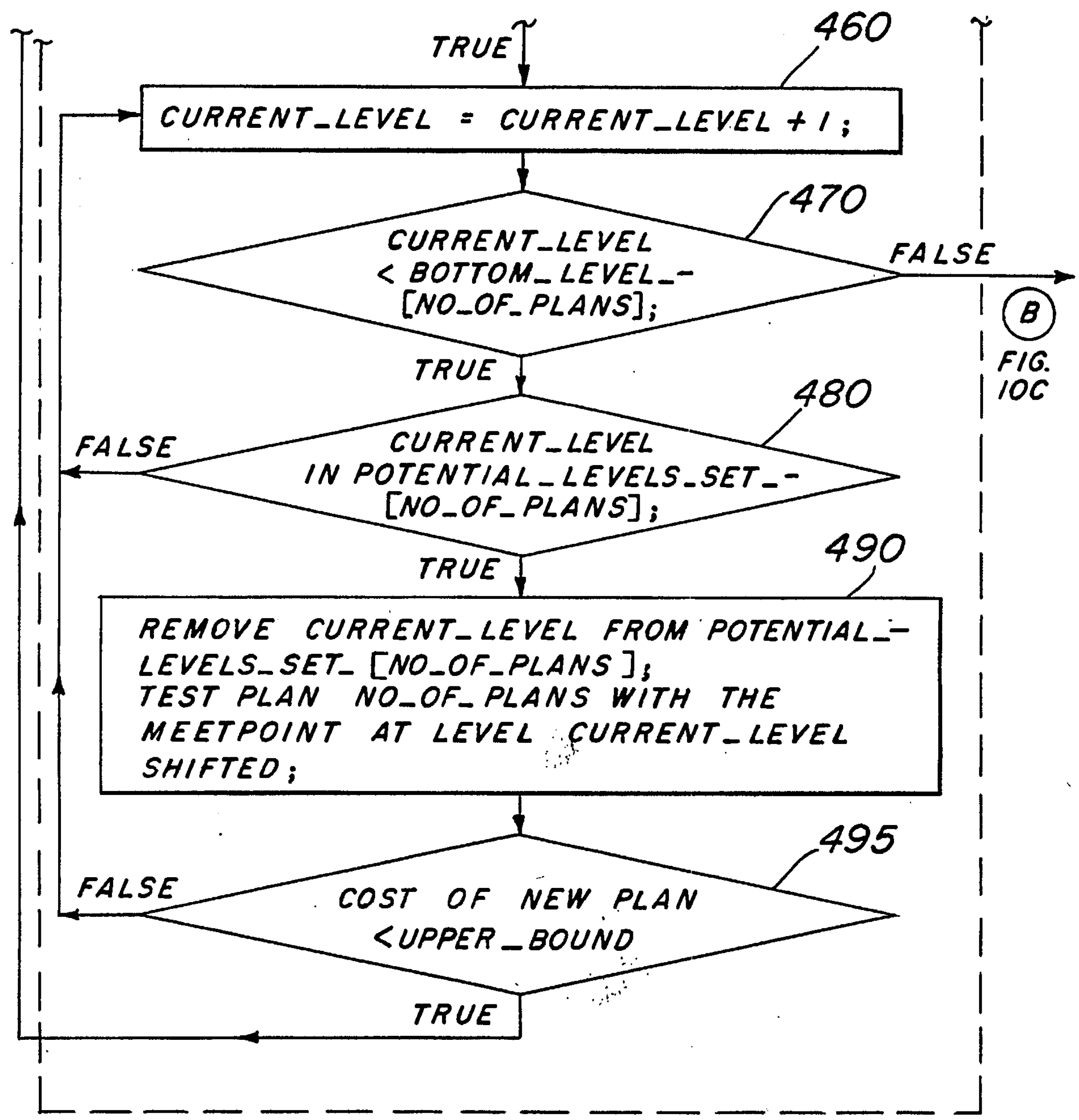
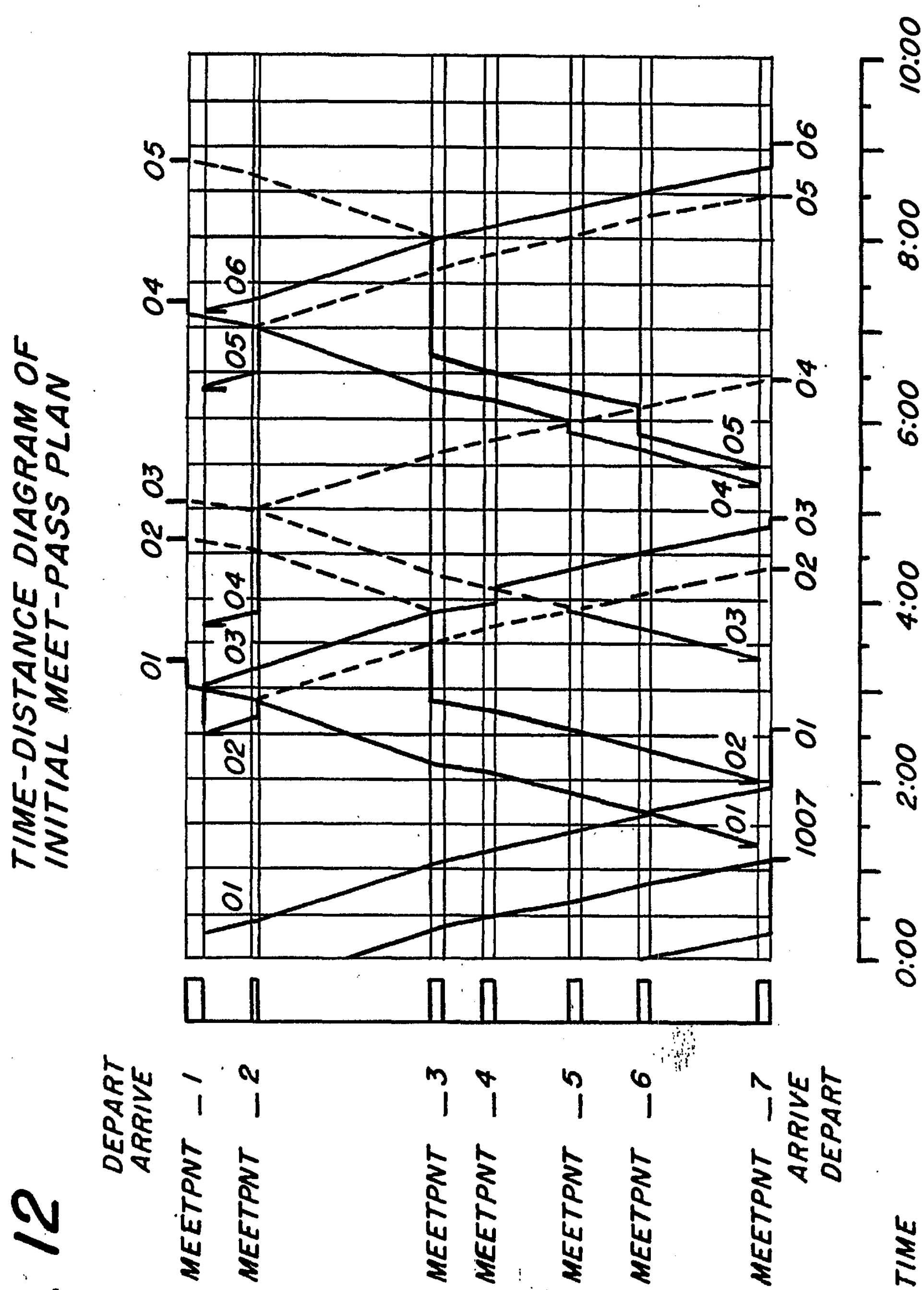

TRUE
460
CURRENT_LEVEL = CURRENT_LEVEL + 1;
470
CURRENT_LEVEL
< BOTTOM_LEVEL_-
[NO_OF_PLANS];
FALSE
B
FIG. 10C
TRUE
480
FALSE
CURRENT_LEVEL
IN POTENTIAL_LEVELS_SET_-
[NO_OF_PLANS];
TRUE
490
REMOVE CURRENT_LEVEL FROM POTENTIAL_-
LEVELS_SET_ [NO_OF_PLANS];
TEST PLAN NO_OF_PLANS WITH THE
MEETPOINT AT LEVEL CURRENT_LEVEL
SHIFTED;
495
FALSE
COST OF NEW PLAN
<UPPER_BOUND
TRUE

