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Final Report

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National Highway
Traffic Safety
Administration

The Minicars Research Safety Vehicle Program Phase III

Volume II—Appendices

V. K. Ausherman
A. V. Khadilkar
S. R. Syson
C. E. Strother
D. E. Struble

Minicars, Inc.
55 Depot Road
Goleta, California 93117

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16. Abstract

The objective of the RSV Program was to provide research and test data applicable to the automobile safety performance requirements for the mid-1980s, and to evaluate the compatibility of these requirements with environmental policies, efficient energy utilization, and consumer economic considerations. The program was designed to answer the question, "Can small fuel-efficient cars be made safe?," and to address such topics as: How safe should cars in general, and small cars in particular, be? What technologies will be required to make them this safe? Are these technologies feasible? Can they be, or have they been, sufficiently developed to justify the promulgation of more stringent safety standards?

The RSV Program has demonstrated that it is possible to make cars much safer than they are presently. It has produced automobile designs that are consistent, at affordable cost, with the national objectives for fuel economy and environmental protection. It has indicated, at least to a limited degree, that the technological findings are applicable, at varying levels, to a variety of car designs. And it has provided evidence that these findings can be wrapped in a package of considerable appeal to the public.

This Final Report is a comprehensive compilation of the findings of the Phase III efforts of Minicars, Inc. It describes the design and testing of the RSV systems, and the performance levels achieved. Specific topics include a vehicle description and performance specification, the structure, occupant restraints, braking and handling, propulsion, the vehicle exterior, driver controls, the radar and electronics, the Large Research Safety Vehicle, and the accident environment analysis.

17. Key Words RSV, Safety, Crashworthiness, Airbags, Radar, Large RSV, Foam-filling, High Technology RSV, Occupant Protection, Anti-skid Braking, Minicars, Automotive Electronics	18. Distribution Statement Document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161

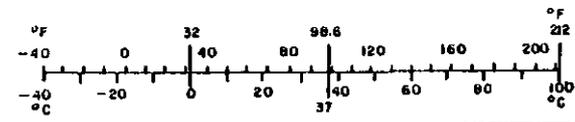| 19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 301	22. Price

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METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.96	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

```
°F
-40        32        98.6                        222
-40    0    40    80    120    160    200
|----|----|----|----|----|----|----|----|----|----|----|----|
-40    -20    0    20    40    60    80    100
°C                     37                          °C
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APPENDIX A

RCA LABORATORIES FINAL REPORT

ELECTRONIC SUBSYSTEMS FOR THE RESEARCH SAFETY
VEHICLE (PHASE III)

ELECTRONIC SUBSYSTEMS

FOR THE RESEARCH SAFETY VEHICLE (PHASE III)

RCA Laboratories
Princeton, NJ 08540

MARCH 1980

FINAL REPORT

Document is available to the U.S. public through the National Technical
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Prepared for

Minicars, Inc.
55 Depot Road
Goleta, CA 93017

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7. Author(s) E. F. Belohoubek, J. J. Risko, M. Ilovich J. Rosen, J. M. Cusack, R. E. Marx, and E. C. McDermott		**8. Performing Organization Report No.** PRRL–80–CR–8
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15. Supplementary Notes

16. Abstract

    This final report covers Phase III of RCA's effort in the DOT sponsored development of the Research Safety Vehicle (RSV) for the mid 80's. Minicars, Inc., is the prime contractor on this program with RCA being responsible for the radar, sensor and display subsystems of the RSV. The radar, an FM/CW system interfaced with a microcomputer, is used to provide: (a) collision-mitigation braking, (b) automatic headway control, and (c) driving-related warning messages.

    The collision-mitigation function of the RSV involves the application of antiskid brakes under conditions where, based on radar and other sensor inputs, it is certain that a severe collision will take place. Other objects, not directly in the immediate path of the vehicle, must not trigger the brakes. The optimization of the radar processing hardware and associated computer algorithm for this function was performed with the help of tape recordings (both video and radar IF) for a large variety of road, traffic, and weather conditions. Separate, simulated collision tests were performed with an expendable target (corner reflector) to demonstrate the short reaction time of the system.

    The automatic headway-control system has the task to keep a safe distance with respect to the car ahead based on speed and range inputs. Without other vehicles close by, the system functions as a standard cruise control. Successful operation of the headway-control system interfaced with the car throttle was demonstrated on an RCA-owned station wagon. The integration of the system into the RSV is a separate follow-on task.

    Driving-related information, such as speed, mileage, fuel economy, fuel level, etc., together with warning messages such as water temperature too high, oil pressure too low, emergency brake on, doors open, etc., are shown on an alphanumeric plasma display which is interfaced through a microcomputer to various sensors.

17. Key Words (Selected by Author(s)) Research Safety Vehicle Collision-mitigation braking Automatic headway control Driving-related warning messages	**18. Distribution Statement** Document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161.	
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PREFACE

This Final Report describes work performed at the Microwave Technology Center of RCA Laboratories, Princeton, New Jersey, from March 1, 1977 to November 15, 1979, under subcontract P.O. 5062 from Minicars, Inc., Goleta, California. The prime contract for this effort was DOT-HS-7-01552, with Mr. Jerome Kossar from National Highway Traffic Safety Administration as contracting officer.

The program was carried out under the direction of Dr. Erwin F. Belohoubek, Head of the Microwave Circuits Technology. The following scientists participated in the development effort: John J. Risko, Mordechay Ilovich, Jerome Rosen, and Joseph M. Cusack (part-time consultant). The major portion of the effort on the radar headway control was carried out under separate RCA funding, with William R. Lile as project scientist.

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SECTION I

INTRODUCTION

This report covers Phase III of the development effort, sponsored by the
National Highway Traffic Safety Administraton (NHTSA) under contract No. DOT-
HS-7-01552, toward the demonstration of various electronic subsystems for the
Research Safety Vehicle (RSV), for the mid-1980s time frame. Specifically,
this effort encompassed extensions of the electronic functions that act as
driver aids and that maximize the vehicle's collision avoidance and mitigation
capabilities, with the final goal of installing these systems in the latest,
high technology version of the RSV. This work was conducted by the Microwave
Technology Center of RCA Laboratories in Princeton, New Jersey, under subcon-
tract from Minicars, Inc., Goleta, California, during the period from March
1977 to November 1979.

The major effort during Phase III was directed toward the development of
an FM/CW radar that, interfaced with a microcomputer, provides the following
functions: (a) collision mitigation braking; (b) automatic safe headway control;
and (c) driving-related warning messages. These warning messages are flashed
on a self-scan alphanumeric plasma display which, driven by another microcom-
puter, also shows general operating and functional data such as speed, mileage,
fuel level, oil pressure, water temperature, etc.

While the provision of safety and warning messages represented merely an
extension and refinement of an existing system developed during Phase II, the
collision-mitigation and headway-control systems required substantial develop-
ment efforts to demonstrate their practical potentials in a real traffic en-
vironment. Early road tests with the initial radar system during Phase II had
clearly shown the need for a more systematic approach to the optimization of
the radar system to ensure proper operation and elimination of practically all
false alarms under a wide variety of driving conditions. A large portion of
Phase III was thus devoted to the tape recording of a wide variety of road,
traffic, and weather conditions to permit a thorough optimization of the radar
processing hardware and associated computer algorithm.

We also proceeded from initial headway-control experiments during Phase II
that provided only speed-up or slow-down messages to a closed-loop system with
the throttle of the car tied to the radar system for truly automatic headway

control. The inclusion of proportional braking into the automatic headway-control action, which would further enhance the acceptability of this function to the driver, was not yet included on the present test car.

The specific goals for the Phase III effort as originally formulated are listed below:

Task 1   Installation of Phase II radar and display into RSV exhibition vehicle.

Task 2   Radar improvements, including dual-mode operation (cooperative/noncooperative).

Task 3   Road tests using tape recordings of radar output, together with video information of traffic conditions to optimize signal processing algorithm.

Task 4   Final system integration and installation in high technology RSV.

Task 5   Cost effectiveness studies.

During the early portion of the program it became apparent that a shift in the operating frequency of the radar to higher values would be beneficial. We also learned at that time of three major government-sponsored programs in Germany [1,2,3], all directed toward radar warning on high-speed expressways. Consequently, we concentrated our efforts mainly on collision mitigation and headway control, rather than long-range warning that was being explored by German companies very extensively using sophisticated 35-GHz radars. In addition, our program experienced a serious slow-down due to funding shortages that eventually led to a stretch of the program from the originally planned 18 months to 33 months.

1.   D. Zur Heiden and H. Oehlen, "Radar Anticollision Warning System for Road Vehicles," Electrical Communications 52(2), 141 (1977).
2.   G. Hahlganss and L. Hahn, "Headway Radar Using Pulse Techniques," Int. Conf. on Automobile Electronics, London, July 1976, pp. 132-135.
3.   E. Dull and H. Peters, "Collision Avoidance System for Automobiles," Society of Automotive Engineers, Publication #780263, March 1978.

The above factors resulted in a redefinition of the program goals, as outlined in a new work statement dated May 1978 and listed in abbreviated form below:

Task 1 - Demonstration of Radar Functions in RCA-Owned Vehicles

(a) Headway control using a cooperative X-band radar
(b) Headway control using the new Ku-band noncooperative radar
(c) Collision-mitigation function tests with expendable target

Task 2 - Radar Improvements

(a) Design, fabricate, and test dual-mode (cooperative/noncooperative) radar at X-band
(b) Develop noncooperative bistatic Ku-band radar
(c) Improve processor algorithm and reliability of microcomputer system
(d) Interface throttle and brakes to microprocessor

Task 3 - Road Test Program

(a) Equip RCA test van with video recorder and synchronized radar IF output recorder
(b) Perform tape recordings of test rides under a wide variety of traffic, road, and weather conditions
(c) Optimize radar processing and computer algorithms of collision mitigation and headway-control* functions
(d) Perform final road tests of both systems in RCA cars under actual traffic conditions

Task 4 - Final System Integration

(a) Fabricate and install Ku-band noncooperative bistatic radar, display, and associated microcomputers in a high-technology version of RSV
(b) Calibrate all sensor functions, optimize radar performance and put all algorithms in the programmable read-only memory (PROM)

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*The development of a digital cruise control, the headway control, and fuel economy experiments with these systems were performed on RCA cars under separate RCA funding.

Task 5 - Cost Study

Estimate the 1985 cost of individual systems in 1979 dollars using RCA's
PRICE program

Practically all of the above tasks have been completed, except that in
the present version of the high-technology RSV, the tie-in between the headway
microcomputer and the automatic, electronically shifted transmission was not
implemented. Due to a series of program delays and the unavailability in time
of a properly functioning computer-controlled transmission, the final optimiza-
tion of the automatic headway control could not be carried out in the RSV. The
basic feasibility of this function was demonstrated instead on a separate RCA
station wagon, which was refurbished specifically for demonstration purposes.

The final integration of the headway control into the RSV is the objective
of a planned follow-up program which will be a joint effort between Dubner Com-
puter Systems,* Minicars, and RCA, and will be performed at RCA Laboratories in
Princeton toward the middle of 1980. The results of this final integration will
be reported separately.

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*Dubner Computer Systems, New York City, NY.

SECTION II

OVERALL SYSTEM LAYOUT

As mentioned before, the use of radars for long-range warning-only purposes has been explored extensively by several companies under government sponsorship in Germany. These radars are geared mainly toward warning the driver of impending dangerous situations and leaving the decision to react to this warning to the driver. Because of the relatively long reaction time of the driver (between 0.6 to 1 s), the warning has to be based on long-range information (typically 100 to 150 m) at the high speeds prevalent on many of Europe's expressways.

The situation in the United States, having a maximum speed limit of 90 km/h (55 mph) throughout, is substantially different. Here we try to effect a societal savings by mitigation of an inevitable collision. The key considerations are elimination of all false alarms and automatic application of antiskid brakes under conditions where, due to human error or mechanical failure, a severe collision is definitely unavoidable. This limits the action range of the radar to 25 to 30 m because for longer distances, the opportunities for false alarms increase rapidly and more importantly, a skilled driver possibly could still perform an avoidance maneuver which could be hampered by the application of antiskid brakes. Thus, the emphasis is on an automatic reaction only where a high-speed collision is unavoidable. This does not exclude the use of the radar for warning purposes over a longer range; the latter subject, however, has been covered extensively by the German radar development efforts and thus was not addressed in this program.

While the collision-mitigation function mentioned above is tailored mainly to safety aspects of the car, the automatic headway control could substantially improve the driver comfort and increase the throughput on high-density highways. Since the collision-mitigation function of the radar would not be used by the average driver so long as he is not involved in an accident, the simultaneous use of the radar for driver convenience is expected to lend a strong sales appeal to the inclusion of a radar in future cars.

In addition to the radar functions, the high-technology version of the RSV includes also a computer-controlled plasma display that provides driving-related information such as speed, mileage, fuel level, water temperature, etc., to the driver in either digital form or as analog bars. The selection

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of the type of display format can be made through a switch by the driver.
Malfunctions or safety hazards are indicated on the display by temporary
flashing of warning messages which interrupt the normal display in 30-second
intervals until the particular hazard has been corrected.

A block diagram of all electronically related functions in the RSV is
shown in Figure 1. The processed radar signal is fed to two separate micro-
processors, one for collision mitigation and one for headway control. A series
of other sensor inputs, such as vehicle speed, steering angle, brake pedal
position, and cruise control inputs are also interfaced with the respective
microprocessors.
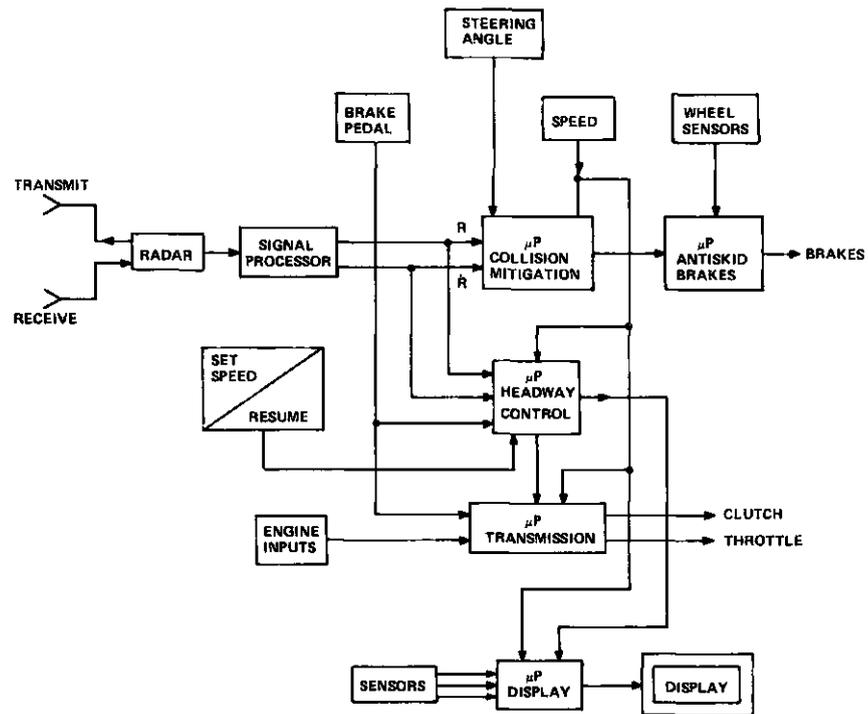
FIGURE 1. BLOCK DIAGRAM OF ELECTRONICALLY RELATED FUNCTIONS IN RSV.

At present, separate microprocessors are used for the collision-mitigation
system (CMS), the headway control, the display, the antiskid system,* and the
automatic gear shift of the car. The latter function, being developed under
subcontract to Minicars by Dubner Computer Systems, Inc., is important for

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*An experimental antiskid system, manufactured by Bendix, is used in the RSV.

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improved fuel economy and interfaces directly with the commands from the automatic radar headway control. Later versions of the RSV could possibly use only two or three microprocessors, whereby one could perform certain vital functions in case of failure of the others to preserve a limp-home ability. Questions of time sharing between microprocessors and interleaving of programs, however, have not been addressed during this program.

SECTION III

RADAR RF DESIGN

A. Ku-BAND, BISTATIC NONCOOPERATIVE RADAR

1. Block Diagram

The Ku-band radar is a forward-looking, bistatic noncooperative FM/CW
radar. A block diagram of the system is shown in Figure 2. The RF section
of the radar consists of a transmitter chain and receiver chain; each with
its own antenna. The transmitter chain consists of a varactor-tuned oscillator
and modulator, power divider, and printed circuit antenna. The receiver chain
consists of a printed circuit antenna (same as in the transmit arm), isolator,
and mixer. The IF section is made up of a shaped preamplifier and shaped
postamplifier. Voltage regulators and ignition noise filters are included in
the amplifiers.
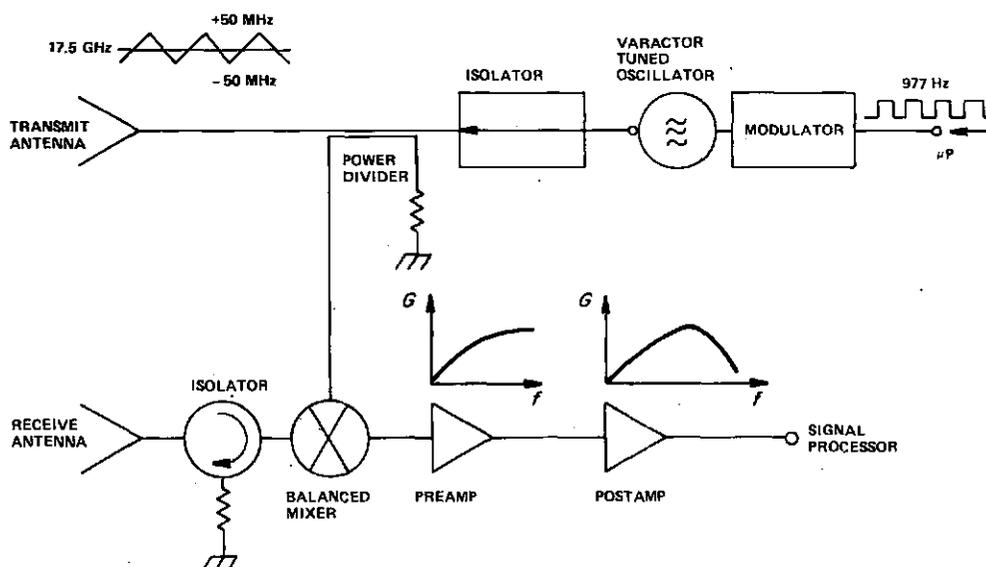
FIGURE 2. BLOCK DIAGRAM OF THE Ku-BAND FM/CW RADAR.

Figure 3 shows front and back views of the radar assembly with the radome
removed. Also shown as part of the radar assembly are the radome supports,
which serve as the transition members between the radar and the hood of the
RSV. The radome conforms to the contour of the RSV and is made up of blocks
of polystyrene covered with expanded polyethylene. The radome will be dis-
cussed in greater detail in subsection III.C below. The performance features
of the radar are given in Table 1.
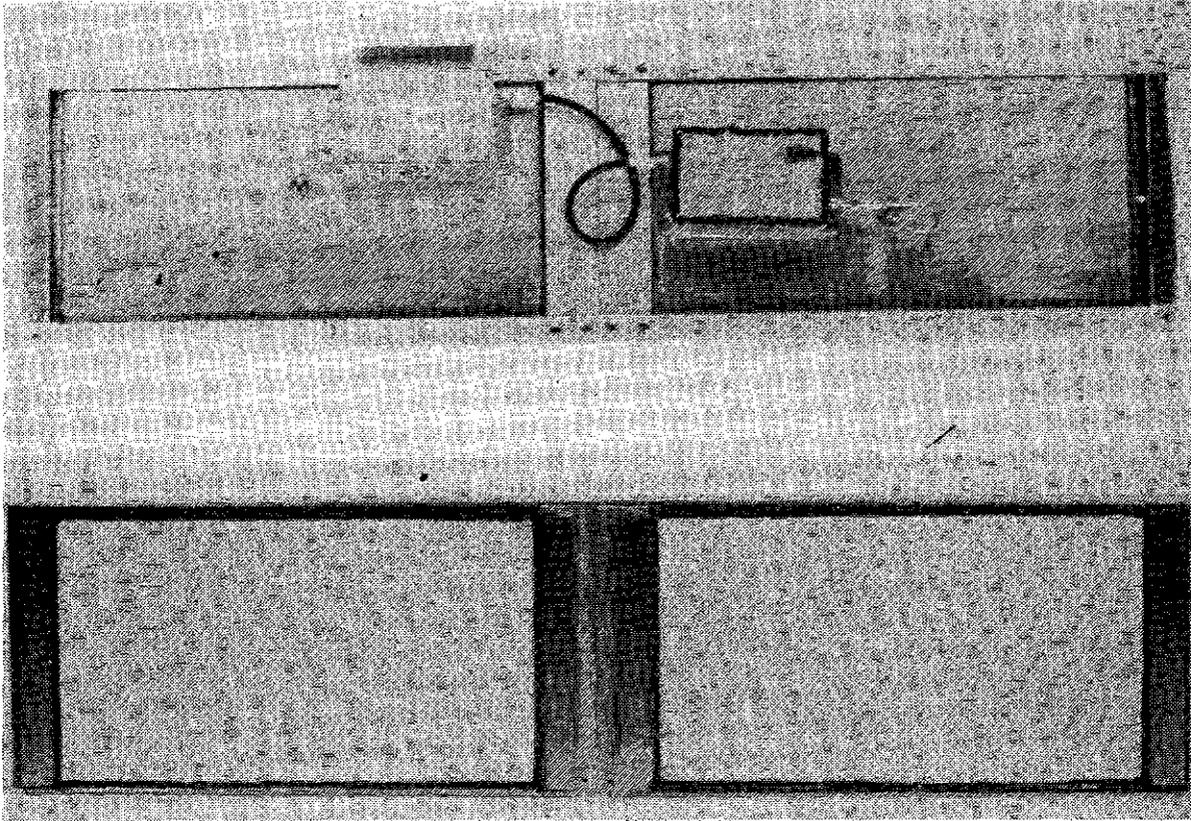
FIGURE 3. FRONT AND BACK VIEW OF THE RADAR ASSEMBLY.

TABLE 1. PERFORMANCE CHARACTERISTICS
OF Ku-BAND RADAR

Parameter	Value
Frequency, f_o	17.5 GHz
Power Output, P_o	10 mW
Frequency Deviation, Δf	± 50 MHz
Modulation Rate, f_m	977 Hz
Beamwidth Horizontal, θ_H	3°
Beamwidth Vertical, θ_V	5°
Antenna Gain, G	30 dB
Bistatic Antenna Assembly Size	77 cm x 20.5 cm x 2.5 cm
Range	7 to 30 m, collision mitigation 8 to 50 m, headway control
Range-Rate	0-60 m/s

The operation of the radar is as follows: referring to Figure 2, the varactor-tuned oscillator and modulator furnish a 15-mW frequency-modulated carrier to the power divider. The carrier frequency is 17.5 GHz and has triangular modulation of ±50 MHz deviation. One output of the power divider (11 mW) is directed to the antenna while the other output (2.75 mW) enters the local oscillator port of the mixer via a rigid cable. The power split is 6 dB to compensate for the 1.6-dB loss in the cable. The transmitted signal is reflected back to the radar from a target and coupled to the signal port of the mixer through the antenna and isolator in the receiver chain.

Due to the time delay between transmission and reception, the frequency of the received signal differs from the transmitted signal (local oscillator signal), and a beat frequency signal will be generated at the IF port of the mixer. The beat frequency contains the desired range and range-rate information which is recovered in the processing circuitry. The details of the signal processing are given in Section IV. Range and range-rate accuracy are discussed in subsection III.A.3 below. Range and range-rate information, speed of the radar-equipped vehicle, and steering angle are processed further to determine if a vehicle control action is necessary. The speed and steering angle are derived from transducers coupled to the speedometer and steering column of the vehicle, respectively. The software algorithms used for the control decisions are discussed in Section V.

2. System Parameters

a. RF Frequency Considerations

To avoid false alarms from vehicles in adjacent lanes or roadside objects, a narrow antenna beam is desirable. For a narrow antenna beam, a large radiating surface is required, large with respect to a wavelength. For example, the X-band antenna used during Phase II is 28 x 17 cm (9.9 x 6 wavelengths) and provides a beam 5 degrees wide in azimuth and 10 degrees wide in elevation. Beamwidths are measured at the 3-dB points of the gain pattern. To decrease the beamwidth by a factor of two in azimuth and elevation, the required cross section becomes (19.9 x 12 wavelengths) or 56 x 34 cm at X-band. However, if the RF frequency were doubled, the same antenna area would provide an antenna pattern of half the beamwidths. Thus from both a size and ultimately cost standpoint, it is desirable to increase the RF frequency. The major limitation

to this trend is the availability and cost of RF components at the higher frequencies. The upper end of Ku-band (17.5 GHz) was chosen as a compromise frequency.

At 17.5 GHz, transferred electron oscillators (TEOs) are still state-of-the-art devices, and microstrip technology can be applied cost effectively to the other microwave components. In addition, microwave absorption through the atmosphere is still small, 0.02 dB/nautical mile for 1% water vapor and 6 dB/nautical mile for heavy rain. From the X-band reference of 10.575 GHz, a 40% size reduction is expected. The actual Ku-band antenna is 33 x 19 cm (19 x 11 wavelengths) and has a 3-degree beamwidth in azimuth and a 5-degree beamwidth in elevation.

A 3-degree beamwidth has been found to be a good compromise between beam confinement at far ranges and target acquisition at close range. For example, at 50 m the beam coverage is $\pm$1.31 m. Although the possibility of missing a target off to the side exists at close range, the decreased probability of false alarms in the far field is of greater importance.

For a well designed antenna, reducing the beamwidth will increase the gain. If the same current distribution would exist at X-band and Ku-band, reducing the beamwidths by a factor of two in azimuth and elevation would yield a 6-dB increase in gain. From the range equation the power returned to the radar is proportional to the square of the antenna gain, and square of the wavelength [4]. The net effect of increasing the gain by 6 dB and decreasing the wavelength would be a 8-dB increase in returned power for constant transmitted power. However, for the actual 17.5-GHz antenna, the gain only increased by 5 dB so that the returned power increased by 6 dB.

The location of multipath nulls is also dependent on the RF frequency. The range at which multipath nulls appear is given by, [5]

$$R = \frac{2h_1 h_2}{\lambda N} \text{ , } N = 0, 1, 2, \ldots \tag{1}$$

where λ is the wavelength, h_1 is the effective height of the antenna above ground, h_2 is the effective height of the target above ground, and $N = 0$ corresponds to $R = \infty$.

4. F. E. Nathanson, Radar Design Principles, (McGraw-Hill Publishing Company, New York, 1969).
5. S. A. Hovanessian, Radar Detection and Tracking Systems, (Artech House, Inc., Massachusetts, 1973).

Experimentally it has been found that the farthest null from the radar, corresponding to $N = 1$, is the most severe. Assuming $h_1 = h_2 = 0.675$ m, the first null occurs at 32 m in X-band. For a headway control system it is desirable to operate out to 50 m. A multipath null at 32 m would result in unstable operation around 32 m. To ensure smooth tracking out to 50 m, the multipath null should be moved beyond 50 m. By increasing the frequency to 17.5 GHz, the first null occurs at 53 m. This has been found to be acceptable.

b. Bistatic Radar Considerations

A shortcoming of CW radars is the lack of complete isolation between the transmitter and receiver. In a monostatic configuration (single antenna for transmit and receive), the antenna mismatch is the basic coupling mechanism between the transmitter and receiver. For example, an antenna with a VSWR of 1.2:1 will reflect 1% of the transmitter power to the receiver. By comparison in Ku-band, a 1-m^2 target 30 m from the radar returns only -67 dB to the receiver. Causes for the antenna reflection may be a slight mismatch between the feedline and the antenna or also the accumulation of snow or dirt on the front of the antenna radome.

The most serious problem caused by the coupled power, or spillover as it is more commonly called, is distortion of the IF amplifier output. In order to process the radar return and extract range and range-rate accurately, a flat amplifier response is required.

Because of spillover, the amplifier baseline is distorted and processing errors occur. Spillover also causes dynamic range problems when the spillover is orders of magnitude above the minimum detectable signal (MDS). A bistatic radar reduces this problem since separate antennas are used for transmit and receive. The basic coupling between transmitter and receiver for the bistatic system is through radiation from the transmit antenna to the receive antenna. The amount of radiation is a function of the antenna radiation pattern and the geometry of the antennas. For the stripline antennas mounted in the RSV that leakage is approximately -60 dB.

Another mode of spillover, even in bistatic radars, is through the mixer. Due to the finite isolation between the LO and signal port, some of the LO power is coupled to the signal port. An isolator before the receive antenna is used to reduce the effects of this source of spillover.

Although bistatic arrangements are larger and thus somewhat costlier, this configuration was chosen for the Ku-band radar to ensure reliable operation with high sensitivity.

c. Modulation Parameters

The general considerations made in choosing triangular FM modulation were given in the final report of Phase II [6] and will not be repeated here. Only the choice of modulation parameters for the Ku-band radar will be discussed.

Range accuracy is proportional to the bandwidth of the transmitted signal, while the range-rate accuracy is proportional to the processing time. Since the processing time is inversely proportional to the repetition frequency, some tradeoffs must be made between response time and range-rate accuracy. These tradeoffs are different for the CMS and the headway-control system. The CMS requires response times of the order of less than 100 ms while 0.5 s is adequate in the headway-control mode. For these response times, the 1-kHz repetition rate used previously for the X-band radar is adequate. In practice, because of greater stability, the 2-MHz crystal in the microprocessor is divided down to 977 Hz and serves as the repetition frequency.

The choice of the frequency deviation, Δf, about the center frequency is based on the following considerations:

The IF frequency, f_B, during the modulation upsweep, f_{up}, and downsweep, f_{down}, is given by [6]

$$f_{up} = \left| \frac{8\Delta f\, f_m\, R}{c} \right| + \left| \frac{2\, f_o\, \dot{R}}{c} \right|$$

$$f_{down} = \left| \frac{8\Delta f\, f_m\, R}{c} \right| - \left| \frac{2\, f_o\, \dot{R}}{c} \right| \tag{2}$$

The first term in equation (2) is often referred to as the range frequency, f_r, and the second term as the doppler frequency, f_d. Since $\dot{R}$ can be positive or negative, depending on whether the target is inbound or outbound, equation (2) holds for an outbound target. For an inbound target, the sign of $\dot{R}$

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6. E. F. Belohoubek et al., "Electronic Subsystems for Research Safety Vehicle (RSV)," Final Report, Phase II, 1976.

is reversed and the beat frequency during upsweep is less than the beat frequency during the downsweep. This allows the determination of the direction of the range-rate during processing. When the range frequency, f_r, is greater then the doppler frequency, f_d, equation (2) becomes

$$f_{up} = \left| f_r \right| + \left| f_d \right|$$

$$f_{down} = \left| f_r \right| - \left| f_d \right| \tag{3}$$

and $\quad \left| f_r \right| = \tfrac{1}{2}(f_{up} + f_{down}) = f_{B\ AVG}$

$$\left| f_d \right| = \tfrac{1}{2}(f_{up} - f_{down}) \tag{4}$$

From equation (4) it is seen that the range is proportional to the beat frequency averaged over a modulation cycle and the range-rate is proportional to the difference between upsweep and downsweep frequencies. When the doppler frequency is greater than the range frequency, the relations are reversed and the average beat frequency is proportional to the range-rate.

To ensure the condition of range frequency being greater than the doppler frequency over the complete set of range and range-rate of interest, the following inequality must hold

$$4\Delta f\ f_m\ R_{min} > v_{max}\ f_o \tag{5}$$

where f_m is the repetition frequency (977 Hz), R_{min} is the minimum range of interest (10 m), v_{max} is the maximum range-rate of interest (60 m/s), and f_o is the carrier frequency (17.5 GHz).

For the given parameters,

$$\Delta f > 27\ \text{MHz} \tag{6}$$

Equation (6) imposes one condition on the frequency deviation.

Another restriction arises from the spectral nature of the signal. Since the modulation is periodic in the repetition frequency, f_m, the transmitted signal can be represented as a Fourier series, with period $1/f_m$. The maximum signal strength occurs at f_m and decreases as the harmonic number increases. Unless filtering is included in the receiver, the receiver will be saturated by strong signal terms at f_m and the first two or three harmonics of f_m. To

simplify the filter problem, the IF frequency, f_B, should be much greater than f_m. Since f_B is proportional to Δf, a large value of Δf is desirable. For example, the minimum value of f_B that the receiver must pass is given by a target at the minimum range, traveling at the maximum velocity. Assuming a maximum velocity of 60 m/s at a range of 10 m and a frequency deviation of 27 MHz, the minimum IF frequency is 3.3 kHz; too close to 3 f_m. A value of 50 MHz for Δf increases the minimum IF frequency to 6.2 kHz. This was considered a reasonable tradeoff between filter requirements and modulator complexity.

3. Range and Range-Rate Accuracy

Implicit in the derivation of equation (2) is the assumption that the modulating signal is a symmetric triangular wave. When the symmetry or the linearity of the triangular wave is perturbed, an error in range and range-rate will occur. To determine these errors, we use the more general equation relating the IF frequency, f_B, to modulation [6]

$$2\pi f_B = \ddot{\Psi}\tau + \dot{\Psi}\dot{\tau} \tag{7}$$

where

$$\Psi(t)_{ch} = 2\pi \left\{ f_o t \pm \Delta f \int_0^t g(x)dx \right\}$$

$$\tau = \frac{2R}{c} \tag{8}$$

and $\Delta f g(x) =$ frequency modulation

In the ideal case,

$$g(x) = 4f_m x \tag{9}$$

From equations (7) and (8)

$$f_B = \pm 2\Delta f \dot{g}(t) \frac{R}{c} + (f_o \pm \Delta f g(x)) \frac{2\dot{R}}{c} \tag{10}$$

Neglecting second-order terms,

$$f_B = \pm \frac{2\Delta f \dot{g}(t)R}{c} + \frac{2\dot{R}f_o}{c} \tag{11}$$

As before, the first term is the range frequency and the second term the doppler frequency.

Equation (11) will be used to evaluate the error when the frequency modulation, $\Delta f\dot{g}(t)$, is not ideal.

When there is an asymmetry in the half-periods of the triangular modulation as shown in Figure 4, $\dot{g}(t)$ will differ on the upsweep and downsweep of the modulation cycle. Therefore, a stationary target will exhibit a range-rate from equation (4). From Figure 4 the half-period during the upsweep T_u, is

$$T_u = \frac{T}{2} - \delta T \qquad (12a)$$

and the half-period during the downsweep, T_d, is

$$T_d = \frac{T}{2} + \delta T \qquad (12b)$$

Using equations (12a) and (12b) to calculate $\dot{g}(t)$

$$f_{up} \cong \frac{8\Delta f \, f_m R}{c} \left(1 + \frac{2\delta T}{T}\right)$$

$$f_{down} \cong \frac{8\Delta f \, f_m R}{c} \left(1 - \frac{2\delta T}{T}\right) \qquad (13)$$
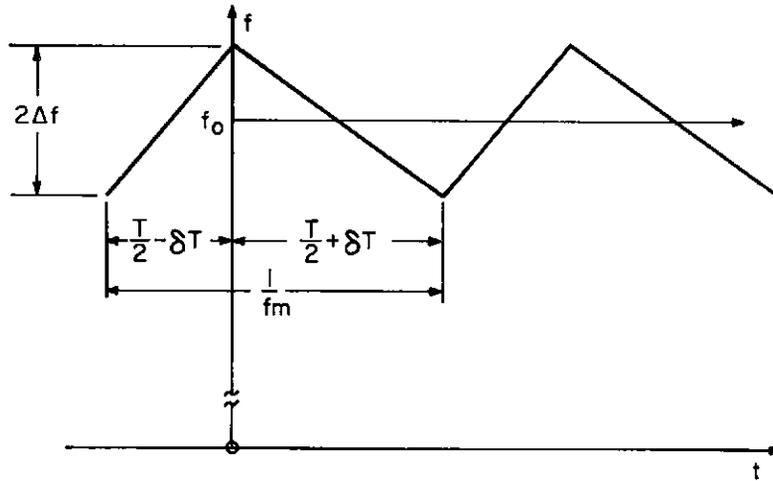
FIGURE 4. ASYMMETRIC TRIANGULAR MODULATION.

From equations (4) and (13), the range error is zero and the apparent doppler frequency, δf_d, is

$$\delta f_d = 2 \, f_r \frac{\delta T}{T} \qquad (14)$$

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Since
$$f_d = \frac{2 \, R\dot{f}_o}{c} \tag{15}$$

The apparent range-rate, $\delta\dot{R}$, is

$$\delta\dot{R} = \frac{f_r c \delta T}{f_o T} \tag{16}$$

For the present modulation parameters and center frequency

$$\delta\dot{R} = 22.33 \, R \, \frac{\delta\dot{T}}{T} \, m/s \tag{17}$$

From equation (17), a 1% modulation asymmetry will cause an apparent range-rate of 6.7 m/s at 30 m. To eliminate this source of error, the repetition rate (and hence symmetry) is derived from the 2-MHz crystal of the microprocessor.

The effect of a nonlinear triangular wave can be derived from the model shown in Figure 5(a). From Figure 5(a), the RF frequency, $f(t)$, is

$$f(t) = f_o \pm 4\Delta f \, f_m \, t + \varepsilon(t) \tag{18}$$

where $\varepsilon(t)$ is the time-dependent nonlinearity

Assuming the target to be stationary,

$$-\frac{T}{2} \leq t \leq 0$$

$$f_B = f_r + \frac{2 \, \dot{\varepsilon}(t) \, R}{c} \tag{19a}$$

$$0 \leq t \leq \frac{T}{2}$$

$$f_B = -f_r + \frac{1 \, \dot{\varepsilon}(t) \, R}{c} \tag{19b}$$

When $f(t)$ has the form shown in Figure 5(a), the decomposition into $\varepsilon(t)$ and $f_o(t)$ is shown in Figures 5(b) and 5(c), respectively. $f_o(t)$ is the ideal
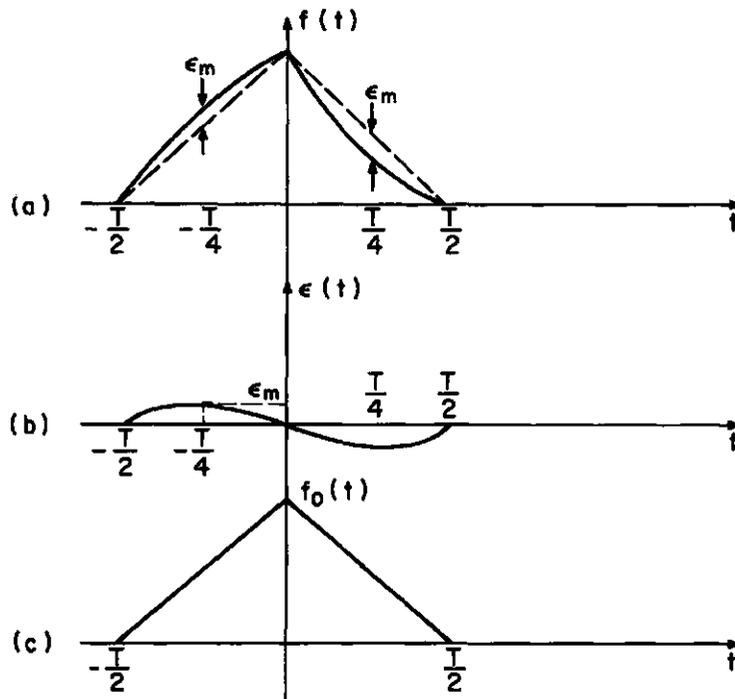
FIGURE 5. SINGLE CYCLE OF NONLINEAR MODULATION WAVEFORM.

linear waveform. If we assume $\varepsilon(t)$ to be quadratic about T/4, $\varepsilon(t)$ can be written as

$$-\frac{T}{2} \leq t \leq 0$$

$$\varepsilon(t) = \varepsilon_m - \varepsilon_m(\frac{4}{T})^2 \ (t + \frac{T}{4})^2 \qquad (20a)$$

$$0 \leq t \leq \frac{T}{2}$$

$$\varepsilon(t) = -\varepsilon_m + \varepsilon_m(\frac{4}{T})^2 \ (t - \frac{T}{4})^2 \qquad (20b)$$

From equations (20a) and (20b)

$$-\frac{T}{2} \leq t \leq 0$$

$$\dot{\varepsilon}(t) = -2\varepsilon_m(\frac{4}{T})^2 \ (t + \frac{T}{4}) \qquad (21a)$$

$$0 \leq t \leq \frac{T}{2}$$

$$\dot{\varepsilon}(t) = 2\varepsilon_m \left(\frac{4}{T}\right)^2 \left(t - \frac{T}{4}\right) \tag{21b}$$

Substituting equation (21a) into equation (19a) and equation (21b) into equation (19b), we have

$$-\frac{T}{2} \leq t \leq 0$$

$$f_B = f_r - 4\varepsilon_m\left(\frac{4}{T}\right)^2 \left(t + \frac{T}{4}\right) \frac{R}{c}$$

$$0 \leq t \leq \frac{T}{2}$$

$$f_B = -f_r + 4\varepsilon_m\left(\frac{4}{T}\right)^2 \left(t - \frac{T}{4}\right) \frac{R}{c}$$

Assuming ε_m to be small so that f_r is the dominant term

$$f_{up} = f_r - 16\varepsilon_m\, f_m\, \frac{R}{c} - 64\varepsilon_m\, f_m^2\, \frac{R}{c}\, t \qquad -\frac{T}{2} \leq t \leq 0$$

$$\tag{22}$$

$$f_{down} = -f_r - 16\varepsilon_m\, f_m\, \frac{R}{c} - 64\varepsilon_m\, f_m^2\, \frac{R}{c}\, t \qquad 0 \leq t \leq \frac{T}{2}$$

Figure 6 is a plot of equation (22). From the figure it is seen that the IF frequency is frequency modulated. The modulating function is a sawtooth of amplitude $\pm\, \dfrac{16\varepsilon_m\, f_m\, R}{c}$ about f_r. From the stationary phase one would expect the IF frequency spectrum to be uniform about f_r and extending $\pm\, \dfrac{16\varepsilon_m\, f_m\, R}{c}$ cycles on either side.