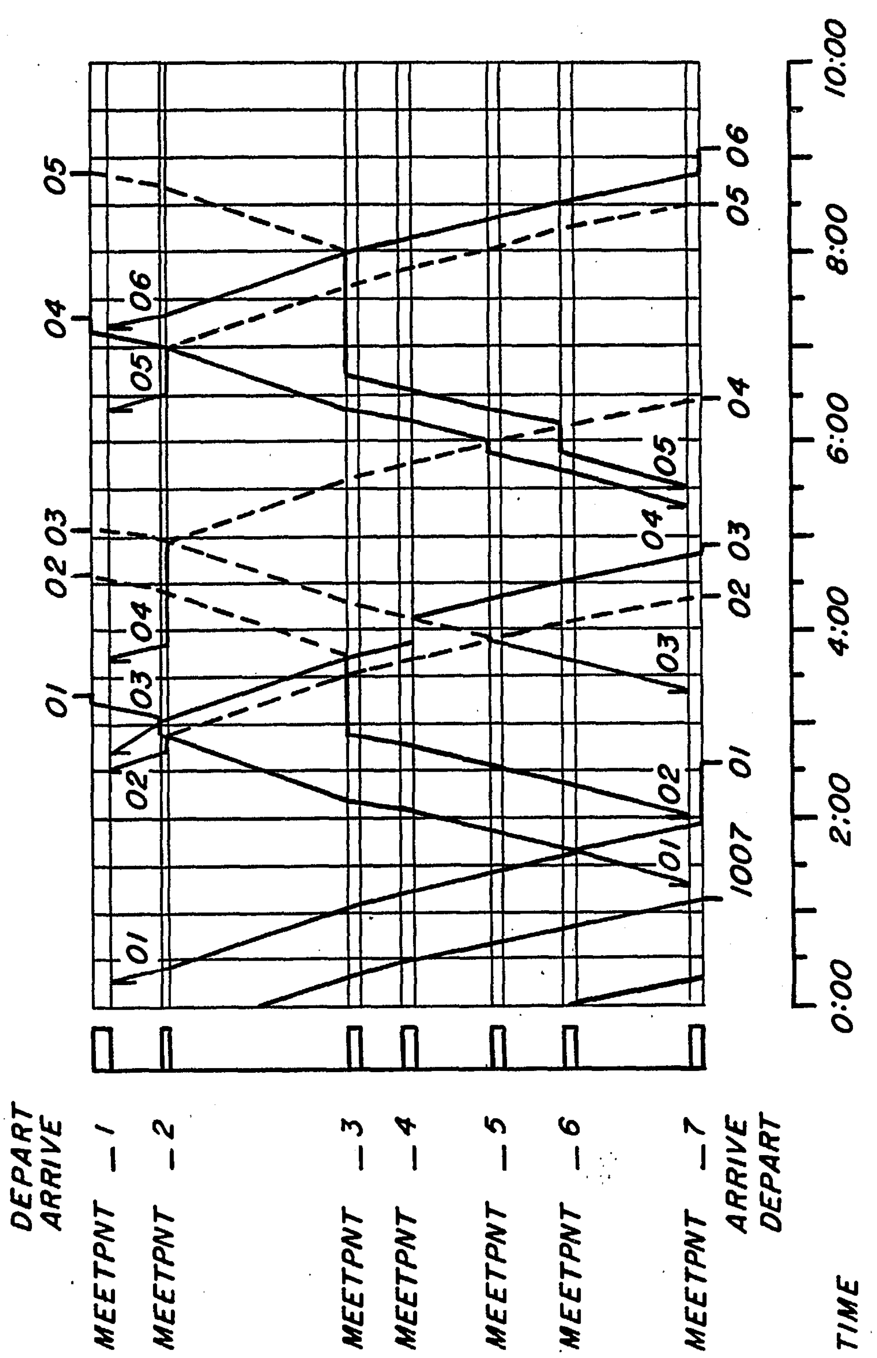
FIG. 12


TIME-DISTANCE DIAGRAM OF
INITIAL MEET-PASS PLAN
DEPART
ARRIVE
MEETPNT _1
MEETPNT _2
MEETPNT _3
MEETPNT _4
MEETPNT _5
MEETPNT _6
MEETPNT _7
ARRIVE
DEPART
TIME
01
02 03
04
05
01
02
03
04
05
06
1007
01
02
03
04
05
0:00
2:00
4:00
6:00
8:00
10:00

Docket No. UPN-0401 Ser.No.: 629,417 Filed: December 18, 1990 Art Unit: 2304 Inventor: H--ker et al. Notice of Allowance: 7/13/93
No.: E45 Sheet 16 of 28

FIG. 13

TIME-DISTANCE DIAGRAM OF OPTIMAL MEET-PASS PLAN USING ONE-MEET-SHIFT LOCAL IMPROVEMENT



Docket No. UPN-0401 Ser.No.: 629,417 Filed: December 18, 1990 Art Unit: 2304 Inventor: Harker et al. Notice of Allowance: 7/13/93 Batch No.: E45 Sheet 17 of 28

FIG. 14A

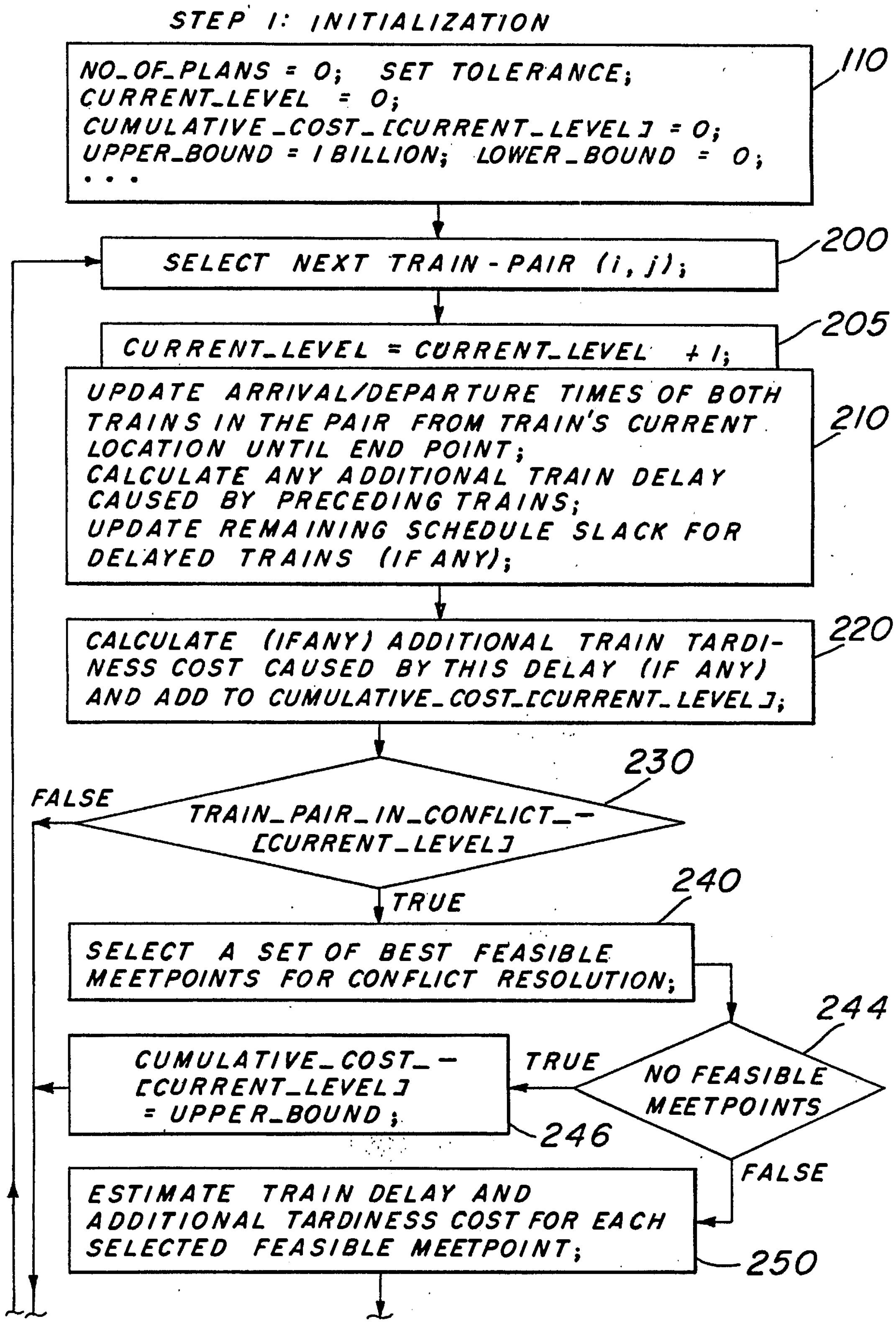


FIG. 14B

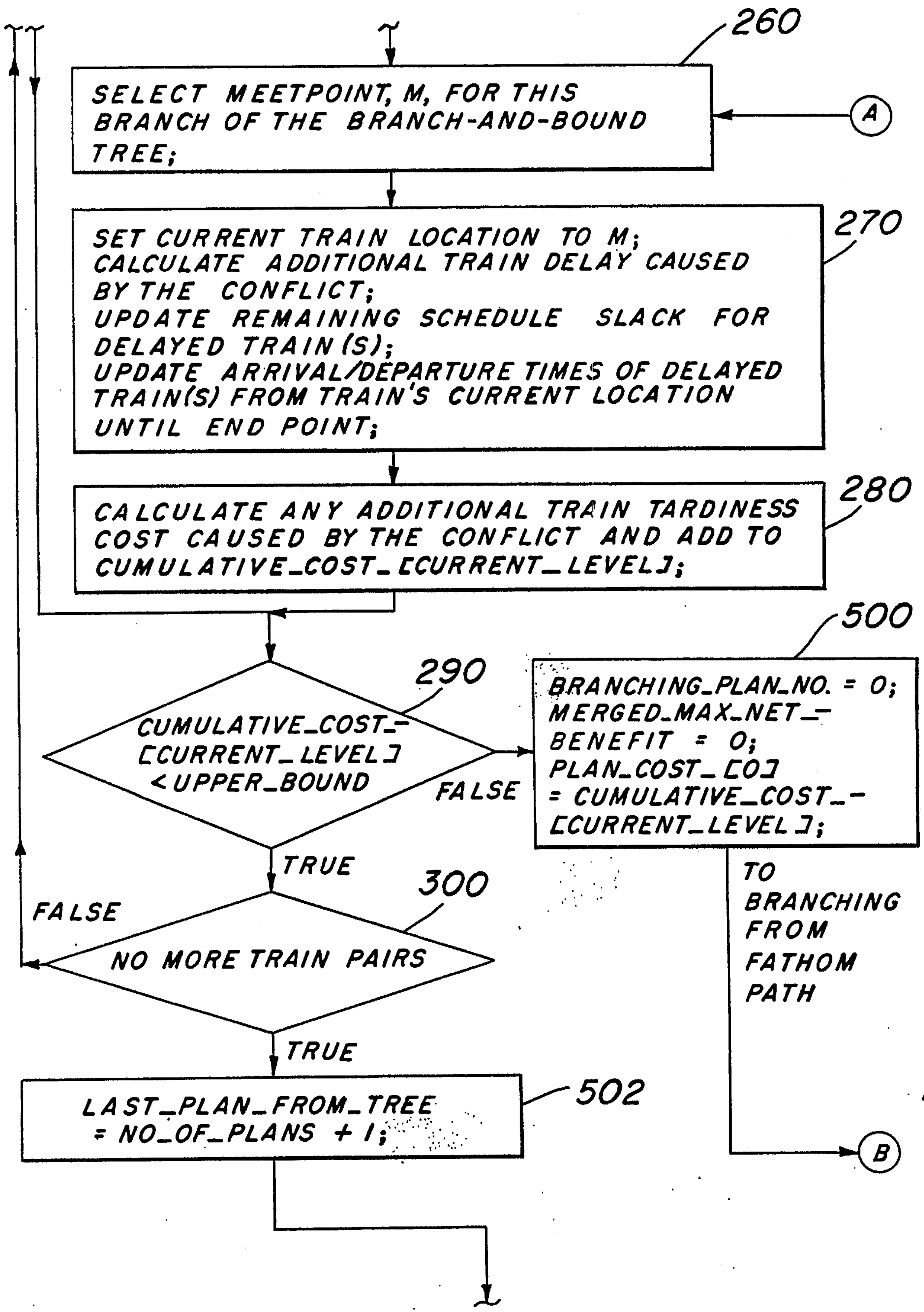
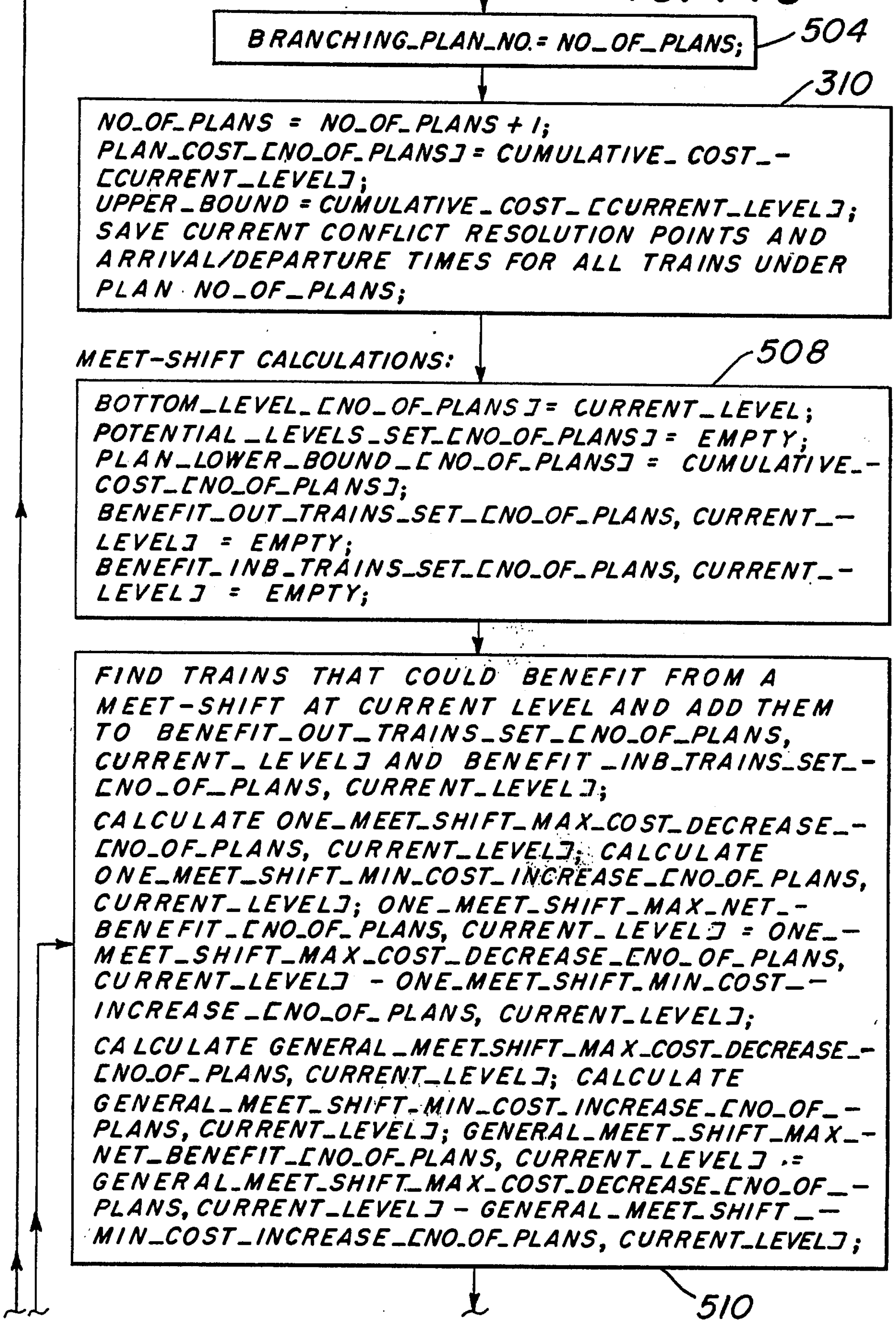
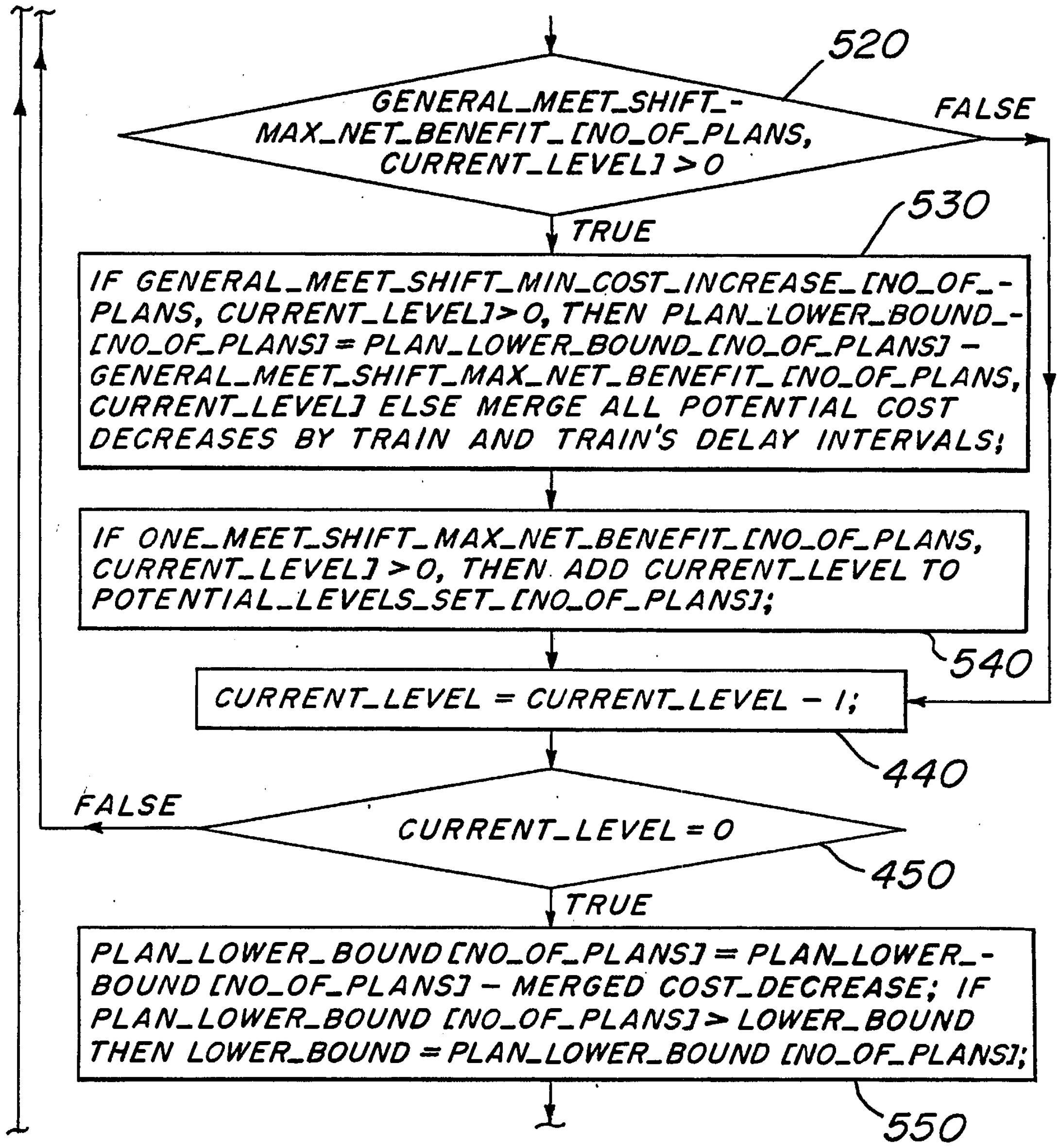