If we let $\dfrac{\varepsilon_m}{2\Delta f}$ be a measure of the nonlinearity, then

$$\frac{16\varepsilon_m\, f_m\, R}{c} = \frac{16\varepsilon_m}{2\Delta f}\, (2\Delta f)\, f_m\, \frac{R}{c}$$
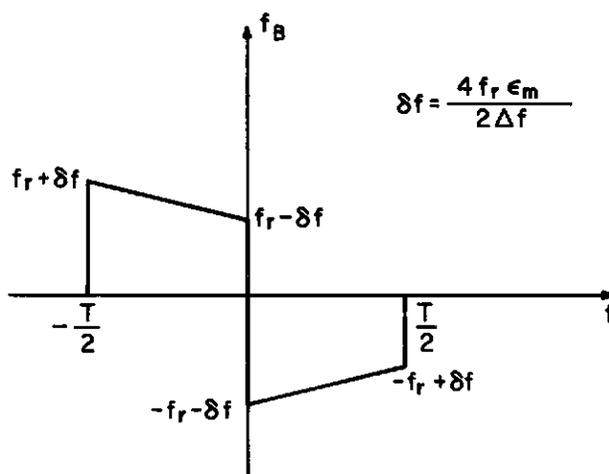
$$\delta f = \frac{4 f_r \epsilon_m}{2 \Delta f}$$

FIGURE 6.   SINGLE CYCLE OF DISTORTED IF FREQUENCY.

or
$$\frac{16 \epsilon_m f_m R}{c} = 4 f_r \frac{\epsilon_m}{2 \Delta f} \qquad (23)$$

From equation (23), we see that a 1% nonlinearity will lead to a $\pm4\%$ frequency spread. This has the net result of causing the IF response to appear noisy and difficult to process. Since the IF frequency is frequency modulated, the frequency between successive cycles will vary. If the variation is great enough, the measurement will be rejected by the signal processor. To avoid these problems a modulator with high linearity is used in conjunction with a linearized voltage-controlled oscillator.

4.   Antenna Design and Measurement

From our road test experience with the X-band antenna design from Phase II, improvements in beam definition were considered definitely desirable. The new design goals for beamwidth in azimuth and elevation were set at 3 and 5 degrees, respectively. This appeared to be the best compromise between avoiding interference from adjacent traffic lanes and not becoming so sensitive to beam alignment that slight steering angle corrections would lead to a temporary loss of target.

In addition, the new design was required to have lower side-lobe levels than the original X-band design, since large targets off to the side could otherwise still be detected. A uniformly illuminated rectangular aperture ideally has side-lobe levels of only -13 dB with respect to the main lobe [7]. To further reduce the side-lobe level, a predetermined current distribution

7.   S. Silver, Microwave Antenna Theory and Design, Rad. Lab Series, Vol. 12, Boston Tech. Publications, 1964.

was established over the antenna aperture, consistent with the side-lobe level desired. A -30 dB Dolph-Chebyshev distribution was chosen for the azimuth pattern and -20 dB for the elevation pattern.

The new Ku-band antenna, shown in Figure 7, uses a construction similar to the original X-band design. The antenna consists of 512 fan-shaped dipoles printed together with the feed structure on both sides of a Duroid circuit board. A ground plane is located $\lambda/4$ behind the printed board as a reflector. This arrangement provides a high-gain antenna in compact form (33 x 19 x 2 cm). Two identical printed circuit antennas, one for transmit and one for receive located next to each other, were used for the Ku-band bistatic radar.

Pattern measurements on the new antennas were performed in a special anechoic chamber. The azimuth and elevation patterns are shown in Figures 8 and 9, respectively. The measured side-lobe levels close to the main lobe were -22 dB in azimuth and -18 dB in elevation. These lower than theoretical levels are probably due mainly to the perturbing effects of the feed structure which is in the same plane as the radiating dipoles. The resulting side lobes are, however, much lower than for the previously used antenna with uniform excitation and should be adequate for the intended purpose.

The measured antenna beamwidth is close to the 3-degree azimuth and 5-degree elevation objective values. The gain is 30 dB above that of an isotropic radiator. For the 19 x 11 wavelength aperture, this represents an efficiency of 50%. Since a nonuniform current distribution is not as efficient as a uniform current distribution, 50% is a reasonable efficiency. By way of comparison, a parabolic reflector is also about 50% efficient.

5. Coverage Pattern Measurements

A coverage pattern of the radar is a series of equipower contours in the plane containing the radar and the target. A 10-m^2 corner reflector was used as target, mounted at the same height from the ground as the radar. Neglecting multipath effects for this position of the target, only the azimuth variation of the target and radar affects the power contours. Moreover, since the corner reflector is much less sensitive to azimuth changes than the antennas in the radar, the entire variation can be attributed to the radar. This allows a simpler mathematical model to be used, as discussed in Appendix A, where computer results are presented. A typical radar-target configuration is shown in Figure 10. The transmit and receive antennas are designated by their normals,
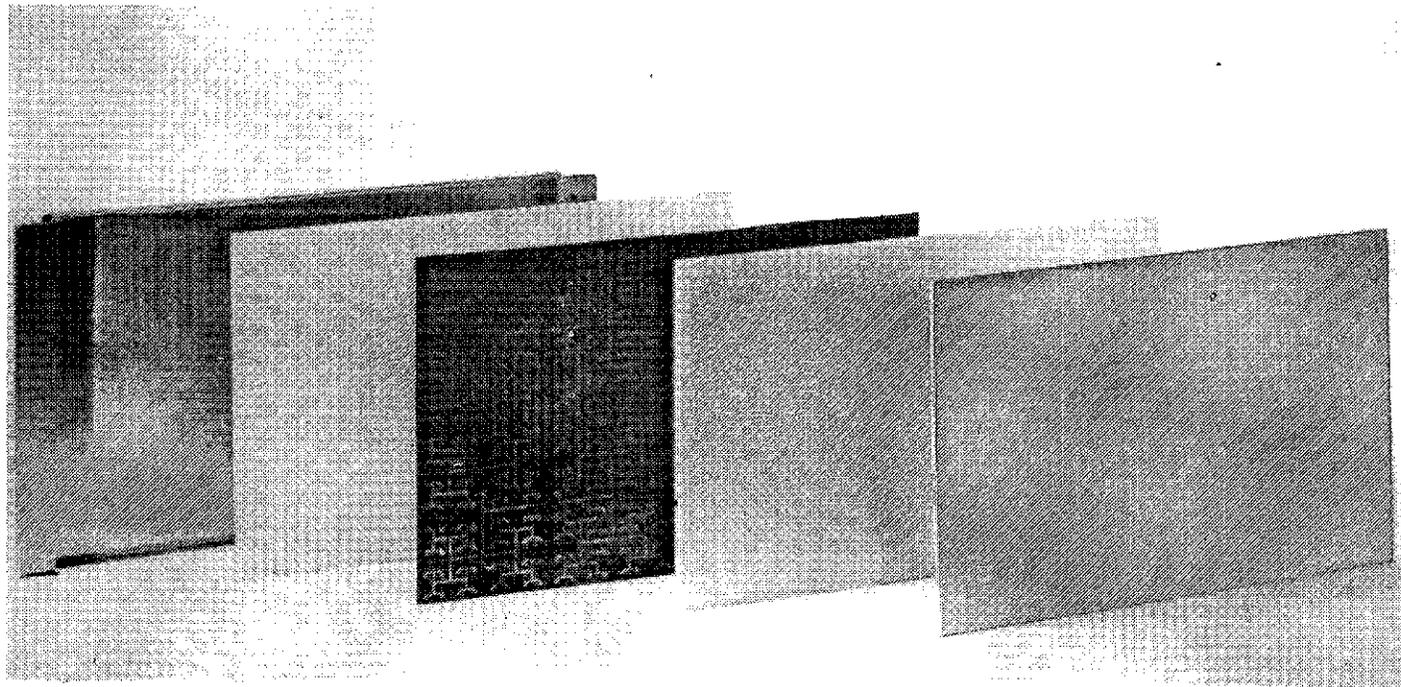
FIGURE 7.   EXPLODED VIEW OF ANTENNA.
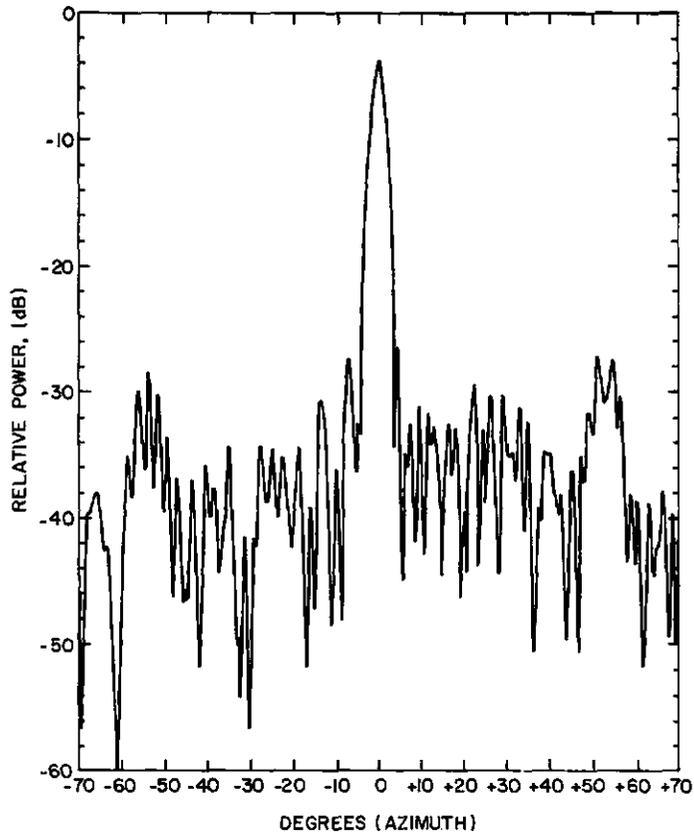
FIGURE 8. AZIMUTH Ku-BAND PATTERN.
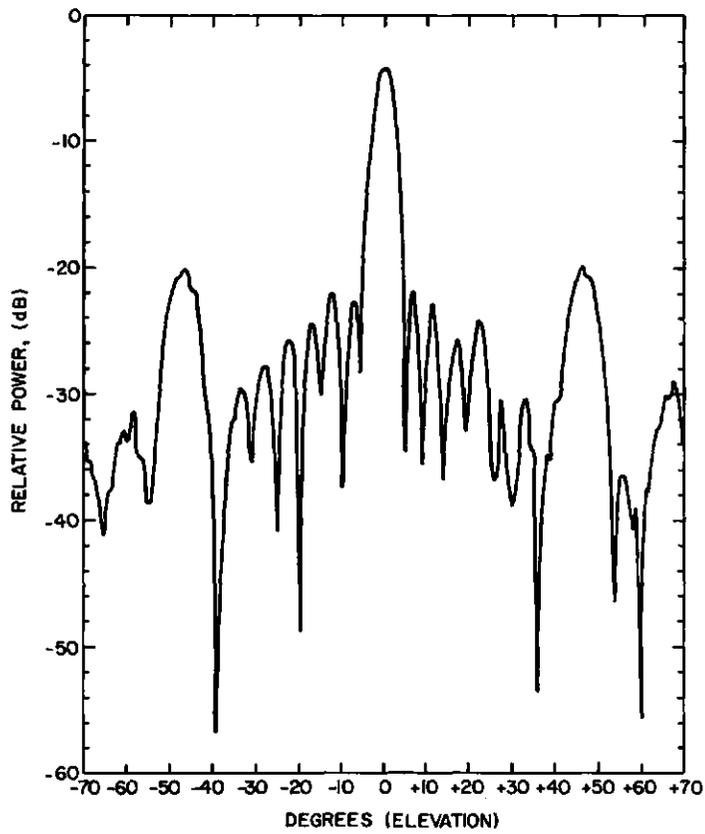
FIGURE 9. ELEVATION Ku-BAND PATTERN.

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Y

(X,Y)

CORNER
REFLECTOR

R_2

R_1

ϕ_2

ϕ_1

$\left(-\frac{S_0}{2}, 0\right)$ $\left(\frac{S_0}{2}, 0\right)$ $S_0 = .388\,m$ X

BISTATIC RADAR
ANTENNAS
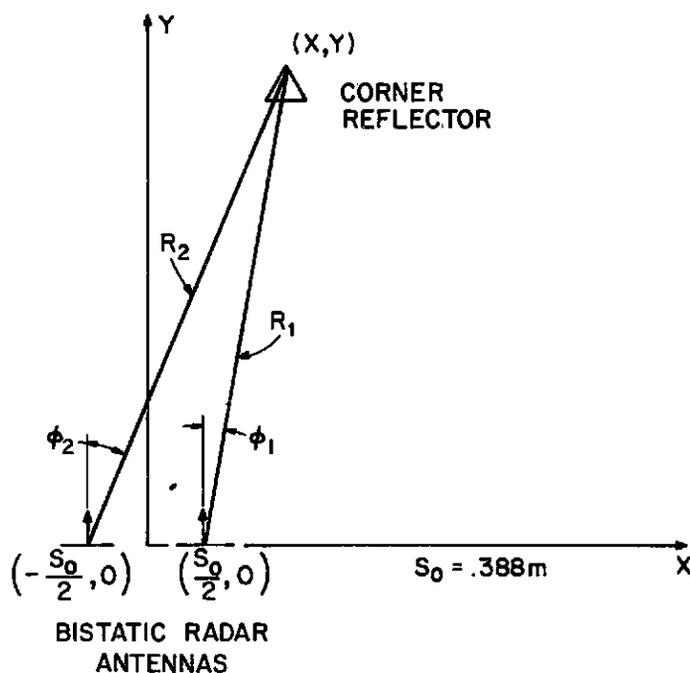
FIGURE 10.   TYPICAL RADAR-TARGET CONFIGURATION FOR
COVERAGE PATTERN MEASUREMENTS.

which are shown on the x axis at $\pm s_0/2$. The target is designated by the coordinates of the apex of the reflector. For a fixed separation, s_0, the geometry is completely defined by the coordinates of the corner reflector.

The determination of the equipower contours was made on a premarked range. Range markings consisted of parallel lines spaced 25 cm apart for the first ± 1 m from the center line (x = 0) and 50 cm apart for x = ± 1 m to x = ± 2.5 m. Because of the narrow antenna beam the range markings were finer for the first ± 1 m. A spectrum analyzer was used as the readout device for the radar return. The analyzer has a wide dynamic range and can measure low-level signals, thus making it a natural candidate for this type of measurement.

Figure 11 shows a contour plot, where the radar return was monitored at the output of the preamplifier, shown in Figure 2. To confine the return to approximately 30 m as needed for CMS operation, a shaped postamplifier was designed with the aid of the computer program discussed in Appendix A. Figure 12 shows the power contour at the output of the shaped postamplifier. An inspection of Figure 12 shows that when the threshold level of detection is set for 30 m, the maximum coverage is within -1.0 m and +0.5 m off axis, a sharply defined microwave beam.
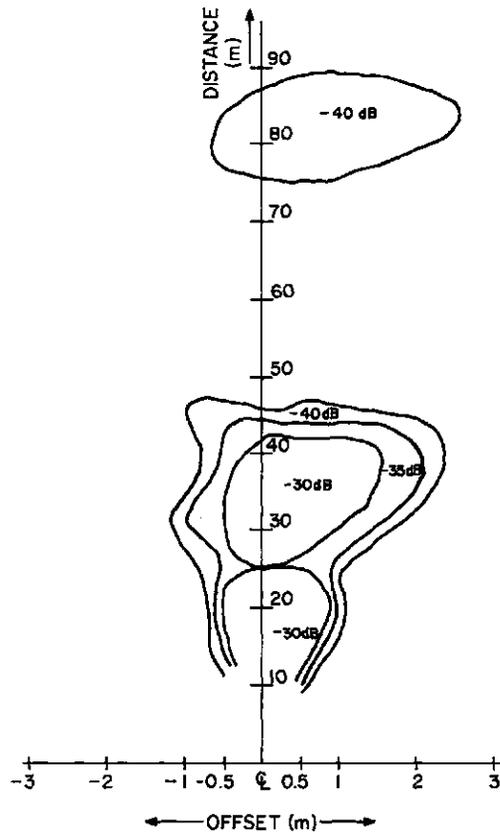
FIGURE 11.   COVERAGE PATTERN Ku-BAND RADAR - OUTPUT OF PREAMPLIFIER.
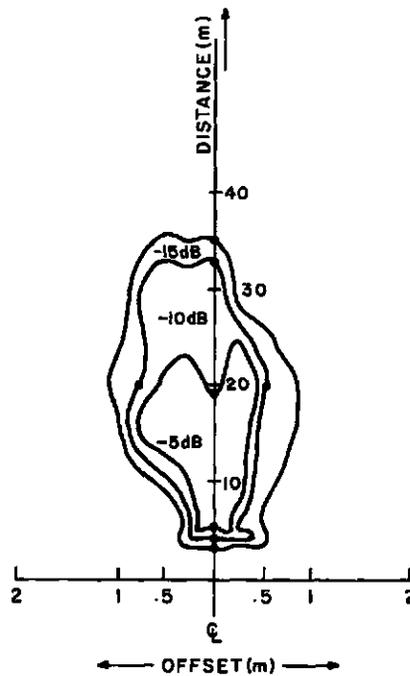
FIGURE 12.   COVERAGE PATTERN Ku-BAND RADAR - OUTPUT OF POSTAMPLIFIER.

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6. IF Amplifier Shaping for CMS

Two amplifiers are used between the radar receiver and the microprocessor. They are referred to as a preamplifier and a postamplifier. The combination of these amplifiers has three functions:

(1) To amplify the return signal (f_B),

(2) To minimize unwanted signals, and

(3) To limit the amplitude of the return signal.

A two-stage preamplifier and a five-stage postamplifier were designed for this purpose. They both use the CA3401 operational amplifier chip as the basic building block.

The preamplifier, located at the mixer output, consists of two stages. Its transfer characteristic is shown in Figure 13. The slope at the low-frequency end of the band is approximately 15 dB/octave, while in the operating band it is 5 dB/octave. The 15 dB/octave is intended to limit low-frequency noise and pickup of the harmonics of the modulating signal at 977 Hz. The 5 dB/octave helps compensate for the 12 dB/octave dropoff of the return signal. The high-frequency end is rolled off slightly to minimize unwanted signals beyond the desired range.
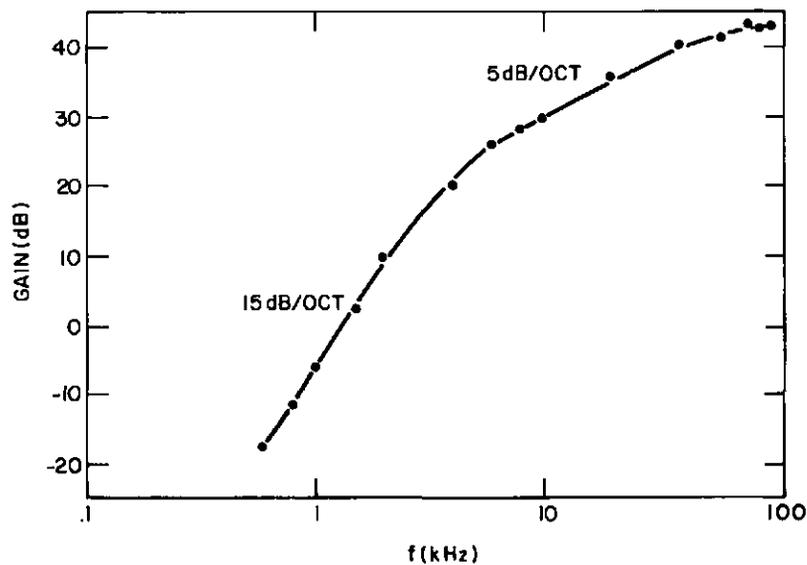
FIGURE 13. TRANSFER CHARACTERISTIC OF Ku-BAND PREAMPLIFIER.

The postamplifier designed for the CMS application has a transfer characteristic as shown in Figure 14. This amplifier consists of five stages. The
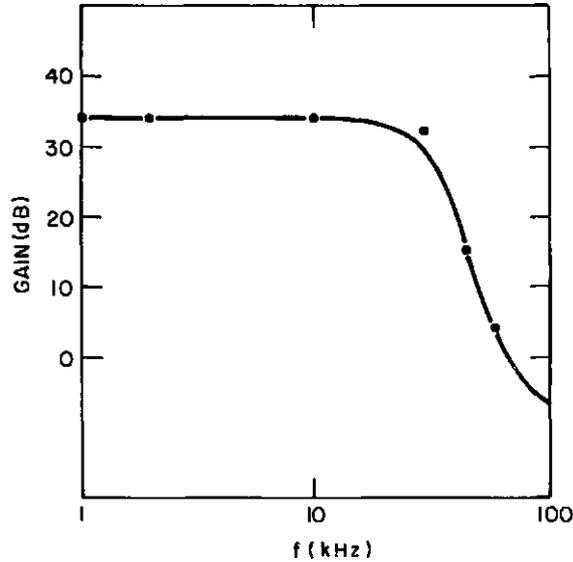
FIGURE 14. TRANSFER CHARACTERISTIC OF CMS POSTAMPLIFIER.

multiple stages are required to sharpen the roll-off at the high-frequency end
of the passband to approximately 28 dB/octave. This roll-off minimizes spurious
signals from beyond the range of interest.

The composite of the two sections, preamplifier and postamplifier, is shown
in Figure 15. This composite band shaping gives us the required characteris-
tics for operation out to a range of approximately 30 m.
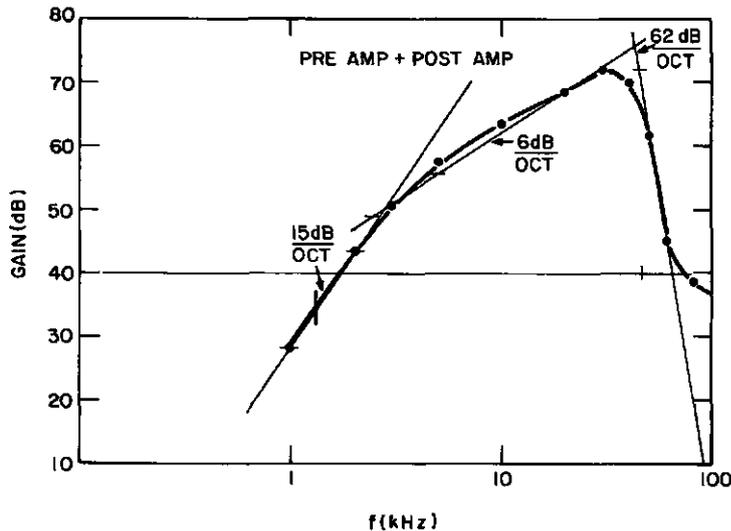
FIGURE 15. COMPOSITE OF PREAMPLIFIER AND POSTAMPLIFIER.

B. DUAL-MODE X-BAND RADAR

1. Block Diagram

As part of this program, the operation of a cooperative radar was to be investigated and compared to the noncooperative radar. Cooperative means targets are identified by a special tag that affects the reflected RF energy in a unique way. The original cooperative radar system [8] demonstrated by RCA in 1973 used frequency doubling in the tag to differentiate the target return from regular backscattering clutter. In a more recent version of the cooperative principle [9], the tag provides phase modulation of the reflected signal.

Two of the major advantages of the cooperative system are the practical elimination of false alarms (only targets provided with a tag are being recognized by the radar) and an accurate, nonambiguous location capability of the target (the tag provides a clean single point of reflection). These characteristics appeared to be especially desirable for the development effort on the headway-control algorithm. Using a cooperative radar at least in the initial development phases has the advantage of eliminating a larger number of possible problem areas and permitting concentration on the actual algorithm development. In this way, the cooperative system would be exposed to a large variety of traffic conditions and its behavior could be conveniently evaluated and optimized. We, therefore, proceeded to modify the existing X-band monostatic radar for cooperative operation using the phase modulated tag principle. A second, higher frequency IF channel was added to the X-band radar to handle the modulated signal. The original baseband response remained unaltered to permit noncooperative operation also. A switch selects the desired mode.

With the cooperative system, alarms are only triggered by 'tagged' targets, so that false alarms due to road signs, bridges, guard rails, or generally any reflecting object in the radar beam are eliminated. Thus the useful warning range can be extended. Also since the radar cross section of the tag is constant, there is no problem with fluctuating returns and the dynamic range is

8. J. Shefer et al., "A New Kind of Radar For Collision Avoidance," SAE Automotive Engineering Congress and Exposition, Detroit, Michigan, February 26, 1974.
9. G. S. Kaplan and F. Sterzer, "Dual-Mode Automobile Collision Avoidance Radar," SAE Automotive Engineering Congress and Exposition, Detroit, Michigan, February 24-28, 1975.

reduced. A tag on a compact car will return as much signal as a tag on a truck. This feature was particularly attractive during the headway-control development. Because of the complex return from a target when a problem arose, it was not clear if the headway-control algorithm was at fault or if the signal had dropped out. With the tag this variable was eliminated. From a long-range view-point, the possibility of encoding other messages also exists. The license number of the car as well as emergency messages could be transmitted from the car via the tag [9].

Potential false-alarm situations which cannot be eliminated with the cooperative radar occur when the tagged vehicle is in the line of sight but is not a collision threat. A car in the adjacent lane rounding a curve is an often-cited example.

A block diagram of the dual-mode radar, including the tag, is shown in Figure 16. The tag consists of an antenna identical to the one used in the radar, terminated in a reflective modulator. The modulator is an inexpensive, low-drain varactor modulator which encodes a 0- to 180-degree phase sequence on the signal received from the radar. This phase-coded signal is reradiated back to the radar where it is preprocessed in the cooperative channel. The resulting baseband signal is processed further in the common processor. The modulation rate of 500 kHz was chosen so that T^2L logic could still be used. Ideally, a large separation between the modulation frequency and the highest expected baseband frequency is desired to eliminate false alarms from massive targets at far distances and to maintain signal fidelity of the modulated wave.

After the phase-coded signal is received by the radar, it is translated to IF via the homodyne mixer. The IF which is at the modulation frequency (500 kHz) is filtered through a bandpass filter. The bandwidth of the filter is twice the baseband frequency. The bandpass filter prevents the target's baseband signal from getting through the cooperative channel and removes harmonics of the modulation frequency. After filtering, the signal is amplified and envelope detected. Figure 17(a) shows the waveshape at the output of the mixer, and Figure 17(b) shows the waveshape at the output of the envelope detector. As seen from Figure 17(b), the output of the envelope detector is at twice the baseband frequency. A low-pass filter at the output of the envelope detector removes the high-frequency components and further conditions the detector output. A shaped postamplifier completes the preprocessing of the cooperative channel.

MODULATOR
TAG
PRINTED CIRCUIT ANTENNA
PRINTED CIRCUIT ANTENNA
POWER DIVIDER
ISOLATOR
VARACTOR TUNED OSCILLATOR
TRIANGULAR WAVE MODULATOR
1 kHz
.5 kHz
BALANCED MIXER
POSTAMP
PROCESSOR
SHAPED PREAMP
MODE SELECTOR SWITCH
BPF
POSTAMP
AMPLIFIER AND ENVELOPE DETECTOR
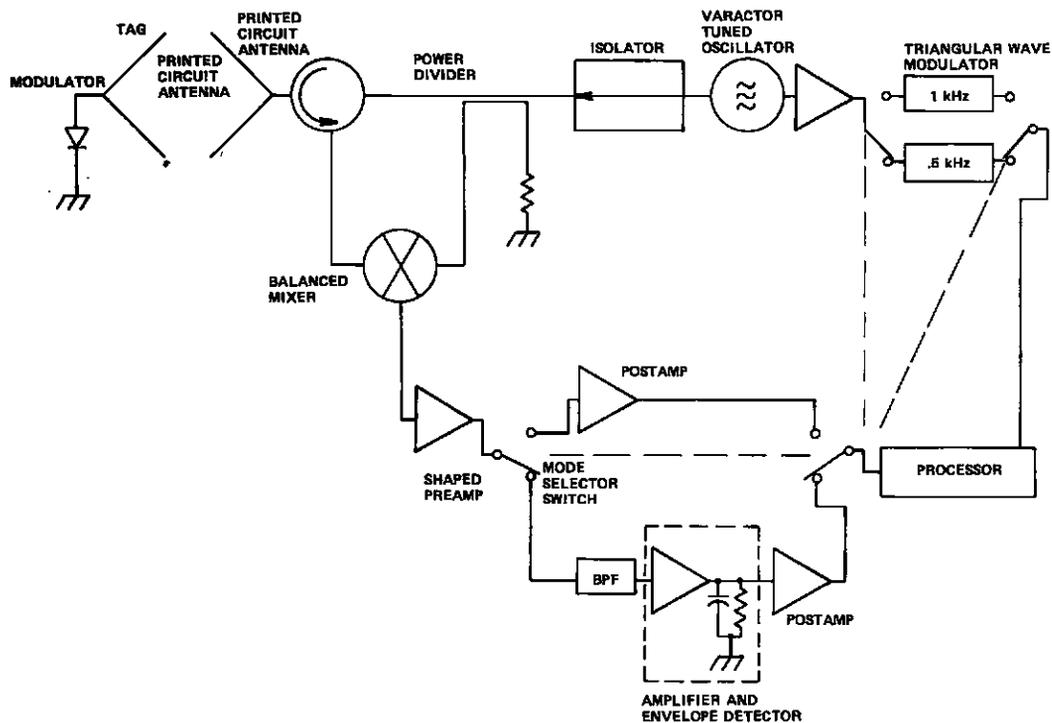
FIGURE 16.   BLOCK DIAGRAM OF DUAL-MODE RADAR.

Earlier, it was mentioned that the output of the envelope detector is at twice the baseband frequency. Since it is desirable to use the same signal processor when the cooperative mode is selected, the frequency modulation repetition rate is reduced by a factor of two to 500 Hz to keep the final baseband frequency the same. When the mode of operation is selected by the switch, the modulation rate and the flow path are selected simultaneously.

2.   System Parameter Selection

The cooperative channel of the dual-mode radar shares the RF front end with the noncooperative channel and, therefore, the modulation parameters with the exception of the repetition frequency, f_m. Because phase modulation doubles the baseband frequency (see Figure 17), f_m is reduced from 1 kHz to 500 Hz to keep the baseband constant. This permits the use of a single processor for the dual-mode radar. The frequency deviation Δf for the X-band radai remains at 25 MHz.

(a)

(b)
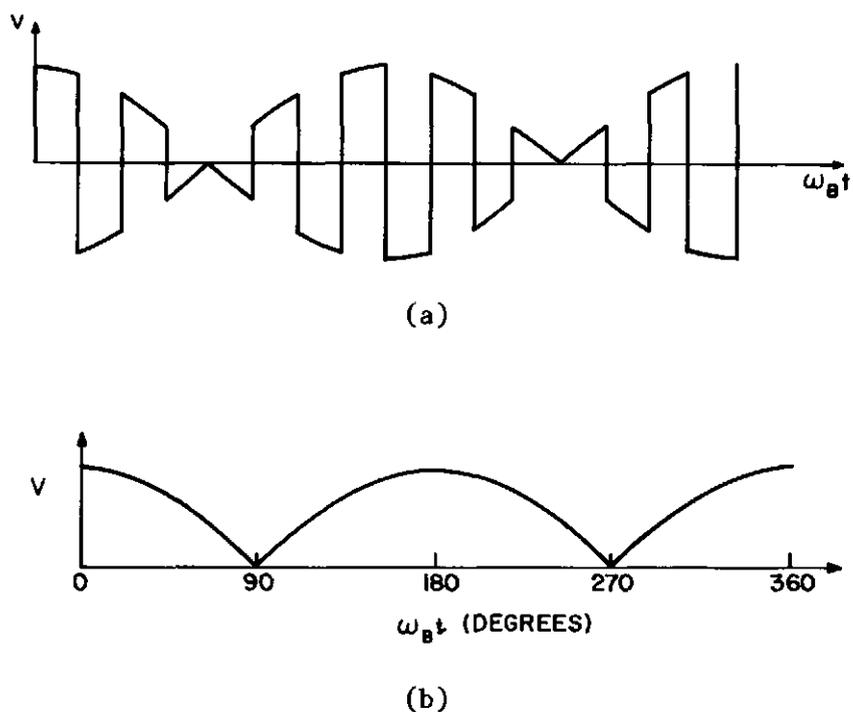
FIGURE 17. (a) TYPICAL IF VOLTAGE WAVEFORM FOR 0- to 180-DEGREE
PHASE MODULATOR. (b) OUTPUT OF ENVELOPE DETECTOR.

A key parameter of the cooperative channel is the modulation rate, f_T.
The reflected radar signal when phase modulated from 0 to 180 degrees can be
represented as

$$\cos(\Psi(t) + \pi \, S'(t)) \tag{24}$$

where $\qquad \Psi(t) = 2\pi\{f_0^/ t \pm \Delta f_0 \int_0^t g(x)dx\}$

and $\qquad S'(t) = 0$ or 1 at the modulation rate

but $\qquad \cos(\Psi(t) + \pi S'(t)) = \cos\Psi(t) \cos\pi \, S'(t)$

and $\qquad \cos\pi S'(t) = S(t)$

where $\qquad S(t) = 1$ or -1 at the modulation rate.

therefore, $\cos(\Psi(t) + \pi \, S'(t)) = S(t) \cos\Psi(t)$ $\hfill (25)$

When the modulated signal is translated to IF via a product mixer, the IF
can be written as

$$u_{IF} = S(t) \cos[\Psi(t+\tau) - \Psi(t)] \tag{26}$$

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because $\quad \Psi(t+\tau) - \Psi(t) = \dot{\Psi}\tau$

the IF response, u_{IF}, becomes

$$u_{IF} = S(t) \cos\dot{\Psi}\tau \qquad (27)$$

When the modulation rate f_T is much greater than the range frequency, $\dot{\Psi}\tau$, equation (27) is the equation of an amplitude-modulated wave. That is, the square wave of amplitude 1 and -1 is amplitude modulated by the slowly varying baseband function $\cos\dot{\Psi}\tau$. Another point of view is that the cosine function is sampled by the square wave and must be at least twice the frequency of the cosine wave. For a range frequency, $\ddot{\Psi}\tau$ per meter of 333 Hz/m corresponding to $\Delta f = 25$ MHz and $f_m = 500$ Hz, the range frequency, f_r, at 100 m = 33.34 kHz. A tag modulation frequency of 500 kHz is 15 times larger than the maximum range frequency and thus is adequate.

In order to remove the baseband envelope, $\cos\dot{\Psi}\tau$, from the high-frequency carrier, $S(t)$, we make use of the fact that $S(t)$ is periodic at the modulation rate, f_T, and can be represented as a Fourier series. Therefore, u_{IF} can be written as

$$u_{IF} = \cos \dot{\Psi}\tau \sum_{K=0}^{\infty} A_K \cos[2\pi(2K+1) f_T t - \phi_K] \qquad (28)$$

$$u_{IF} = \frac{1}{2} \sum_{K=0}^{\infty} A_K \cos[2\pi(2K+1) f_T t + \dot{\Psi}\tau - \phi_K] + \frac{1}{2} \sum_{K=0}^{\infty} A_K$$

$$\cos[2\pi(2K+1) f_T t - \dot{\Psi}\tau - \phi_K] \qquad (29)$$

where $\quad A_K = \dfrac{4}{(2K+1)\pi} \qquad (30)$

From equation (29) we see that each Fourier component is DSB modulated by $\cos\dot{\Psi}\tau$. The bandwidth around each line of the spectrum is $\pm \dfrac{\ddot{\Psi}\tau}{2\pi}$. To prevent spectral overlap

$$f_T > \frac{\ddot{\Psi}\tau}{2\pi} \qquad (31)$$

Equation (31) is less restrictive than the condition derived earlier from sampling considerations. When u_{IF} is passed through a bandpass filter centered at f_T (500 kHz), the result is a DSB-modulated signal centered at 500 kHz.

The bandwidth of the filter must be wide enough to accommodate the highest frequency of $\dot{\Psi}\tau$ or 70 kHz, and selective enough to remove the baseband response at the third harmonic. A three-section Butterworth filter, with a 3-dB bandwidth of 180 kHz was found to be adequate.

After filtering, an envelope detector is required to strip the baseband signal from the carrier. To improve the detector efficiency, the signal is amplified before detection. The signal-to-noise ratio of a linear detector is better than the signal-to-noise ratio of a square law detector in the region of low signal-to-noise [4]. Figure 17(b) shows a sketch of the signal after envelope detection. Because of the 0- to 180-degree modulation, the waveshape corresponds to a full wave rectified sine wave.

To eliminate the harmonics associated with a full wave rectified sine wave, a low pass filter follows the detector. Since the second harmonic of the rectified sine wave is 14 dB below the fundamental [10], a single R-C filter was used. A shaped amplifier provides the final signal conditioning before range and range-rate are derived in the common dual-mode processing circuitry. The shaping is similar to that used for the baseband amplifier of the noncooperative channel, the basic difference being that the bandwidth is increased to accommodate the anticipated range of up to 100 m.

3. Coverage Pattern Measurements

Coverage pattern measurements similar to those described in subsection III.A.5 above were made for both channels of the dual-mode radar. The tagged channel can be seen in Figure 18 and the baseband channel in Figure 19. The targets consisted of an electronic tag, mounted at license plate height (0.385 m), as shown in Figure 20, and a 10-dB corner reflector mounted at the radar height for baseband tests. A photograph of the radar mounted on an RCA vehicle is shown in Figure 21. The height of the target affects the position of the multipath nulls. For example, using equation (1), the first multipath null for the tagged channel should occur at 18.4 m, whereas the baseband channel null should occur at 32.6 m. This is in good agreement with the measured results shown in Figures 18 and 19.

10. A. G. Kandoian et al., Reference Data for Radio Engineers, International Telephone & Telegraph Corp., New York, 1964.
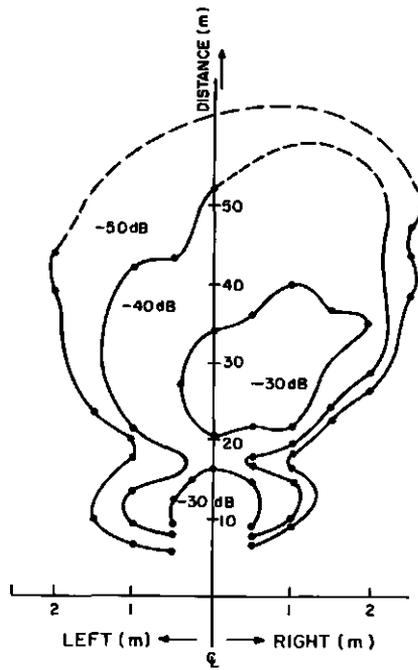
FIGURE 18.   COOPERATIVE CHANNEL OF DUAL-MODE X-BAND RADAR.
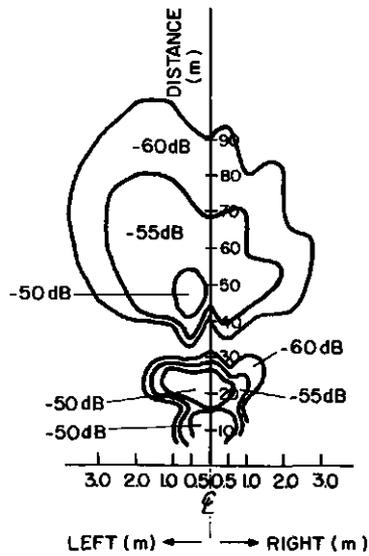
FIGURE 19.   BASEBAND CHANNEL OF DUAL-MODE X-BAND RADAR.
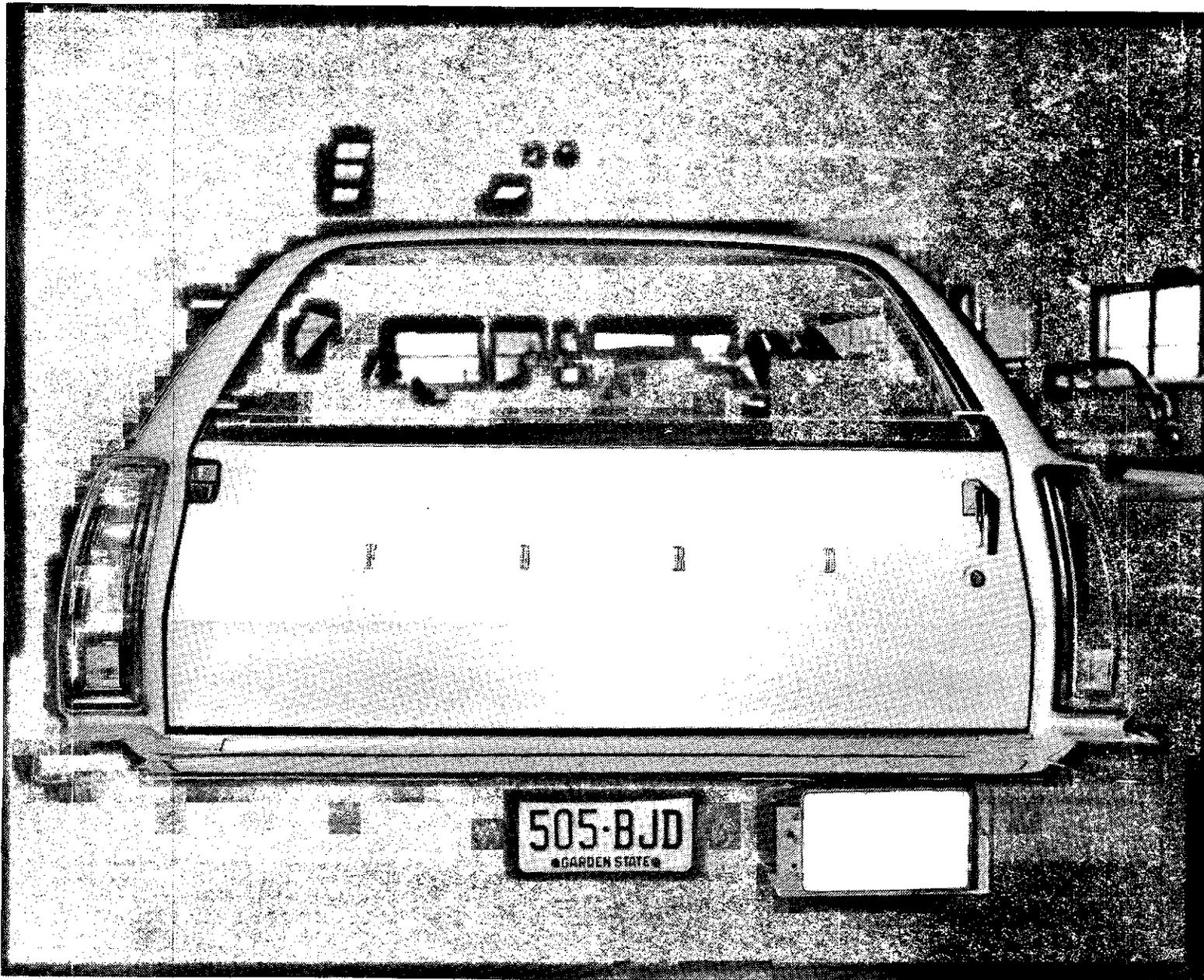
FIGURE 20. LOCATION OF MICROWAVE TAG MOUNTED ON VEHICLE.