260
SELECT MEETPOINT, M, FOR THIS BRANCH OF THE BRANCH-AND-BOUND TREE;
A
270
SET CURRENT TRAIN LOCATION TO M;
CALCULATE ADDITIONAL TRAIN DELAY CAUSED BY THE CONFLICT;
UPDATE REMAINING SCHEDULE SLACK FOR DELAYED TRAIN (S);
UPDATE ARRIVAL/DEPARTURE TIMES OF DELAYED TRAIN(S) FROM TRAIN'S CURRENT LOCATION UNTIL END POINT;
280
CALCULATE ANY ADDITIONAL TRAIN TARDINESS COST CAUSED BY THE CONFLICT AND ADD TO CUMULATIVE_COST_[CURRENT_LEVEL];
500
290
CUMULATIVE_COST_[CURRENT_LEVEL] < UPPER_BOUND
FALSE
BRANCHING_PLAN_NO. = 0;
MERGED_MAX_NET_BENEFIT = 0;
PLAN_COST_[0] = CUMULATIVE_COST_[CURRENT_LEVEL];
TRUE
300
FALSE
NO MORE TRAIN PAIRS
TO BRANCHING FROM FATHOM PATH
TRUE
LAST_PLAN_FROM_TREE = NO_OF_PLANS + 1;
502
B

FIG. 14C


BRANCHING_PLAN_NO.= NO_OF_PLANS;
504
310
NO_OF_PLANS = NO_OF_PLANS + 1;
PLAN_COST_[NO_OF_PLANS] = CUMULATIVE_COST_[CURRENT_LEVEL];
UPPER_BOUND = CUMULATIVE_COST_[CURRENT_LEVEL];
SAVE CURRENT CONFLICT RESOLUTION POINTS AND ARRIVAL/DEPARTURE TIMES FOR ALL TRAINS UNDER PLAN NO_OF_PLANS;
MEET-SHIFT CALCULATIONS:
508
BOTTOM_LEVEL_[NO_OF_PLANS] = CURRENT_LEVEL;
POTENTIAL_LEVELS_SET_[NO_OF_PLANS] = EMPTY;
PLAN_LOWER_BOUND_[NO_OF_PLANS] = CUMULATIVE_COST_[NO_OF_PLANS];
BENEFIT_OUT_TRAINS_SET_[NO_OF_PLANS, CURRENT_LEVEL] = EMPTY;
BENEFIT_INB_TRAINS_SET_[NO_OF_PLANS, CURRENT_LEVEL] = EMPTY;
FIND TRAINS THAT COULD BENEFIT FROM A MEET-SHIFT AT CURRENT LEVEL AND ADD THEM TO BENEFIT_OUT_TRAINS_SET_[NO_OF_PLANS, CURRENT_LEVEL] AND BENEFIT_INB_TRAINS_SET_[NO_OF_PLANS, CURRENT_LEVEL];
CALCULATE ONE_MEET_SHIFT_MAX_COST_DECREASE_[NO_OF_PLANS, CURRENT_LEVEL]; CALCULATE ONE_MEET_SHIFT_MIN_COST_INCREASE_[NO_OF_PLANS, CURRENT_LEVEL]; ONE_MEET_SHIFT_MAX_NET_BENEFIT_[NO_OF_PLANS, CURRENT_LEVEL] = ONE_MEET_SHIFT_MAX_COST_DECREASE_[NO_OF_PLANS, CURRENT_LEVEL] - ONE_MEET_SHIFT_MIN_COST_INCREASE_[NO_OF_PLANS, CURRENT_LEVEL];
CALCULATE GENERAL_MEET_SHIFT_MAX_COST_DECREASE_[NO_OF_PLANS, CURRENT_LEVEL]; CALCULATE GENERAL_MEET_SHIFT_MIN_COST_INCREASE_[NO_OF_PLANS, CURRENT_LEVEL]; GENERAL_MEET_SHIFT_MAX_NET_BENEFIT_[NO_OF_PLANS, CURRENT_LEVEL] := GENERAL_MEET_SHIFT_MAX_COST_DECREASE_[NO_OF_PLANS, CURRENT_LEVEL] - GENERAL_MEET_SHIFT_MIN_COST_INCREASE_[NO_OF_PLANS, CURRENT_LEVEL];
510

Docket No. UPN-0401 Ser.No.: 629,417 Filed: December 18, 1990 Art Unit: 2304 Inventor: Harker et al. Notice of Allowance: 7/13/93 Batch No.: E45 Sheet 20 of 28

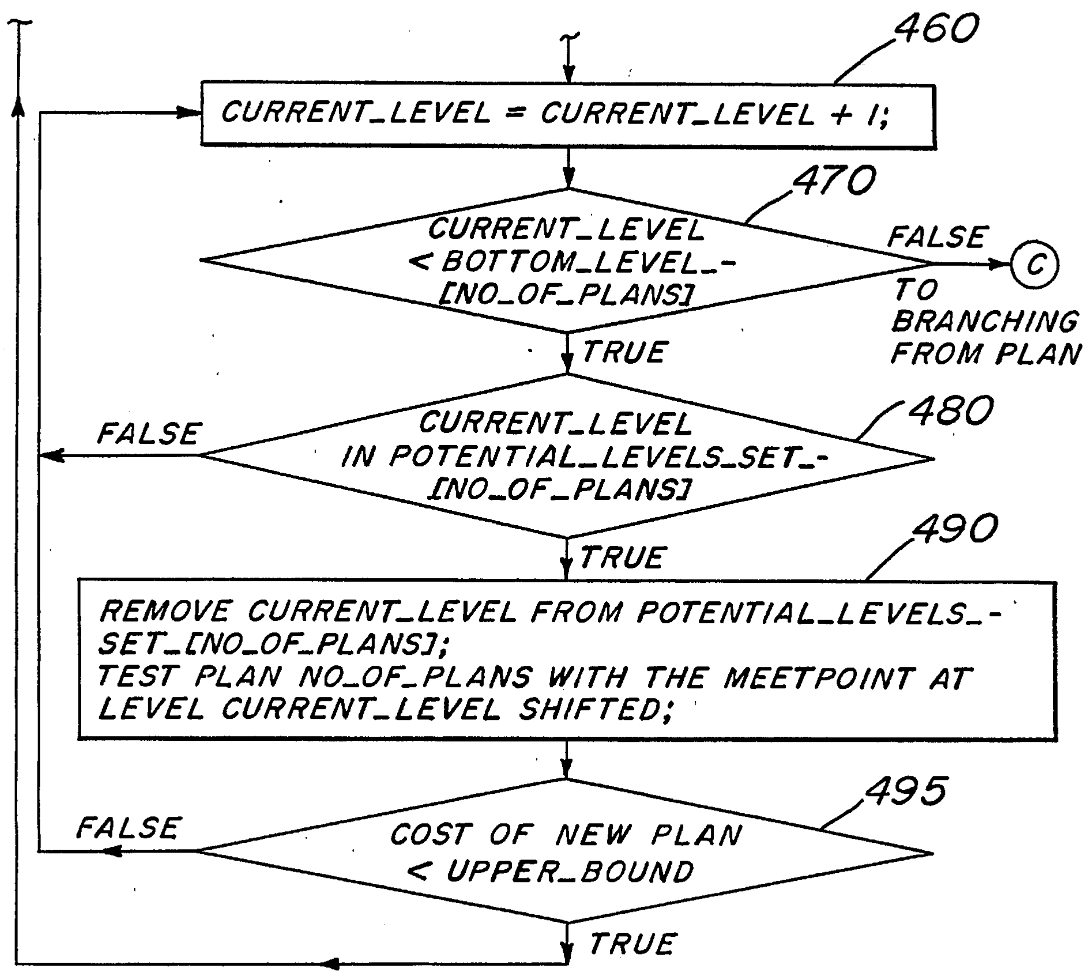
FIG. 14D



20

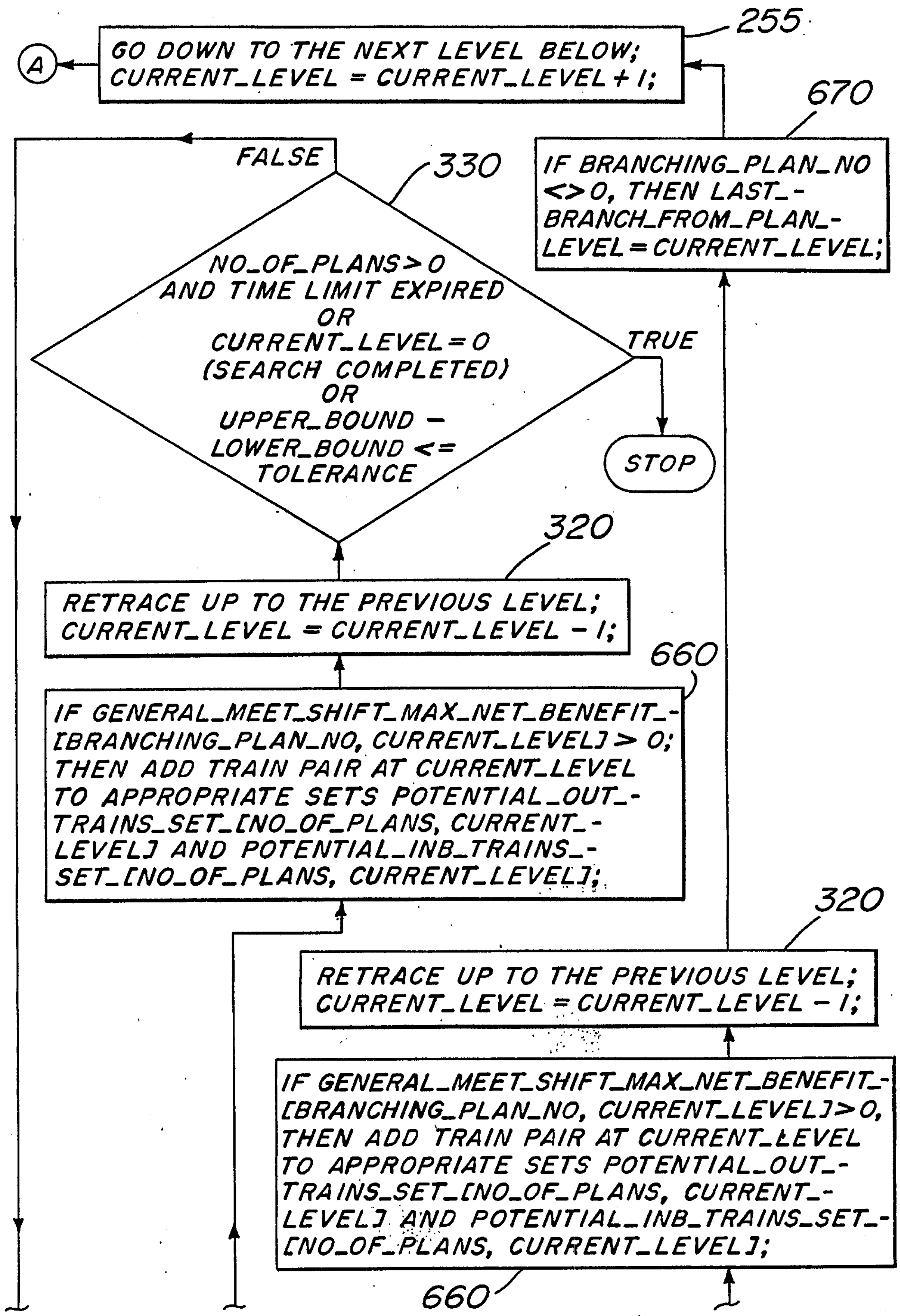
Docket No. UPN-0401 Ser.No.: 629,417 Filed:
December 18, 1990 Art Unit: 2304 Inventor:
Harker et al. Notice of Allowance: 7/13/93
Batch No.: E45 Sheet 21 of 28

FIG. 14E



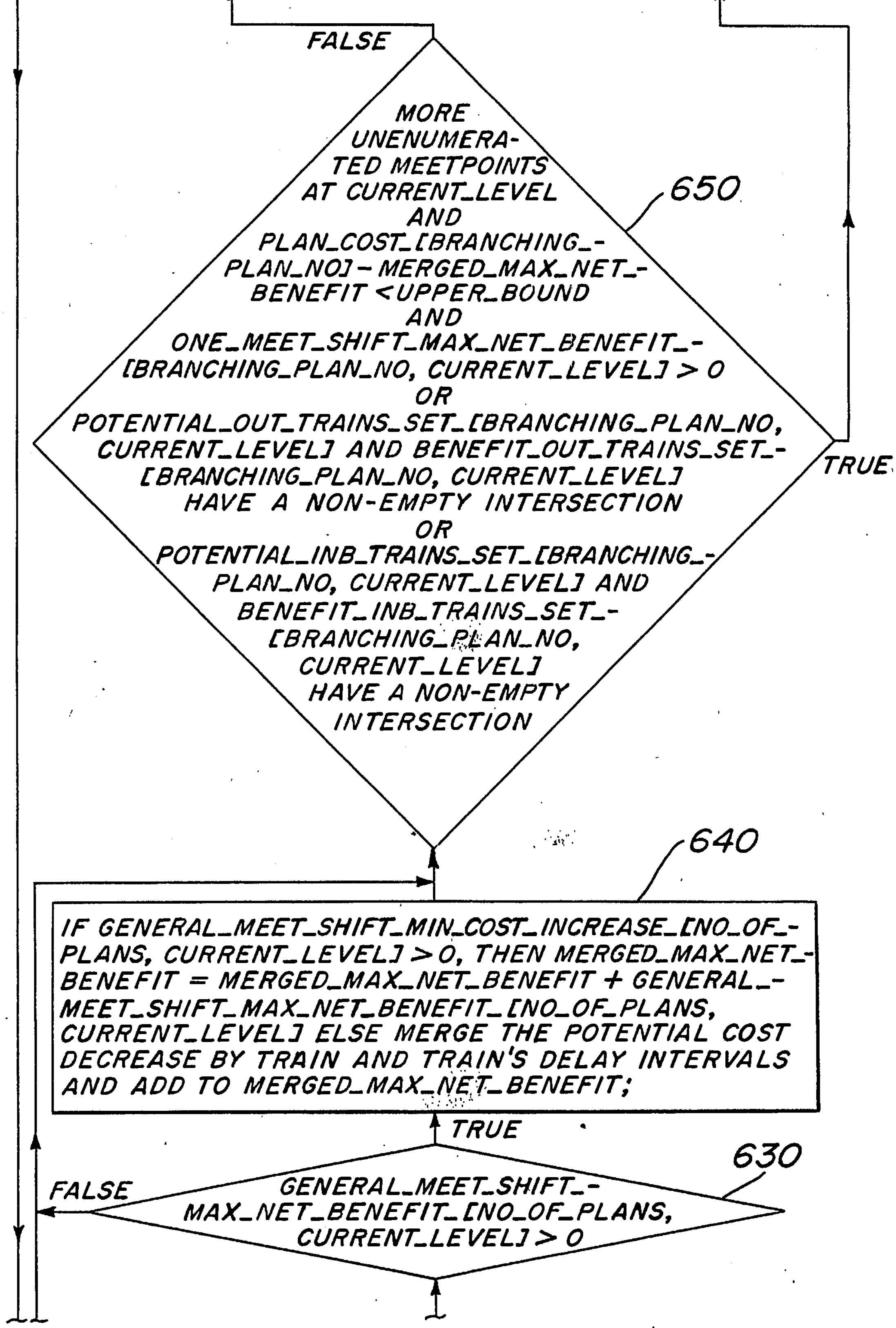
Docket No. UPN-0401 Ser.No.: 629,417 Filed: December 18, 1990 Art Unit: 2304 Inventor: Harker et al. Notice of Allowance: 7/13/93 Batch No.: E45 Sheet 22 of 28

FIG. 14F



Docket No. UPN-0401 Ser.No.: 629,417 Filed:
December 18, 1990 Art Unit: 2304 Inventor:
Harker et al. Notice of Allowance: 7/13/93
Batch No.: E45 Sheet 23 of 28

FIG. 14G



Docket No. UPN-0401 Ser.No.: 629,417 Filed:
December 18, 1990 Art Unit: 2304 Inventor:
Harker et al. Notice of Allowance: 7/13/93
Batch No.: E45 Sheet 24 of 28