FIGURE 21. X-BAND DUAL-MODE RADAR MOUNTED ON VEHICLE.

Although a complete one-to-one comparison between Figures 18 and 19 cannot be made due to the differences in amplifier gains and bandwidths between channels of the dual-mode radar (the tagged channel output was taken at the envelope detector and the preamplifier output was used for the baseband channel), it can be seen that the cooperative mode has no severe signal dropout and has a narrower coverage pattern out to 50 m. A theoretical treatment of coverage pattern is given in Appendix A which also indicates a narrower pattern for the tagged channel.

C. RADOME FOR RSV INSTALLATION

To evaluate the various radome structures, we constructed a fixture that supports the entire nose of the RSV, as well as different radome structures under test. This mount was attached to a pedestal in the microwave anechoic chamber located at RCA's facility in Moorestown, NJ. The chamber, mount, and nose structure are illustrated in Figure 22. The pedestal on which the structure is mounted can be rotated 360° for azimuth measurements. At the top of the pedestal, the head to which the fixture is attached can also be tilted 90° for elevation measurements. The antenna is at the center of rotation so that it remains bore-sighted with the transmitting antenna located at the far end of the chamber.

Antenna patterns were originally taken on an antenna without a radome to be used as a bench mark. These patterns were shown in Figures 8 and 9. At first, an attempt was made to beam directly through the existing structure; that is, the RIM (Reaction Injection Molded outer skin of the RSV) and an ABS plastic air scoop. Due to the different dielectric properties of the two materials directly in the radar beam, the side lobes are degraded as shown in Figures 23 and 24. This is particularly severe in elevation. As can be seen from the illustrations, one of the side lobes comes within 6 dB of the main lobe. This could result in false targets from overhead structures such as bridges and signs. There is also an additional 5-dB insertion loss due to the lossiness of the material. Since the radome loss affects both transmit and receive, a total sensitivity reduction of 10 dB results. We, therefore, decided to investigate the development and fabrication of a separate radome structure.
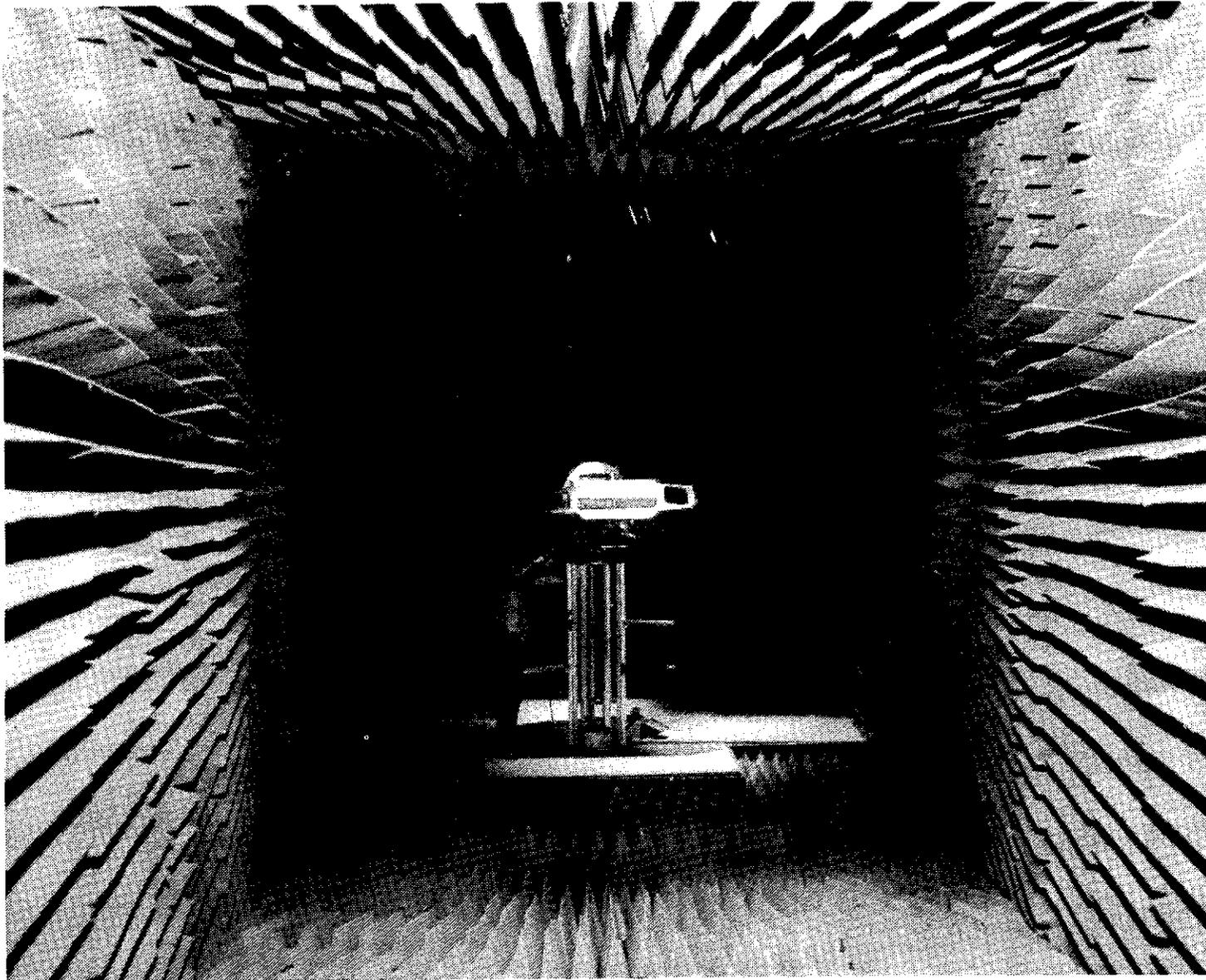
FIGURE 22.   ANECHOIC CHAMBER FOR ANTENNA MEASUREMENTS.
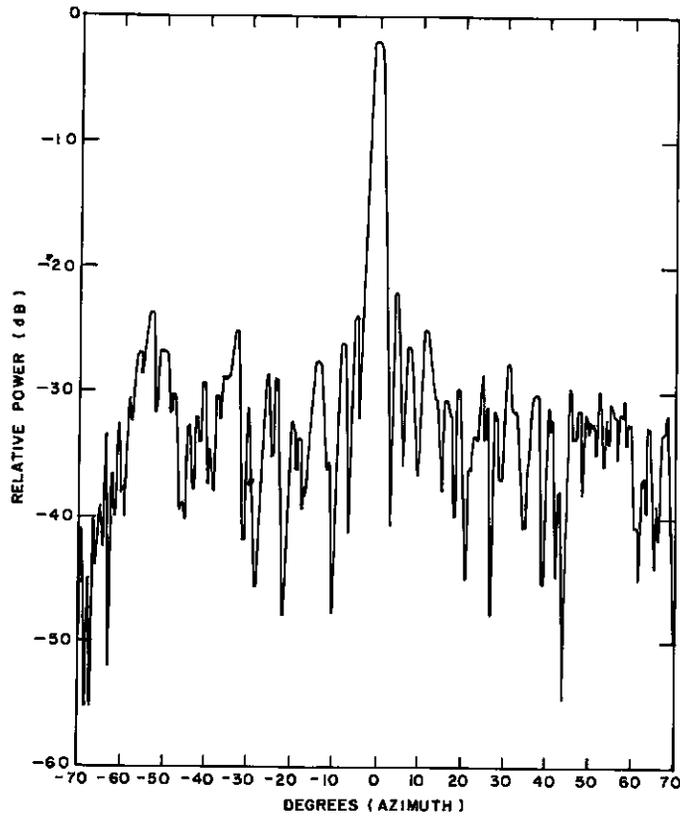
FIGURE 23.   AZIMUTH ANTENNA PATTERN (NOSE AND AIR SCOOP).
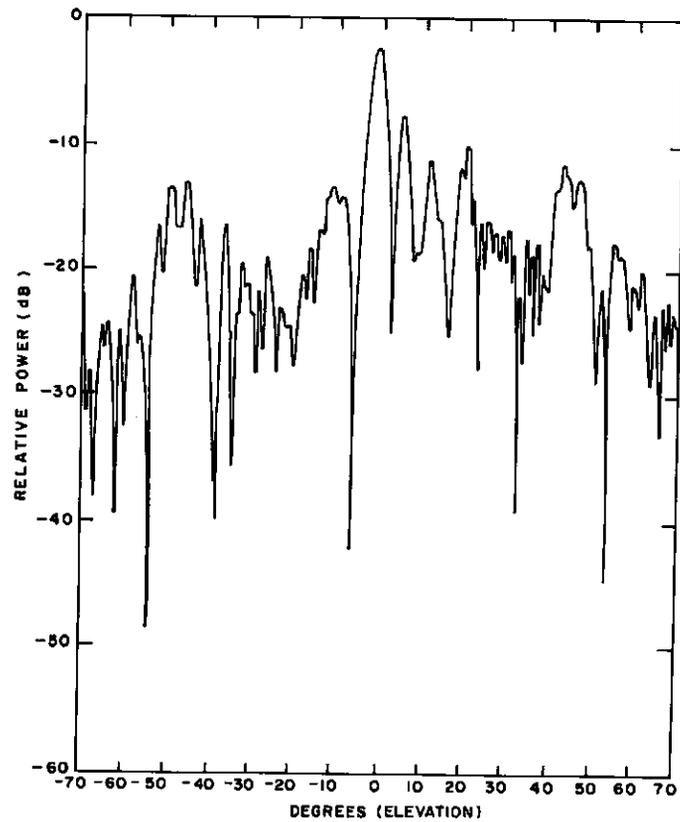
FIGURE 24.   ELEVATION ANTENNA PATTERN (NOSE AND AIR SCOOP).

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The radome has to conform to several requirements, such as:

(1) It must have the same shape as the body of the vehicle;

(2) It must have suitable electrical properties (low dielectric constant and low loss);

(3) It must be environmentally sound (waterproof and fuel resistant).

Several materials were considered, as shown in Table 2, for this purpose. Early in the program, we approached Emerson & Cuming* to cast a block of low dielectric, low loss, closed cell foam in a mold provided by RCA. After considerable delay, they declined to quote on small production numbers, and they recommended the use of Eccofoam FPH foam-in-place. We were, however, not equipped for handling a structure of this size and complexity by ourselves.

TABLE 2. CHARACTERISTICS OF MATERIALS CONSIDERED FOR RADOME CONSTRUCTION

Material	Constant	Dielectric Loss Factor	Comment
Hardman Epoweld 3672	~3	0.021	Hard/brittle
Foamed Polystyrene	1.03	0.0001	Light/porous
Polyethylene*	2.26	0.0031	Flexible/nonporous
Eccofoam FPH	1.04/1.25	0.001/0.005	Hard to handle
Eccoseal High-Q	2.55	<0.0004	Solvent attacks substrate
Eccocoat FP3	4.40	0.006	Too fluid/absorbed by substrate

*The polyethylene used is expanded approximately 4:1, which reduces the dielectric constant and dissipation factor.

As the next best alternate to a solid block, we chose a laminated structure from standard blocks of foamed polystyrene, shaped to conform to the body contour, and sealed. The sealer is required to prevent moisture absorption into the foamed polystyrene which would deteriorate its electrical properties. Several sealers, listed in Table 2, were tested. The Eccoseal High-Q could not be used because its solvent dissolved the foamed polystyrene substrate.

*Emerson & Cuming, Inc., Canton, MA.

The Eccocoat FP3 was better, but still too thin; it entered the cell structure of the foamed polystyrene, forming an irregular inner surface. The most promising coating was Hardman Epoweld 3672. A mock radome was constructed and tested. Electrically it was satisfactory, but, physically, the epoxy coating was too hard and shattered on minor impact.

The foamed polystyrene seemed the best building block because of its extremely low dielectric constant and dissipation factor. It still, however, required a suitable coating. A sheath of closed cell, cross linked, expanded polyethylene was finally selected as cover. This material does not absorb moisture and is highly resistant to automotive solvents as well as having acceptable electrical properties. A full scale radome was constructed, as shown in Figure 25.

The blocks of foamed polystyrene were shaped to conform to the contour of the RSV. The end and center supports are fastened to the antenna frame. The expanded polyethylene sheet is stretched over the foamed polystyrene and secured to the three solid polystyrene plates with plastic molding and nylon screws. The top and bottom edges are secured with aluminum battens. The natural gasket effect of the expanded polyethylene seals the edges while all other openings are sealed with RTV.
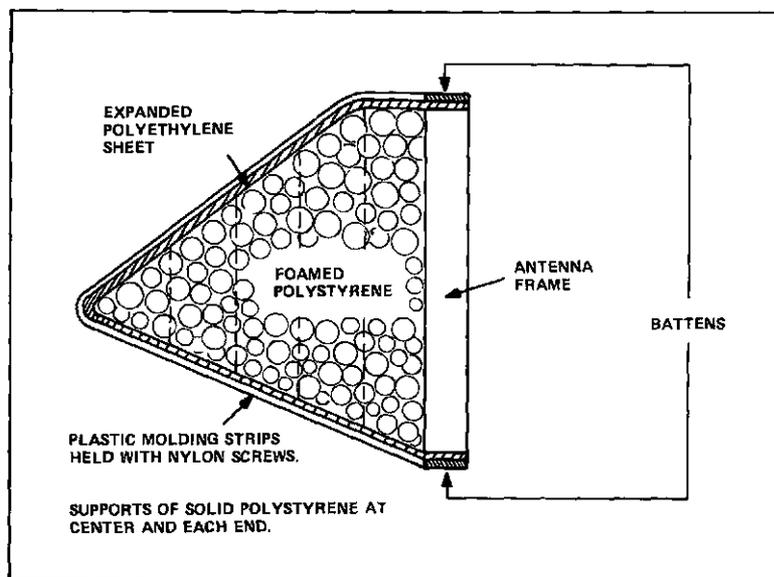
FIGURE 25. RADOME CONSTRUCTION.

The final structure was tested in the anechoic chamber with satisfactory results. Figures 26 and 27 show the resulting azimuth and elevation pattern. The side lobes in the worst case, elevation, are only 11 dB below the main lobe. This, however, occurs at an angle of 40° which is far removed from the general range of interest. The side lobes closer-in are at least 16 dB below the main lobe. There is also a loss of approximately 2 dB over an antenna without radome, but this is within acceptable limits.
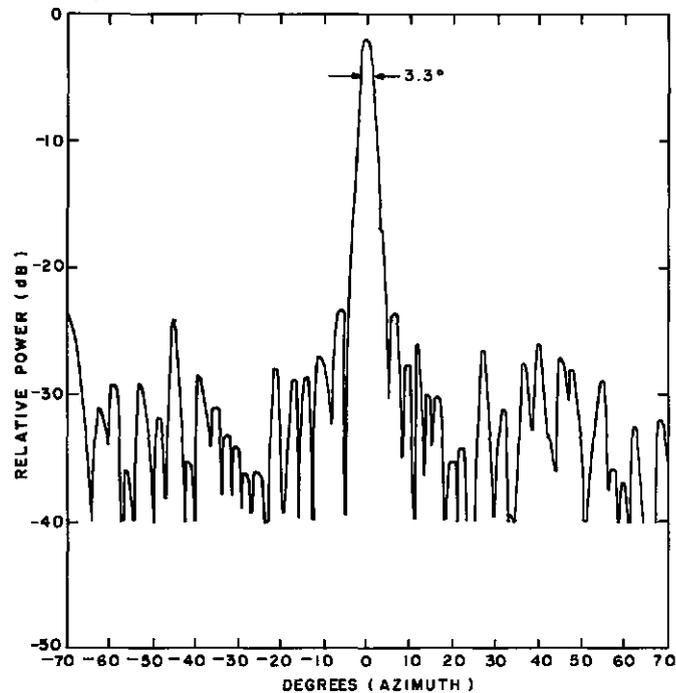
FIGURE 26. AZIMUTH ANTENNA PATTERN WITH RADOME.

The final configuration of the antenna and radome forms a separate unit, as shown in Figure 28, which fits into a cutout in the nose section of the RSV. A photograph of the RSV with the radar and radome inserted but before finishing off the joining areas is shown in Figure 29.
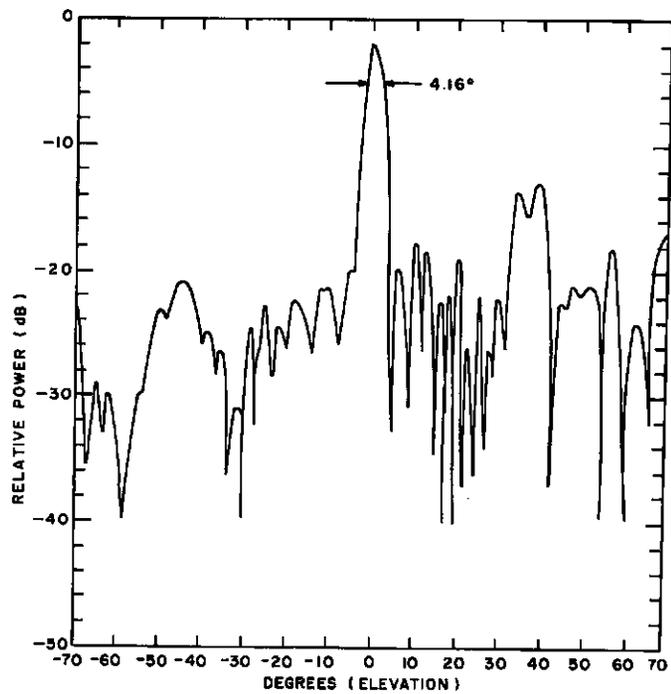
FIGURE 27.   ELEVATION ANTENNA PATTERN WITH RADOME.
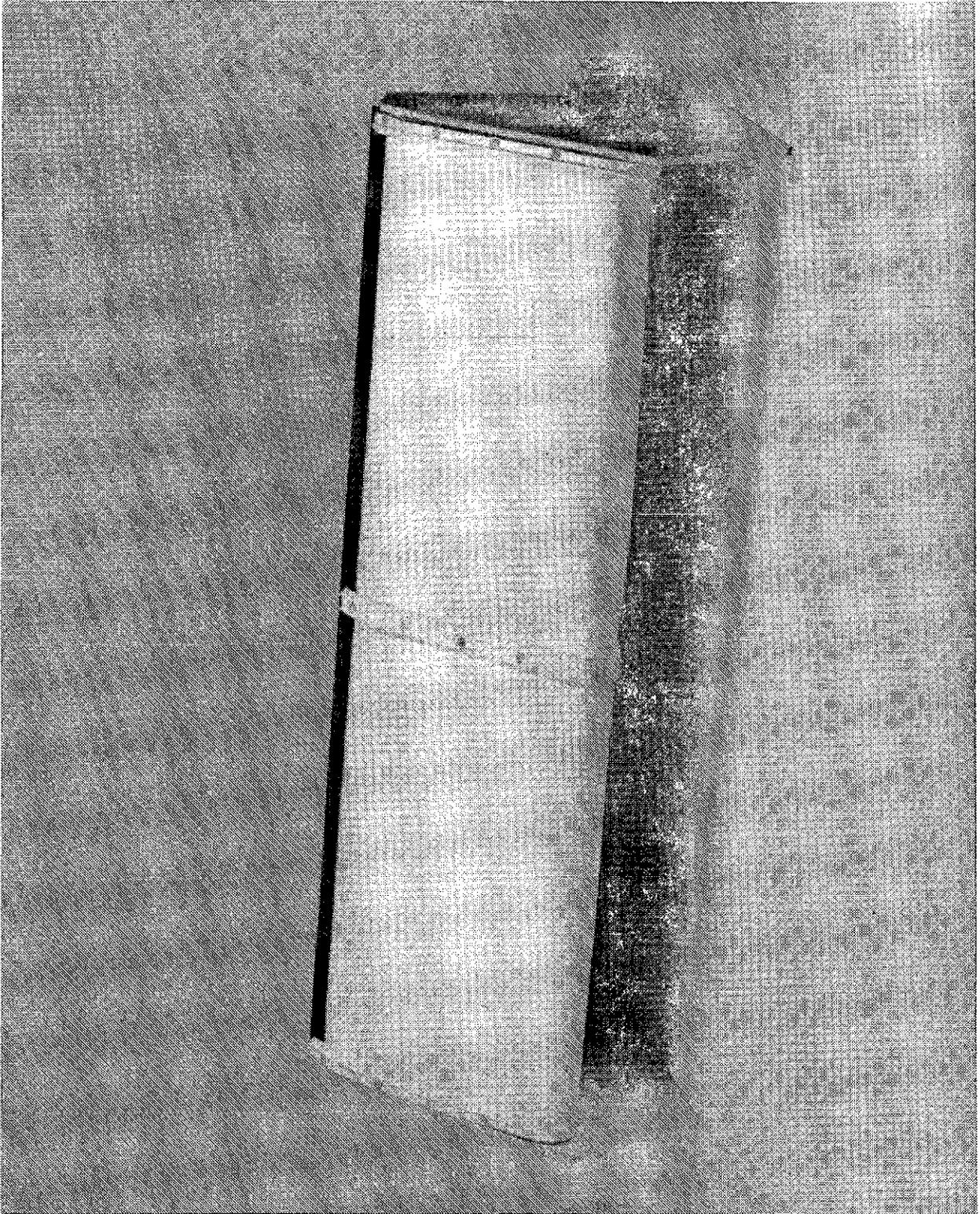
FIGURE 28. BISTATIC Ku-BAND RADAR WITH RADOME.
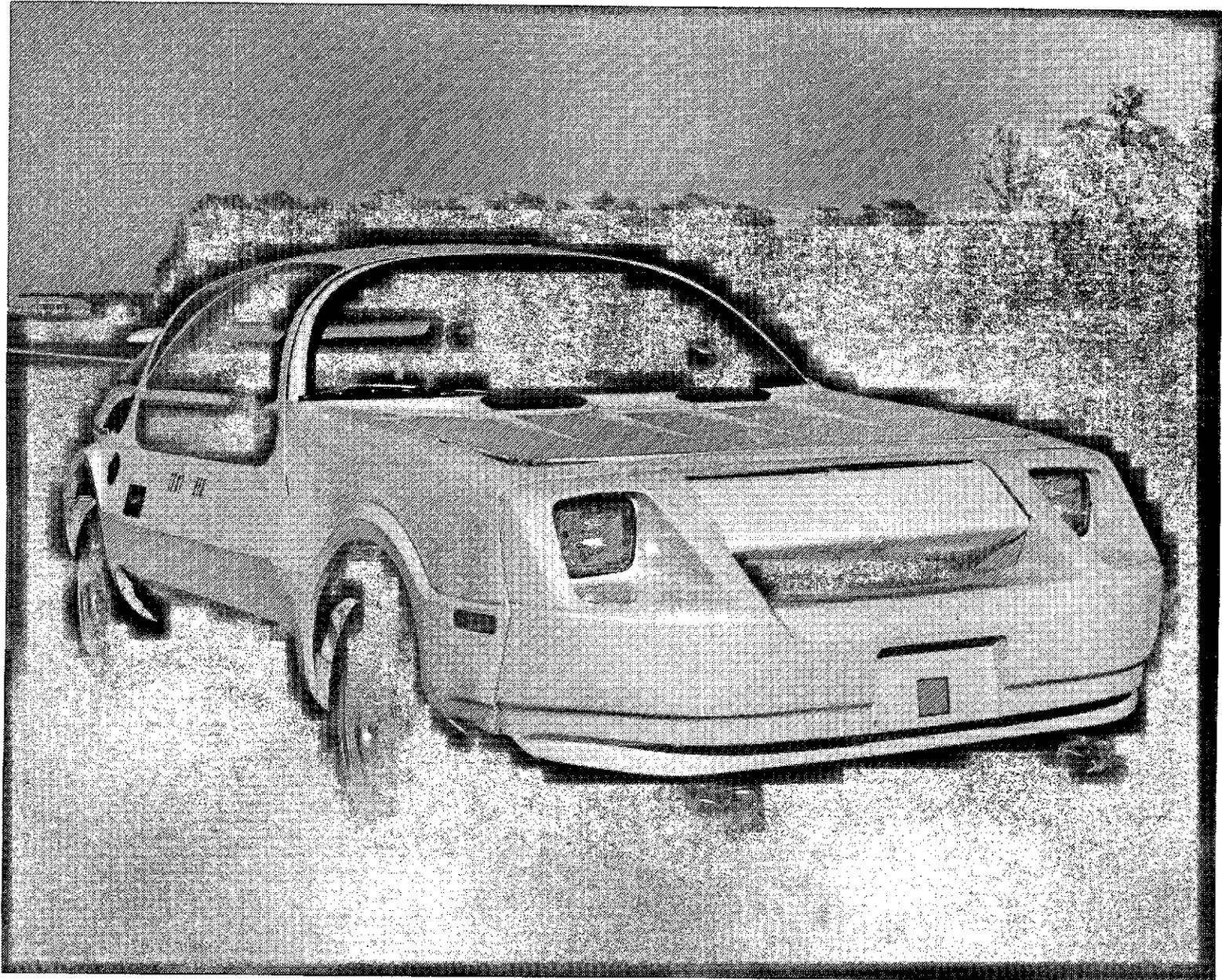
FIGURE 29. RSV WITH RADAR AND RADOME IN PLACE.

SECTION IV

PROCESSOR HARDWARE

A. RADAR CARDS FOR CMS AND HEADWAY CONTROL

1. Introduction

The radar card is hardware that converts the analog signal input from the radar system to useable data for the microprocessor. During Phase II and Phase III of the Minicars program, three versions of radar interface cards were constructed. Each of the three cards during the course of their respective programs had minor modifications, as the need arose, to improve performance.

The first radar card, used in Phase II, measured an accumulated count over a predetermined number of periods selected by software within the measurement interval. The square wave that was used to generate the triangular wave for the TEO and blanking at the radar card originated at the radar system. The blanking of the turnaround transient started at the beginning of each turn-around transient for a set time period (hardware-determined). The weakness of this radar card was that it needed eight consecutive modulation cycles with the same number of periods within the measurement interval in order to obtain one processed data output of range and range-rate.

The second radar interface card (Phase III) measured each period individ-ually within the measurement interval. The greater the range from the target to the radar, the greater the number of periods within the measurement interval and, therefore, the greater the number of periods individually measured. The second card was designed to not only measure each period within the measurement interval, but also the periods up to the time of a dropout that may occur. This type of adaptive processing improved the range accuracy and reduced the number of rejected readings. The blanking arrangement for the second radar card was the same as the first radar card, except that the square wave was now derived from the microprocessor by dividing down the 2-MHz clock frequency. This card was used in the headway-control processor to provide range data with high accuracy but slow update rate.

The third card tailored for CMS operation had to provide range and range-rate in very short time intervals. Range-rate was derived directly from the doppler information. To improve the accuracy of the range-rate information, a symmetrical blanking pulse had to be used that overlapped the turnaround

points of the triangular wave equally on both sides. The hardware of the card was simplified to accumulate a count through the measurement interval and up to any dropouts within the measurement intervals if they occurred.

The Phase III radar cards achieved increased responsiveness to all targets presented to the radar system. This increased system sensitivity placed the burden of false-alarm rejection in the case of the CMS system heavily on software.

2. Phase II Radar Card

A block diagram of the Phase II CMS radar card is shown in Figure 30. The radar provides a 1-kHz input and a sinusoidal signal input to the radar interface, f_B; this is shown in Figure 31. The transitions of the 1-kHz square wave correspond to the turnaround points of the triangular modulation waveform. The positive transition of the 1-kHz square wave is the beginning of the positive-going slope of the triangular waveform. The negative-going transition of the square wave corresponds to the beginning of the negative slope of the triangular wave. The signal input into the interface contains both transients occurring at the turnaround points of the triangular waveform and sinusoidal waveforms generated on the upswing and the downswing of the modulation containing range and range-rate information. The greater the range, the larger the number of periods between the transients available for measurement will be. The amplitude of the input signal is a function of the multipath nulls, range, and type of target.

The 1-kHz input signal is applied to a network that generates a 20-μs pulse at each transition of the incoming square wave. The pulses are called the "reset" pulses. The reset pulses, in turn, are applied to a variable-period one-shot multivibrator which generates the blanking pulses. The blanking pulses occur at the transitions of the 1-kHz square wave which corresponds in time to the transient period from the turnaround.

The total signal input consisting of transient pulses and information-carrying sinusoidal waveforms is applied to the threshold circuit. The timing relationships between the triangular wave, blanking, and sinusoidal input from the radar are shown in Figure 32. The function of the threshold circuit is to shut off any input that falls below a preset value either initially or during the time of measurement between the transient pulses. If the input falls below the preset value at any time, the circuit shuts off and is reset by the reset
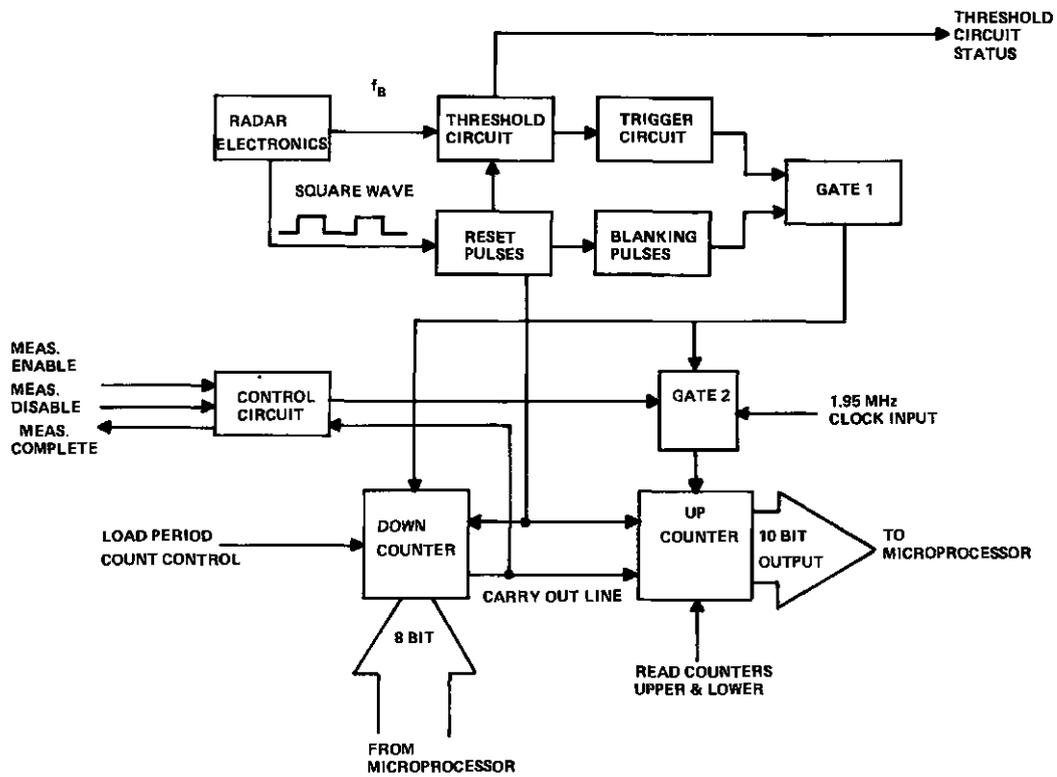
FIGURE 30.   BLOCK DIAGRAM OF PHASE II CMS CARD.
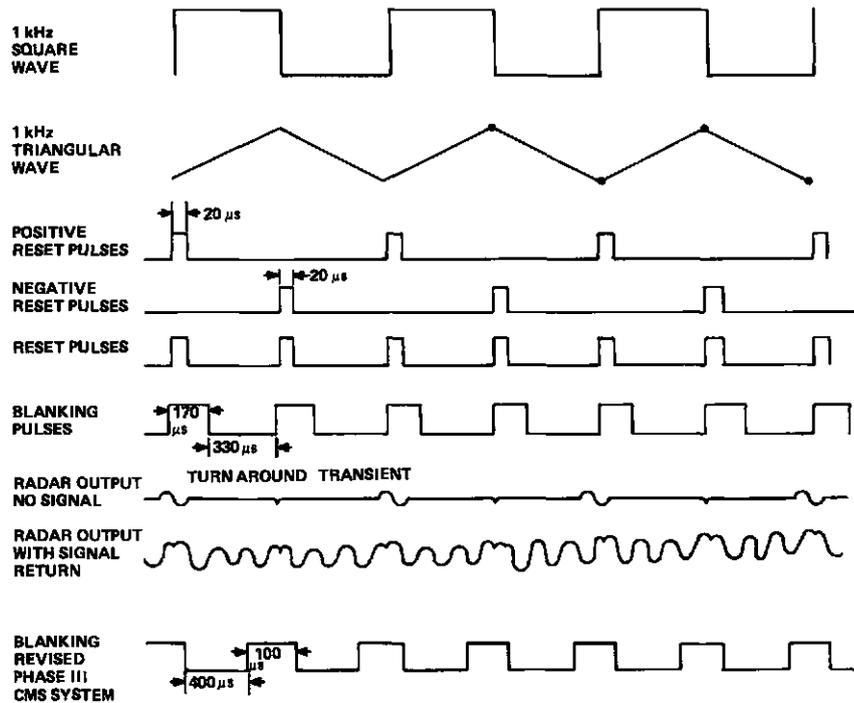
FIGURE 31.   WAVEFORMS ON RADAR INTERFACE CARD.

pulse at the beginning of the next modulation cycle. The transient pulse is
filtered out and the only pulses passing through to the counter are trigger
pulses whose spacing is a function of range.

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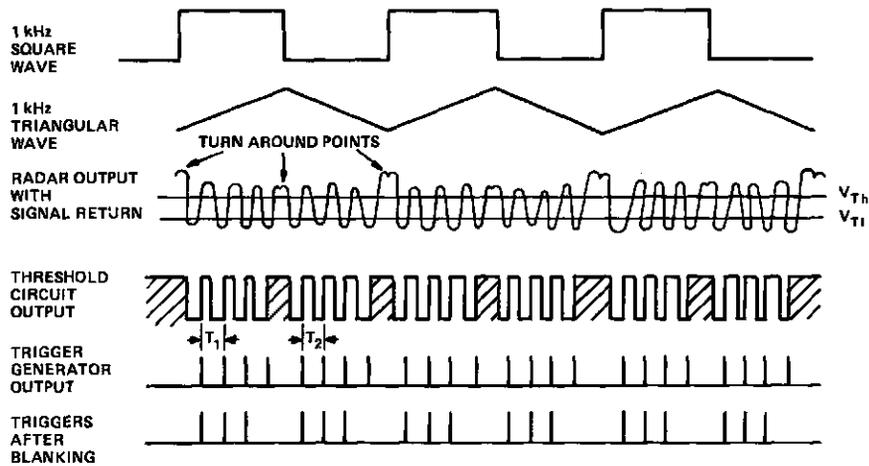
FIGURE 32. SIGNAL-PROCESSING TIME RELATIONS.

Two counters are used in the circuit, a "down" counter and an "up" counter. The down counter is loaded by the microprocessor with the number of periods that would be desirable to measure. When the down counter counts to "0," it generates a "carry out" pulse. The up counter is a high-speed counter which uses 1.95-MHz clock pulses as drivers. The counter is turned on by the first trigger pulse from the input signal and then turned off when the desired number of periods is measured. The reset pulses, which occur during the blanking time, are used to load the down counter with the number of periods to be measured and to reset the up counter to a zero count. Also available at the up counter transmission gate is information as to whether the threshold circuit shuts down during a measurement interval. The blanking pulse is also available at the up counter transmission gate to define the allowed measurement interval. The interface card runs asynchronously with the microprocessor. The control circuit allows the microprocessor to call for a measurement. A flag line is used to indicate that the measurement is complete. Another control line disables the "measurement ready" line.

One of the major problems associated with the use of this particular radar interface card was the possible loss of significant data during consecutive measurements. The Phase II CMS system measured either 1, 2, 3, 4, or 5 periods within a measurement interval. Eight full modulation cycles with the same "set" number of periods must be obtained for a successful measurement. However, during the actual radar measurement process, complex returns from the target cause dropouts during measurement intervals. The dropouts that occurred during the measurement interval would cause the system software to reject readings

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until eight consecutive full modulation cycles could be read with the same set period count. This rejection of data during dropouts in the measurement interval makes the overall system seem insensitive to a variety of target situations that should be detected.

Two other problems were associated with the Phase II CMS system. First, selecting the proper period count to be measured within a measurement interval required auto-ranging software which required additional run time for the overall software. The second problem associated with the Phase II CMS system was that at the higher ranges, it is possible to have more than five periods within the measurement interval. An inherent one count error is usually averaged by dividing by the total number of periods; if the number of periods is limited to five, the one count error has a greater effect on the accuracy of the system since one count is a large percentage of the total period count.

3. Phase III Radar Card

A new radar interface card, shown in block diagram form in Figure 33, was constructed for Phase III. A square wave to provide the triangular wave modulation for the radar is generated by dividing down the 2-MHz clock frequency of the CPU to obtain 977 Hz. The square wave is passed on to the radar system, so that the triangular wave can be generated, and to the radar interface card. The 977-Hz square wave, 1 kHz nominal, is used to trigger blanking pulses and it is also used as a system reference for the software by means of the status latch. The blanking pulse output from the blanking pulse generator goes to a gate and the system status latch. If we refer to Figure 31 we see that the square-wave level appearing at the status latch during the blanking interval indicates whether the measurement is on the upswing or downswing of the measurement interval.

The beat frequency output, f_B, of the radar system after passing through the threshold circuit becomes a 5-V pulse train which contains range and range-rate and the turnaround phase discontinuity. A trigger generator generates narrow pulses at the positive transitions of each of the pulses coming from the threshold circuit. The blanking pulse is used to filter out unwanted data for approximately 170 μs after the turnaround point.

A high-speed clock of 2 MHz from the microprocessor is used to drive a 12-bit T^2L counter. The triggers, corresponding to the positive transitions of the beat frequency, are passed to three locations in the radar interface card.

A-50
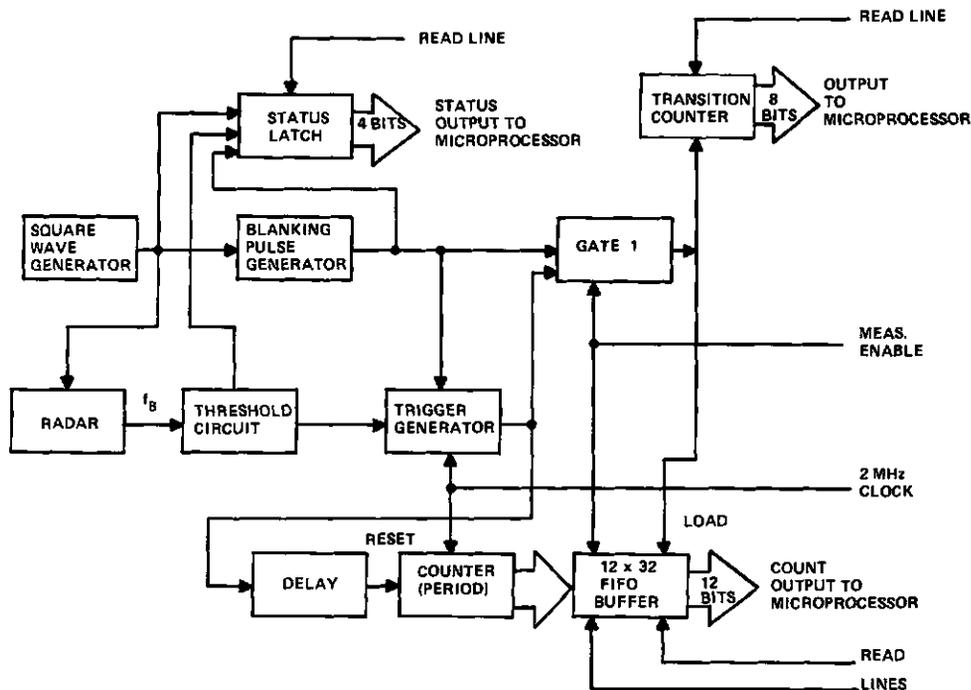
FIGURE 33. BLOCK DIAGRAM OF PHASE III CMS CARD.

When the measurement is enabled by software, the trigger output is passed
through the "gate 1" circuit to the transition counter and the buffer. In
addition, the first trigger pulse which corresponds to the first positive
transition of the beat frequency is fed through a delay to the period counter.
This trigger pulse is delayed always by two counts for the reset mode. The
reset line initializes the high-speed counter to the count of two. Before the
counter is reset, the data from the counter is read into a 12-bit wide x 32-bit
deep first-in first-out buffer (FIFO). The measurement enable strobe which
allows the measurement also resets the FIFO. The second positive transition
of the beat frequency corresponds to the first period. The count corresponding
to one period is loaded into the FIFO, and two clock periods later by virtue of
a hardware delay, the high-speed clock is reset to a count of two. The two-
count delay eliminates the one error usually associated with a high-speed clock
measuring technique.