FIG. 14H

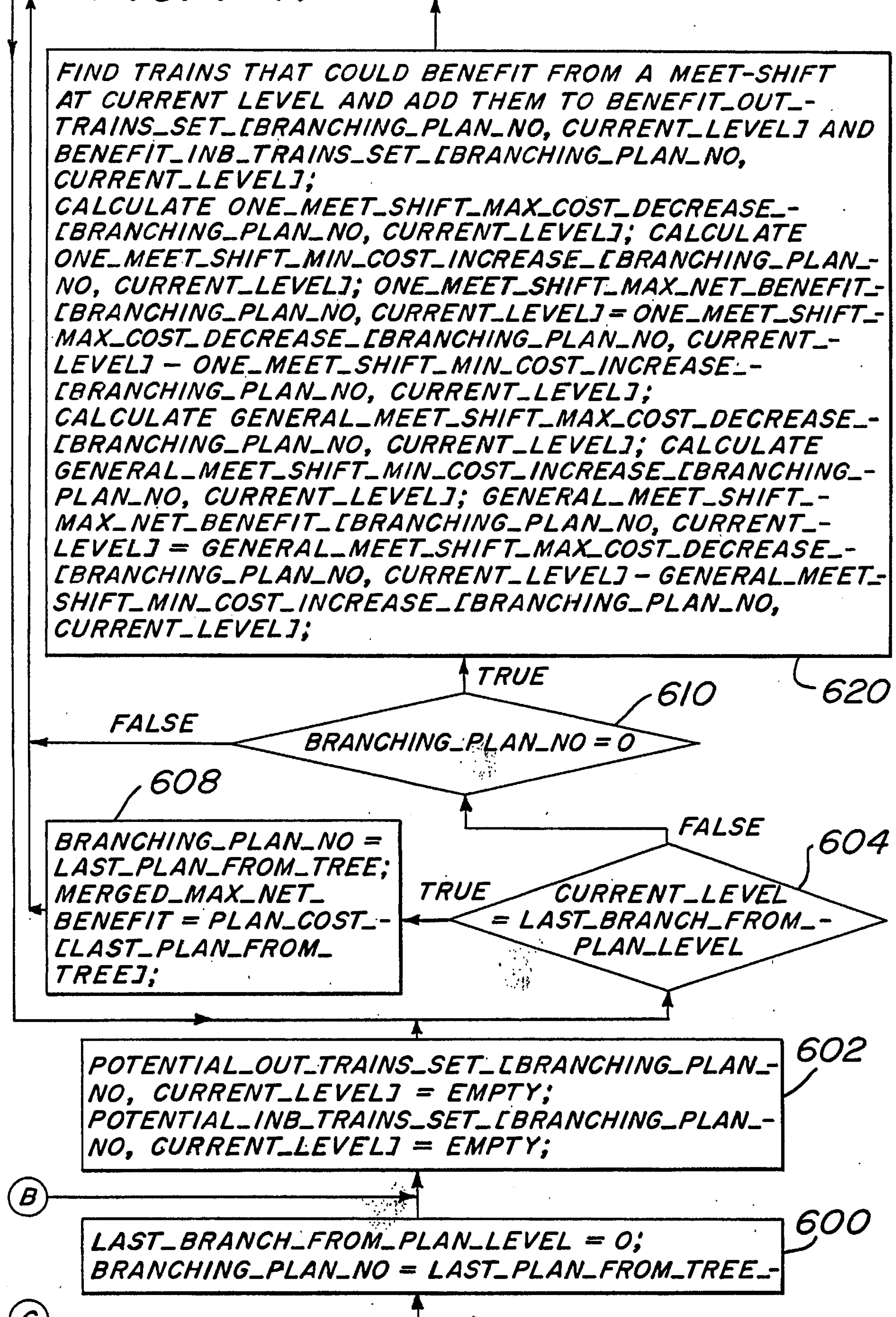
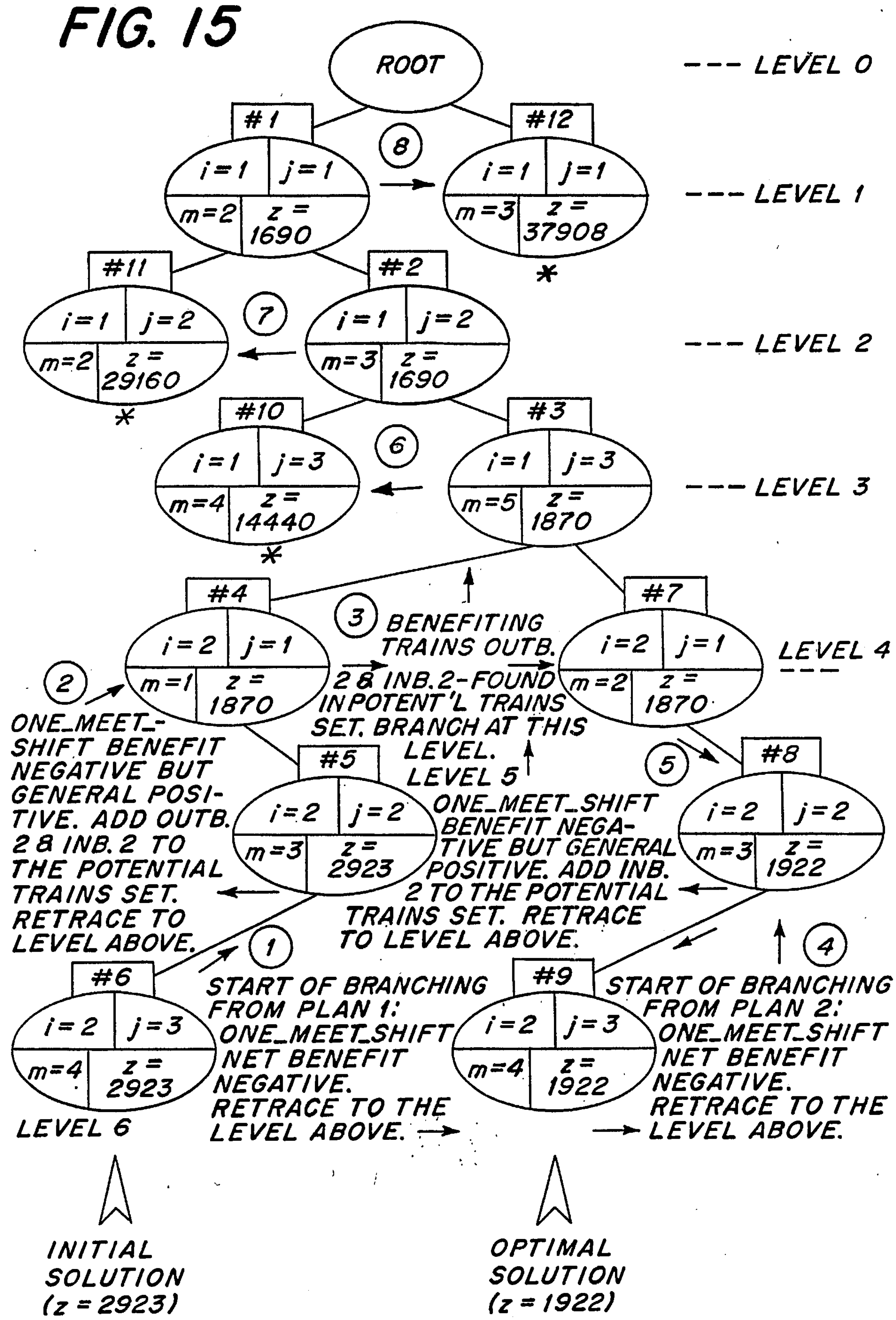


FIG. 15

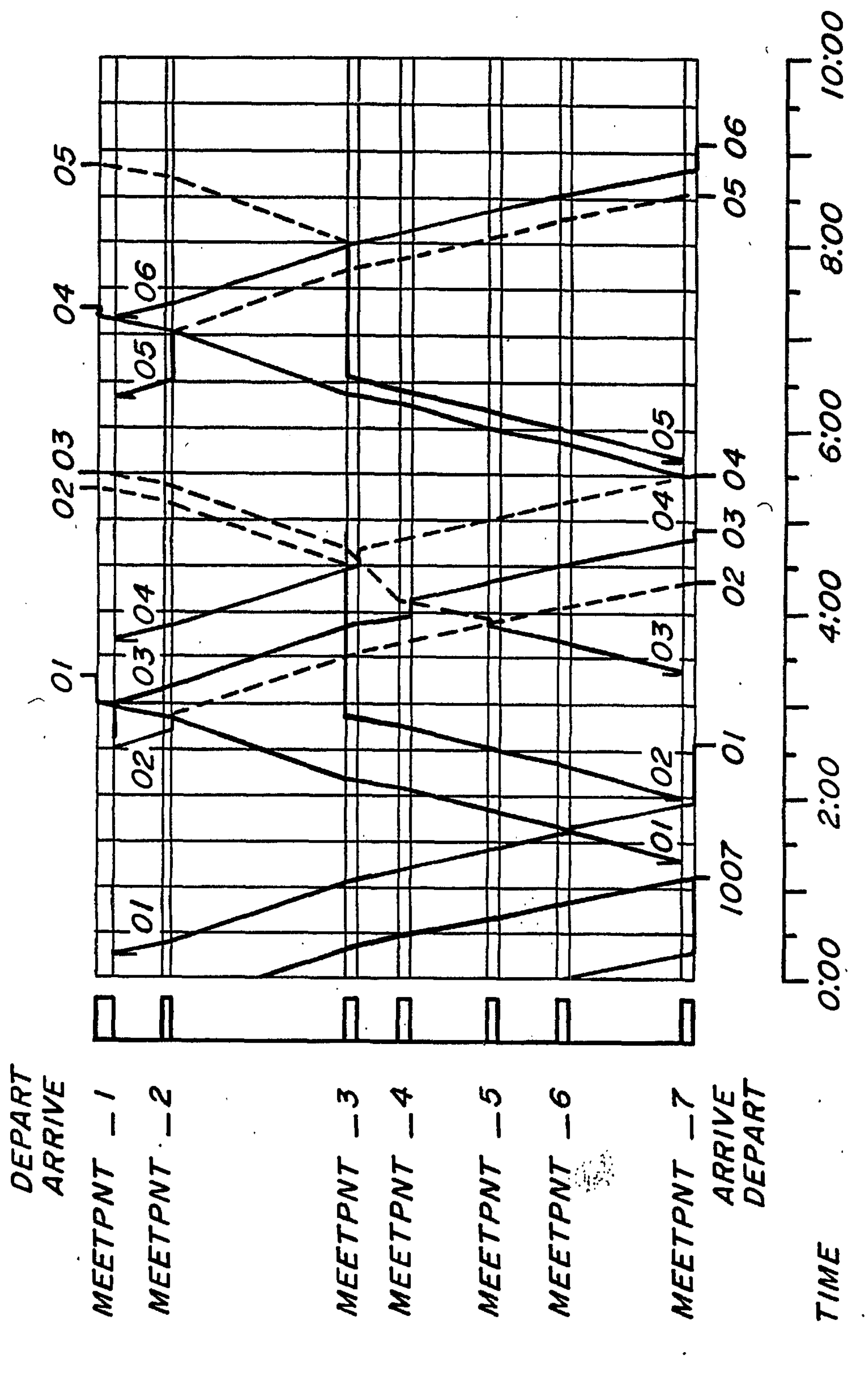


NODES ENUMERATED USING THE BRANCH-AND-BOUND METHOD OF THE LOWER-BOUND EXACT PRUNING ALGORITHM

Docket No. UPN-0401 Ser.No.: 629,417 Filed:
December 18, 1990 Art Unit: 2304 Inventor:
Harker et al. Notice of Allowance: 7/13/93
Batch No.: E45 Sheet 26 of 28

FIG. 16

TIME-DISTANCE DIAGRAM OF
AN INITIAL MEET-PASS PLAN



Docket No. UPN-0401 Ser.No.: 629,417 Filed: December 18, 1990 Art Unit: 2304 Inventor: Harker et al. Notice of Allowance: 7/13/93 Batch No.: E45 Sheet 27 of 28