   The number of periods in a measurement interval is stored in the FIFO. The
square wave and blanking pulse relationship indicates either an up- or downswing
of the triangular wave. A dropout that occurs during the measurement interval
is noted by reading the threshold circuit condition from the status latch.
Software can, therefore, select to accept readings up to the dropout since
individual periods are measured and average the partial set of acquired data

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in the measurement interval. The new Phase III CMS radar card can, therefore, measure up to 32 periods within a measurement interval. The card will also acquire and use the data up to a dropout in the measurement interval. This particular radar interface card was demonstrated and is used presently with the headway-control system.

4. Revised Phase III Radar Card

Early experiments had shown that the accuracy of the doppler information was not sufficient for proper CMS operation. The problem was traced to the asymmetrical blanking pulse. Since the tuning curve of the TEO in general is not perfectly linear, it is important to operate over the same tuning range of the TEO, both on the upswing of the triangular wave and on the downswing. Referring to Figures 31 and 32, we see that if the blanking starts at the turnaround point, an asymmetric tuning curve results. The beat frequency is read 170 μs after the beginning of the positive slope of the triangular wave up to the peak or turnaround point. Then, 170 μs later, the beat frequency is read back from the peak to the turnaround point or valley of the triangular wave. A nonlinearity of the TEO tuning curve under the described conditions causes only minor range measurement problems because the range readings average. However, an offset in doppler frequency will occur because of the nonlinearities creating a difference in frequencies of the periods on the upswing and down-swing.

The revised Phase III radar interface card, which overcomes this diffi-culty, is shown in Figure 34. Once again, the square-wave generator divides down the 2-MHz microprocessor clock to obtain the 977-Hz square wave. A status latch is used to monitor the level of the square wave with respect to a blanking pulse which originates at the turnaround point. The blanking pulse generator also generates a blanking pulse that overlaps the turnaround points 50 μs on each side, as shown in Figure 31. The symmetrical blanking pulse causes the same part of the TEO tuning curve to be swept through on the upswing and downswing of the triangular wave. The status latch monitors the threshold condition line and a data out ready line from the FIFO. The thresh-old condition line goes high when the data drops below V_{Th} (Figure 32) anytime during the measurement interval. The data out ready line indicates the FIFO has at least one set of useful data.
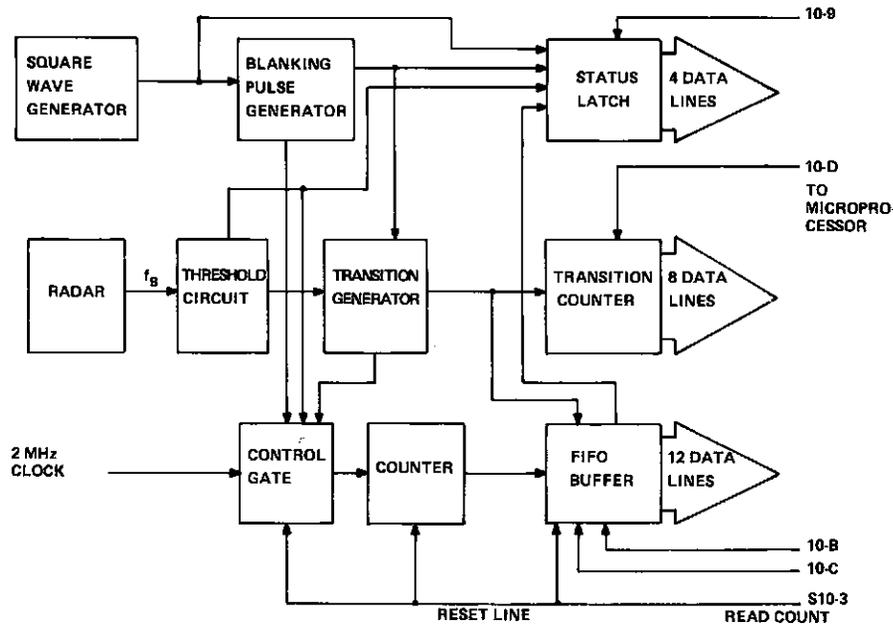
FIGURE 34. REVISED PHASE III CMS CARD.

In order to simplify the hardware, it was decided to accumulate a count
across the entire measurement interval and divide out the inherent one count
error by averaging the large number of periods. The output of the threshold
circuit once again is used to generate narrow trigger pulses within the tran-
sition generator. The positive transitions of the beat frequency are counted
by a transition counter. The first transition pulse or trigger after blanking
turns on the high-speed counter. Each successive transition loads the accumu-
lated count to that respective time in the FIFO. If a dropout occurs during
the measurement interval, the count accumulated up to that point is used for
the signal processing. The control gate that allows the counter to be ini-
tially started is disabled by the blanking pulse or the threshold circuit.
A reset line is used to zero the counter initially and to enable the control
gate. The data from the status lines, 4 bits, a nibble, is read by a IO-9
pulse. The 12-bit-wide FIFO is read twice. An 10-B pulse is used to read
the lower eight bits. An IO-C pulse reads the upper four bits (nibble).
The revised Phase III card is now used in the CMS algorithm.

5. Threshold Circuit

Figure 35 shows two versions of the threshold circuit used with the radar
interface cards of the CMS and headway-control system. The threshold circuits

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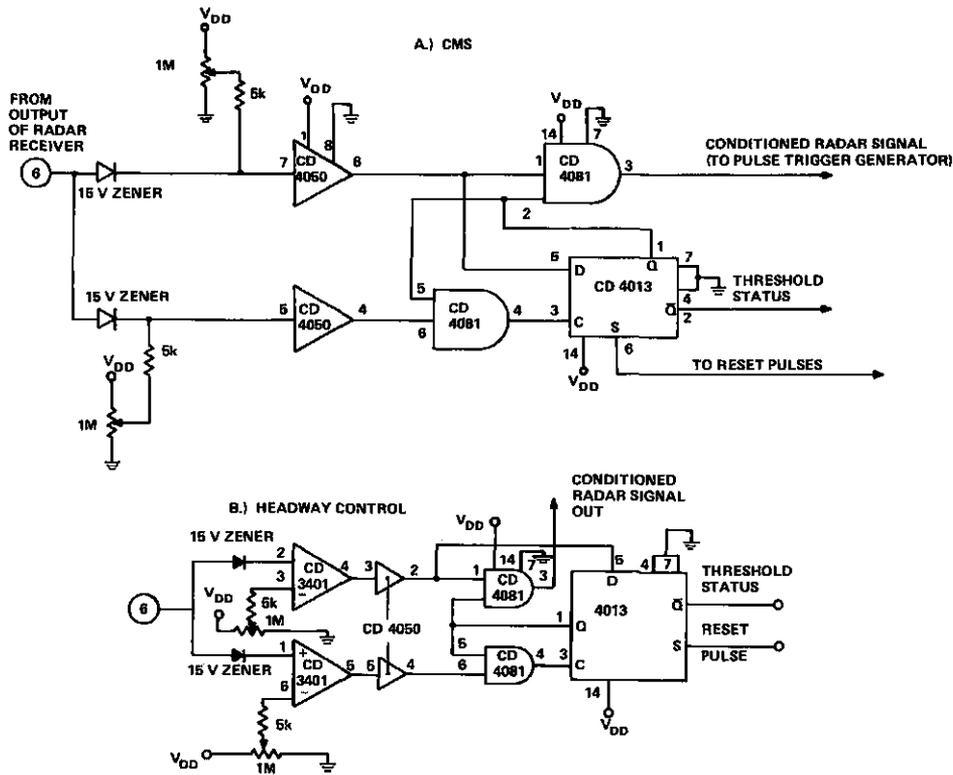
FIGURE 35. THRESHOLD DETECTION CIRCUITS.

differ from each other in the manner in which the analog input, f_B, is converted to a digital pulse train. The threshold circuit used with the CMS biases the inputs of two buffers to provide a low and high threshold value that must be exceeded for the circuit to perform properly. The threshold circuit used with the headway-control system uses two comparators instead of two digital buffers at the input. After passing through the buffers or comparators, both threshold circuits are the same. The two different input circuits were tried to determine if there were any operational differences between the standard comparator using an OP-AMP and reference voltage, and the voltage-biased digital buffer. At this point, no conclusive data indicates that one comparator circuit is better than the other.

Basically, the threshold circuit consists of two buffers or comparators, two AND gates, and a flip-flop. The input signal is split into two paths to their respective buffers or comparators. A diode in the series leg of each of the paths limits the bipolar signal to a positive-going signal only. (A negative-going signal greater than -0.75 V would cause the buffer to clamp a large signal at this level and create problems in setting threshold levels.)

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The threshold level of each buffer with V_{dd} = 5 V is 2.5 V; therefore, a DC level is applied to each buffer or comparator to provide an upper- and lower-threshold level. The lower-threshold level setting has a significant voltage applied to the input so that a small signal of only a few tenths of a volt generates an output from the buffer or comparator. The upper-threshold level provides a low-level bias at the input of the second buffer or comparator and a large signal of the order of 2 V is required to generate an output from this stage. The circuit uses an AND gate to control the signal from the threshold circuit into the rest of the doubler circuit. The other AND gate controls the clocking of the flip-flop used to turn the circuit on or off.

Initially, the CD4013 flip-flop is set by the reset pulse of the radar interface. A high level appears at both AND gates, enabling both circuits. The low-level signal threshold generates a pulse out of the buffer or comparator which is used to clock the flip-flop. If the high-level threshold allows a pulse output from the buffer or comparator, then a pulse will be appearing at the "D" or data input to the flip-flop. Since the clock input is delayed by propagation time through the AND gate, the high-logic level at the "D" input corresponding to the signal will be present when the CD4013 is clocked. Clocking it with a high level keeps Q high and maintains the enabled state of both AND gates; therefore, the threshold circuit is "on."

If at any time the upper-level threshold is not exceeded while the lower-level threshold is generating a pulse from the buffer or comparator, the net result is a clock signal to the CD4013 which sees a zero at the "D" input, and, therefore, Q goes low, shutting off both AND gates. No signal is allowed to pass to the doubler, and additional clock pulses are not allowed to pass to the flip-flop. The Q output of the flip-flop goes high, signaling the microprocessor that the threshold circuit is shut down. The reset pulses of the radar interface are then needed to turn the threshold circuit on again.

B. CPU AND MEMORY

1. Introduction

During the initial stages of hardware and software development a flexible microcomputer system for prototyping purposes is required. The RCA COSMAC development system (CDS) has the necessary memory size required for a prototype system in the form of RAM space so that software can be easily loaded

from another storage area or host computer. To aid in this storage and re-writing function, some type of ROM chip continuing a "utility" routine is also included. The utility software enters and retrieves data from the RAM space and, if necessary, can be used to modify the data and then restore the data to any selected location or address.

During Phase II we used exclusively the COSMAC development system for prototyping both hardware and software. The CDS consisted of a card nest, control panel, and a basic set of plug-in modules. The card nest provided user space for the development of interface hardware between external hard-ware and the control processing unit (CPU) system. A large variety of inter-face cards was developed for the radar, display, and various sensors on the RSV. Two major problems were, however, noted for the CDS. The plug-in mod-ules that formed the basic microcomputer system were interconnected at the backplane by a printed circuit (PC) structure that connected each card of the module to other modules within the card rack. The continuous insertion and removal of cards during the development period and vibrations from the test vehicle caused the printed circuit connections eventually to deteriorate and some open- and short-circuit conditions on the backplane of the CDS oc-curred. A second problem was the difficulty in using the system to debug the hardware. A hardware failure in an interface card usually caused one of the plug-in modules of the microcomputer system to fail.

During Phase III, therefore, we switched to the newly released RCA evalu-ation board, single PC card (24 x 36 cm) that contains all of the necessary components for prototyping. The evaluation board was finally replaced by an-other standard PC board that fit within the normal card cage to form a compact single-enclosure computing system.

2. Phase III Evaluation-Board System

The evaluation board uses an RCA CDP 1802 one-chip microprocessor with a 2-MHz crystal to provide the system clock frequency. Control chips are pro-vided for resetting and starting either a previously loaded program in RAM space or the utility routine located on a ROM chip on the card. Additional chips are provided for addressing the 4K of RAM space on the board and for I/O decoding. Three transistors on the card provide a RS-232 interface which allows communication between the evaluation board, an "execuport" terminal, and the host computer system. A set of LEDs on the card provides a visual

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indication of the data address status lines of the microcomputer system. The evaluation board with RAM and ROM operates from a single 5-V supply.

During Phase II, a large number of interface cards had been developed for the radar, display, and sensors of the RSV, using the COSMAC development system. To avoid redesigning the hardware of the interface cards, we designed another card that made the evaluation board look like the CDS to the existing interface hardware; this new card was called the CPU interface card. A card cage was constructed that would hold five standard 11.5 x 16.5 cm cards capable of mating with a 44-pin connector. A picture of the evaluation-board card cage system is shown in Figure 36. The card cage and evaluation board are powered by a single 5-V supply. Connections are made between the card cage via the CPU interface card and the evaluation board by two 16-lead flat ribbon connector cables which mate to standard DIP sockets. Also shown in the photograph is a self-scan display which was found useful for visual readout during testing and debugging.

A typical card cage assembly for CMS testing included the CPU interface card, the radar interface card, and a display interface card. The display was used during testing to indicate range and range-rate data. Early tests of the electronic dashboard display microcomputer also made use of the evaluation-board card cage system. For testing the dashboard display, the card cage assembly contained a CPU interface card, A/D-trip odometer card, clock-fuel economy-tachometer card, and the card which contained the display-binary switches and velocity interface. Both card cage systems were able to use a standard CPU interface card and the evaluation board. As mentioned above, the main purpose of the CPU interface card was to make the evaluation board look like the CDS with regard to I/O functions such as input and output data lines and input and output strobes.

Closer examination of the evaluation board later in the program indicated that the elimination of the circuitry for the utility ROM, two CD 1852 I/O ports, the LEDs with their associated drivers, and the three-transistor RS-232 interface would produce a compact design for a CPU card that could fit within the standard card cage. If the output lines from the CPU card were made the same as the output lines (ribbon cable) from the evaluation board, it would create a system that could be used for initial prototyping and then, with the addition of a CPU card, become a stand-alone microcomputer. This concept is illustrated in Figure 37. The CPU card, CPU interface card, and evaluation board are common to all card cage systems.
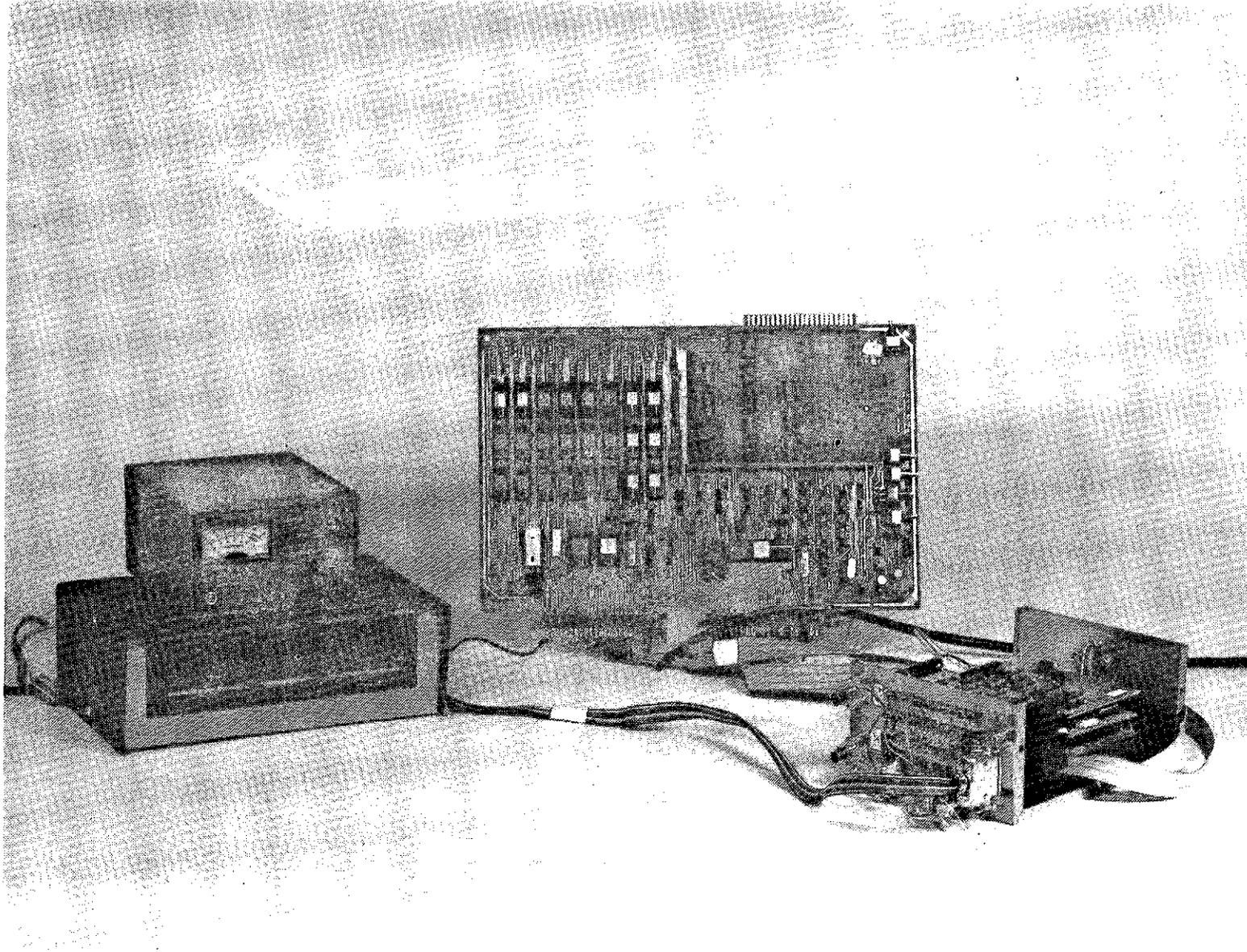
FIGURE 36. EVALUATION BOARD WITH CARD CAGE AND DISPLAY.
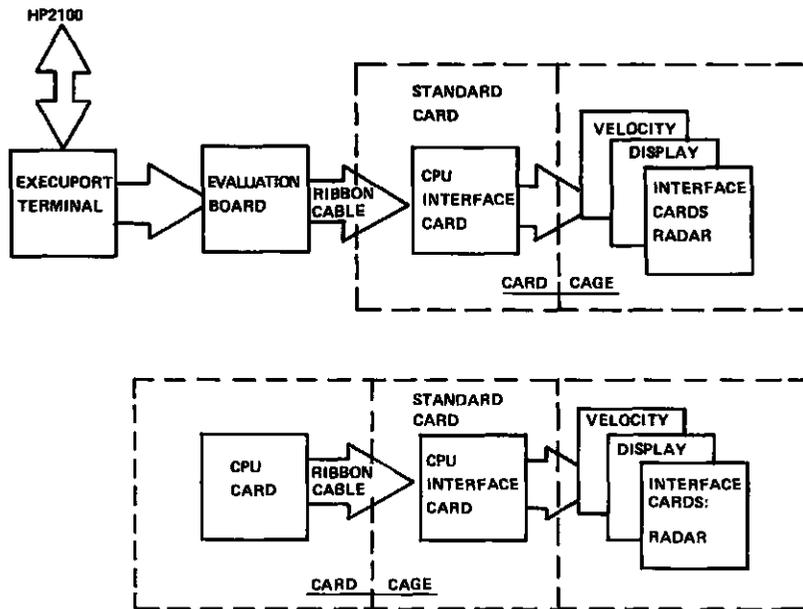
FIGURE 37. EVOLUTION FROM DEVELOPMENT BOARD TO FULL CARD CAGE SYSTEM.

3. CPU and Memory Card Cage for RSV Installation

A block diagram of the final CPU card is shown in Figure 38. The card consists of a CDP 1802 microprocessor with a 2-MHz crystal for the system clock. Two CDP 1822 RAM chips provide ½K of memory space for available storage. Either 2758 or 2716 EPROMs can be used with the CPU card. The 2758 is a 1K EPROM, and the 2716 is a 2K EPROM. From 1K to 8K of EPROM space is available on the CPU board. Both types of EPROMs are convenient to program and erase, and both operate from a single 5-V supply. An 1852 chip is used as an address latch and a 4555 chip is used for address decoding. A CD4028 is used for I/O decoding. A photograph of the CPU card is shown in Figure 39.

When the EPROM programming is complete, the CPU card, CPU interface card, and hardware interface cards form a stand-alone microcomputer system. A photograph of the complete CMS microcomputer system is shown in Figure 40. Another photograph, Figure 41, shows the CMS with the cover removed. Figure 42 gives a size comparison between the microcomputer system and the CDS. The CMS card cage contains two additional cards intended for the headway-control system in the RSV. The CMS card and headway-control card share the same CPU interface card by means of transmission gates at the connections between the CPU and CPU interface cards. An interrupt throttle controller card is backplane wired to the headway CPU card. A switch is used to select between either the CMS or headway-control system.

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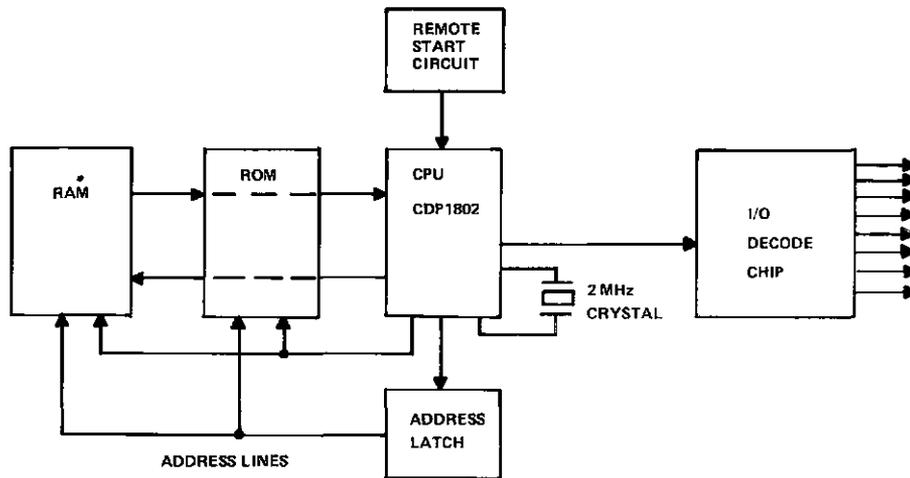
FIGURE 38. BLOCK DIAGRAM OF CPU CARD.

The electronic dashboard microcomputer is the same size as the CMS micro-
computer. It consists of a CPU card, CPU interface card, and three additional
cards which interface to the hardware and sensors of the RSV. Thus two card
cages, each measuring approximately 9 cm x 15 cm x 26 cm contain all computer
circuitry for CMS, headway control, and display functions.

4. Remote-Start Circuit for CPU

Both CPU cards contain a special start-up circuit to reset the CPU card
and to start the software running at the proper location when the ignition is
turned on. A low level on the $\overline{\text{WAIT}}$ line of the CDP 1802 microprocessor will
reset all registers of the microprocessor and start the software running at
location 00. The $\overline{\text{WAIT}}$ line has to be held low until the crystal oscillator
stabilizes after turn on (approximately 50 ms).

Figure 43 shows the remote-start circuit of the CPU card. An R-C network
is used as input to an inverter. The transient response when the power is
applied to the circuit from t=0 is shown at different points (A, B, C, D) on
the figure. The capacitor charges as a function of the R-C time constant.
The inverter output B remains high until the charging capacitor exceeds the
CMOS threshold level of the inverter. At t_1, the inverter output at B goes
low. Examination of diagram (B) shows that when the power is turned on a
spike is generated that can be used for initializing hardware. This particu-
lar pulse is used to reset the CD4047 one-shot circuit so that $\overline{\text{Q}}$ is high.

A-60
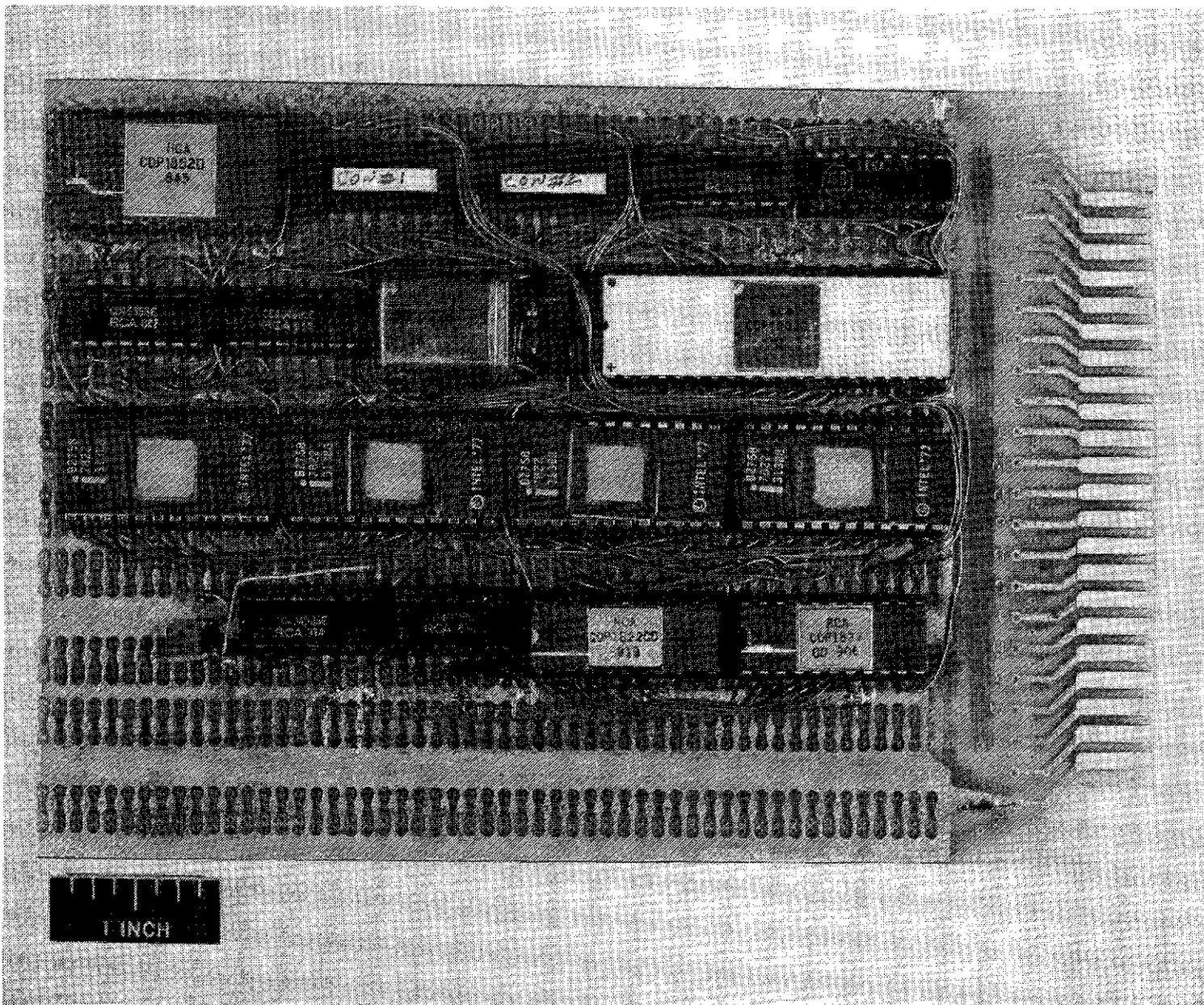
FIGURE 39.   PHOTOGRAPH OF CPU CARD.
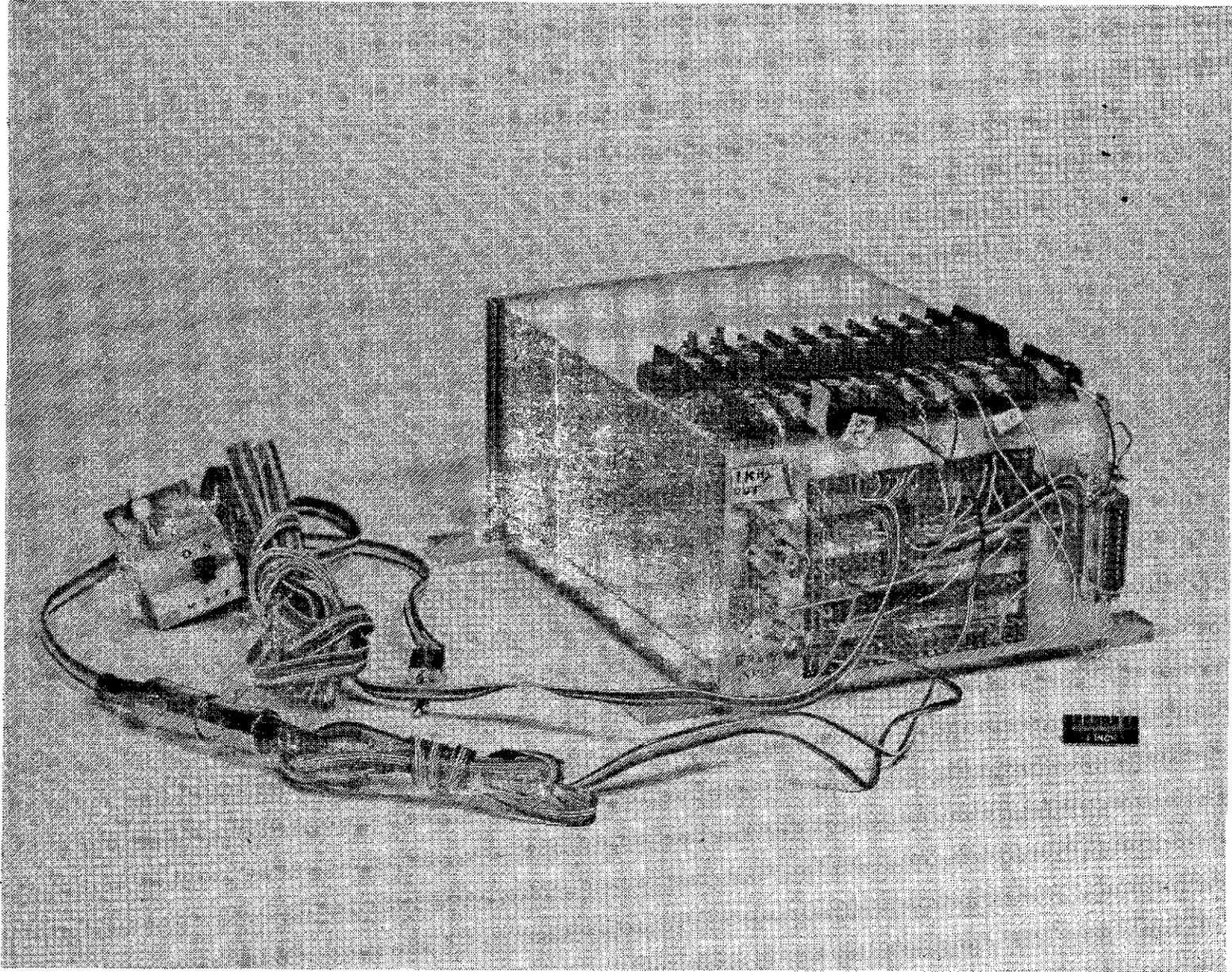
FIGURE 40. COMPLETE CMS CARD CAGE.
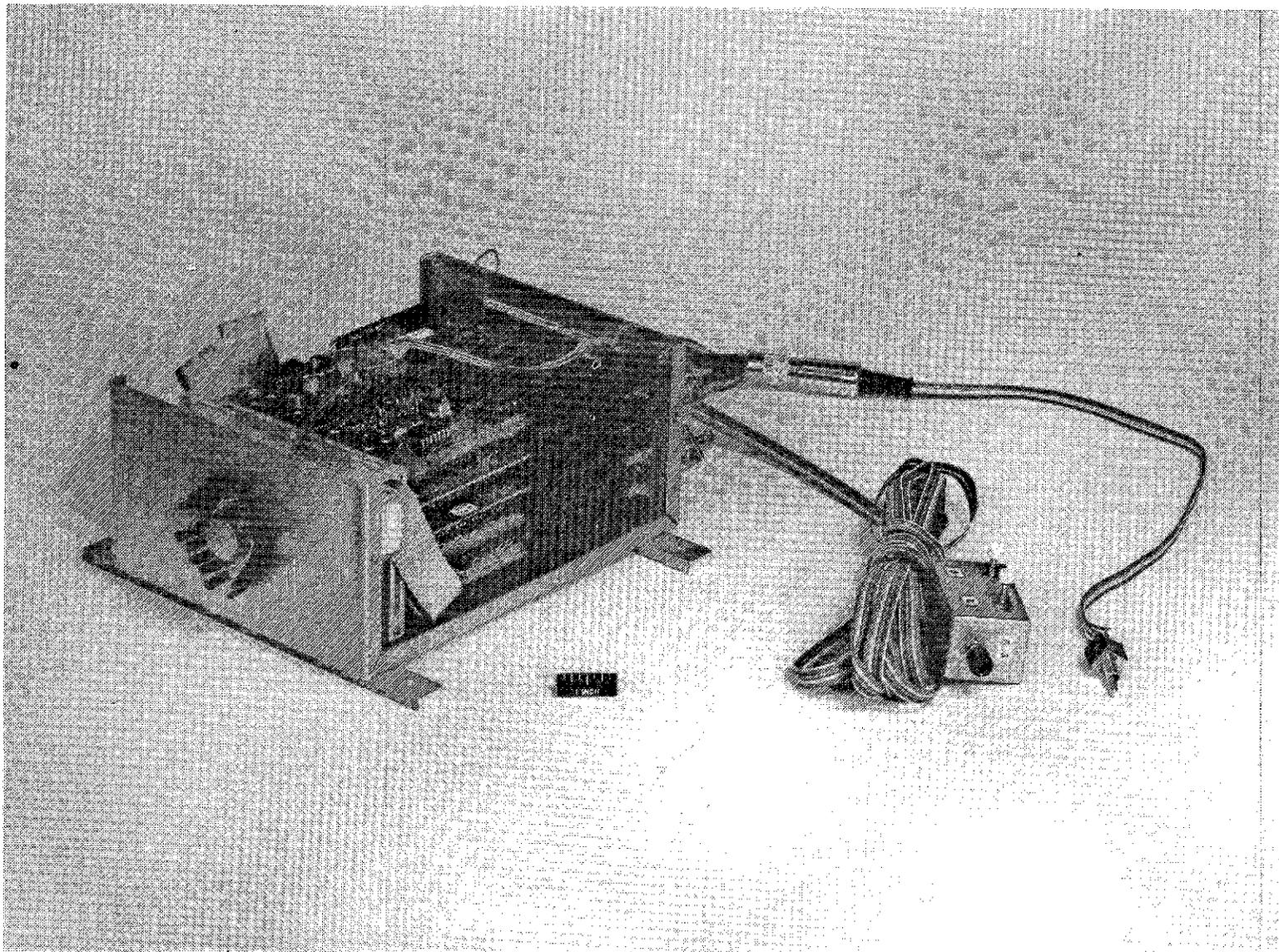
FIGURE 41.   CMS CARD CAGE WITH COVER REMOVED.
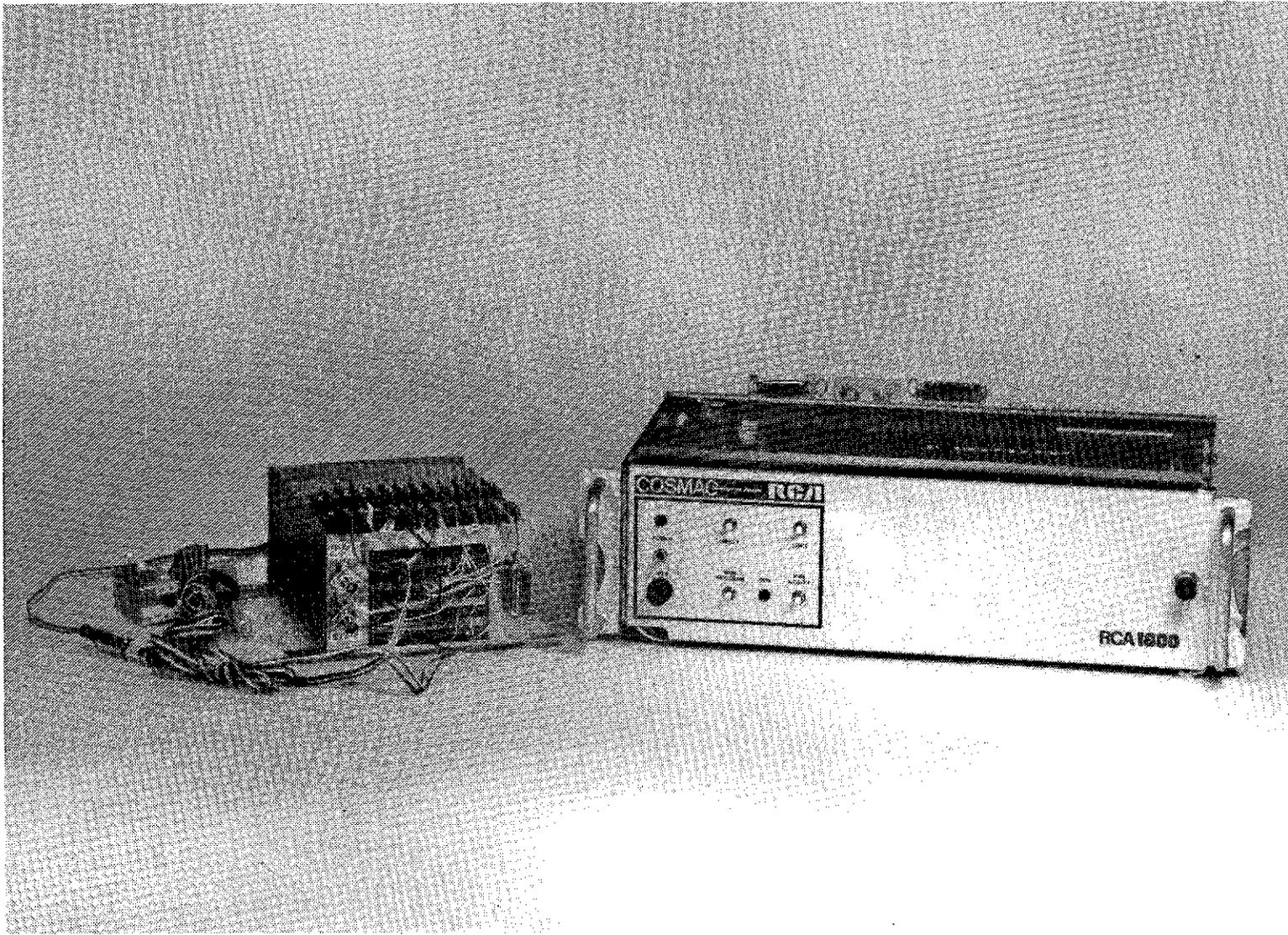
FIGURE 42.   SIZE COMPARISON - MICROCOMPUTER AND CDS.
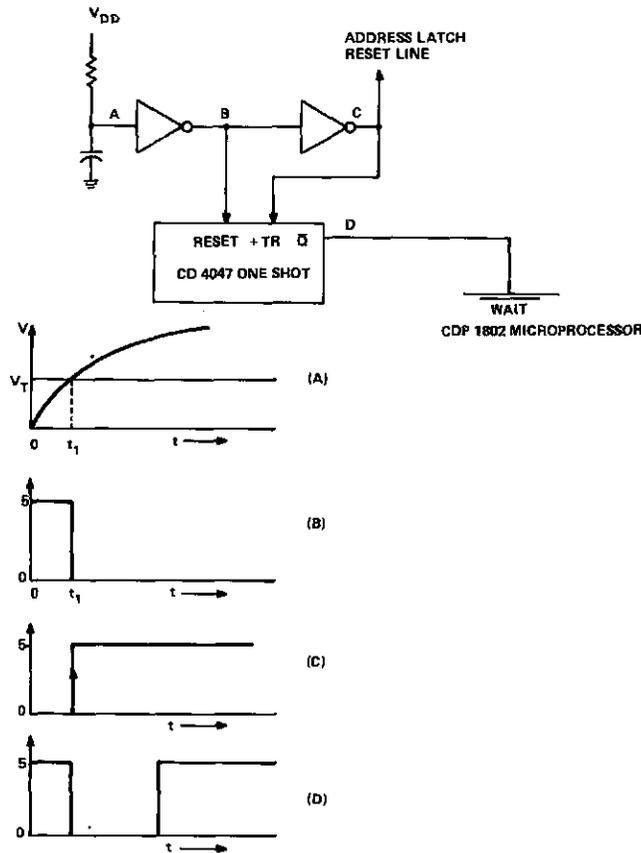
FIGURE 43.   REMOTE-START CIRCUIT.

Since point B is high until t_1 and is also the input to another inverter,
point C, the output of the second inverter is low until t_1. This low level
is used to reset the address latch to zero. The positive transition shown in
diagram (C) is used to generate the pulse to reset and start the microcomputer.

The $\overline{\text{WAIT}}$ pulse is low in diagram (D) for a time determined by an R-C net-
work associated with the CD4047 one-shot. The output of the second inverter
(C) cannot be used to restart the microprocessor because of a conflict in
timing between resetting the address latch and restarting the microprocessor.
The remote-start circuit for the dashboard display microcomputer is the same
except for an additional circuit which is used to inhibit interrupt pulses
until the microprocessor is running.

C. DISPLAY AND SENSOR INTERFACES

The display and sensor interface hardware that originally had been devel-
oped for the COSMAC development system during Phase II was consolidated to fit
on three standard cards within the card cage system. The three interface cards,

the CPU interface card and the CPU card, form the electronic dashboard display microcomputer.

The top of the dashboard display card cage has the 8-input analog-to-digital conversion circuit and a trip odometer circuit. The A/D circuit uses three of its inputs to monitor fuel level, water temperature, and oil pressure. A voltage divider is formed between 5 V and ground by a series resistance and the resistance of the respective sensor. The voltage developed across the sensor is converted by the A/D system.

The 8-input analog-to-digital circuit is shown in Figure 44. The heart of the circuit is a Burr-Brown* ADC80AG-10 A/D converter that has a 17-μs conversion time for an 9-bit output. The A/D has a 0- to 10-V input voltage range. The ±15 V necessary to operate the A/D chip is provided by a Datel** DC-DC converter. A CD4051 multiplex chip has 8-channel capability. The 9, 10, 11 pins of the chip are internally decoded to select a channel and connect it to the A/D converter. The multiplex chip is tied to the ±15 V of the DC-DC converter through a voltage-dropping resistor, so that only 10 V actually appears across the chip. The 10 V at the multiplex chip allows 10-V-level signals to be present at the input of the multiplex chip, which can still be switched by 5-V logic levels applied to the channel select pins.

The selection of one of eight channels to be connected to the A/D is accomplished by setting a level at the three binary-coded select pins 9, 10, 11. This level is placed there by the presence or absence of OTD-0, OTD-1, OTD-2 pulses at the "D" input of a CD4013 flip-flop, and is clocked through to the Q outputs (1, 13, 1) by an SIO-4 pulse.

The A/D converter is enabled by an SIO-3 pulse. The completion of the conversion cycle is indicated by the status of the EF-1 flag line. The 8-bit output of the A/D converter is applied to the data bus lines by pulsing a pair of CD4016 transmission gates with a IO-C pulse.

The second circuit located on the top card with the A/D circuit is the trip odometer, shown in Figure 45. The trip odometer must have the capability of retaining distance data when the vehicle is not operating. A connection is made directly to the vehicle battery, and the battery voltage is dropped to the

*Burr-Brown Research Corp., Tucson, AZ.
**Datel Systems, Inc., Canton, MA.
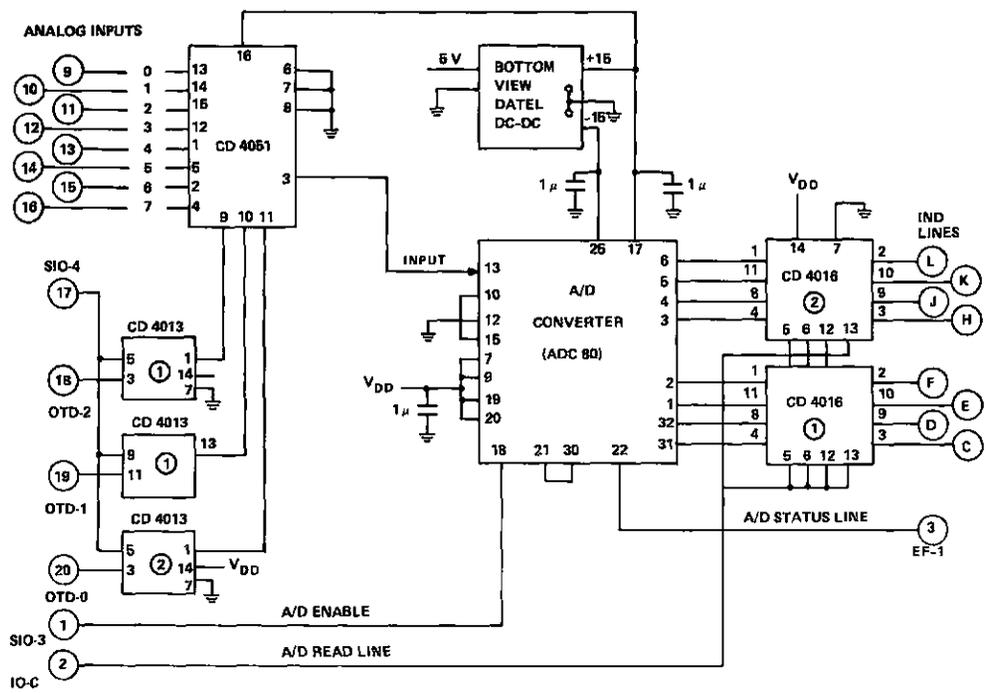
FIGURE 44.   8-INPUT ANALOG/DIGITAL CIRCUIT.
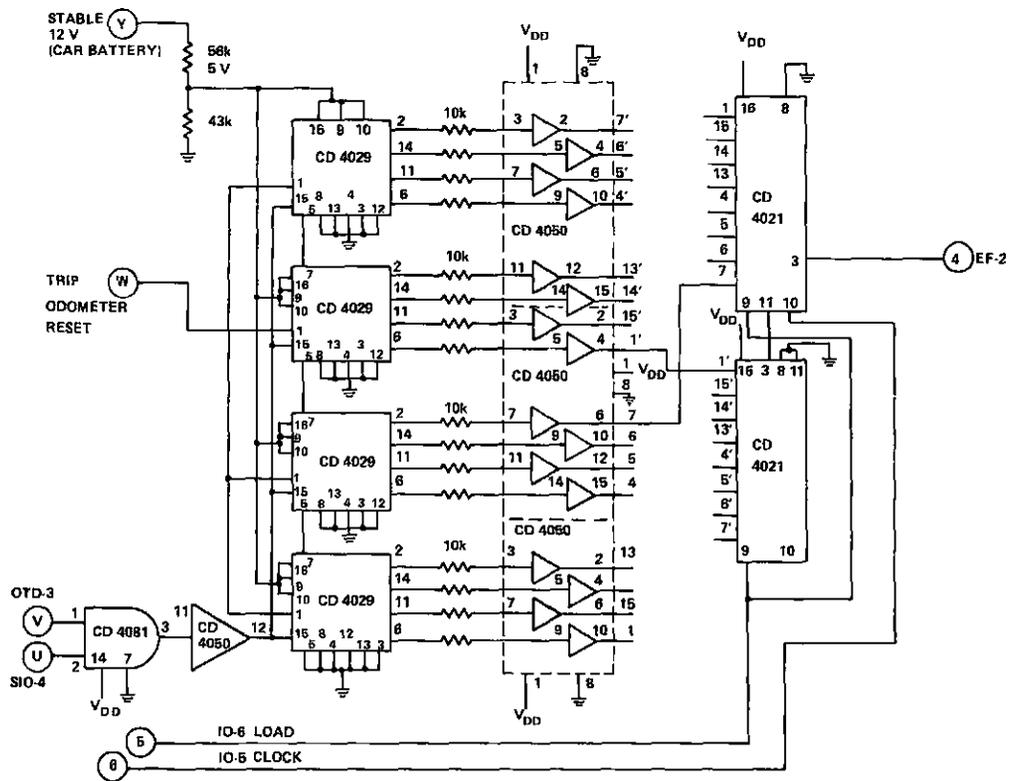
FIGURE 45.   TRIP ODOMETER CIRCUIT.

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5-V level for operating the CMOS counter by use of a voltage divider. Four CD4029s are used for the trip odometer counters. The counter is updated by a level generated by the simultaneous application of a SIO-4 pulse and an OTD-3 pulse. The 16-bit output of the four counters is connected to 16 buffers through individual 10-kΩ resistors.

The purpose of the 10-kΩ resistors in series with each input to the buffer is to provide protection to the buffer when the computer is in the "off" position. The counters will retain the logic level at their respective outputs because of the stable 12-V supply. During normal operation, the 16-bit output of the buffer is loaded by a IO-6 pulse into two shift registers (CD4021) and the 16 bits are then read serially by the application of a IO-5 clocking pulse onto a flag line EF-2. The trip odometer can be reset by applying a level to reset pin 1 of each of the CD4029 counters. The trip odometer is reset by a debounced switch which provides 5 V for this function.

The second card from the top of the dashboard display card cage is the clock, fuel-economy, tachometer interface. The automobile clock is designed to keep accurate time whether the car's ignition is on or off. The automobile clock circuit is shown in Figure 46. A stable 12 V is applied to the counting circuits by the vehicle battery. The voltage to the respective CMOS chips is reduced to 5 V by a 10-kΩ voltage-dropping resistor connected in series. An inverter (CD4007) is used for isolation between the oscillator and the four CD4029 counters. The four CD4024 counters are used as dividers, dividing down successively from 32768 to 2048 to 128 to 8 and, finally, to 1 Hz. The 8 Hz is applied to the interrupt circuit section of the remote start. The 1-Hz pulse is applied through a buffer to two CD4017 decade counters which count to 60 and generate a pulse per minute.

Figure 47 shows the pulse-per-minute input applied to two CD4029s, whose function is to count to 59 and then at the next minute reset to 0. The CD4082 at the output lines of the CD4029s provides the logic necessary for the "reset after 59" function. The reset pulse 1 minute after 59 is the hour pulse, which is applied to a single CD4029. This counter counts to 12 and then the next hour resets by jam loading to 1. The CD4073 is used for the "reset to 1" logic function.

The manual minute advance is accomplished by the use of a level derived from a debounced switch and applied to the clock line of the two CD4029s. The incrementing or decrementing of the minute counter is accomplished by use of a CD4049 inverter. A "0" at the input results in a high applied to the up/down

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FIGURE 46.   CLOCK CIRCUIT DIAGRAM (OSCILLATOR AND MINUTE COUNTER).

FIGURE 47.   CLOCK CIRCUIT DIAGRAM (HOUR ADVANCE).

count pin, which causes the counter to count up. A high level at the input of the inverter makes the inverter output go low, and the counter decrements when a level is applied to the clock line. The hour advance uses a voltage-level from another debounced switch to advance the hour function. The buffer outputs are loaded into two shift registers by a IO-6 pulse and then clocked out serially by IO-5 clock pulses. Note that the load and clock pulses are the same for both the trip odometer and the clock. However, the automobile clock output is read out on flag line EF-3, while the trip odometer is read out on flag line EF-2.

The tachometer interface and the fuel economy interface are also located on the card with the automobile clock. The circuits are shown in Figures 48 and 49. The tachometer interface obtains its input from the point side of the coil. The input is applied through a buffer to a one-shot multivibrator (CD4047). The one-shot multivibrator generates a pulse that is noise-free and free from ringing effects and therefore can be used to drive a counter. The pulse output is applied to a CD4029 counter whose 4-bit output is read by pulsing a transmission gate (CD4016) with a IO-D pulse. The counters are set to "0" initially by the CLEAR-P line.
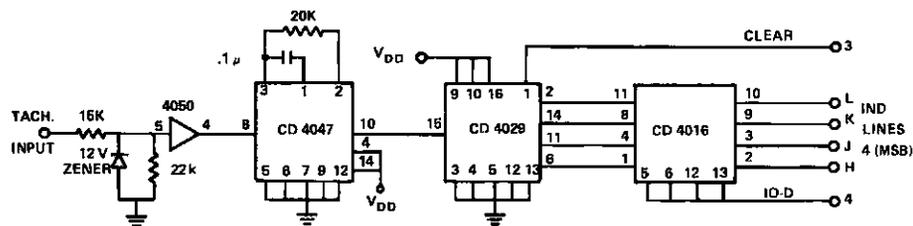
FIGURE 48. TACHOMETER INTERFACE CIRCUIT.
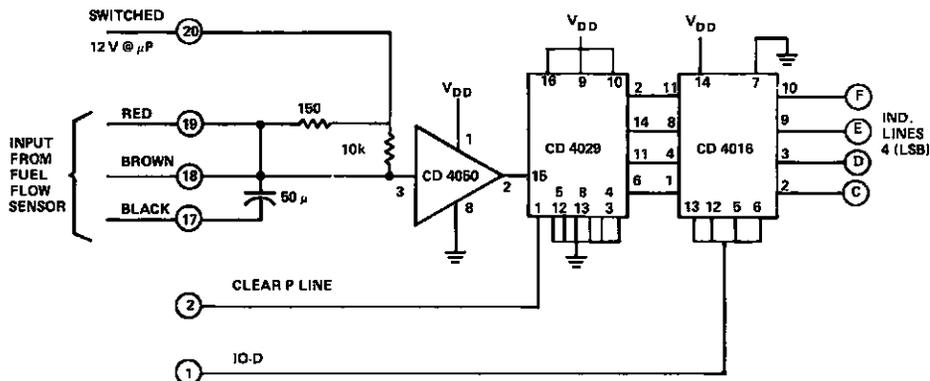
FIGURE 49. FUEL ECONOMY SENSOR CIRCUIT.

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The circuitry necessary to operate the Model 261PB-15 flow transducer*
is connected at the input to the fuel-economy sensor interface card. The pulse
output of the sensor is applied to a CD4050 buffer for logic level conversion
from 12 to 5 V. The pulses clock a CD4029 counter which, in turn, is gated on
to the transmission bus by the application of an IO-D pulse to a transmission
gate. The CLEAR-P line is used to initialize the counter. Note that the IO-D
pulse gates simultaneously the tachometer and fuel economy interfaces by gating
the upper 4 bits onto the bus for the fuel economy data and the lower 4 bits
for the tachometer data.

The third card from the top of the dashboard display card cage contains
the display interface, the binary interface, the velocity interface, and a
circuit used to check the condition of the restraint system. The display in-
terface circuitry is shown in Figure 50. Eight bits of data are read from the
CPU card interface bus lines and stored in CD4042 latches by use of a stretched
SIO-1 pulse. Six bits of data are applied to the self-scan unit by use of
CD4049 inverters. A "data present" pulse from the latch coincident with the
SIO-1 pulse applied to a CD4023 NAND gate provides a logical 0 which causes
the "Data Present" line of the self-scan to go low, thereby permitting the data
on the line to enter the memory of the self-scan unit.

Another pulse from the latch is used to clear memory by use of a second
CD4023 NAND gate. Pin 14 of the latch is the control bit for "Data Present"
or "Clear." Pins 1 and 15 are the latched outputs of the pin 14 input, pin 15
is the complement of pin 1. The two CD4011 NAND gates, the CD4050 buffer, and
1N461 diode and the RC network comprise the pulse stretching network for the
SIO-1 pulse. The blank disable line is always tied low so that it is inoper-
ative.

The control function provided by the computer is the same for both the
"high brightness" and conventional self-scan display. The conventional self-
scan unit makes use of 7 latched data outputs to obtain the 128-character
repertoire. The switch located on the clear line of the display is used to
stabilize the display from update flicker. If the overall system voltage
supply is free from noise, the switch can be left open and the display will
not flicker. However, if noise spikes are present on the vehicle's 12-V
system,

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*Flo Scan Instrument Co., Seattle, WA.
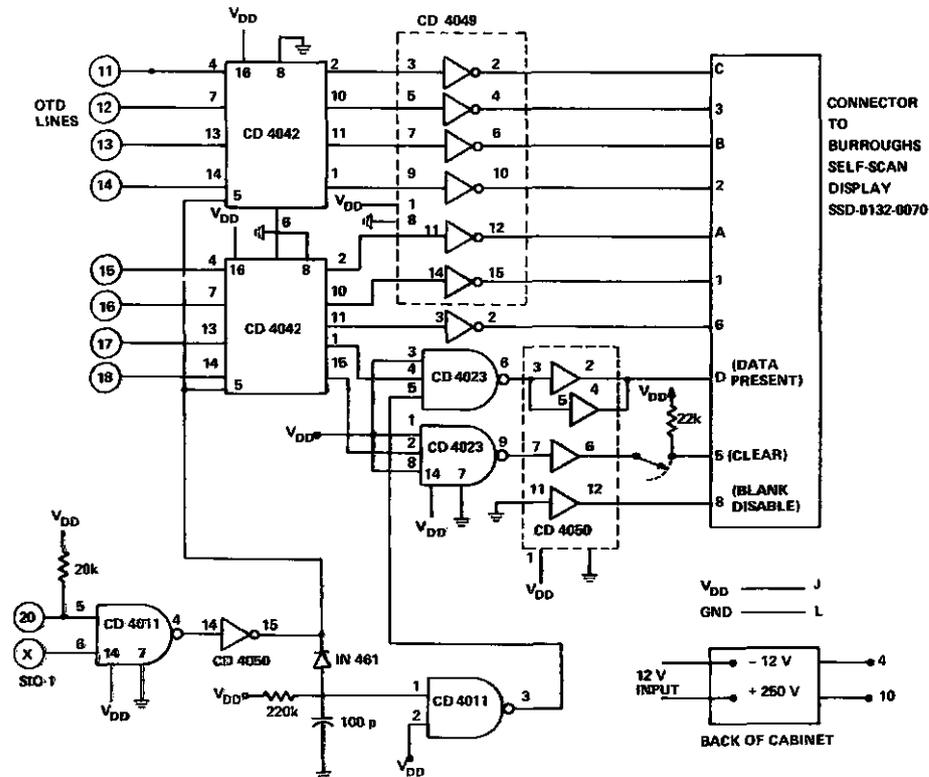
FIGURE 50.   SCHEMATIC OF DISPLAY INTERFACE.

the display data will offset because the T^2L circuitry of the self-scan unit is affected by noise. Closing of the clear switch will eliminate the data shift on the display but will cause some minor update flicker.

The binary input card of the display microcomputer is shown in Figure 51. It makes use of 9 buffers and 3 transmission gates (CD4050 and CD4016, respectively). The card is broken down into families of buffers and quad-latches. The input of each of the buffers is tied to ground through a 22-kΩ resistor. A 12-V input at the input of any buffer is converted by the buffer to a 5-V logic level at the output. The 12-V inputs are derived from switch sensors. The output of the buffer is read onto the 8-bit data line by gating the proper pair of quad-latches. The quad-latches are selected by IO-9 or IO-A pulses in the display card cage. The binary inputs monitor door switches, service brake switches, brake fluid level switches, battery indication, the selection of the display format, and the airbag or restraint system status.

The circuit used to monitor the voltage from the top of the airbag squib to ground is shown in Figure 52. Two comparator circuits monitor the squib voltage. The voltage from the squib to ground is considered in tolerance if
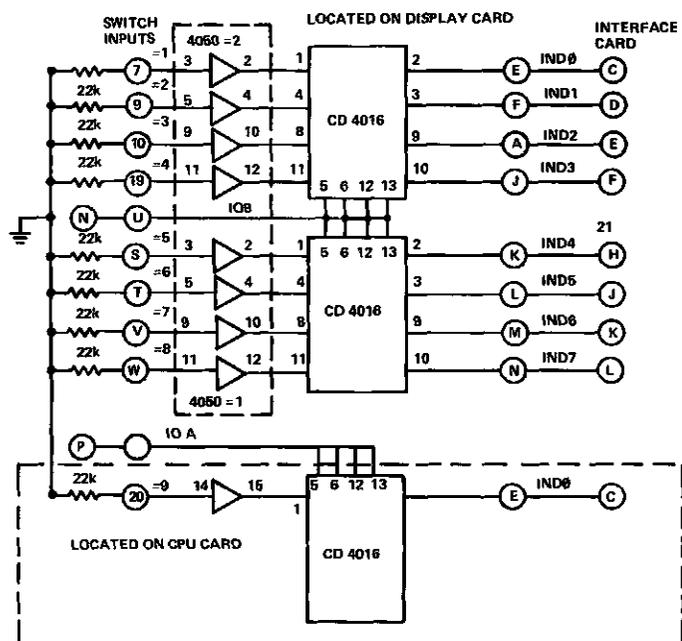
FIGURE 51. BINARY INPUT CARD FOR SWITCHES.
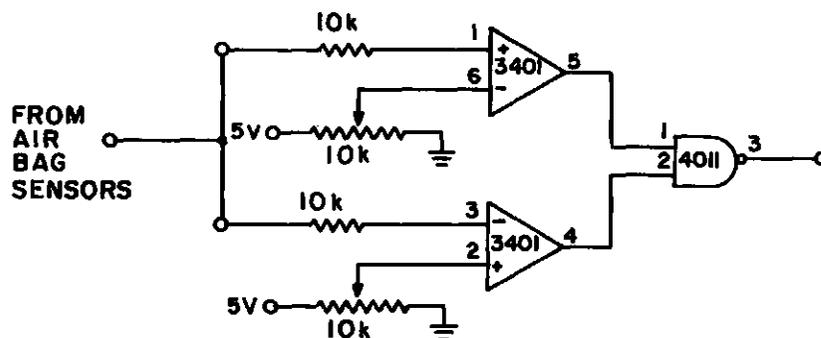
FIGURE 52. SCHEMATIC OF AIRBAG INDICATOR.

it is between 6 and 10 V. Under this condition, the comparator outputs are both high; therefore, the output of the NAND gate is low which in turn is connected to one of the binary input parts. If the voltage from the squib-to-ground should go to 0 or 12 V, one of the comparators will go low; therefore, the NAND gate output will go high thereby causing a 5-V level to appear at a binary input port to trigger the "Restraint System Out" message.

The final circuit on the third card is the velocity sensor interface, shown in Figure 53. A pulse train input is received at the input of the circuit. The pulse frequency is directly proportional to velocity. This pulse
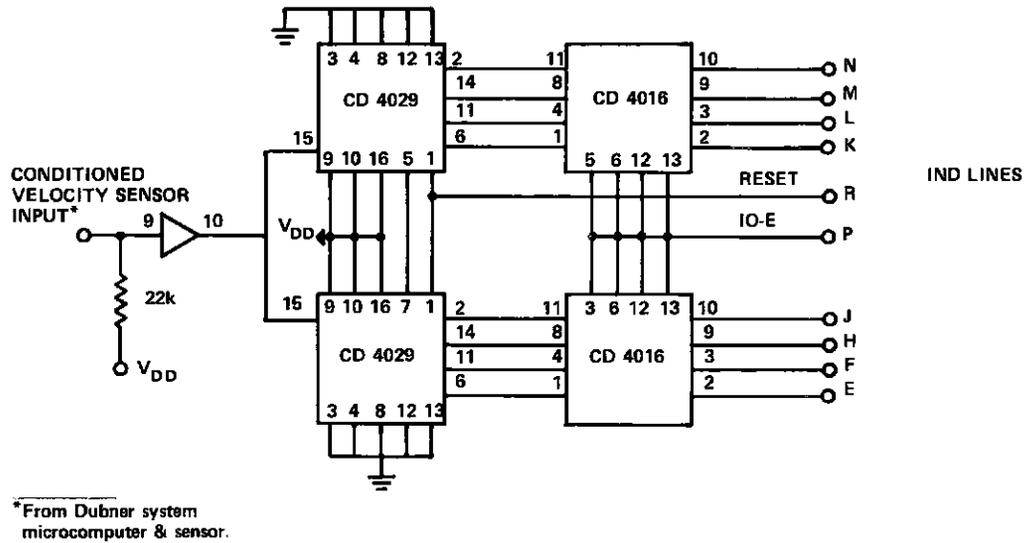
FIGURE 53. SCHEMATIC OF VELOCITY INDICATOR.

train is read by a sensor located on the RSV drive train, buffered by the
Dubner system automatic transmission microcomputer, and then passed on via
cable to the RCA electronic dashboard display microcomputer. The input cir-
cuit is also buffered. The output of the buffer drives a counter which is
read through the transmission gates by an 10-E strobe.

SECTION V

CONTROL FUNCTIONS AND SOFTWARE IMPLEMENTATION

A. COLLISION-MITIGATION BRAKING CONSIDERATIONS

The two key features of the collision-mitigation system are (1) the automatic application of antiskid brakes in case a high-speed collision is definitely unavoidable and (2) the complete elimination of false alarms (i.e., no application of brakes in cases where no real collision is imminent or where the driver could have avoided the collision by himself). For a better understanding of the boundaries that guide automatic braking, a simplified summary of braking dynamics is presented.

The general case of two vehicles moving toward each other, with one being braked, is illustrated by the time-distance relationship shown in Figure 54. The following assumptions are made:

v_1 is the initial velocity of the radar-equipped car

v_2 is the initial velocity of the target vehicle ($v_2 < 0$)

v_I is the impact velocity of the radar-equipped car

v_{It} is the total impact velocity ($v_{It} = v_I - v_2$)

μg is the maximum braking deceleration (0.9 g for dry road, antiskid brakes)

R_t is the radar detection range

Δt is the reaction delay (0.1 s for the radar processor and algorithm and 0.1 s for the brake system to reach full braking action)
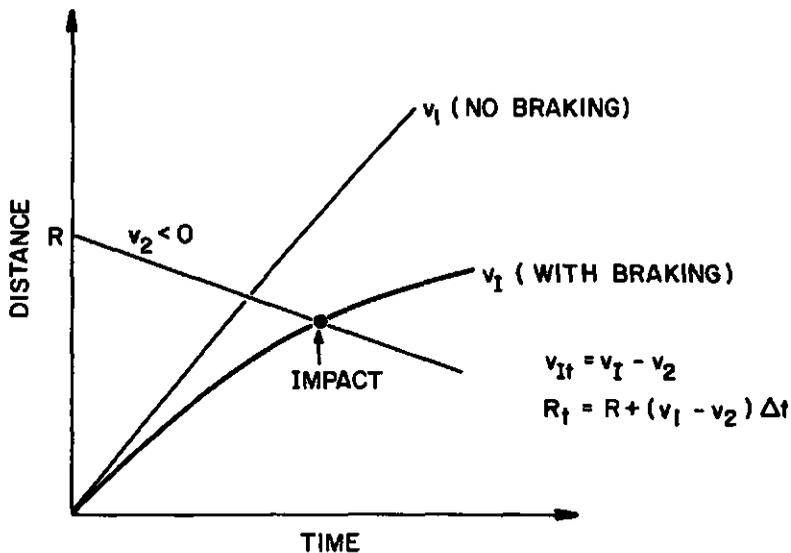
FIGURE 54. DISTANCE/TIME RELATION BETWEEN TWO VEHICLES, ONE OF WHICH IS BEING BRAKED.

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The relation between impact velocity, v_{It}, and the radar detection range, R_t, can be expressed as

$$R_t = \frac{1}{2\mu g}\left\{(v_1 - v_2)^2 - v_{It}^2\right\} + (v_1 - v_2)\,\Delta t \qquad (32)$$

This equation applies, of course, also for the case of impact with a fixed object by setting $v_2 = 0$. Since $v_1 - v_2$ can be replaced by the measured range-rate, $\dot{R}$, we obtain the more general relation

$$v_{It} = \sqrt{\dot{R}^2 - (R_t - \dot{R}\Delta t)\,2\mu g} \qquad (33)$$

The impact velocity as a function of different radar detection ranges, R_t, and initial closing rates, $\dot{R}$, is shown in Figure 55. For a collision with a fixed object, for example, the impact velocity v_{It} is reduced from an initial speed of 25 m/s (55 mph) to 13.7 m/s (30 mph) if a detection distance of 30 m is maintained. This corresponds to a reduction in impact energy by 70%.
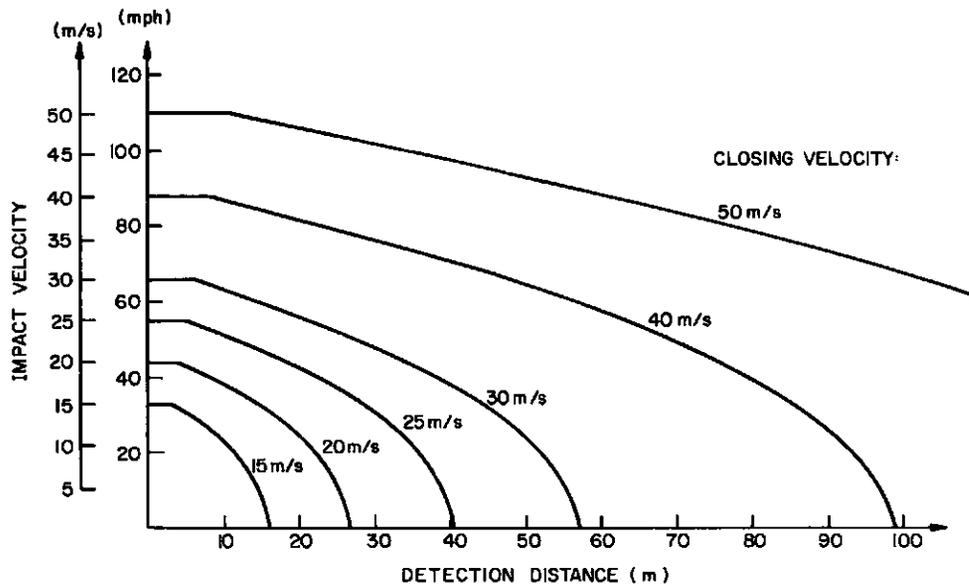
FIGURE 55. IMPACT VELOCITY AS FUNCTION OF DISTANCE BETWEEN RADAR CAR AND COLLISION OBJECT (SYSTEM DELAY 0.2 s; BRAKING COEFFICIENT $\mu = 0.9$).

For head-on collisions where both vehicles are going at a speed of 25 m/s (55 mph), the impact velocity is being reduced by 8.8 m/s (17 mph), provided both cars have CMS braking with a detection range of 30 m. The impact energy

is correspondingly reduced by 30%. Here the energy reduction is not so pro-
nounced, but still significant enough to make a substantial difference in the
severity of the injury sustained by the driver. Figure 56 shows the resulting
impact velocity, v_{It}, as a function of closing rate, $\dot{R}$, for different detection
ranges. Also indicated are lines of constant energy reduction.
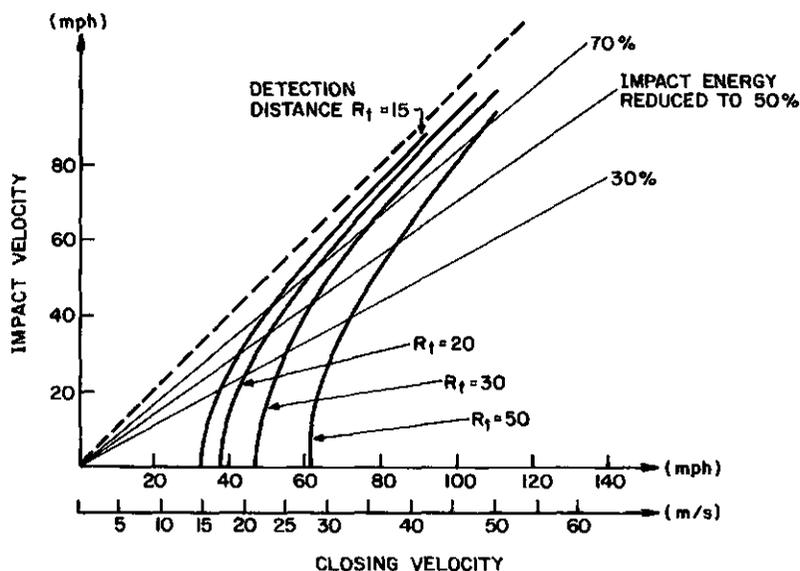
FIGURE 56. ENERGY REDUCTION AS FUNCTION OF DETECTION DISTANCE
AND CLOSING RATE.

The above calculations clearly indicate the importance of having a large
detection range, R_t, for the radar and a fast reaction time for the overall
system. These requirements are counteracted by the need for keeping all false
alarms at an absolute minimum and, equally important, for ensuring that a
driver remains in control of the car as long as there is any possibility of
avoiding an accident by skillful driving maneuver.

Based on a typical maximum lateral acceleration of 0.3 g (which is rarely
exceeded by the average driver), a minimum distance of 32 m is required [11]
to avoid an obstacle straight in line with a vehicle driven at 25 m/s (55 mph).
We, therefore, selected a maximum detection distance, R_t, of 30 m for a car
driven at 25 m/s. If a driver at this speed approaches an obstacle without

11. R. Limpert, Motor Vehicle Accident Reconstruction and Course Analysis,
     Michie Company, Charlesville, VA, December 1978.

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steering wheel or brake pedal activation, the automatic antiskid braking should take over. At lower speeds, this distance should obviously be reduced further.

B. COLLISION-MITIGATION SYSTEM

The inputs to the CMS algorithm consist of range, range-rate, steering angle ϕ, brake pedal status indicator, and car velocity. The range-rate is derived directly from the beat counts during the up- and downswing of the frequency modulation cycle, and is not generated by differentiating range with time. Range-rate can, therefore, be used to independently check the validity of range data obtained at different time points.

The entire CMS algorithm (a complete program listing is included in Appendix B) is conveniently subdivided into two parts. The first part includes the acquisition of radar data, calculation of range, range-rate, car velocity, and a check of steering wheel angle and brake pedal position. The second part contains the actual decision subroutine which activates the antiskid brakes if all conditions for two sets of data separated by a time interval, Δt, are fulfilled. Two flags and a status bit, DF, keep track of the decisions made at various points within the algotithm.

GETRAN is the data acquisition part of the algorithm and is shown in flow chart form in Figure 57. First, the number of transitions within a measurement interval are counted. From the number of transitions within the measurement interval, we can determine the number of periods within the measured interval. If we do not have at least one period within either the upswing or downswing measurement interval, we repeat the entire measurement process. The accumulated count is read for both the upswing and downswing modulation interval. The count in each case is averaged by dividing by the number of periods within the respective measurement interval. A deviation check is performed on each period measurement of the up- and downswing. A failure of the deviation check restarts the entire measurement process. If only one period was measured on the up- and downswing of the modulation cycle because of a close target or dropouts, the periods are compared to each other and, if they exceed a set tolerance, the measurement process is restarted.

If after passing the transition counter check, deviation check, and if necessary the single period check, the data is considered acceptable, range and range-rate values are determined from a table using the up and down count
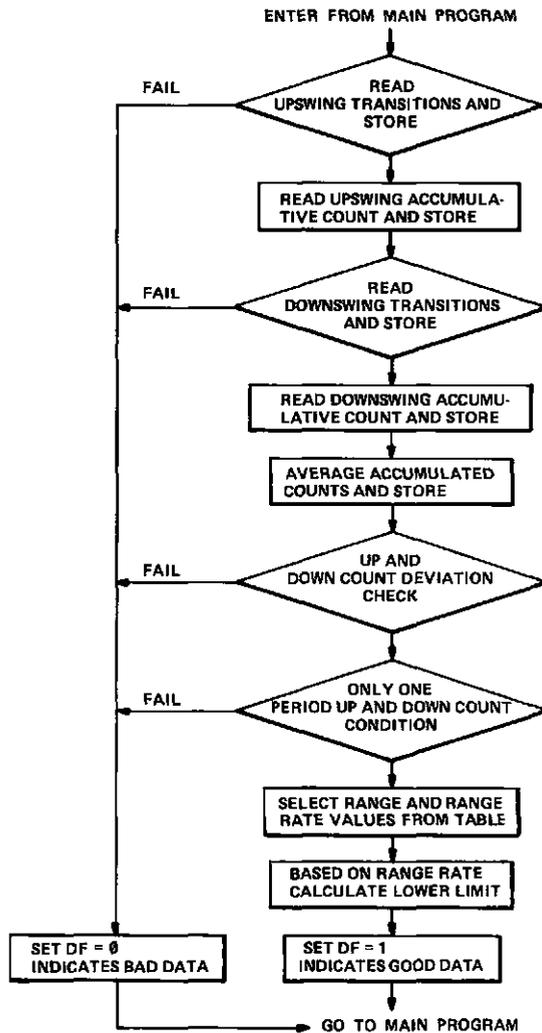
FIGURE 57. FLOW CHART OF GETRAN (DATA ACQUISITION).

readings as a parameter. A 1-bit status indication, DF, is set to indicate
good data readings after a lower limit value has been calculated from range-
rate data. The good data readings are either taken over a full measurement
interval during the full modulation upswing and downswing or over part of a
cycle, from the beginning of the interval up to the point of a dropout.

Once range and range-rate data have been computed, the primary purpose
of microprocessor software is to sort out real emergency situations from false
alarms. This is performed in the main CMS algorithm, shown in Figure 58. A
target moving toward a radar-equipped car does not always require automatic
braking, as for example in tight turns or parking maneuvers. The speed cutoff
eliminates the possibility of emergency braking if the car velocity is less
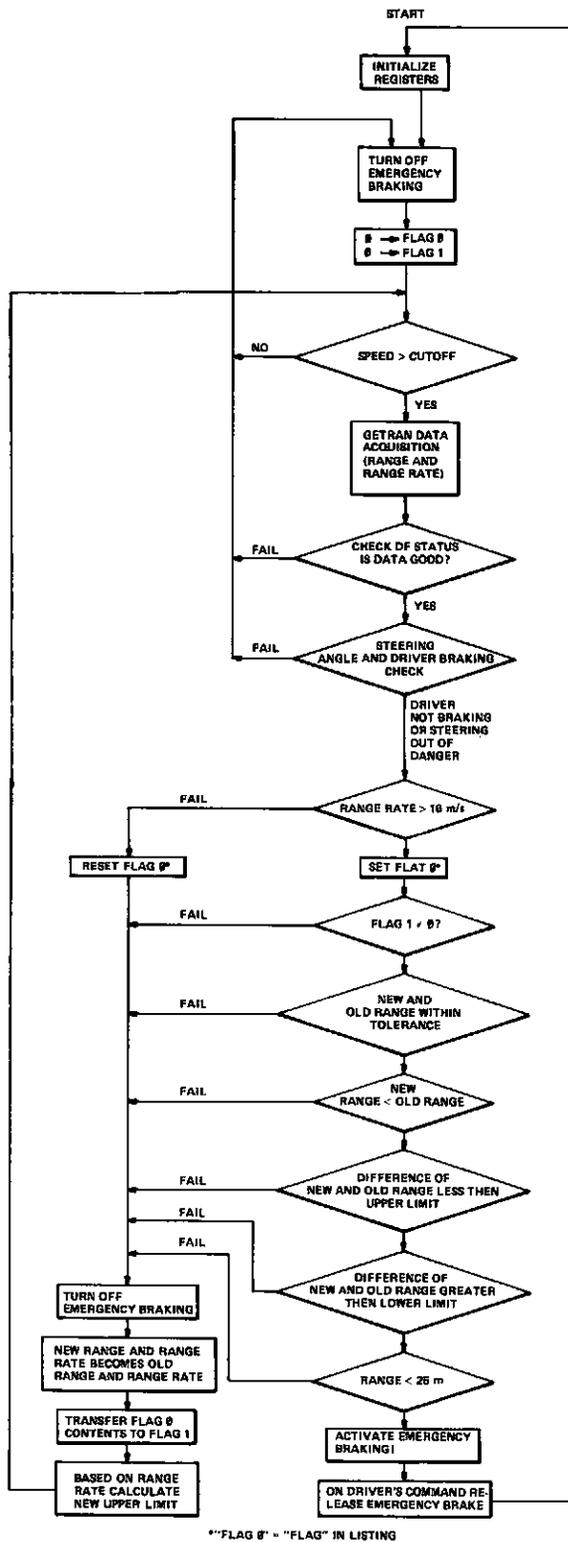
FIGURE 58. FLOW CHART OF MAIN CMS PROGRAM.

than 10 m/s. The velocity cutoff computation is done in the electronic dash-
board display software. If the cutoff velocity is exceeded, a flag is set by
the dashboard display microcomputer and is read by the CMS algorithm. An in-
dication of bad data acquired by GETRAN is signaled by the status bit DF = 0
and the software restarts the overall measurement process. An indication that
a driver is taking action by steering or braking also causes the software to
begin again.

If we have reached a point where the vehicle is operating above a set
speed and has acquired a target and there is no reaction in the form of braking
or steering by the driver, further analysis is then made of the potential threat.
If the closing rate between the target and the radar-equipped RSV is less than
16 m/s, the target is not considered a severe threat, emergency braking is pro-
hibited, and the range and range-rate data are stored as a reference. Based on
range-rate a new value of range difference is calculated for an upper limit,
which is later used in the algorithm. In case the driver is not reacting and
the closing rate or range-rate is greater than 16 m/s, a flag is set. Another
flag (called flag 1) is checked to see whether this is the first or second test
of acquired data. If flag 1 is 0, which corresponds to the first test of ac-
quired data, the range and range-rate data are stored as a reference or "old
data" and a new upper limit is computed. The contents of flag 0 which has been
set previously are then tranferred to flag 1.

Now the process starts again; once data is acquired a second time, the
set speed is exceeded, and there is no reaction by the driver, and the closing
rate is above 16 m/s, additional checks are performed by software to verify the
presence of a real target. Checks are also made to determine if the difference
between the newly acquired range-rate and the old range-rate is within a certain
tolerance. The newly acquired range must be less than the first range reading.
The difference between the new range reading and the previous one must fall
between a lower and upper limit value that is a function of range-rate.
Finally, the range measured has to be less than the cutoff range of 25 m.
Only if all of these conditions are met is the emergency braking activated.

The automatic activation of the antiskid brakes will be disabled if the
driver takes over the braking maneuver. This is considered an indication that
the driver is in control. Also, if any of the conditions for range comparison
are rejected, automatic emergency braking is prohibited. The newly acquired
data then becomes the reference or old data, and a new value is calculated for

the range difference upper limit. A target threat is still considered because a flag is set to indicate the successful acquisition of one set of data. Another consecutive set of data is therefore needed which, if it passes all of the test conditions, will enable the automatic emergency braking condition that applies the antiskid brakes.

The computation and decision making time for the CMS algorithm during Phase II was approximately 160 ms. For the new CMS algorithm, which includes more sophisticated decision making, this time is only approximately 80 ms. The reduction in software processing time can be attributed to two reasons. First, the new RCA CDP 1802 microprocessor has a larger instruction set than the 1801 unit used during Phase II. Secondly, the software is greatly improved together with the use of look-up tables and faster multiplying chips.

C. HEADWAY/CRUISE CONTROL

1. Introduction

A car equipped with a collision-mitigation system has limited sales appeal because under normal conditions, a driver would be totally unaware of the system's presence. As discussed before, emergency braking is to take place only when a severe collision is unavoidable, and a good driver should, hopefully, never find it activated. Public acceptance of the radar could be greatly increased if it were also to provide improvements in convenience and traffic flow. Automatic headway control that governs the safe spacing of successive cars on limited-access highways is such an application.

The difference between regular cruise control and radar headway control is illustrated in Figure 59. In the normal cruise control, a fairly popular option in American cars, the driver can select a particular cruising speed, v_{set}, and the car will maintain this speed ($v_1 = v_{set}$) until a new speed is set or the brake pedal is tapped. This convenience feature is, unfortunately, not very useful when traffic density increases. Cars ahead, going at only slightly lower speeds, force the temporary disablement of the cruise control or lead to rather dangerous weaving in and out of traffic lanes to avoid having to reset the cruise control.