FIG. 17

TIME-DISTANCE DIAGRAM OF AN OPTIMAL MEET-PASS PLAN USING LOWER-BOUND BASED PRUNING ALGORITHM

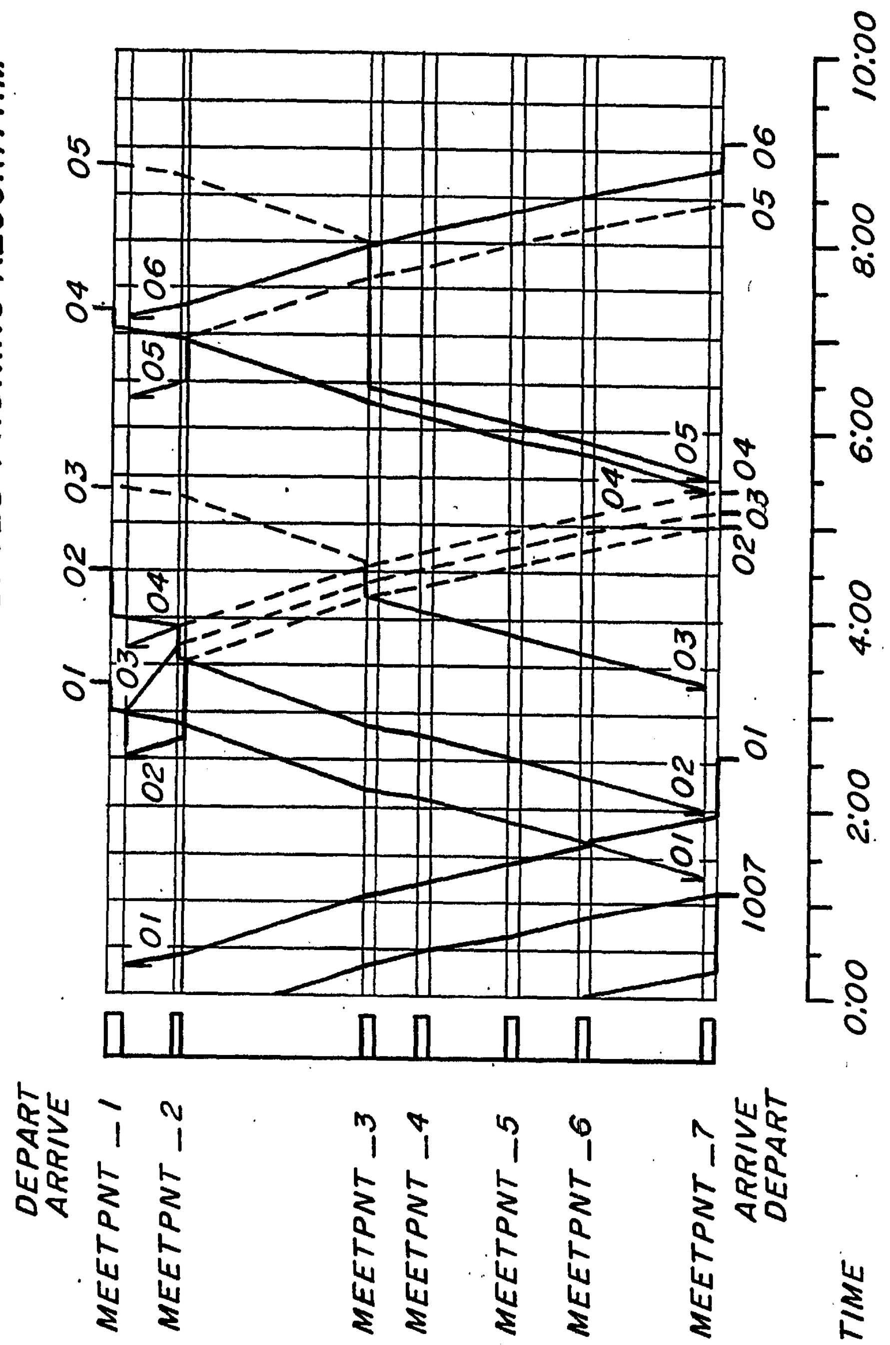
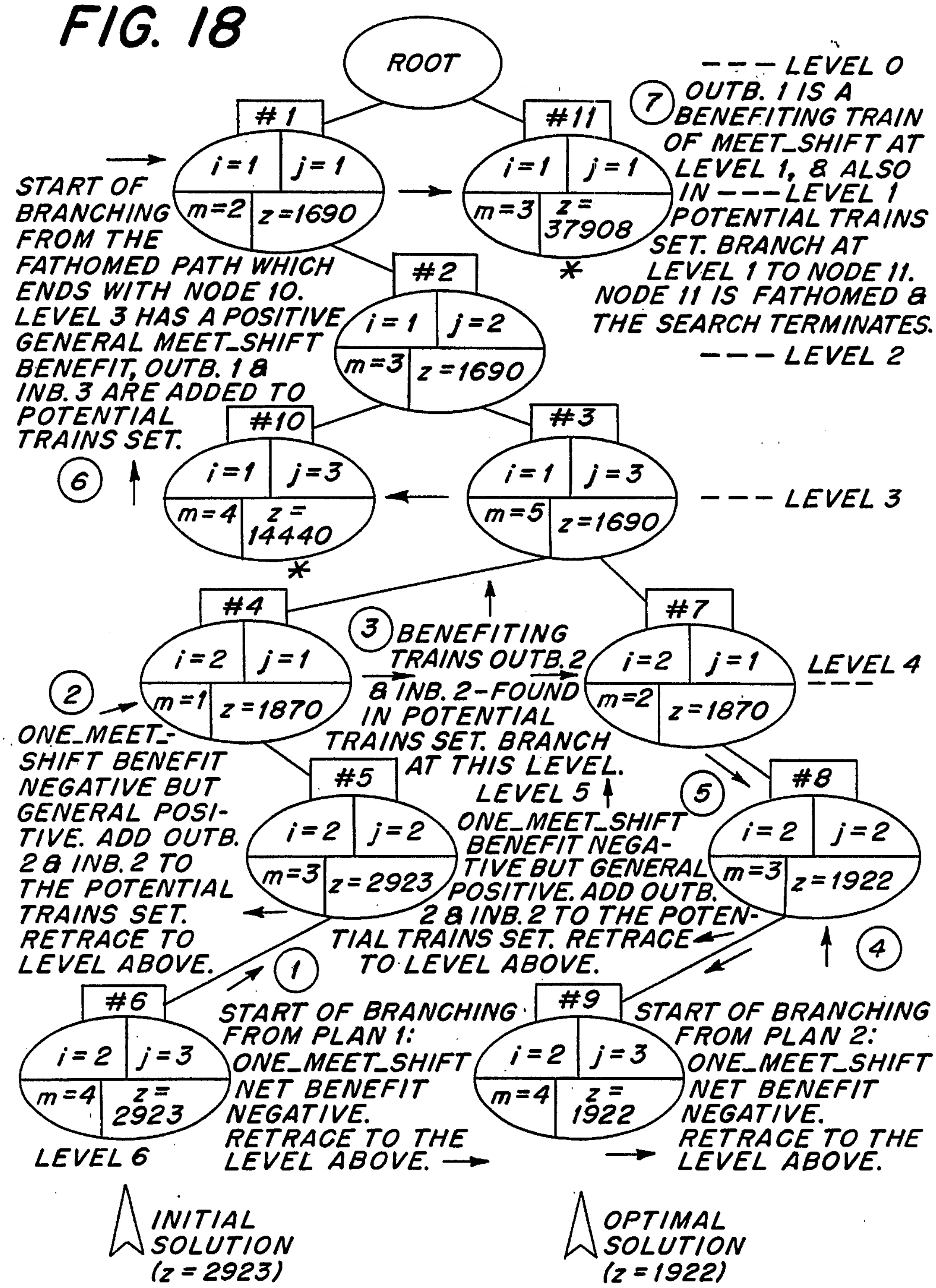


FIG. 18



NODES ENUMERATED USING THE BRANCH-AND-BOUND METHOD OF THE ACCELERATED HEURISTIC LOWER-BOUND BASED ALGORITHM

Transaction History Date 1992-10-15
Date information retrieved from USPTO Patent Application Information Retrieval (PAIR) system records at www.uspto.gov

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UPN-401

PART B - ISSUE FEE TRANSMITTAL

#585.00 - 242 B

BC

MAILING INSTRUCTIONS: This form should be used for transmitting the ISSUE FEE. Blocks 2 through 6 should be completed where appropriate. All further correspondence including the Issue Fee Receipt, the Patent, advanced orders and notification of maintenance fees will be mailed to addressee entered in Block 1 unless you direct otherwise, by: (a) specifying a new correspondence address in Block 3 below; or (b) providing the PTO with a separate "FEE ADDRESS" for maintenance fee notifications with the payment of Issue Fee or thereafter. **See reverse for Certificate of Mailing.**

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STEVEN J. ROCCI
WOODCOCK, WASHBUR, KURTZ, MACKIEWICZ & NORRIS
ONE LIBERTY PLACE - 46TH FLOOR
PHILADELPHIA, PA 19103

2. INVENTOR(S) ADDRESS CHANGE (Complete only if there is a change)

INVENTOR'S NAME
Street Address
City, State and ZIP Code
CO-INVENTOR'S NAME
Street Address
City, State and ZIP Code

☐ Check if additional changes are on reverse side

SERIES CODE/SERIAL NO.	FILING DATE	TOTAL CLAIMS	EXAMINER AND GROUP ART UNIT		DATE MAILED
07/629,417	12/18/90	016	AUCHTERLONIE, T	2304	07/13/92

First Named Applicant: HARKER, PATRICK T.