Under radar headway control, the radar senses the distance and closing rate with respect to the vehicle ahead and controls the throttle to match the speed of the first car ($v_2 = v_1$) and keep a safe headway. If there is no other vehicle ahead, cruise control takes over and the car resumes the preset speed. In the present implementation, only the throttle is interfaced with the radar;

$V_1 = V_{set}$ SELECTED CRUISING SPEED

$V_2 < V_{set}$

$$V_1 = V_2 \quad \begin{bmatrix} m/s \\ \end{bmatrix}$$
$$R = 1.34 V_2 \quad \begin{bmatrix} m \end{bmatrix}$$

} AUTOMATICALLY MAINTAINED
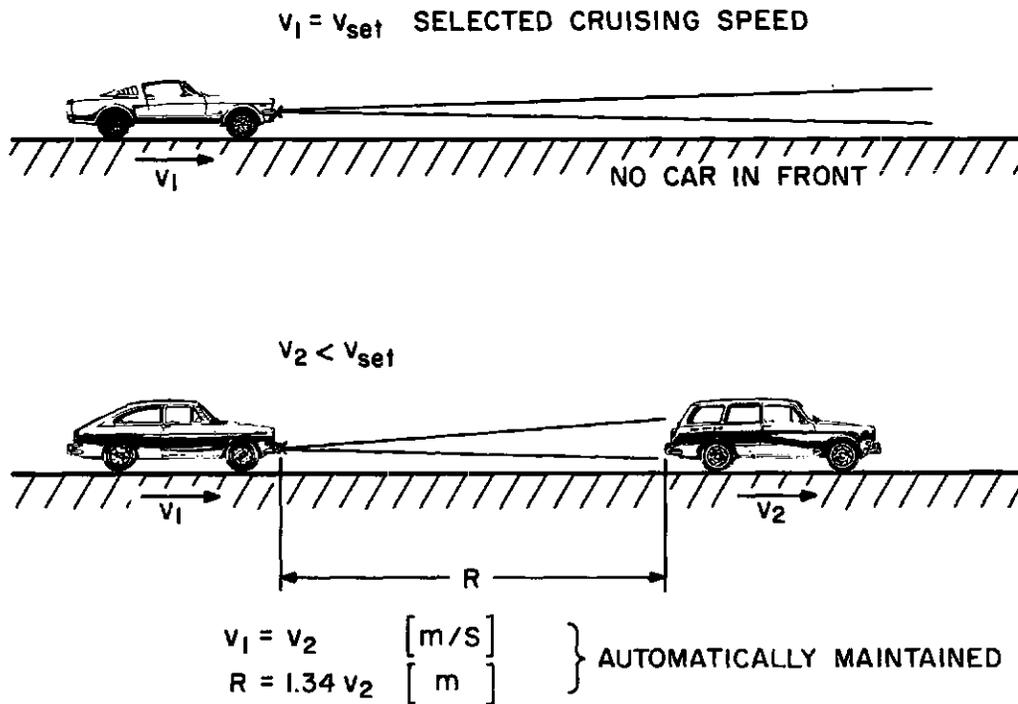
FIGURE 59.   COMPARISON BETWEEN CRUISE CONTROL AND RADAR HEADWAY CONTROL.

if the closing rate becomes too high, a warning signal is given on the electronic display and the driver has to take over.

2.   Design Considerations

A block diagram of RCA's headway-control system is shown in Figure 60. The driver makes his inputs through switches located on the turn signal stalk. An RCA 1802 based microcomputer monitors ground speed and interprets signals from the radar. Throttle control signals are computed and delivered in the form of variable width pulses to a linear DC motor which is connected to the car's throttle by a chain. The computer has control of the full travel of the throttle, but cannot at present initiate brake activation. Limited deceleration due to air friction and engine drag is achieved when the throttle is fully released. When more rapid deceleration is required the driver must intervene by personally applying the brakes. Whenever the computer senses driver application of the brakes, it responds by fully releasing the throttle and relinquishing control back to the driver until instructed by the driver to resume control.

For diagnostic and demonstration purposes we have interfaced a Burroughs*
self-scan single-line display to the computer. Although it is not required for

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*Burroughs Corp., Plainfield, NJ.

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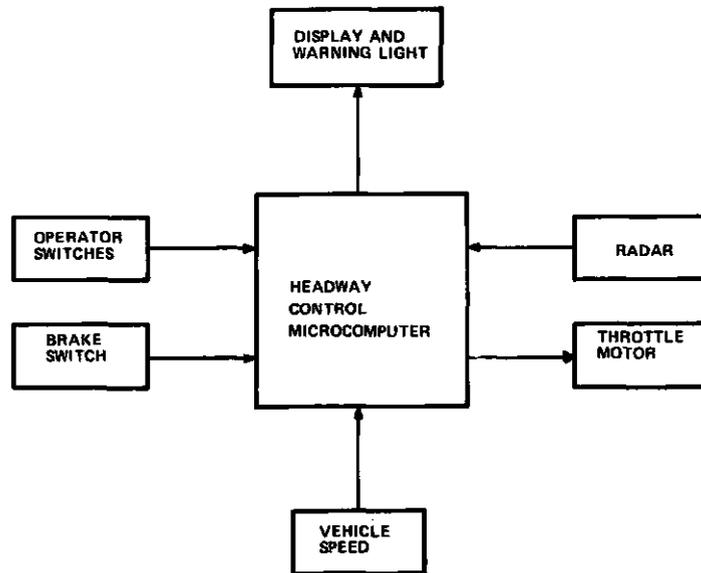
FIGURE 60. BLOCK DIAGRAM OF HEADWAY-CONTROL SYSTEM.

operation of the system, the display is useful for indicating radar-measured range, range-rate, vehicle speed, and other system state information. A yellow warning light on the display is turned on when the closing rate is too high (over 3 m/s) or the following distance is dangerously close (less than 10 m).

Control for the throttle is implemented entirely within microprocessor software as a sequence of discrete-time computations. A diagrammatic representation of these computations is shown in Figure 61. Computed expressions are shown by their z transform equivalents, while events external to the computer are shown as continuous time LaPlace transforms. The fundamental inputs to the computer are range, R, and velocity, v. Range-rate, $\dot{R}$, is computed as

$$\dot{R} = \frac{R_1 - R_o}{t_s} \tag{34}$$

where R_1 is present range, R_o is previous range, and t_s is the sampling time of 0.5 s.

There is some inherent "noise" in range data in headway control because the radar beam looks at different positions on the irregular surface of the target car. Road bounce of the radar and target aggravate the noise. There is also quantization noise of range due to the way the radar signal is processed and to the finite precision of the microprocessor computations. Range measurements are quantized in steps of 5 cm. Velocity is quantized in steps of 0.1 m/s. Input noise is propagated to the throttle control causing annoying jerky motions which can be sensed by passengers.

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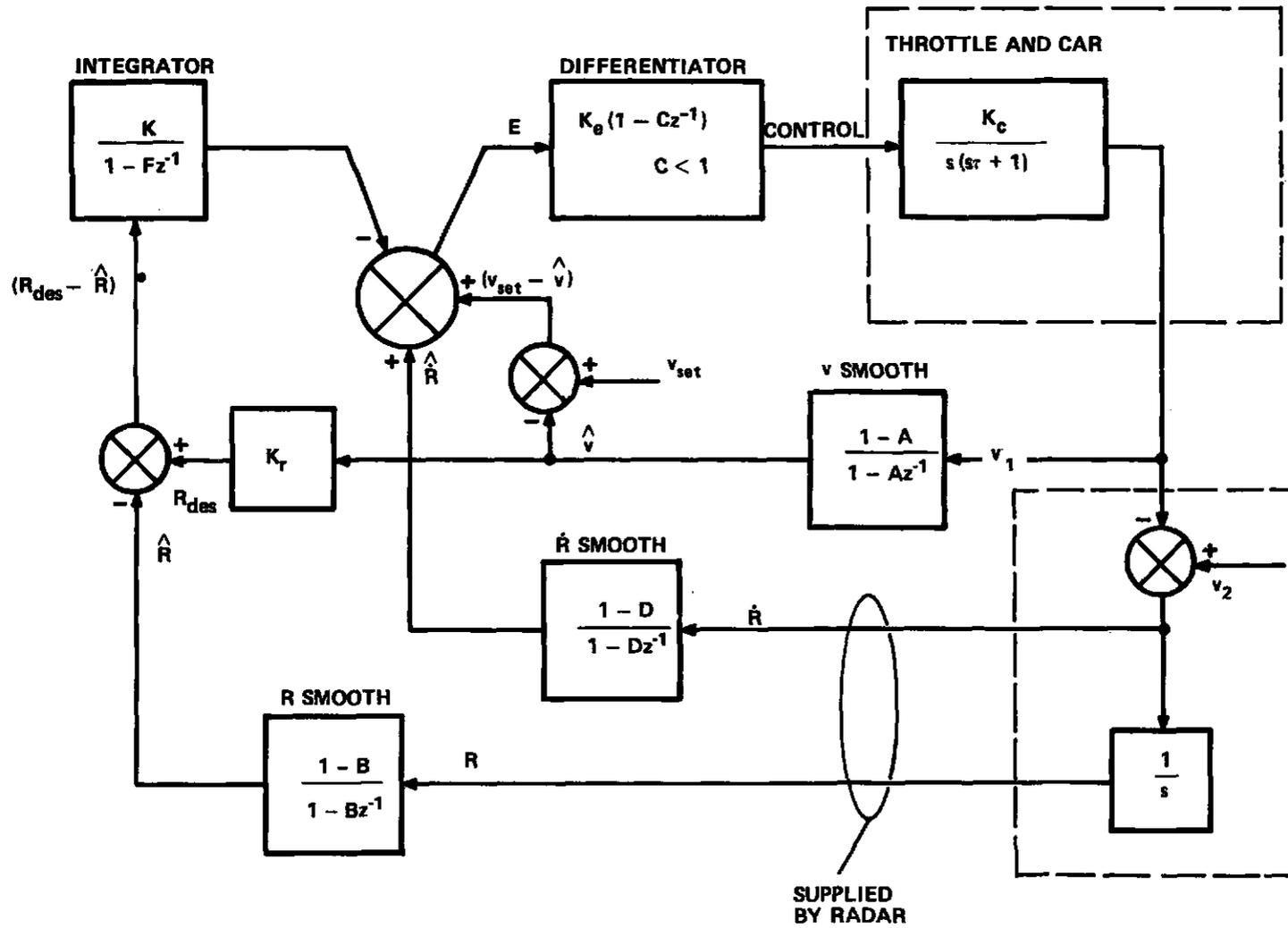
FIGURE 61. AUTOMATIC CRUISE/HEADWAY-CONTROL ALGORITHM.

In an effort to reduce the effects of noise, smoothing functions are used on R, $\dot{R}$, and v to generate $\hat{R}$, $\hat{\dot{R}}$, and $\hat{v}$. Heavy smoothing provides the quietest outputs, but there is a decline in responsiveness as smoothing is increased. Since $\dot{R}$ is a time derivation of range it is potentially quite noisy and therefore has heavy smoothing. Care must be taken in choosing the $\dot{R}$ smoothing constant D so that sudden changes in closing rate are reflected quickly enough in $\dot{R}$.

The desired headway distance is computed as

$$R_{des} = K_r \, v \tag{35}$$

This headway distance increases linearly with road speed. Constant K_r is presently 1.5 m per m/s; for example, the desired distance at 25 m/s (55 mph) is 38 m. The difference between R_{des} and $\hat{R}$ constitutes a range error which we attempt to minimize. Similarly, the difference between v_{set}, the cruise control set speed, and v constitutes a velocity error which is minimized in a conventional cruise control. Referring again to Figure 61 we see that velocity difference between the two vehicle, $\hat{\dot{R}}$, and a term representing an integrated range error are fed into the main summing junction to produce error E. This error is compensated by a differentiating expression $K_e \, (1-Cz^{-1})$, C < 1, to generate throttle control. The feedback compensation is designed to force E toward zero at all times.

In general, increasing E will produce more throttle acceleration and decreasing E will cause throttle release. If the radar car is moving at less than v_{set}, a positive velocity error is present at the summing junction. The range error integrator permits the velocity error to be canceled out at the junction, even as the range error is reduced toward zero. In the present system we were so far not able to implement a perfect integrator (F = 0.9 instead of 1.0 is being used) because of some instability problems. The remaining residual error has the same polarity as the velocity error and has a magnitude of about 1.45 m for each 1 m/s of velocity error.

The residual error results in a headway distance which is smaller than desired, an effect that becomes more pronounced when the set cruising speed is much higher than the actual speed. We believe that this deficiency can definitely be eliminated by properly adjusting the integrator term. However, since any changes also affect other constants of the loop, work priorities and available time restrictions did not permit us to fully optimize these

counter dependent system parameters. In practice, the deviation from the correct headway distance does otherwise not affect the proper operation of the headway control.

As indicated earlier the control output is in the form of a signed number which is converted by digital circuitry to a pulse, the width of which is proportional to the magnitude of the number. The throttle motor is turned on for the duration of the pulse. Thus the microcomputer generates relative position control for the throttle, rather than absolute or direct positioning. For this reason the throttle is modeled as an integral controller (1/s). The car has a response time τ, and the combination of throttle and car are modeled in the diagram as $K_c/[s(s\tau+1)]$.

In an ordinary driving situation the radar is constantly acquiring targets and losing them again as they go out of range. At any instant the system can be considered to be in any of the five states, as shown in Figure 62. In addition to "Cruise" and "Resume" found in conventional cruise controls, we also have "Headway," "Capture," and "Lost Targets." The arrows in the diagram show permitted state transitions. "Resume" permits the car to go from present speed to previous set speed after "Cruise" has been disengaged by the brake. "Resume" is implemented as a special form of "Cruise" in which the reference speed to be obtained is gradually raised from present speed to set speed at the rate of 3.3 m/s per second. Thus if set speed were 25 m/s and "Resume" is engaged at
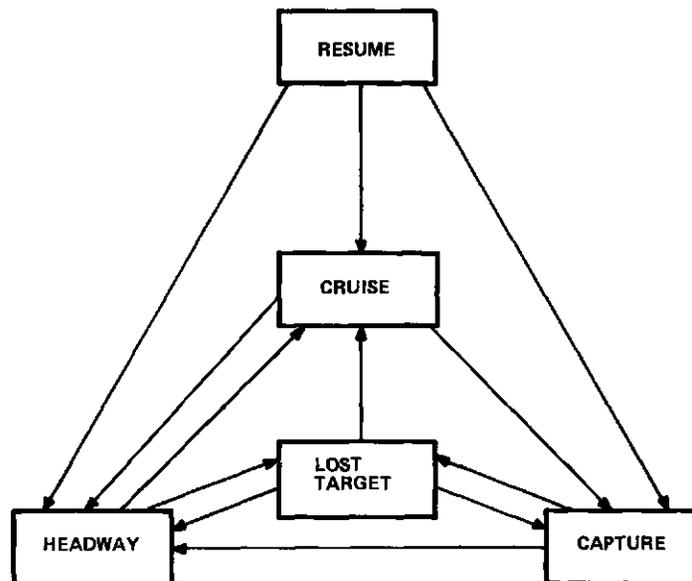
FIGURE 62. STATE TRANSITION DIAGRAM.

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15 m/s, the resume state will last approximately 3 seconds. Without a "Resume" state, the car would accelerate very rapidly and overshoot the set speed considerably.

When a target is acquired the system will go from "Resume" or "Cruise" to "Headway" or "Capture." "Capture" is intended as a transition state from "Cruise" to "Headway." "Capture" is implemented as the opposite of "Resume" with "Cruise" reference speed reduced from set speed at the rate of 1.8 m/s. Figure 63 shows how "Capture" begins at range R_D and terminates when range is 1.1 R_{des}. "Capture" range is computed as

$$R_D = K \dot{R}^2 + R_{des} + 3 \text{ m} \tag{36}$$

Increasing the closing rate increases R_D, lengthening the capture distance. If a target is acquired at a range of less than 1.1 R_{des}, or if the closing rate is very low, the "Capture" state is bypassed and we go directly to "Headway."

$$R_D = K \cdot \dot{R}^2 + R_{des} + 3m$$
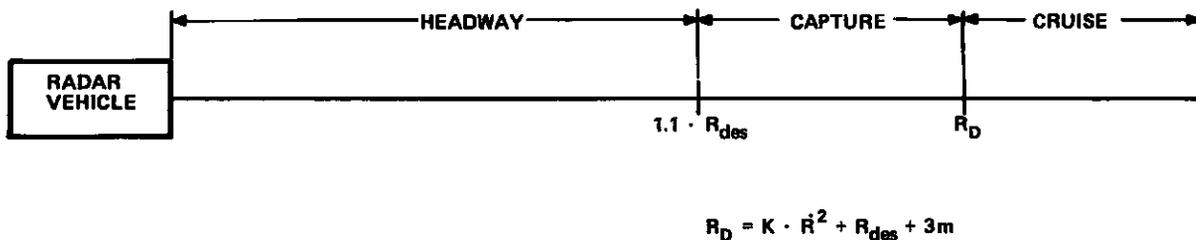
FIGURE 63. CAPTURE MODE.

The "Lost Target" state is needed because a target may appear to drop out occasionally, due to signal multipath or multiple target detection. It is undesirable to return immediately to "Cruise" because of a momentary signal loss. In the "Lost Target" state, the throttle is held steady for up to 1.5 seconds while the radar tries to reacquire the target. If at the end of this time there is still no target, the system transits from "Lost Target" to "Cruise."

The important transition rules are summarized below:

(1) From "Resume" or "Cruise" to "Capture" -- Target is acquired
     and 1.1 $\cdot$ R_{des} < $\hat{R}$ < R_D

(2) From "Resume" or "Cruise" to "Headway" -- Target is acquired and
     $\hat{R}$ < R_D and R < 1.1 $\cdot$ R_{des}

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(3) From "Capture" to "Headway" -- $\hat{R} < 1.1 \cdot R_{des}$

(4) From "Headway" to "Cruise" -- $(v - 1.4 \text{ m/s}) > v_{set}$ or $\hat{\dot{R}} > 2.3 \text{ m/s}$

Rule 4 inhibits the target car from "towing" the radar car.

3. Algorithm Flow Diagram

The headway-control software is written in RCA Level II Assembly language and is stored in 3K bytes of EPROM. It consists of an interrupt service routine which executes whenever the driver presses a switch or the timer interrupts, and a main program loop, which runs continuously. The interrupt service routine has the following functions:

When a switch is pressed on the driver's stalk, a status bit is set in a microprocessor register, provided the current velocity is above 9 m/s (20 mph). The main program later tests this status bit to determine if the switch has been pressed. For the SET SPEED or SET 55 switches, the interrupt routine will store v_{set} as present speed or 55 mph (90 km/h), respectively. When the foot brake is depressed, the interrupt routine will release the throttle completely, giving the fastest possible response. When the timer interrupts, the velocity sensor is read and v is computed. In addition, timer status is used to synchronize the main program so that range measurements are taken at precise intervals.

The main program loop is shown in flowchart form in Figure 64. A description of the basic algorithm using block numbers from the flow chart is given below.

  I Initialize microprocessor registers and memory locations.

  II Release throttle completely (normally not engaged) and erase start-up message from display. This step requires about 2 seconds.

  III Wait for driver to press SET SPEED or SET 55.

  IV Loop synchronization. Wait for timer interrupt indication. Time interrupt occurs every 0.5 second.

  V Input data from radar card. Determine validity of data using deviation check.

VI, VII If data valid, compute range, R.

 VII-X If target has been lost for 1.5 seconds, leave headway state; otherwise hold throttle.

XI-XIII	Warning light management. If R < 10 m or there are two consecutive measurements with R < -3 m/s, warning light is turned on; otherwise it is turned off.
XIV-XVI	If this is first valid range measurement, variables must be initialized. Two consecutive valid range measurements are required to compute radar control.
XVII	Compute smoothed range, range-rate, smoothed range-rate, and summing junction error.
XVII-XXI	If not in HEADWAY state, transition rules are used to see if we should go to CAPTURE.
XXI	If in CAPTURE state, capture processing is done.
XXIII	If $\hat{v} > v_{set}$ or $\hat{\dot{R}} > 2.3$ m/s transition to RESUME or NORMAL is made.
XXIV	Control is computed using headway control compensation equation.
XXV-XXVIII	If RESUME switch has been pressed, do RESUME state processing until $v_{ref} > v_{set}$; otherwise $v_{ref} = v_{set}$.
XXIX	Control is computed using normal cruise compensation equations.
XXX-XXXII	If brake has been pressed, we want to avoid sending further control outputs to the throttle since it has been disengaged by the interrupt service routine. Wait until driver releases brake and presses a switch before continuing.
XXXIII	Control is sent to the throttle pulsing circuitry.
XXXIV	Self-scan display is formatted according to current state. This is not essential to system operation.
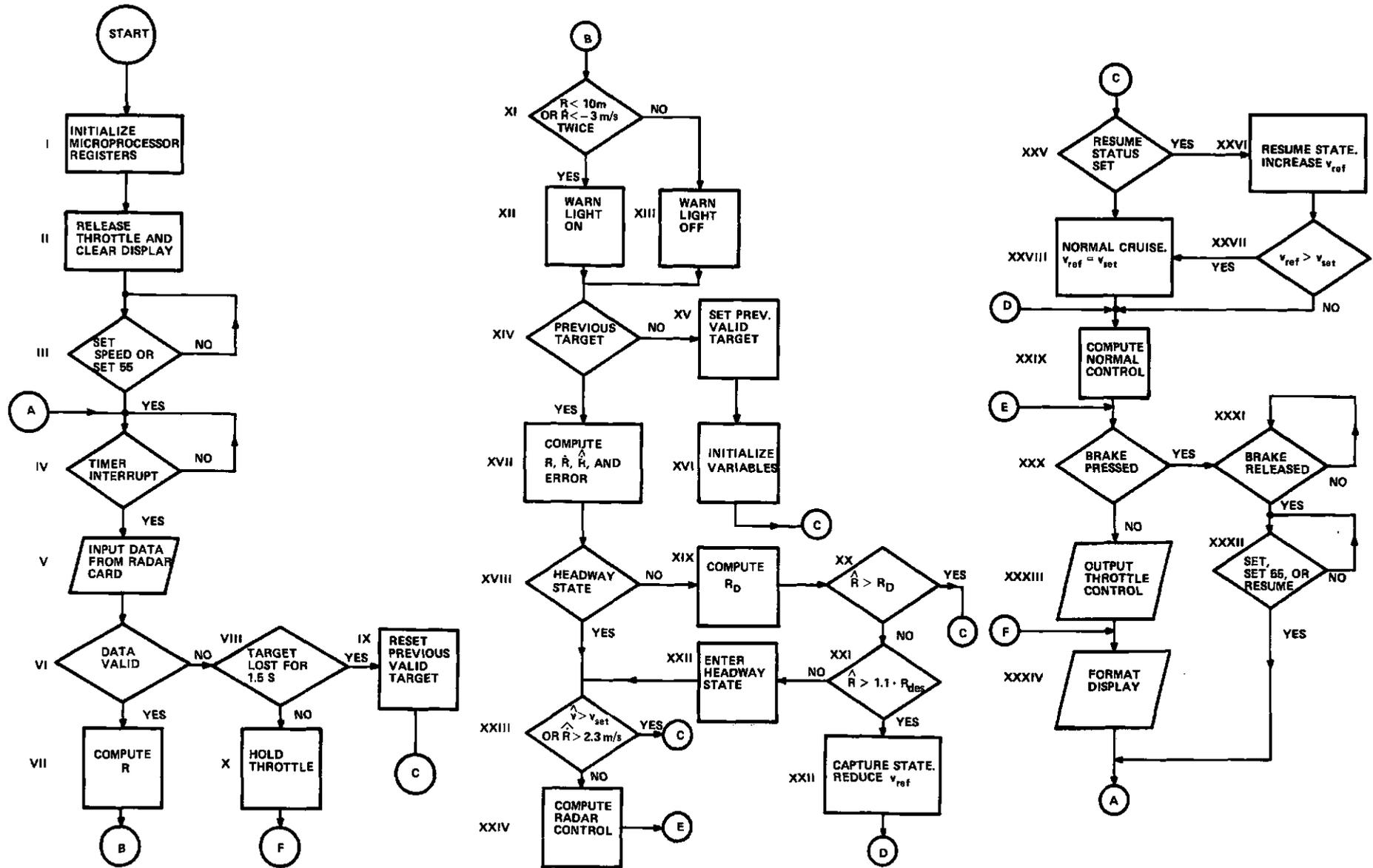
FIGURE 64. HEADWAY-CONTROL FLOW CHART.

SECTION VI

PERFORMANCE TESTS

A. TEST VAN INSTRUMENTATION

A special test vehicle was equipped to permit the recording of radar and video data for optimization of the radar hardware and software. Aside from providing a test platform for the radar, the vehicle is also fully instrumented with recording equipment and other test gear for evaluating the performance of various components of the radar system. A Ford "Econoline" van, shown in Figure 65 houses all of the test equipment and acts as a mobile laboratory. The front of the van is fitted with a support structure that accommodates different antenna configurations. Figure 65 also shows the Ku-band bistatic system radar without radome assembly mounted on the van. The metal plate underneath the radar antenna assembly is covered with an RF absorber material and shaped to simulate the front of the RSV. By use of the absorber material and metal plate, the near-field effects of the nose assembly of the RSV were studied as a function of the positioning of the absorber material relative to the plate and antenna.

The interior of the van is fitted with instrument benches and a seat for the equipment operator. Figure 66 shows the video camera in front and the radar recorder in back of the van with its supporting equipment. The camera is fitted with a wide-angle lens to give a panoramic view of road conditions. It is mounted next to the driver, strapped down on the motor housing. A view of the scene presented to the camera through the windshield is shown in Figure 67.

In addition to the camera, the test van is also equipped with a velocity sensor and steering wheel indicator. The velocity sensor is a generator-type unit attached to the speedometer cable whose output is a frequency directly proportional to velocity. The steering wheel sensor is a potentiometer attached to the front wheel linkage. The resistance of the potentiometer is part of an R-C network of an astable multivibrator whose frequency therefore varies as a function of steering wheel angle. Information from the three sensors, camera, steering wheel, and velocity sensor is recorded by the Panasonic* video tape recorder.

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*Panasonic Co., Secaucus, NJ.

FIGURE 65.   TEST VAN FOR RECORDING OF VIDEO AND RADAR INFORMATION.

A block diagram of power sources for instrumentation and environmental control is shown in Figure 68. AC power for the instrumentation, especially the video equipment, is provided by a Deltec* static inverter. This unit provides a sinusoidal output of 110 VAC at 60 Hz $\pm0.15\%$. The inverter has a power capacity of 1.2 kW. The power input to the inverter is provided by an additional heavy duty 135-A Leece-Neville** alternator with a 250-A/hour battery backup. The AC power for the environmental control and the less frequency-sensitive instruments is provided by a 4-kW Onan[†] motor generator mounted in a separate compartment at the rear of the vehicle. The environmental control for the mobile lab is provided by an Intertherm[††] RV roof-mount airconditioner. The unit provides 12,600 BTUH of cooling and 5400 BTUH

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*Deltec Corp., San Diego, CA.
**Sheller Globe Corp., Leece Neville Div., Cleveland, OH.
 †Onan, Huntsville, AL.
††Intertherm, St. Louis, MO.
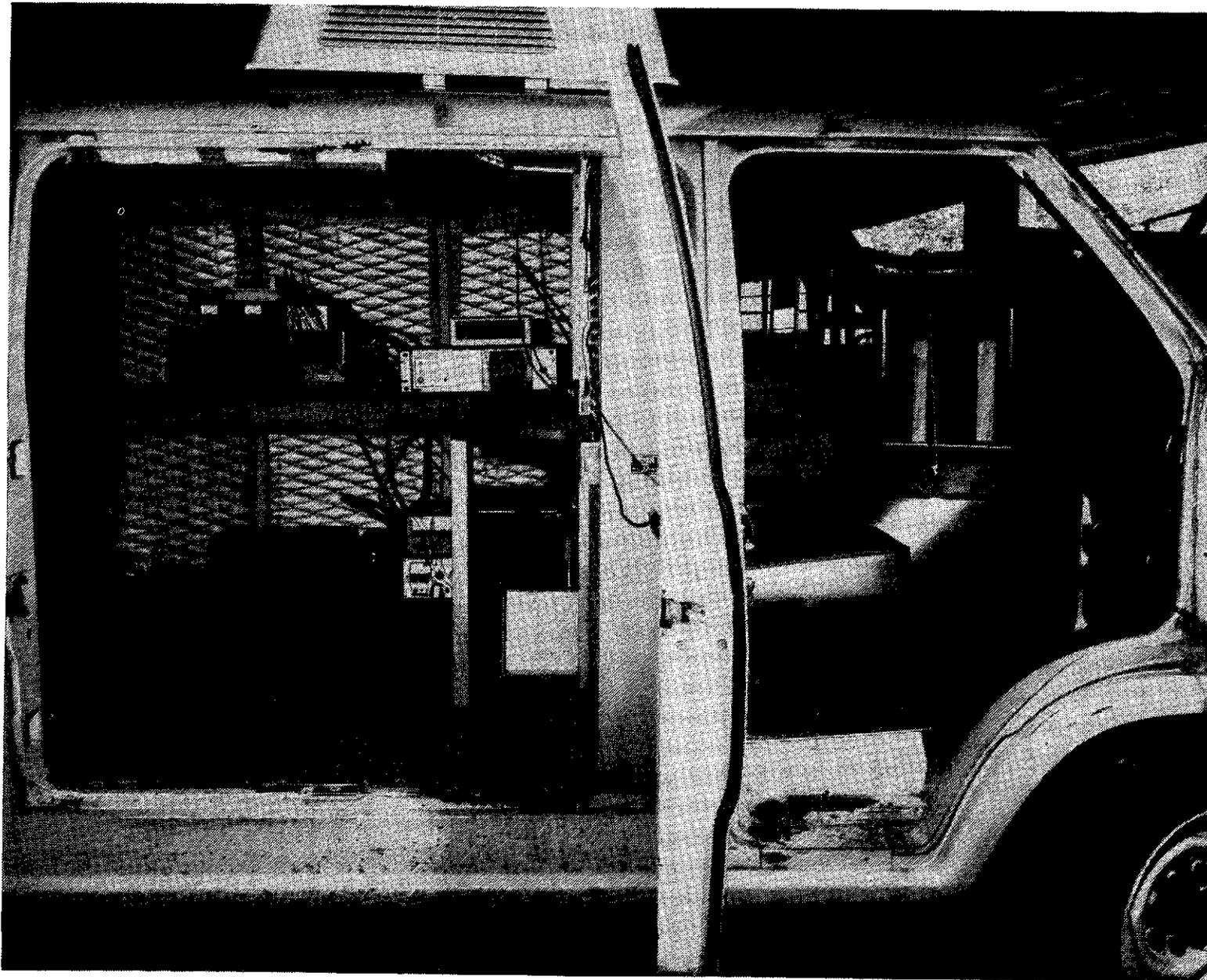
FIGURE 66. INTERIOR OF TEST VAN.
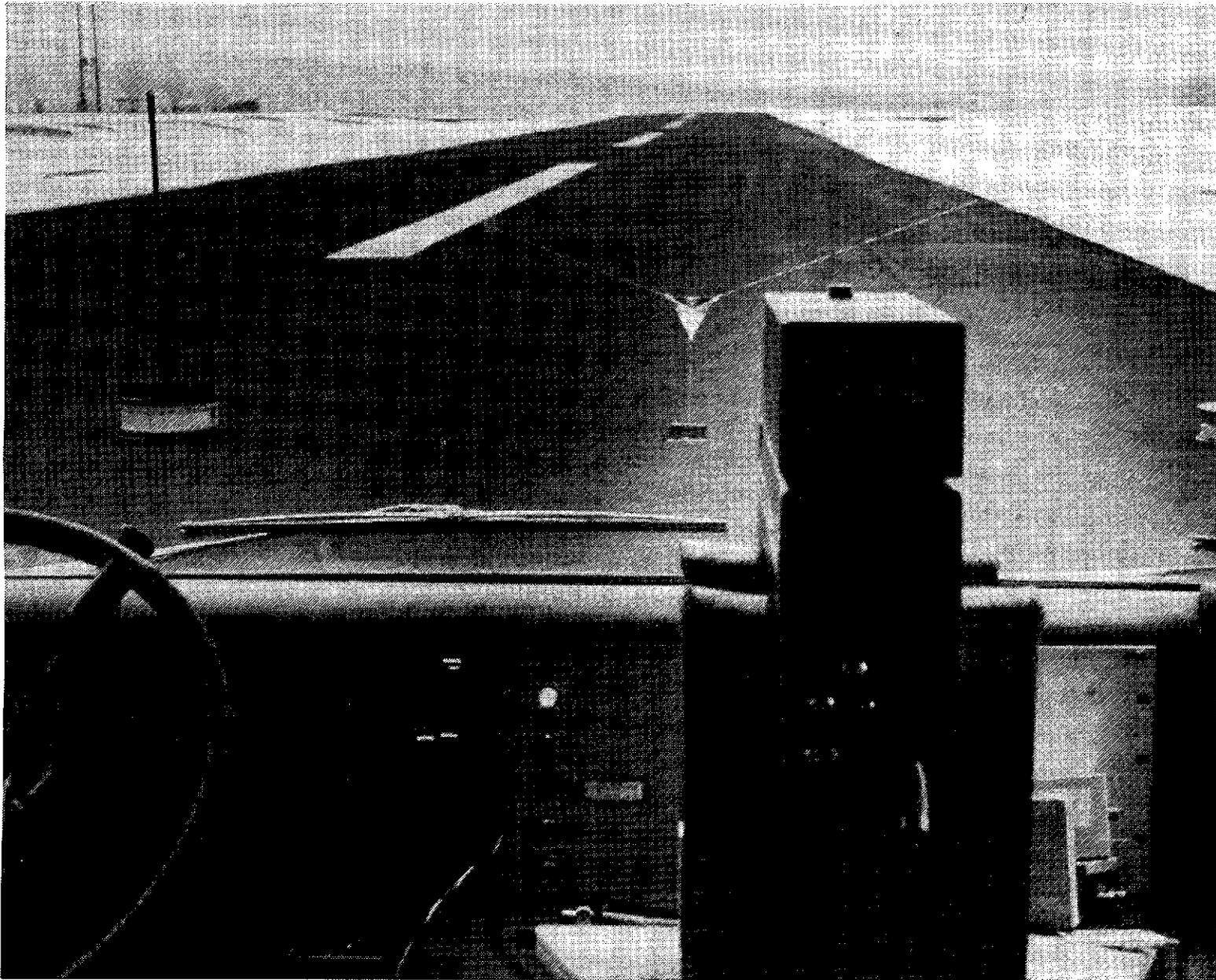
FIGURE 67. VIEW FROM TEST VAN DURING CMS TESTS ON AIRPORT RUNWAY.
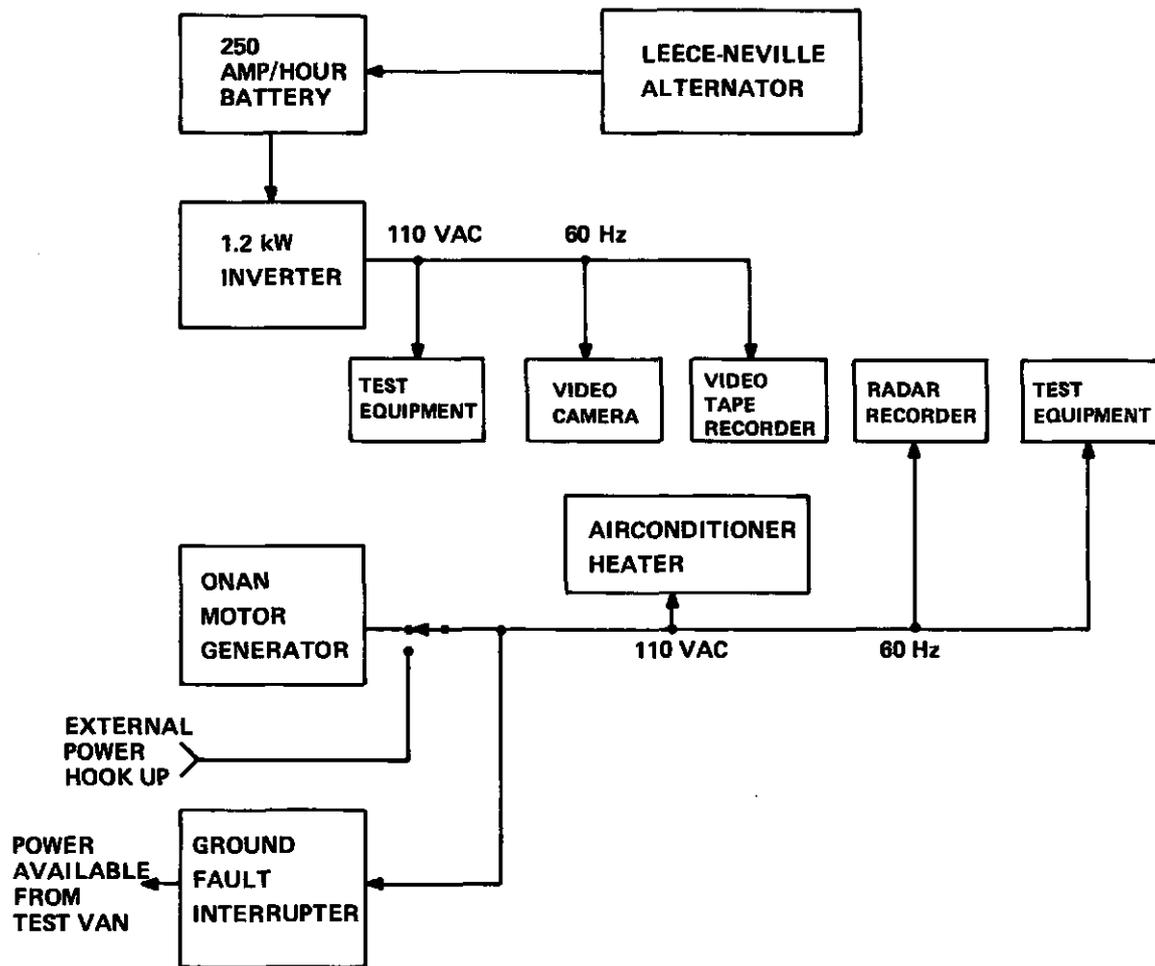
FIGURE 68. BLOCK DIAGRAM OF POWER DISTRIBUTION IN TEST VAN.

of heat. The Intertherm unit has been rewired to operate in a bucking mode to alternately heat and cool so that a relative humidity of 40% maximum could be maintained. The low humidity is necessary for the tape used with the recorders. A switching arrangement is available to power all equipment in the van from an external AC line voltage. In the field, AC voltage is available from the van through a ground fault interruptor protected circuit.

The test van has proved itself extremely valuable in the testing of all X- and Ku-band monostatic and bistatic radar systems. It was also used in simulated crash tests with disposable 1- and 10-m^2 targets at various speeds, on a runway at a nearby airport, as shown in Figure 69. The most extensive use of the vehicle was for recording radar returns and video representations

FIGURE 69. TEST VAN DURING CMS TEST WITH EXPENDABLE TARGET.

of actual traffic situations. These radar recordings, which were used for
the optimization of the CMS algorithm, were performed during different weather
conditions and with a variety of road and traffic scenarios.

B. COLLISION-MITIGATION SYSTEM TESTS

One of the problems encountered during Phase II was the testing and evalu-
ation of hard- and software for the mitigation system. Rather than repeatedly
drive a fixed route and possibly tailor a system to operate only for that
peculiar case, we found that a better, more true-to-life approach is to drive
as much as possible in many different scenarios. However, following the random
driving procedure still made system evaluation subjective. For example, an
event that occurred in a particular location on a road with a particular traf-
fic pattern and under unique weather conditions might cause a false alarm dur-
ing testing. Corrective software and/or hardware changes would therefore be
made to the system. Returning to the same location where the original false
alarm occurred would possibly indicate that we no longer receive a false alarm.
The question is, have we really accomplished anything? The answer can only
be perhaps. Returning to the same location only partially ensures a repeat of
road condition. The traffic pattern and weather condition during the initial
test that may have given a false alarm can not easily be repeated.

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During Phase III, we resorted, therefore, to a more rigorous approach for testing and algorithm optimization. A system was developed that recorded both the beat frequency return from the radar and the video information from the scene that the radar was illuminating. In addition to the radar and video recording, the audio track of the video recorder was used to read both speed and steering ·information. By use of this recording system a tape library of a variety of traffic situations was acquired. Playback of the recording system through the microprocessor would thus give perfect repetition of events. Hard- and software changes could be made and the effect of these changes could repro- ducibly be observed when the tapes were played back.

A block diagram of the recording system is shown in Figure 70. The video output from the camera, trace (a) of Figure 70, shows the video format. The camera generates horizontal sync pulses every 63 µs. Between the 10-µs-long sync pulses, the video information is contained which represents a single line (horizontal) on a video monitor. The video system uses random interlace which means a vertical sync pulse moves through the horizontal sync pulse every 1/16 of a second. The horizontal line frequency of the camera was chosen as the system clock.

The video output from the camera feeds into a video tape recorder (VTR), a switch, and a sync stripper circuit. The sync stripper circuit picks up the sync pulses from the video. To eliminate the effect of the vertical sync pulse moving through the horizontal sync pulses, the horizontal sync pulses are fed to a digital phase lock loop (DPLL) which operates at the horizontal line frequency. The output of the DPLL is divided down to give 977 Hz, which corresponds to the repetition frequency of the radar modulation. To further smooth the square wave generated from the horizontal line frequency, the divided-down signal is fed to a DPLL operating at 977 Hz. The output of this circuit, a 977-Hz square wave, goes to three locations. First, the 977-Hz square wave is used to generate the triangular wave to modulate the radar system TEO. The 977-Hz square wave is also used to provide external sync for a radar recorder, thereby electrically synchronizing the video and radar re- corder, and finally the 977-Hz square wave goes to the sync pulse generator and combining circuit. The positive and negative transitions of the square wave trigger one-shot circuits.

The relationships between the sync pulse generator and the incoming square wave are shown in diagrams (b) and (c) of Figure 70. The wider sync pulse
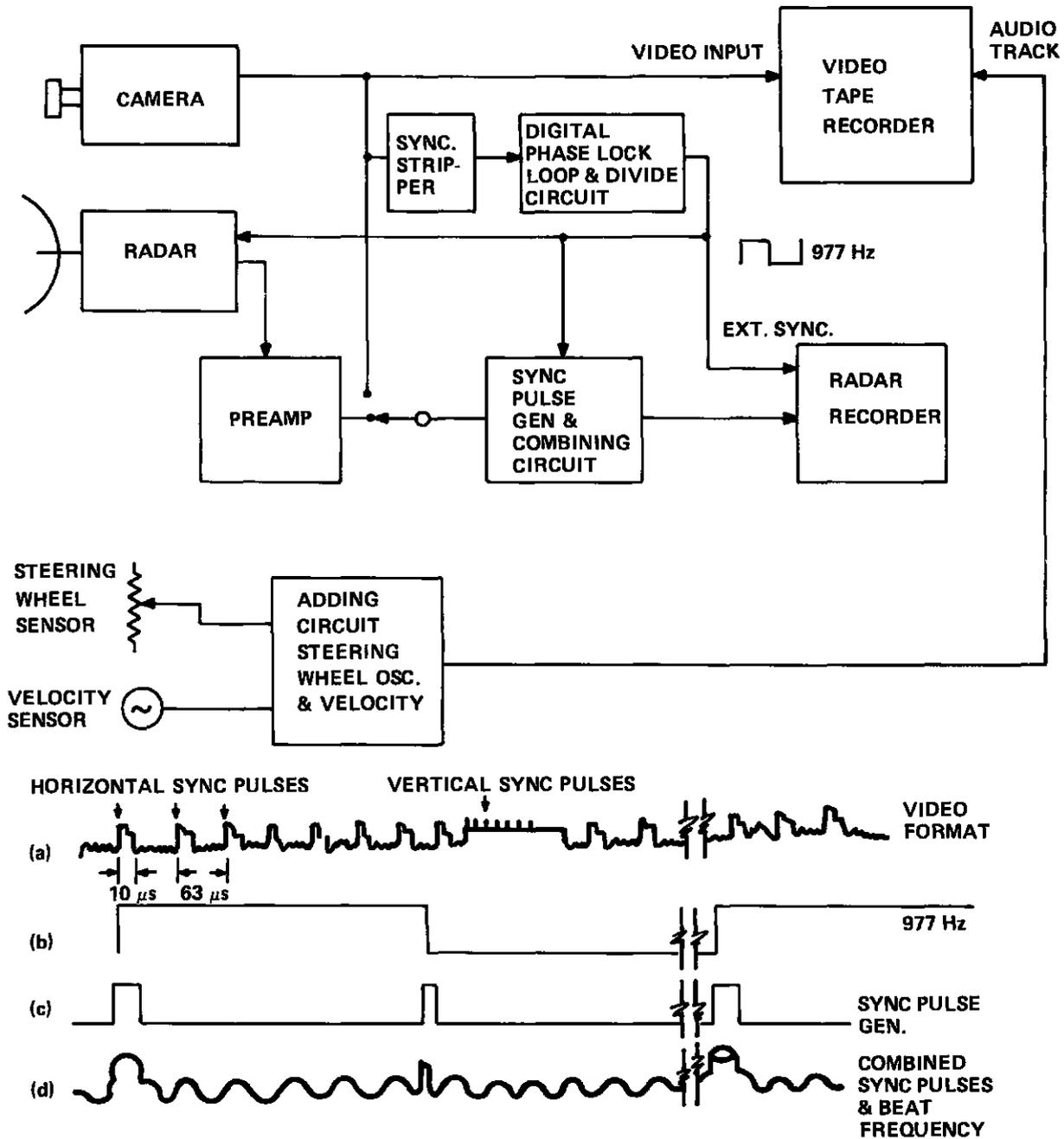
FIGURE 70. BLOCK DIAGRAM AND WAVEFORMS OF RECORDING SYSTEM.

corresponds to the positive transient of the square wave. The sync pulses generated from the square wave are combined with the beat frequency return from the radar preamplifier and recorded. The reason for the simultaneous recording of the sync pulse and the beat frequency is to maintain the proper phase relationship between the beat frequency waveform and the square wave that is used to modulate the TEO.

Two additional sensors on the test van are used to record velocity and steering angle. The pulse train from the steering-wheel angle sensor and the velocity information are combined and both recorded on the audio track of the VTR. The recording system therefore records the beat frequency return from the radar postamplifier in correct phase relationship with respect to the modulating square wave.

The video tape recorder used with the system is a Panasonic NV-5120, a standard consumer type cartridge unit with a recording time of 30 minutes. The radar recorder is a flight test "Star" manufactured by RCA in Camden, NJ for military use. This unit has a 3-MHz bandwidth (modified) and is capable of being synched to an external source (977-Hz square wave). The "Star" recorder uses standard video tape and can record about 20 minutes.

The block diagram of the playback system is shown in Figure 71. The output of the VTR is fed to the TV monitor. The video recorded on the tape recorder is also passed on to a sync stripper circuit and DPLL divider circuit that generates a 977-Hz square wave from the horizontal line frequency of the recorded video. The 977-Hz square wave is used to externally sync the radar recorder. The output from the radar recorder goes to another sync stripper circuit which strips off the pulses corresponding to the transitions of the original waveform. The output of this circuit goes to two locations. The first location is a DPLL and square-wave reconstruction circuit which restores the original modulating square wave. A switch is used to determine the positive transition by referring to the wider sync pulse that had been recorded. The second location that receives the stripped sync pulse is a sync canceling circuit. Another input to this particular circuit is the beat frequency which includes the sync pulses from the radar recorder. The sync canceling circuit subtracts the stripped sync pulse from the beat frequency, which then goes through a radar postamplifier to the microprocessor.

The audio track of the VTR is separated by filtering, and velocity information and speed information are fed separately to the microprocessor. The microprocessor thus receives the beat frequency input, a 977-Hz square wave, and the sensor inputs. The microprocessor response is indicated by a self-scan unit or by reading out memory locations from the evaluation board using an execuport terminal. A photograph of the system set up in the playback mode is shown in Figure 72. At the left is the "Star" recorder; next to the "Star" recorder is the Panasonic recorder. The monitors and self-scan display are visible in the photograph as well.
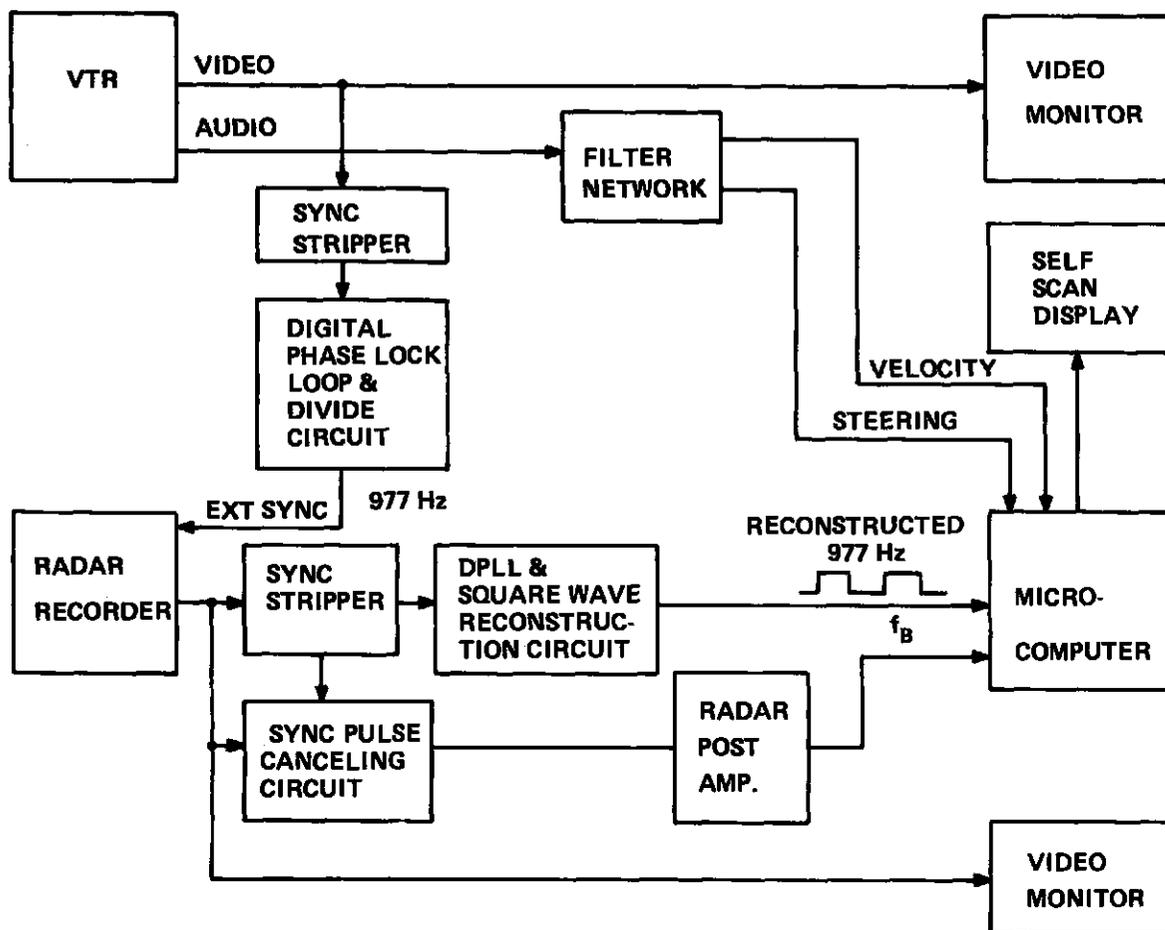
FIGURE 71. BLOCK DIAGRAM OF PLAYBACK SYSTEM.

The purpose for using two video monitors is to synchronize the data recorded by both recorders. The two recorders are always electrically synchronized, but only in multiples of the sync pulses. To sync the two recorders in time, video information is simultaneously recorded on both recorders for a short period of time. During playback, the video recorder is started first, advanced to an easily identifiable scene, and frozen. (The Panasonic VTR has stop-action capability.) The radar recorder then is started and when the video scenes of both monitors match, the Panasonic unit is restarted and both recorders are in time synchronization.

With the recording system loaded in the test van, a large variety of scenarios were taped. Several runs were made on Route 1, a four-lane divided highway with moderate-to-heavy traffic. These runs were made with both the X-band and Ku-band bistatic radar systems. Two tapes were made during light
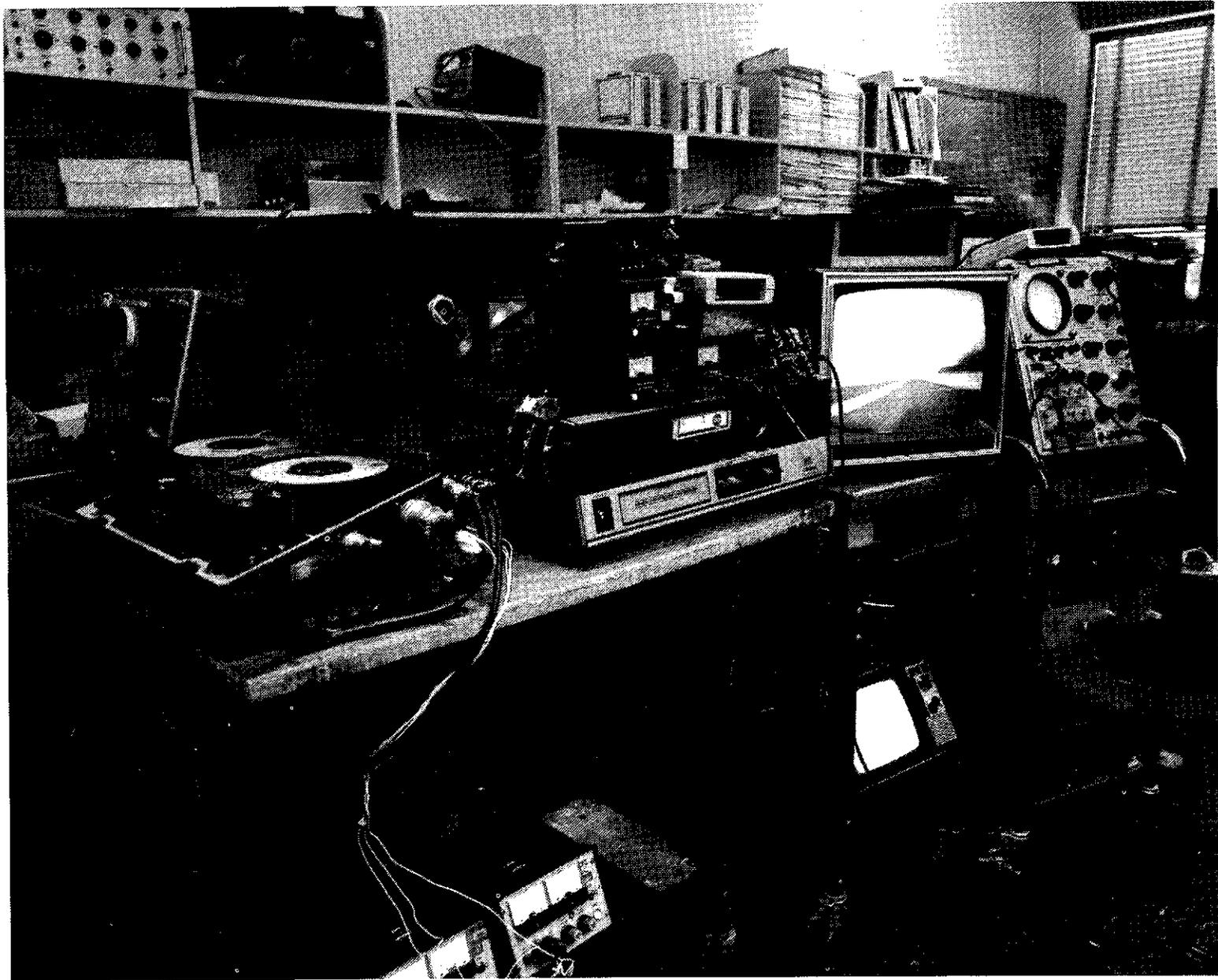
FIGURE 72. SYSTEM FOR SIMULTANEOUS PLAYBACK OF RADAR AND VIDEO INFORMATION.

and moderate snow conditions on Route 1. An attempt to record data during a severe blizzard failed because only video data was inadvertently recorded on both recorders. Recording runs were also made on Route 206, a heavily travelled two-lane road with a variety of curves. The effect of very hilly terrain was recorded northwest of Princeton.

In order to investigate the effects of bridges and tunnels, several recording runs were made to New York City. A recording run was also made on the NJ Turnpike, a six-lane divided highway with limited access. When it became clear that the Ku-band bistatic system was definitely superior to the X-band system, several of the X-band tapes were erased and recorded over with Ku-band data. Runs through a disposable target at a nearby airport were also recorded. The airport runs were made for 1-m^2 and 10-m^2 targets at 20, 30, 40, 50 and 60 mph.

The use of this recording system greatly helped in the systematic evaluation and optimization of the radar system. By playing back the tapes, the early version Phase III CMS radar interface hardware could clearly be identified as more sensitive to a variety of target conditions than the Phase II CMS radar interface card. This was demonstrated to DOT and Minicars personnel in September 1978. Another recorded tape during playback through the microprocessor indicated a constant offset in the range-rate readings. While the tapes were rerun, the microprocessor was halted and memory locations that contained the up and down counts were examined. An analysis of this data showed that the range-rate offset was caused by a nonlinear FM deviation in the TEO of the radar system.

The majority of the tapes had been recorded in situations that had a high probability of giving a false alarm with the CMS system. Two examples of tapes that initially gave us false alarm indications were the bridge and tunnel runs to NYC and the curve-rich part of the Route 206 run. False alarms were generated by one of the towers that supports the suspension cables of the Verrazano Narrows Bridge. Modification of the CMS software, specifically the deviation check constant, eliminated this problem. Once this correction was made to the software, the tapes were rerun to ensure that the correction did not destroy the sensitivity of the system. The deviation check tolerance tightening that eliminated the bridge tower false alarm in the first tape also eliminated the problem in the second tape.

The most informative tapes about the operation of the CMS were the airport tapes. These tapes of runs through the disposable target were considered the standard by which any changes in hardware or software were measured. The runway tapes were particularly useful to determine when a brake signal is given. The reaction time of the braking system was measured by putting a stop in the CMS software when the braking command is given. The memory contents of the evaluation-board card cage system can then be used to measure reaction time. For a given run through a target, the velocity of the vehicle is known. From the data in memory we can determine when the target was acquired (range), and the range-rate when the braking signal was given is also available. From these data the reaction time of the CMS can accurately be determined. The brake signal appeared reproducibly at a distance of at least 23 m from the target for all targets and speeds. Based on a car speed of 25 m/s (55 mph) and a brake system delay of 0.1 s, the automatic application of antiskid brakes with the above system would result in a 45% reduction in crash energy.

C. HEADWAY-CONTROL TESTS

1. System Optimization

The main requirements on a radar headway-control system are safety, driver convenience (smooth control, with minimum action required from driver), and fuel economy. Whereas false alarms are totally unacceptable in the collision-mitigation mode, which limits the active range to below 30 m, the headway control requires range information up to at least 45 m, but permits some false alarms, provided they do not lead to jerky movement of the car. Satisfactory headway control under actual traffic conditions is difficult to realize because it requires low-fluctuation, high-accuracy range and range-rate data that constantly act upon the car's throttle and thus are continuously preceived by the driver.

Since it is very difficult to separate problems caused by the control loops from radar processing problems, the initial optimization and program development for the headway control was performed with a cooperative radar system. An existing X-band FM/CW radar was modified to accept only return signals from tagged targets, as discussed in subsection III.B. By use of the cooperative system, problems with false alarms, signal dropouts, target scintillation, etc., are greatly reduced or totally eliminated. The headway-

control algorithm can thus be investigated and optimized under idealized conditions; this is important for separating the possible causes of erratic or jerky performance and helped greatly in the initial phases of the headway algorithm development.

The tagged target car provided a clean reliable return signal which could be processed to give stable, highly accurate range readings. Tests with two tagged cars simultaneously pointed to the possibility of false alarms, even with the cooperative system. For example, in gradual curves and at great distances, a tagged vehicle in the outer lane may easily be mistaken for a vehicle in the radar car's lane. Thus, although the cooperative system was very instrumental in the headway-control development, it does not represent the complete solution to the false alarm problem when there are many tagged vehicles on the road.

The initial headway-control system optimization was performed using RCA-owned station wagons for the radar car and as tagged target vehicles. The radar-controlled car was equipped, aside from the cooperative X-band radar and its associated computer, with a strip chart recorder and an inverter to permit the use of an execuport terminal in the car for on-the-road program changes of algorithm constants. The strip chart recorder provided accurate readouts of vehicle velocity, range, throttle position, and throttle control voltage as a function of time. For later fuel economy runs the car was also equipped with a highly accurate fuel metering device. A photograph of the experimental computer and recorder installation is shown in Figure 73. The system was mounted in place of one of the front seats which was removed for the testing period. The throttle of one car was activated through a chain by a linear DC motor, which in turn was controlled by the computer. This arrangement is shown in Figure 74. The potentiometer attached to the throttle axis was used only for monitoring and diagnostic purposes.

2. Road Tests

The flow chart algorithm of the headway control shown in Figure 61 is the outgrowth of a series of other algorithms that were tried and step-by-step improved to arrive at a workable control system. Initial tests with a simple vacuum-based throttle controller proved unsatisfactory until a more reproducible and linear DC motor was installed as control element. Single-loop control laws originally tried had to be abandoned in favor of more complex ones to obtain suitable, stable operation under a variety of operating conditions.
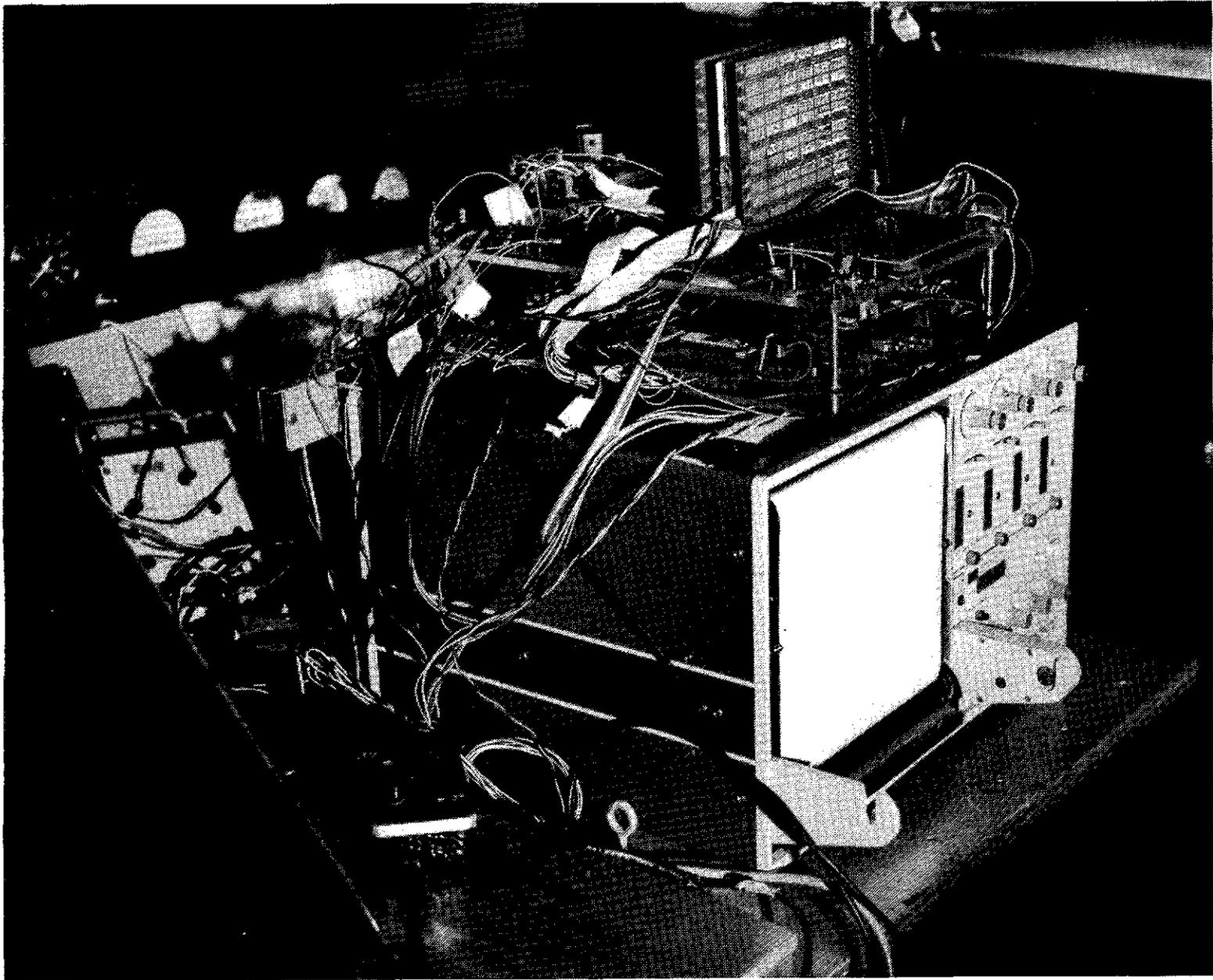
FIGURE 73. HEADWAY-CONTROL COMPUTER AND STRIP CHART RECORDER MOUNTED IN FRONT OF RCA STATION WAGON.
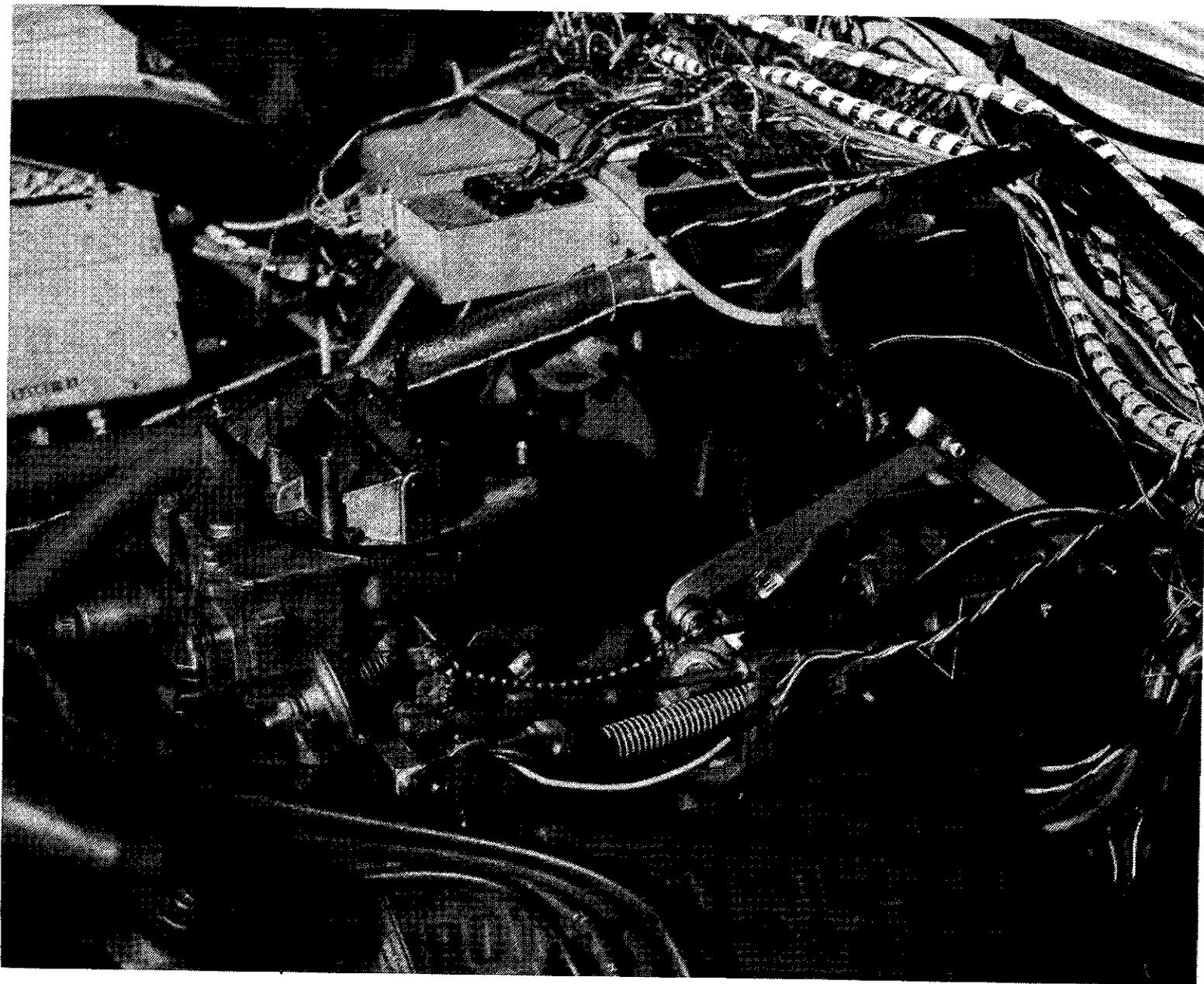
FIGURE 74. LINEAR THROTTLE ACTIVATOR.

Initial values for the constants in the final algorithm shown in Figure 61 were derived from dynamic tests performed on the car with a dynamometer and from certain driving tests. The optimization of these constants was then performed experimentally with the help of the strip chart recorder and by driving with the cooperative radar system over the same stretches of road to ensure reproducibility. The final fine tuning of the algorithm was performed with the noncooperative Ku-band radar in open traffic driving.

Figure 75 shows a typical strip chart recording from early tests. The tick marks on the uppermost line represent 1-minute intervals. The next trace represents the radar car velocity ranging from 13.6 to 25 m/s (30 to 55 mph). The next lower trace shows the range to the tagged target car ahead which in this case was operating under cruise control at 45 mph. The two lowest traces are the actual throttle position, θ_{Th}, and the control voltage, V_{Th}, to the throttle. This particular run represents early results on the cooperative system. Although the range and the velocity are kept reasonably constant (range deviations remain within ±1.5 m), the throttle control voltage fluctuates widely causing a very jerky and erratic driving behavior.

For comparison, Figure 76 shows a run obtained with the noncooperative Ku-band radar following a standard passenger car at the final stages of algorithm optimization. Here, in spite of the fact that the radar faces the full road environment in the noncooperative mode, velocity and range variations remain acceptably small while short-term throttle angle fluctuations have decreased to approximately 1 degree, providing a smooth ride free from perceptible jerks.

Aside from headway control, the system is also capable of providing regular cruise control operation and includes special programs for the transition modes of target capture, lost target, and resume speed. All of these functions were finally optimized under actual traffic conditions found on typical high-speed, limited-access freeways.

A series of controlled test runs were performed toward the end of the program to investigate the possibility of cruise and headway control having a beneficial effect on fuel consumption. Contrary to some earlier, not well documented tests which showed a superiority of cruise/headway control, no significant differences could be established within the bounds of run-to-run fluctuations (±2%) between cruise/headway control and average "sensible" driving behavior. Some drivers indeed had the habit of using a "heavy" foot on the gas pedal and, consequently, ended up with poor fuel economy. However, anybody aware
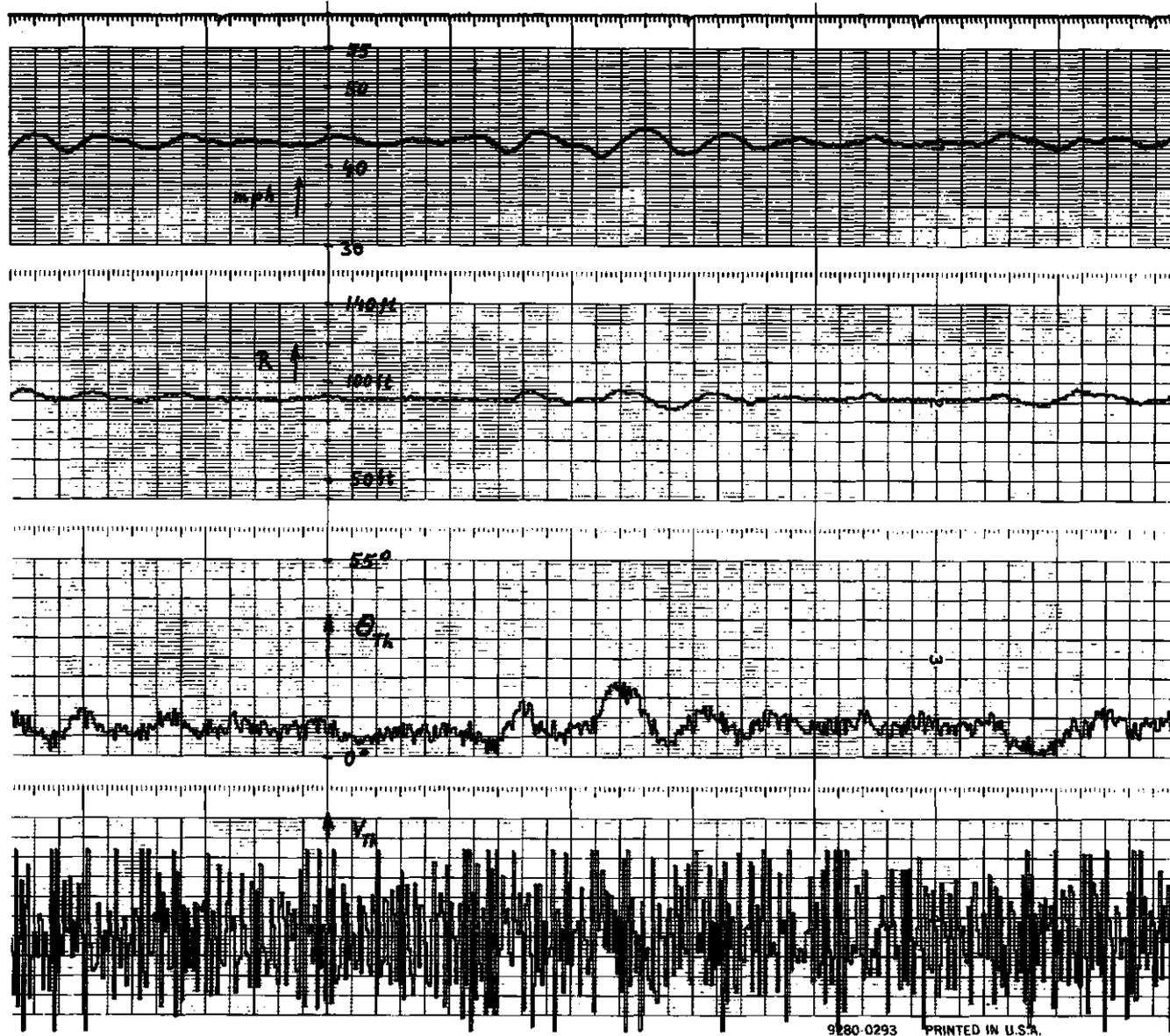
FIGURE 75. EARLY RECORDING OF COOPERATIVE RADAR CAR FOLLOWING A TARGET
CAR OPERATING IN CRUISE CONTROL AT 45 mph.
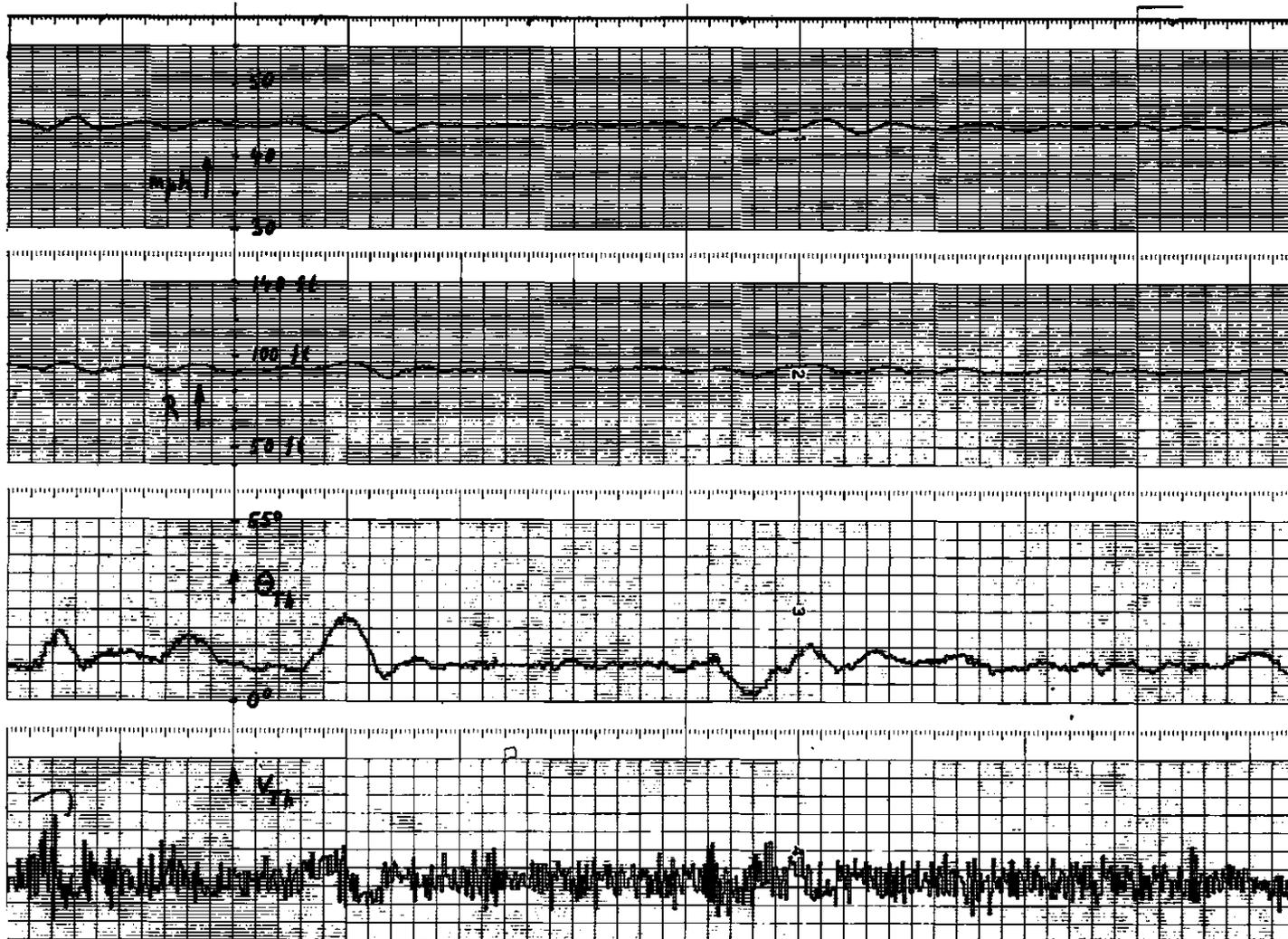
FIGURE 76. NONCOOPERATIVE Ku-BAND RADAR CAR FOLLOWING STANDARD PASSENGER CAR
(PINTO) USING OPTIMIZED ALGORITHM.

of what causes poor fuel economy could, without difficulty, duplicate the fuel economy of the cruise control. The tests were performed over a 26-mile stretch of highway in both directions to average wind loading; each type of test consisted of several runs. The fuel consumption was measured by a Fluidyne* fuel flow meter.

The following test runs were taken:

(a) Driver only (asked to keep reasonably constant speed)

(b) Cruise control

(c) Radar car following cruise control car

(d) Driver asked to keep constant distance after cruise control car

(e) Driver asked to intentionally accelerate and slow down while keeping average speed equal to cruise-control car ahead.

Tests a, b, and c did not show any significant differences in fuel consumption. Only test e showed clearly poorer performance whereas test d, while demonstrating much poorer performance in keeping a constant distance to the car ahead (± 5 m versus ± 1.5 m for the radar headway control), showed only a slight ($\sim 10\%$) increase in fuel consumption.

Based on these admittedly limited tests, we concluded that no significant claims to better fuel economy could be made. The headway-control system, however, did perform equally to a cruise-control system or the average conscientious driver and is capable of keeping the spacing between cars to much closer values than average drivers can. The latter effect may be quite beneficial in establishing better column stability and higher throughput for high-density "safe" traffic flow. However, these factors require considerably more theoretical and practical studies.

3. Headway-Control Demonstration Vehicle

The unavailability of a suitable RSV for headway-control development made it necessary to use an RCA station wagon for algorithm optimization. For demonstration purposes the car was finally stripped of all the excessive electronic attachments and prepared as a demonstration vehicle. Figure 77 shows the RCA headway/cruise control car with a Ku-band bistatic radar attached to the front.

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*Fluidyne Instrumentation, Oakland, CA.

FIGURE 77. HEADWAY-CONTROL RADAR MOUNTED ON RCA STATION WAGON.

The car is also equipped with a display which provides range, range-rage, distance error, and vehicle speed information. This display is used for demonstration purposes only and would not be present in a regular headway-control-equipped car.

Operation of the headway-control system is similar to operation of a conventional cruise control, since the computer makes all decisions concerning how the radar information is to be used. The directional signal control stalk has three momentary contact switches added for "Set," "Set 55 mph," and "Resume." None of the momentary switches can be activated below a speed of 9 m/s (20 mph). The "Set 55 mph" switch is a convenience feature not found on conventional cruise controls, but is easily implemented in software. An on/off toggle switch is used to inhibit control of the throttle, but in the present system the display will be actively updated even in the off position. This is useful for checking the operation of the radar.

In general, drivers adapt quickly to the headway-control system, learning to use it within a few minutes. The major difficulty is learning which circumstances require driver braking, and which can be handled adequately by computer release of the throttle. As a rule the computer can handle closing rates on the order of 2.3 to 4.5 m/s (5 to 10 mph), depending on where the target is acquired. The system has been driven extensively in real traffic, following cars and trucks of various sizes and shapes, and found to perform smoothly in most situations.

Figure 78 shows the format of the Burroughs display when the system is in the headway control state. The values $\hat{R}$, $\hat{\dot{R}}$, $(R_{des} - \hat{R})$ and $\hat{v}$ are displayed. The warning light requires two consecutive range-rates smaller than -3 m/s for activation. Nonsmoothed range-rate is used for rapid response. The light goes out when $\dot{R} > -3$ m/s. The light is also activated if range is less than 10 m. If the driver activates the brake, the throttle immediately returns to the closed position and the display information disappears. The car is then fully under the control of the driver.

A-113

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R = 1 0 2   - 0 3 E R R = + 1 5   F t   S = 4 0   M P H     +   ⊛
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↑ DISTANCE TO TARGET IN ft

↑ ± RANGE RATE IN ft/s

↑ ± ERROR

↑ SPEED IN mph

↑ + FOR ACCELERATE
– FOR DECELERATE

↑ WARNING LIGHT
$\hat{R} < 10$ m
$\dot{R} < -3$ m/s

FUNCTIONS: NORMAL CRUISE CONTROL
CAPTURE
HEADWAY CONTROL
LOST TARGET
RESUME CRUISE CONTROL

CONTROL STALK: SET: CHOOSE CRUISING SPEED
SET 55:   CRUISING SPEED 55 mph
RESUME: RETURN TO LAST SET SPEED
ON/OFF: DISABLES THROTTLE CONTROL

FIGURE 78. DISPLAY FORMAT FOR HEADWAY-CONTROL DEMONSTRATION.

SECTION VII

INSTALLATION OF EQUIPMENT INTO THE RSV

A. GENERAL

The original program plan called for the integration of all electronic systems into a high-technology version of the RVS. This includes, aside from the RCA-developed components, an antiskid system, an airbag deployment system and a computer-controlled automatic transmission. Due to delays in getting the RSV to RCA Laboratories for installation of our systems and difficulties with the operation of the automatic transmission, the final integration of the CMS and headway control into the RSV had to be postponed to mid-1980 at which time the car should return to RCA Labs and be equipped with all other electronic systems and be completely operational. In the meantime, the RSV was instrumented with the alphanumeric display and associated microcomputer and sensors. The CMS computer was installed and interconnected for tryouts of the basic functions and then removed again. Also the fitting of the antenna radome into the nose section of the RSV was completed; it awaits final installation after all other body work on the RSV is finished. The performance of the CMS and headway-control system has been demonstrated so far only on RCA-owned vehicles.