TITLE OF INVENTION: METHOD FOR ANALYZING AND GENERATING OPTIMAL TRANSPORTATION SCHEDULES FOR VEHICLES SUCH AS TRAINS AND CONTROLLING THE MOVEMENT OF VEHICLES IN RESPONSE THERETO (AS AMENDED)

	ATTY'S DOCKET NO.	CLASS-SUBCLASS	BATCH NO.	APPLN. TYPE	SMALL ENTITY	FEE DUE	DATE DUE
2	UPN-401	364-436.000	E45	UTILITY	YES	* $565.00	10/13/92

*Check enclosed for $585.00 in accordance with the fees effective 10/01/92.

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1 Woodcock Washburn Kurtz Mackiewicz & Norris
2
3

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DF11390 10/26/92 07629417 23-3050 110 561 36.00CH

5. ASSIGNMENT DATA TO BE PRINTED ON THE PATENT (print or type)
(1) NAME OF ASSIGNEE: The Trustees of the University of Pennsylvania
(2) ADDRESS: (City & State or Country) Philadelphia, Pennsylvania
(3) STATE OF INCORPORATION, IF ASSIGNEE IS A CORPORATION: Pennsylvania

A. ☐ This application is NOT assigned.
☒ Assignment previously submitted to the Patent and Trademark Office.
☐ Assignment is being submitted under separate cover. Assignments should be directed to Box ASSIGNMENTS.

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☒ Issue Fee ☐ Advanced Order - # of Copies ____ (Minimum of 10)

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☒ Any Deficiencies in Enclosed Fees

The COMMISSIONER OF PATENTS AND TRADEMARKS is requested to apply the Issue Fee to the application identified above.

(Signature of party in interest of record) John W. Caldwell Reg. No. 28,937 (Date) 10/13/92

NOTE: The Issue Fee will not be accepted from anyone other than the applicant; a registered attorney or agent; or the assignee or other party in interest as shown by the records of the Patent and Trademark Office.

TRANSMIT THIS FORM WITH FEE-CERTIFICATE OF MAILING ON REVERSE

PTOL-85B (REV 12-88) (OMB Clearance is pending)

UPN-401
Serial No.629,417

Certificate of Mailing

I hereby certify that this correspondence is being deposited with the United States Postal Service with sufficient postage as first class mail in an envelope addressed to:

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(Date)

John W. Caldwell Reg.No.28,937
(Name of person making deposit)

(Signature)

10/13/92
(Date)

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PTO UTILITY GRANT
Paper Number 12

The United States of America

The Commissioner of Patents and Trademarks

Has received an application for a patent for a new and useful invention. The title and description of the invention are enclosed. The requirements of law have been complied with, and it has been determined that a patent on the invention shall be granted under the law.

Therefore, this

United States Patent

Grants to the person or persons having title to this patent the right to exclude others from making, using or selling the invention throughout the United States of America for the term of seventeen years from the date of this patent, subject to the payment of maintenance fees as provided by law.

PATENT AND TRADEMARK OFFICE * UNITED STATES OF AMERICA *

Douglas B. Comer

Acting Commissioner of Patents and Trademarks

Marcia L. Campbell

Attest

PTO-1584

FPI-LOM

File History Content Report

The following content is missing from the original file history record obtained from the United States Patent and Trademark Office. No additional information is available.

Document Date - 2005-02-02

Document Title - USPTO Communication Re: Expire Patent

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PATENT APPLICATION FEE DETERMINATION RECORD **For Fees Effective Nov. 5, 1990**	Application or Docket Number 08/629417

CLAIMS AS FILED - PART I

FOR	NUMBER FILED (Column 1)		NUMBER EXTRA (Column 2)	SMALL ENTITY RATE	SMALL ENTITY FEE	OR	OTHER THAN SMALL ENTITY RATE	OTHER THAN SMALL ENTITY FEE
BASIC FEE					$ 315.00	OR		$ 630.00
TOTAL CLAIMS	1	minus 20 =	*	x $10=		OR	x $20 =	
INDEPENDENT CLAIMS	1	minus 3 =	*	x 30 =		OR	x 60 =	
MULTIPLE DEPENDENT CLAIM PRESENT				+ 100 =		OR	+ 200 =	
				TOTAL		OR	TOTAL	630.00

* If the difference in column 1 is less then zero, enter "0" in column 2

CLAIMS AS AMENDED - PART II

AMENDMENT A	(Column 1) CLAIMS REMAINING AFTER AMENDMENT		(Column 2) HIGHEST NUMBER PREVIOUSLY PAID FOR	(Column 3) PRESENT EXTRA	SMALL ENTITY RATE	ADDITIONAL FEE	OR	OTHER THAN SMALL ENTITY RATE	ADDITIONAL FEE
Total	* 30 ~~36~~ ~~28~~	Minus	** 20	+10	x $10=		OR	x $20 =	200 ~~160~~
Independent	* 2	Minus	*** 3	=	x 30 =		OR	x 60=	
FIRST PRESENTATION OF MULTIPLE DEPENDENT CLAIM					+ 100 =		OR	+ 200 =	
					TOTAL ADDIT. FEE		OR	TOTAL ADDIT. FEE	200

AMENDMENT B	(Column 1) CLAIMS REMAINING AFTER AMENDMENT		(Column 2) HIGHEST NUMBER PREVIOUSLY PAID FOR	(Column 3) PRESENT EXTRA	SMALL ENTITY RATE	ADDITIONAL FEE	OR	OTHER THAN SMALL ENTITY RATE	ADDITIONAL FEE
Total	* 17	Minus	** 30	=	x $10 =		OR	x $20 =	
Independent	* 2	Minus	*** 3	=	x 30 =		OR	x 60 =	
FIRST PRESENTATION OF MULTIPLE DEPENDENT CLAIM					+ 100 =		OR	+ 200 =	
					TOTAL ADDIT. FEE		OR	TOTAL ADDIT. FEE	

AMENDMENT C	(Column 1) CLAIMS REMAINING AFTER AMENDMENT		(Column 2) HIGHEST NUMBER PREVIOUSLY PAID FOR	(Column 3) PRESENT EXTRA	SMALL ENTITY RATE	ADDITIONAL FEE	OR	OTHER THAN SMALL ENTITY RATE	ADDITIONAL FEE
Total	*	Minus	**	=	x $10 =		OR	x $20 =	
Independent	*	Minus	***	=	x 30 =		OR	x 60 =	
FIRST PRESENTATION OF MULTIPLE DEPENDENT CLAIM					+ 100 =		OR	+ 200 =	
					TOTAL ADDIT. FEE		OR	TOTAL ADDIT. FEE	

* If the entry in column 1 is less than the entry in column 2, write "0" in column 3.
** If the "Highest Number Previously Paid For" IN THIS SPACE is less than 20, enter "20".
*** If the "Highest Number Previously Paid For" IN THIS SPACE is less than 3, enter "3".
The "Highest Number Previously Paid For" (Total or Independent) is the highest number found in the appropriate box in column 1.

PTO/SB/06 (11-90) **For Fees Effective Nov. 5, 1990** Patent and Trademark Office; U.S. DEPARTMENT OF COMMERCE

PTO-1130 (REV. 8-87)

FORMAT NO 07

U.S. DEPARTMENT OF COMMERCE—PATENT & TM OFFICE

PALM III APPLICATION FILE DATA CODING SHEET

PREPARED BY [illegible] DATE 9/14/91

2 Serial No.	TYPE APPL	FILING DATE Month Day Year	SPECIAL HANDLING	GROUP ART UNIT	CLASS	SHEETS OF DRAWINGS	ASGT?	TOTAL CLAIMS	INDEPENDENT CLAIMS	SMALL ENTITY?	FILING FEE RECEIVED	SECURITY CASE?	FOREIGN LICENSE?
07 [illegible] 417	1	12 18 90		234	364	28	Y	21	01	N	630	N	Y

ATTORNEY DOCKET NUMBER (12 spaces): UPN-401

Atty.'s Reg. Nos. ☑ APPL. PAPERS ☐ CODING SHEET

FORMAT NO. 4 Applicant's Name & Address ☑ APPL. PAPERS ☐ CODING SHEET

FORMAT NO. 5 Title of Invention ☐ ~~APPL. PAPERS~~ ☐ CODING SHEET

FORMAT NO. 6&7 Correspondence Address ☑ APPL. PAPERS ☐ CODING SHEET

FORMAT NO. 8

		CONTINUITY CODE	PARENT APPLICATION SERIAL NUMBER	PARENT FILING DATE Month Day Year	STATUS CODE	PARENT PATENT NUMBER
RECORD	8 0 1		0			
RECORD	8 0 2		0			
RECORD	8 0 3		0			
RECORD	8 0 4		0			
RECORD	8 0 5		0			
RECORD	8 0 6		0			
RECORD	8 0 7		0			
RECORD	8 0 8		0			
RECORD	8 0 9		0			
RECORD	8 1 0		0			

☐ MORE ON SUPPLEMENTAL CODING SHEET

FORMAT NO. 9

FOREIGN PRIORITY CLAIMED?
☐ YES
☑ NO

'ICATION

		COUNTRY CODE	PCT/FOREIGN APPLICATION SERIAL NUMBER	FILING DATE Month Day Year
RECORD	9 0 1			
RECORD	9 0 2			
RECORD	9 0 3			
RECORD	9 0 4			
RECORD	9 0 5			
RECORD	9 0 6			
RECORD	9 0 7			
RECORD	9 0 8			
RECORD	9 0 9			
	9 1 0			