B. MICROCOMPUTER AND SENSOR INSTALLATION

The dashboard display and CMS/headway-control microcomputers were installed in the luggage compartment of the RSV. Proper sensor connections to both microcomputers were made with conventional twisted wire pairs. Only the radar was connected via two coaxial lines to avoid spurious pickups on the modulation and IF return lines. A dedicated 12-V and ground line was run from the battery to a terminal strip mounted on the side wall of the front compartment near the two RCA microcomputers. The purpose of running dedicated lines to the microcomputers and radar was to minimize the effects of possible ground loops or excess voltage drops between the battery and the respective systems.

The following sensors were interfaced, calibrated where necessary, and checked for proper operation: hand-brake switch, brake fluid level switch, door switch, water temperature sensor, oil pressure sensor, velocity sensor, fuel flow sensor, fuel level sensor, tachometer, battery status indicator, restraint system status, and brake and steering wheel position switches. All

sensor wires were connected to a terminal strip mounted on the top of the dash-
board display microcomputer. In this way, if necessary, each sensor could be
tested individually for proper operation. A set of instrument gauges that came
with the RSV was used as reference to calibrate the dashboard display micro-
computer with respect to water temperature and oil pressure. The sensors that
monitored these functions were connected by dashboard mounted switches to either
the gauges or the dashboard microcomputer.

Two intra-microcomputer connections were also made. The first connection
was between the Dubner system microcomputer and the RCA dashboard display micro-
computer. This connection, after buffering, is used to pass on the velocity
pulse train monitored by the Dubner microcomputer system. A connection between
the dashboard display microcomputer and the CMS microcomputer passes on infor-
mation when the calculated velocity is above the set speed in the CMS algorithm
by setting an appropriate level.

The steering angle microswitch and associated hardware were mounted in an
enclosed area adjacent to the luggage compartment that afforded protection from
harsh automotive environmental conditions. An illustration of the electro-
mechanical arrangement used to determine when the preset steering wheel angle
cutoff is exceeded is shown in Figure 79. The cams and microswitches are ad-
justed to allow 1-1/2 degrees of steering on either side of center. Exceeding
this limit on either side provides a 5-V level to a flag line on the CMS micro-
computer. A calibration of the wheel's center alignment was made by following
a 40-m-long line on the test range and noting the steering wheel position.
Using alignment plates marked in degrees with the front wheels, the micro-
switches and cams were set to allow 1-1/2 degrees steering on either side
of the center position before triggering the flag level. The lock-to-lock
steering for the RSV is approximately 30 degrees on either side of the center
position. The 1-1/2-degree steering angle was chosen as a compromise between
having a good margin against false alarms on one hand, and not being too sen-
sitive on the other hand. The steering wheel angle tolerance can be adjusted
independently to have a greater or smaller cutoff angle on either side of the
wheel's center line.

The airbag sensor circuit consists of resistances associated with the
three impact sensors in series with the two paralleled airbag squibs. The air-
bag sensor interface (see Figure 52) monitors the voltage drop from the squib
to ground. Thus, should any one of the six sensor switches (each impact sensor
includes two sensor switches) have accidentally shorted out or more than two
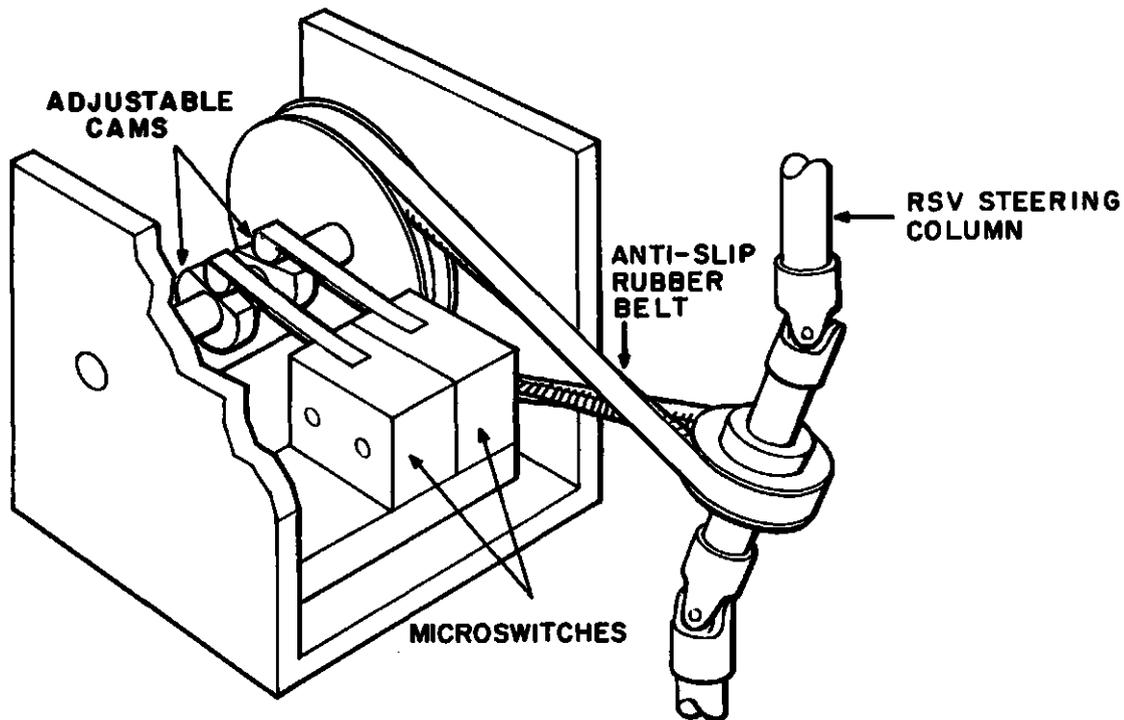
FIGURE 79. ELECTROMECHANICAL ARRANGEMENT FOR
STEERING ANGLE DETERMINATIONS.

be open-circuited, the sensor interface will provide a warning message on the
display. The problem of determining whether the squibs themselves are possibly
either open or short circuited is being addressed separately by Minicars.

A Burroughs high brightness display with two bezels and edge lighting was
mounted in the display housing that was delivered with the RSV. The assembly
was temporarily mounted by a bracket to the RSV dashboard and interfaced with
the dashboard display microcomputer through a set of connectors for ease in
installation and servicing. A switch was installed on the dashboard to select
either the upper or lower bezel with the corresponding proper display format.
A potentiometer permits variation of the intensity of edge lighting of the
bezels. The final installation of the display in the proper dashboard location
will be made after Minicars replaces the present experimental dashboard with
the final version.

C. RADAR SAFETY CONSIDERATIONS

In view of the growing concern on part of the public and the government
with nonionizing radiation effects, the microwave power typically radiated from
a collision-mitigation/headway-control radar was investigated theoretically as
well as practically.

Our present Ku-band radar emits nominally a power of 10 mW from an antenna
with a gain of ~30 dB. In the far field of the antenna, the power density de-
creases as $\frac{1}{R^2}$ with R, the distance from the antenna. Closer to the antenna
this law does not hold since we are in the near field or Fresnel region of the
antenna. By normalizing the field in the far-field region, we can recalculate
the field intensities closer to the antenna, as shown in Figure 80. The field
pattern undergoes various spatial maxima and minima due to interference in the
near field. Based on a radiation of 10 mW from a 30-dB antenna, the maximum
power density is 20 $\mu W/cm^2$ at a distance of 0.6 m.
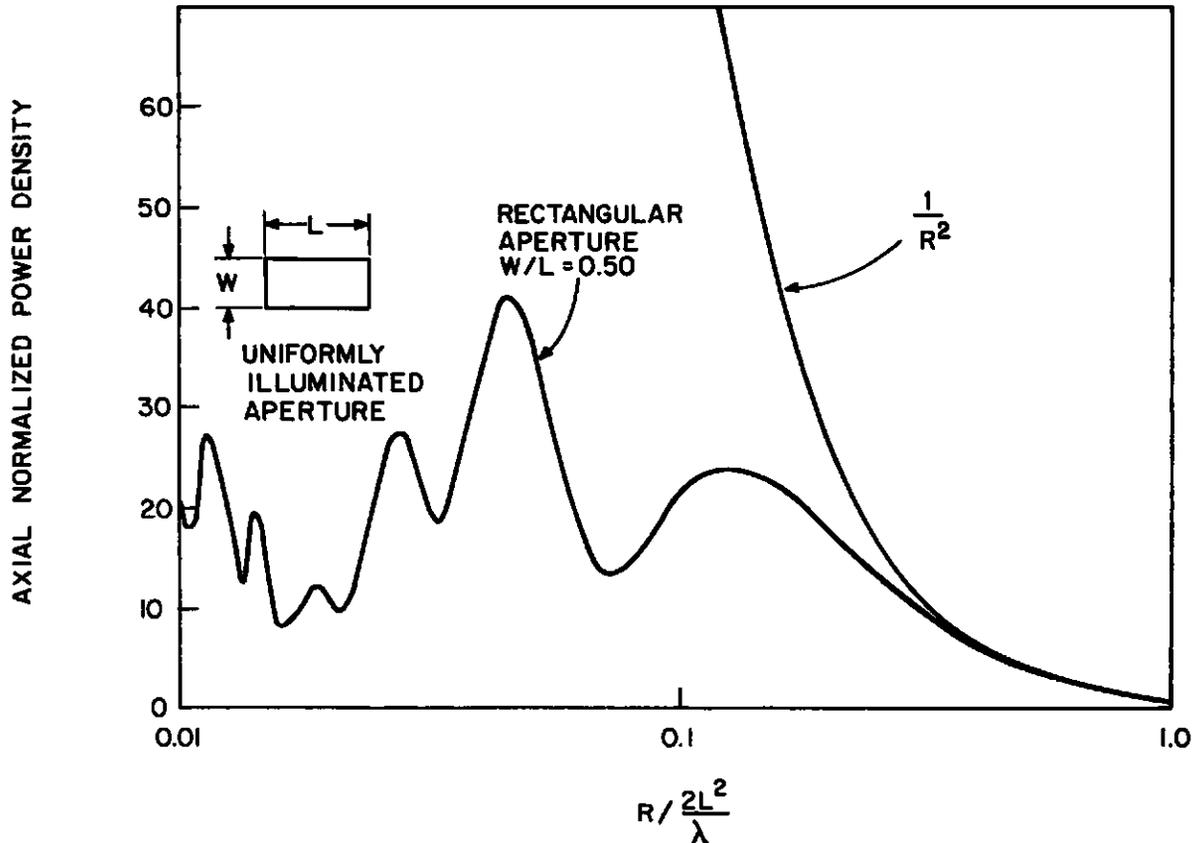
FIGURE 80. ANTENNA FIELD INTENSITIES.

Actual measurements performed with a small waveguide antenna in the near-field area of the antenna showed a maximum power density of 15 $\mu W/cm^2$ at a distance of approximately 1 m from the antenna. These measurements are not to be considered very accurate since the presence of the waveguide distorts the existing field pattern; however, the measured values give a good order-of-magnitude indication of what fields can be expected in front of the antenna.

At present, the United States microwave radiation limit is 10 mW/cm^2, which is based on the onset of thermal effects in the human body. The Soviet Union, on the other extreme, maintains a limit for continuous exposure as low as 10 $\mu W/cm^2$ to avoid possible neurological and physiological effects. Substantial controversy exists as to where a realistic safe limit should be drawn. In any case, the amount of nonionizing radiation to which humans may be exposed from CMS/headway radars is very low, and for distances above a few meters is even below Russia's very stringent standards. In addition, the radar could be easily equipped with a solid-state switch that prohibits radiation below a certain critical speed, which would further reduce the radiation exposure of humans in actual traffic.

SECTION VIII

COST ESTIMATES

A production cost analysis of the CMS and headway-control system was pre-
pared using RCA's PRICE program [12].   The system analysed consists of an FM/CW
Ku-band bistatic radar and a three-chip microprocessor controller set (since
large production quantities are assumed, VLSI would be implemented) in a metal-
lized weather-tight plastic box.   The cost of the velocity and steering wheel
position sensor, the throttle controller for the cruise control system, inte-
gration, and testings are included in the overall production cost figure.   The
complete CMS and radar cruise control system is estimated to have a production
cost figure of $177.   This production cost figure is based on 100,000 units,
1979 dollars and 1985 technology.

The PRICE program gives a range of production costs for each item.   The
upper value is the worst-case prediction.   The actual production cost of an
item will be somewhere between the high and low extremes.   The cost breakdowns
are as follows:

The electronics for the radar and processor are assumed to be contained
within a metallized weather-tight plastic box.   The box also contains the
bistatic radar system consisting of two antennas and associated electronics.
The purpose of metallizing the box is to provide a ground plane for the printed
circuit antennas.   The predicted production cost range of the metallized weather-
tight plastic box varies between $12.92 to $18.77, with $15.07 the average cost.
The microprocessor system that will provide the CMS and cruise control functions
is assumed to require a total of three VLSI chips.   The production cost for the
three-chip system including the PC board on which the ICs would be mounted
ranges from $7.99 to $12.98.   The average cost of the three-chip microprocessor
controller including the necessary ROM and RAM is $9.58.

The cost evaluation of the radar system, antennas, transmitter and receiver
is based on the use of microwave IC technology.   The bistatic antennas are fab-
ricated in PC form.   The modulating and analog processing circuitry is assumed
to be in IC form.   The computed cost range low is $92.67; the maximum cost com-
puted for the Ku-band radar production system is $144.95 with an average of

12.   R. F. Freiman, "PRICE - A Parametric Cost Modeling Methodology," RCA
      Government and Commercial Systems, Cherry Hill, NJ, May 1978.

$112.50. An electromechanical solenoid that is used to control the throttle was also estimated by a description of the size and complexity of the device. The PRICE system predicts a cost range between $18.48 and $28.31.

The steering and speed sensor were the final components of the CMS/headway-control system that were cost evaluated. The speed sensor is described as a device that outputs a pulse train at logic voltage levels whose frequency is a function of velocity. The steering wheel sensor is a geared potentiometer attached to a steering arm on the front wheel. Based on a description of the function of both sensors and the approximate size of each unit, the sensors have a predicted production cost of $7.06 to $10.89. The assembling of the overall systems and testing is computed by PRICE to be $10.00 per unit.

The production cost of the complete CMS/headway-control system (excluding braking system) ranges from $147.26 to $228.51. The average $177.00 figure is based on a production run of 100,000 units.

SECTION IX

CONCLUSIONS AND RECOMMENDATIONS

The present effort under DOT sponsorship has contributed greatly to establishing the viability of the radar concept for automotive applications. Truly promising results have been obtained with a radar-controlled collision-mitigation system. With the help of tape recordings of a large number of traffic, road, and weather conditions, a systematic approach to the optimization of the hard- and software of the radar-controlled safety system has been made possible. The importance of these tests lies in the recording of raw radar data that permit a thorough comparative study of how different signal-processing techniques affect the false alarm rate while, at the same time, giving valuable information about the minimum detection distance and the speed with which a proper alarm (output to initiate antiskid braking) is being generated from experimental targets of various cross sections.

With the present system adjusted for practically no false alarms, a target as small as 1 m^2 is recognized at a distance of at least 23 m, and braking is initiated if the closing rate is high enough to make a severe collision unavoidable. In a car traveling 25 m/s (55 mph) against a fixed object, this action results in a reduction of crash energy by ~45%, an amount that can be very significant with respect to the injuries sustained by the car's occupants. Obviously such a system does not provide the full solution to crash survivability but, if combined with other means such as car structures with higher impact tolerance and use of airbags, a substantial societal savings can be achieved.

It also has to be realized that the system discussed here represents only a feasibility demonstration of the present state-of-the-art; further work in radar processing certainly could still increase the minimum detection range to around 30 m while keeping false alarms in check. Some of the desirable improvements that are considered feasible, but were not implemented during this program, are a further reduction in size of the antenna by using higher frequencies and the introduction of range gate processing to reduce weather interference and multiple-target problems. Also, it can be assumed that further progress in signal processing can be made to increase the safety margin against false alarms.

Aside from the collision-mitigation safety aspects, the present DOT program also addressed two other important areas, an electronic display as driver

aid and automatic cruise/headway control. The final high-technology version of the RSV was equipped with an alphanumeric display which presents driving-related data as well as a series of warning messages if a vital part of the car malfunctions. The display system corresponds closely to the one developed originally during Phase II of the program and includes some refinements and additions, among others a conversion to metric readouts of all measured parameters.

The final version of the high-technology RSV was also to have an automatic cruise/headway control using the existing radar. Since a suitable RSV test vehicle was not available in time, the development of this system was carried out exclusively with RCA-owned station wagons. An experimental system was successfully developed and the algorithm optimized for operation on typical limited access highways using a noncooperative Ku-band FM/CW radar identical in design to the one used in the RSV for collision mitigation.

The cruise/headway control operates either in standard cruise control or automatically switches to a safe headway spacing mode when a vehicle in front is driving at a slower speed than the chosen cruising speed. Since the spacing between cars by the radar system can be maintained considerably more accurately than can be achieved by average drivers, such a system holds promise to provide a better throughput on highways while reducing the common safety hazards of bunching and tailgating. In addition, such a system can be expected to add greatly to the overall sales appeal of the radar and enhance the driver's convenience.

Duplicates of the hard- and software of the cruise/headway-control system were prepared for the RSV but could not be included and fully optimized because of time and certain compatibility problems. A proposal is presently being submitted for a subsequent joint effort between Minicars, Dubner Computer Systems, and RCA to solve the compatibility problems and include the headway control in the final RSV. The high-technology RSV will be returned to RCA at a future time after installation of an antiskid brake system, a new dashboard, and an improved electronically controlled transmission for the final incorporation of the radar and the above-mentioned joint effort.

While substantial progress has been made during this program to show the basic feasibility of cruise/headway control under real, every day traffic conditions, it must be realized that a large amount of work still remains to be done before such a system can be implemented in passenger cars. First, low-g

proportional braking should be included to handle most of the frequently occur-
ring situations where a slightly faster deceleration is needed than can be ob-
tained from engine braking alone; second, radar improvements such as recommended
above for the collision-mitigation system (smaller antenna and multiple target
resolution) would further enhance the system's versatility; and third, the
question of the stability of long columns of cars (under study for some time
with the driver as part of the feedback loop) will have to be looked at under
the special conditions and restrictions of radar headway control.

Finally, we want to suggest that the time has come to take a serious look
at the benefits that radar can add to the automotive environment. Plans for
fabrication of a limited number of systems should be initiated to permit a more
detailed and thorough testing of the concepts discussed here under actual road
conditions by average drivers. Extensive road tests on many cars for a pro-
longed period of time would certainly be required before a radar-based system
could be considered by the rule-making body of the government.

APPENDICES

APPENDIX A

COVERAGE PATTERN CALCULATIONS

A. BISTATIC Ku-BAND RADAR

1. Statement of the Problem

To determine the detection area of the Ku-band radar, contours of constant power were calculated. An ideal bistatic radar above a ground plane was assumed. The target was assumed to be an isotropic point source. Based on the above assumptions, the power, P_r, returned to the radar becomes

$$P_r = \frac{P_T \, G_\phi(\phi_1) \, G_\phi(\phi_2) \, \lambda\sigma \, P_m}{(4\pi)^3 \, R_1{}^2 \, R_2{}^2} \tag{A-1}$$

where,

ϕ_1 = Azimuth angle between transmit antenna and target

ϕ_2 = Azimuth angle between receive antenna and target

G_ϕ = Antenna azimuth gain function

λ = Wavelength in free space

P_m = Multipath factor

R_1 = Distance from transmit antenna to target

R_2 = Distance from receive antenna to target

A typical configuration defining the coordinate system is shown in Figure 10 in the main body of the report. The transmit and receive antennas are located at $(S_o/2, 0)$ and $(-S_o/2, 0)$, respectively, and the target is located at (x, y). The radar and target are at the same height above ground. From Figure 10, R_1 and R_2 are given by

$$R_1 = \sqrt{(x - \frac{S_o}{2})^2 + y^2}$$

$$R_2 = \sqrt{(x + \frac{S_o}{2})^2 + y^2} \tag{A-2a}$$

$$\phi_1 = \tan^{-1} \frac{\frac{S_o}{2} - x}{y} \tag{A-2b}$$

$$\phi_2 = \tan^{-1} \frac{\frac{S_o}{2} + x}{y} \tag{A-2c}$$

The multipath factor, P_m, is given by [6]

$$P_m = \left\{ (1-P)^2 + 4P \sin^2 \frac{2\pi h_1 h_2}{\lambda R} \right\}^2 \tag{A-3a}$$

where R = mean range, $(\frac{1}{2} (R_1 + R_2))$

$$P^2 = \frac{G_\theta(\theta_2)}{G_\theta(\theta)} |\Gamma|^2 \tag{A-3b}$$

$|\Gamma|$ = reflection coefficient of the road ≈ 0.5

h_1 = radar height above ground

h_2 = target height above ground

$\dfrac{G_\theta(\theta_2)}{G_\theta(\theta)}$ = relative gain of multipath component

G_θ = antenna elevation gain function

θ = elevation angle between antenna and target (0 degrees)

θ_2 = elevation angle between antenna and ground

Assuming the mixer to be linear, the output of the mixer P_r' is proportional to P_r. Since only the relative variations in power level are significant and not the absolute power levels, P_r' can be written as

$$P_r' = \frac{G(\phi_1) \, G(\phi_2) \, P_m}{R_1^2 \, R_2^2} \tag{A-4}$$

Similarly, the output, P_r'' of the preamplifier is

$$P_r'' = P_r' \, \left| H_{HP}(f) \right|^2 \tag{A-5}$$

and the output of the postamplifier P_r''' is

$$P_r''' = P_r'' \, \left| H_{LP}(f) \right|^2 \tag{A-6}$$

A-128

where $\left| H_{HP}(f) \right|^2$ = preamplifier gain function

$\quad\quad\quad \left| H_{LP}(f) \right|^2$ = postamplifier gain function

$\quad\quad\quad\quad\quad f$ = IF frequency

2. Mathematical Models

a. Multipath

The mathematical model of the multipath is given in equations (A-3a) and (A-3b). Since the target and radar are at the same height (h = 0.67 m), θ is zero and θ_2 is

$$\theta_2 = \tan^{-1} \frac{2h}{R} \tag{A-7}$$

Experimentally, $|\Gamma|$ has been found to be approximately 0.5. Knowing the gain function, G_θ, the multipath is also known as a function of distance.

b. Antenna

The gain function of the antenna is modeled as

$$G = G_H(\phi,\theta) \, G_V(\phi,\theta) \tag{A-8}$$

with $\quad G_H$ = gain function corresponding to a horizontal 32-element linear array of dipoles with a Chebyshev illumination function to realize -30-dB side lobes.

$\quad\quad\quad G_V$ = gain function corresponding to a vertical 16-element linear array of dipoles with a Chebyshev illumination function to realize -20-dB side lobes.

The array function $\psi_H(x_H)$ or $\psi_V(x_V)$ for a Chebyshev distribution can be written as [7]

$$\psi_H(x_H) = \frac{T_{nH}^2 (a_H x_H)}{T_{nH}^2 (a_H)} \tag{A-9}$$

$$T_n(\mu) = \cos(n \cos^{-1}\mu) \quad \mu \le 1$$

$$T_n(\mu) = \cosh(n \cosh^{-1}\mu) \quad \mu \ge 1 \tag{A-10a}$$

$$x_H = \cos\left(\frac{\pi S_H}{\lambda}\sin\phi\cos\theta\right) \tag{A-10b}$$

$$S_H = \text{horizontal dipole spacing}$$

$$a_H = \cosh\frac{1}{n_H}\cosh^{-1}r_H \tag{A-10c}$$

r_H = ratio of peak field to side-lobe field for horizontal array (e.g., for 30-dB side lobes $r = 31.62$).

n_H = number of elements in horizontal array −1

ψ_V is derived from a parallel development with H replaced by V

$$\text{and } X_V = \cos\left[\frac{\pi S_V}{\lambda}\sin\theta\right]$$

The effect of the ground plane is taken into account by the method of images; the ground plane is replaced by a dipole of negative polarity and spaced a half-wavelength from the given dipole. In effect one has a two element array of out-of-phase current elements $\lambda/2$ apart.

$$G_H = D\,\psi_H$$

$$G_V = D\,\psi_V$$

where D is the element directivity function with ground plane

$$D = \cos\theta\,\sin[90°\,\cos\theta\,\sin\phi] \tag{A-11}$$

Equations (A-10) and (A-11) are sufficient to calculate the azimuth and elevation gain functions.

c. Preamplifier

Since only normalized values of the return power are significant, the magnitude of the gain will be unity and only the shaping will be specified.

A maximally flat high pass filter response, $\left| H_{HP}(f) \right|^2$, was used to represent the shaping. That is,

$$\left| H_{HP}(f) \right|^2 = 1 + \left(\frac{f_c}{f} \right)^{2N} \tag{A-12}$$

where f_c = cut-off frequency

f = frequency at which response is measured

N = number of filter sections

For a stationary target, the range is proportional to frequency, so that equation (A-12) can be written as

$$\left| H_{HP}(R) \right|^2 = \left(1 + \frac{R_c}{R} \right)^{2N} \tag{A-13}$$

where $\qquad R = \dfrac{f}{1.302}$ m $\tag{A-14}$

d. Postamplifier

The gain of the postamplifier $\left| H_{LP}(f) \right|^2$ will also be represented by the shaping; a low pass maximally flat response

$$\left| H_{LP}(f) \right|^2 = \left(1 + \frac{f}{f_c} \right)^{2N} \tag{A-15a}$$

As in the preamplifier, the frequency can be expressed in terms of range and equation (A-14) becomes

$$\left| H_{LP}(R) \right|^2 = \left(1 + \frac{R}{R_c} \right)^{2N}$$

3. Calculated Results

Power contours at the output of the mixer $P_r{'}$, at the output of the pre-amplifier $P_r{''}$, and at the output of the postamplifier $P_r{'''}$ were computed using the above models. The results are shown in Figures A-1 through A-3. Because of reflection symmetry about the y axis, only the results for the positive x axis were computed.

```
          FCL,N1,FCH,N2=1,1,1,1
   100— .EEEEEEEEEEEEEEEEEEEEEE        DDDDDDDD        CCC
       .EEEEEEEEEEEEEEEEEEEEEEE        DDDDDDD         CCC
       .EEEEEEEEEEEEEEEEEEEEEEE        DDDDDDD         CCCC
       .EEEEEEEEEEEEEEEEEEEEEEEE       DDDDDD          CCCCC
       .EEEEEEEEEEEEEEEEEEEEEEEE       DDDDDD          CCCCC
    90— .EEEEEEEEEEEEEEEEEEEEEEEE      DDDDDD          CCCC
       .EEEEEEEEEEEEEEEEEEEEEEEEE      DDDDDD          CCCC
       .EEEEEEEEEEEEEEEEEEEEEEEEE      DDDDDD          CCCC
       .EEEEEEEEEEEEEEEEEEEEEEEEE      DDDDD         CCCC      BB
       .EEEEEEEEEEEEEEEEEEEEEEEEE      DDDDD         CCCC      BBB
    80— .EEEEEEEEEEEEEEEEEEEEEEEE      DDDDD         CCCC     BBB
       .EEEEEEEEEEEEEEEEEEEEEEEE       DDDDD         CCCC     BBB
       .EEEEEEEEEEEEEEEEEEEEEEE        DDDDD         CCCC   BB   AA
       .EEEEEEEEEEEEEEEEEEEEEE         DDDDD         CCCC   BB   AAA
       .EEEEEEEEEEEEEEEEEEEEE          DDDDD         CCC   BBB   AAAA
    70— .EEEEEEEEEEEEEEEEEEE           DDDDD         CCC   BB    AAAAAA
       .EEEEEEEEEEEEEEEEEE             DDDDD         CCCC  BB    AAAAAAA
       .EEEEEEEEEEEEEEE               DDDDDD         CCC   BB    AAAAAAAA
       .EEEEEEEEEEEEE                 DDDDD          CCC   BB    AAAAAAAAA
       .EEEEEEEEE                    DDDDDD          CCC   BB    AAAAAAAAAAA
    60— .EEE                         DDDDD           CCCC  BBB   AAAAAAAAAAAA
       .                            DDDDDDD          CCCC  BB    AAAAAAAAAAAAA
       .                            DDDDDD           CCC   BB    AAAAAAAAAAAAAA
       .                           DDDDDDD           CCCC  BB    AAAAAAAAAAAAAAA
       .                            DDDDDD           CCC   BB    AAAAAAAAAAAAAAAA
    50— .                            DDDDD           CCC   BB    AAAAAAAAAAAAAAAAA
       .EEEEEEEE                     DDDDD           CC    BB    AAAAAAAAAAAAAAAAAA
       . EEEEEEEEEEE                  DDD            CC   BB  AAAAAAAAAAAAAAAAAAAAA
       .      EEEEE                   DDD            CC   B  AAAAAAAAAAAAAAAAAAAAAA
       .FFFFF                        EEEE            DD    C   BAAAAAAAAAAAAAAAAAAAAAA
    40— .FFFFFFFFFF                   EEE            DD    C   BAAAAAAAAAAAAAAAAAAAAAAA
       .        FFFFFFF               EEE            DD  C  BAAAAAAAAAAAAAAAAAAAAAAAAA
       .         FFFF                 EEE  DD  C   AAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
       .         FFFF                 EE    D  C  AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
       .        FFFF                 EE  DD  CBAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
    30— .       FFFF                 EE    D  C  AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
       .FFFFFF                       EE    D  C   AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
       .FFFFF                       EEE  DD  CBAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
       .           FFF              EE   D   A   AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
       .GGGGG              F        E     B   BAAAAAAAAAAAAAAAAAAAAA   AAAAAAAAAAA
    20— .GGGGG             FF   E    A    AAAAAAAAA  AAAAAAAA    AAAAAAA      AAA
       .GG         F   E   D   B   BAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
       .GGGGG   F  EDACCBAAA   AAAAAA    AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
       .    GGG  FED      AA  B  AAAA    AA  AA    AA  AA    AA   AAA  AA    A
       .     G FEAD  BABB  AA  BBAAA   BBAAAA  BBAAAA  B  A   AA  BAA    A    A   A
    10— .H   G E   C  B   AB  BAAB  BAAABB  AA  BBAAA  BB  A  A  BBA   A
       .HH    BED ACABC  ABC  A  CC  A  C  AA     AAB   A  AB  BA  AB  BAB
       .HH FEED   C       CCAC   ACC  BCC    CC  A  CC    BCCB    B    B  B
       . CF  DA  DADB  CA  CCACCC      A  CAC  CABC   B   C   B   B
       .DEFFDC  DEDDD    C  D  CD  CDDBA    ACC  B    AB  CC    BBAAAA
    0— ........................................................................
          |    |    |    |    |    |    |    |    |    |    |
          0         1         2         3         4         5
                                  Offset, m
```

FIGURE A-1.   CALCULATED DETECTION PATTERN (NO SHAPING).

Axial Range, m

A-132

```
     FCL,N1,FCH,N2=1,1,30.7,2
100—.EEEEEEEEEEEEEEEEEEE          DDDDDDD        CCC
    .EEEEEEEEEEEEEEEEEEEE         DDDDDDD        CCCC
    .EEEEEEEEEEEEEEEEEEEE         DDDDDDD        CCCC
    .EEEEEEEEEEEEEEEEEEEEE        DDDDDDD        CCCCC
    .EEEEEEEEEEEEEEEEEEEEE        DDDDDD         CCCCC
 90—.EEEEEEEEEEEEEEEEEEEEEE       DDDDDDD        CCCCC
    .EEEEEEEEEEEEEEEEEEEEEE       DDDDDD         CCCCC
    .EEEEEEEEEEEEEEEEEEEEEE       DDDDD          CCCC   B
    .EEEEEEEEEEEEEEEEEEEEE        DDDDDD         CCCC   BB
    .EEEEEEEEEEEEEEEEEEEE         DDDDDD         CCCC   BBB
 80—.EEEEEEEEEEEEEEEEEEEE         DDDDD          CCCC   BBB
    .EEEEEEEEEEEEEEEEEEE          DDDDD          CCCC   BB   A
    .EEEEEEEEEEEEEEEEEE           DDDDD          CCC    BB   AA
    .EEEEEEEEEEEEEEEEEE           DDDDD          CCC    BBB  AAA
    .EEEEEEEEEEEEEEEEE            DDDDD          CCCC   BB   AAAAA
 70—.EEEEEEEEEEEEEEE             DDDDD          CCCC   BB   AAAAA
    .EEEEEEEEEEEEEE              DDDDD          CCC    BBB  AAAAAA
    .EEEEEEEEEEEE                DDDDD          CCCC   BB   AAAAAAAA
    .EEEEEEEEE                   DDDDD          CCC    BBB  AAAAAAAAA
    .EEEEE                       DDDDDD         CCCC   BB   AAAAAAAAAA
 60—.                            DDDDDDD        CCC    BB   AAAAAAAAAAAA
    .                            DDDDDD         CCC    BBB  AAAAAAAAAAAAA
    .                            DDDDDDD        CCCC   BB   AAAAAAAAAAAAAA
    .                            DDDDDDDD       CCCC   BBB  AAAAAAAAAAAAAAAA
    .                            DDDDDDD        CCC    BBB  AAAAAAAAAAAAAAAA
 50—.                            DDDDDD         CCC    BB   AAAAAAAAAAAAAAAAA
    .EEEEE                       DDDDD          CCC    BB   AAAAAAAAAAAAAAAAA
    .EEEEEEEEEE                  DDDD           CC     B    AAAAAAAAAAAAAAAAAA
    .          EEEEEE            DDD            CC     B   AAAAAAAAAAAAAAAAAAA
    .          EEEEE             DD             CC     B  AAAAAAAAAAAAAAAAAAAA
 40—.FFFFFFFF            EEEE            DD     C   B  AAAAAAAAAAAAAAAAAAAAAAA
    .FFFFFFFFFF            EEE          DD  CC      AAAAAAAAAAAAAAAAAAAAAAAAA
    .     FFFFFFF           EEE         D    CB  AAAAAAAAAAAAAAAAAAAAAAAAAAA
    .       FFFFF            EE    D  C  BAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
    .       FFFFF            EE    D  C   AAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
 30—.FFFFFF             EE    D   CBAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
    .              EEE   D   CB  AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
    .             EEE   DD  C  BAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
    .FFFFF        EE  D  CBAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
    .          FFF    E  DCB  B  AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
 20—.          FF    E  DCABBAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
    .    FFF    E  D  B  B  AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
    .     FF  E   A  B  AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
    .       F  E  C    BAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
    .GG     F    AC   AA  AAAA  AAAAAAAAAAAAAAAAAAAAAAAAAAAA
 10—.GG  F D   BAA  AAA   AAA  AAAA    AAAA  AAAAAAAAAAAAAAAA
    .GG   ADCBA AAB AAB AA   AAA   AA    AAA   AAAA  AAAAA  AAA
    .G    D   A  BAABAABBA  BAABBAABBAA  BAAAB  AAA    AAAA   AAA
    .F   EBAA A AB AB   A    BABBAAB A B  AABBAAAA   AAAAAAA
    .BCDDBAA BCBBB    A B   BAA BAA B  AAAAAAAAAA   AAAAAAA
  0—.................................................
    |    |    |    |    |    |    |    |    |    |    |
    0         1         2         3         4         5
                        Offset, m
```

FIGURE A-2. CALCULATED DETECTION PATTERN (HIGH-PASS: 1 SECTION, CUTOFF AT 30.7 m).

A-133

FCL,N1,FCH,N2=32.2,5,15.4,2

Axial Range, m

100—
90—
80—
70—
60—
50—
40—
30—
20—
10—
0—

0   1   2   3   4   5

Offset, m

FIGURE A-3.   CALCULATED DETECTION PATTERN (LOW PASS: 4 SECTION, R_c = 32.2 m;
HIGH PASS: 1 SECTION, R_c = 15.4 m).

The target location varied from 2 to 100 m in the axial direction and 0 to 5 m in the x direction. Letters ranging from A to H are used to represent the relative power received from a target located at that letter position. The power levels increase from A to H in approximately 10-dB steps, and each letter ranges in value about 5 dB.

For the calculation P_r'', the cutoff range was specified as 30.7 m and the slope was 6 dB/octave. For the calculation of P_r''', the high and low pass filter cutoff frequencies (ranges) were taken from the measured composite preamplifier and postamplifier characteristics. From Figure 15, the high pass filter was modeled as a single-section filter with cutoff at 15.4 m. Similarly, the low pass filter was modeled, as a four-section filter with cutoff at 32.2 m. Using the composite filter characteristic takes into account the interaction when the preamplifier is integrated with the postamplifier.

Comparisons between the calculated and measured contours of P_r'' show good agreement if letter E of Figure A-2 is the -40 dB level, shown in Figure 11. Similarly for P_r''', when letter F of Figure A-3 is the -15 dB level shown in Figure 12, Figure A-3 demonstrates the range containment that can be achieved by shaping the postamplifier.

B. MONOSTATIC COOPERATIVE X-BAND RADAR

1. Tagged Channel Operation

The detection area of the cooperative X-band radar was also determined from contours of constant power. The power returned to the radar is calculated in a two-step process. First the power received by the tag is formulated and then this power is considered to be reradiated back to the radar. That is

$$P_{TAG} = \frac{P_T \; G_R \; G_T \; \lambda^2}{(4 \; \pi \; R)^2} \sqrt{P_m} \qquad (A-16)$$

$$P_R = \frac{L \; P_{TAG} \; G_R \; G_T \; \lambda^2}{(4 \; \pi \; R)^2} \sqrt{P_m} \qquad (A-17)$$

From equations (A-16) and (A-17)

$$P_R = \frac{L\,P_T\,G_R^2\,G_T^2\,\lambda^4}{(4\,\pi\,R)^4}\,P_m \tag{A-18}$$

where L = loss in modulator

          G_R = antenna gain of radar

          G_T = antenna gain of tag

When $G_R = G_T = G$

$$P_r = K\left(\frac{G}{R}\right)^4 P_m \tag{A-19}$$

$$K = \frac{L\,P_T\,\lambda^4}{(4\pi)^4} \tag{A-20}$$

The factor K is normalized to unity for the calculation of the power contours as before and P_m is given by equation (A-3). The geometry of the radar and tag for a typical power calculation is shown in Figure A-4. From the figure, the distance to the tag R, is given by

$$R = \sqrt{x^2 + y^2 + (h_1 - h_2)^2} \tag{A-21a}$$

The azimuth angle ϕ is given by

$$\phi = \tan^{-1}\frac{x}{y} \tag{A-21b}$$

and the elevation angle θ

$$\theta = \sin^{-1}\frac{h_1 - h_2}{\sqrt{x^2 + y^2 + (h_1 - h_2)^2}} \tag{A-21c}$$

The multipath angle θ_2 is

$$\theta_2 = \tan^{-1}\frac{h_1 + h_2}{\sqrt{x^2 + y^2}} \tag{A-22}$$

h_1 = height of radar above ground = 0.675 m

h_2 = height of tag above ground = 0.385 m

A-136
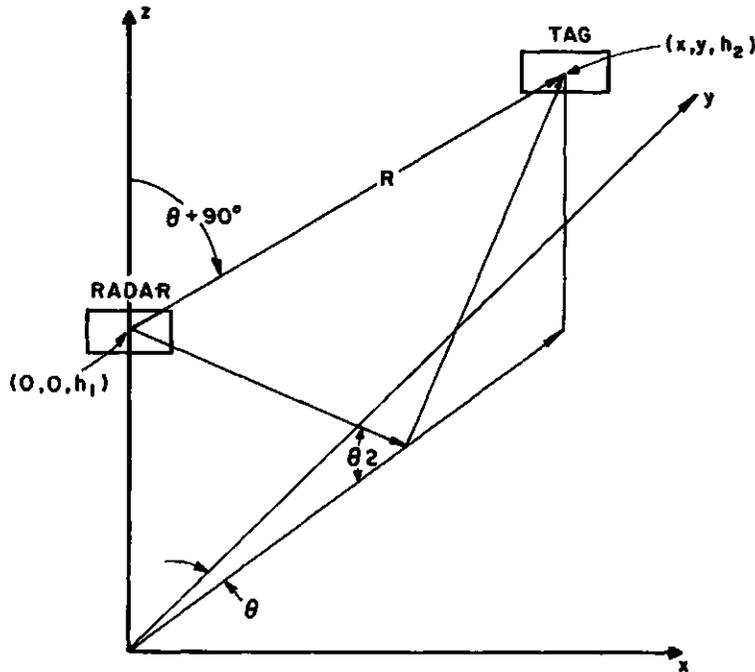
FIGURE A-4. COOPERATIVE RADAR-TAG GEOMETRY FOR
COVERAGE PATTERN MEASUREMENTS.

The power contours are calculated at the output of the detector P_r'' and at the output of the postamplifier, P_r'''. (See Figure 16.) The output of the detector P_r'' is given by

$$P_r'' = \left(\frac{G}{R}\right)^4 P_m \qquad \text{(A-23)}$$

Equation (A-23) assumes a linear detector and a flat response from the preamplifier at the tag modulation frequency. The output of the postamplifier P_r''' is given by

$$P_r''' = \left(\frac{G}{R}\right)^4 P_m \left|H_{LP}(f)\right|^2 \qquad \text{(A-24)}$$

where $\left|H_{LP}(f)\right|^2$ = gain function of the postamplifier.

The amplitude of the gain is normalized to unity and the shape is given by a maximally flat filter response as in subsection A.2.c above.

2. Mathematical Models

a. Multipath

The same model is used as in subsection A.2 above with the following changes: Θ is given by equation (A-21c) and Θ_2 by equation (A-22).

A-137

b. Antenna

The gain function of the antenna is modeled as $G = G_H(\phi,\Theta) \, G_V(\phi,\Theta)$ as before. However, the side lobe-level is only -20 dB in azimuth and elevation, and the number of elements is reduced from 32 x 16 to 16 x 8 to approximate the antenna used at X-band.

The elevation gain $G_V(\Theta)$, is taken into account, with Θ given by equation (A-21c).

c. Preamplifier

The preamplifier is modeled as a high pass filter of unit gain. At the tag modulation frequency and over the signal bandwidth, the preamplifier is assumed to be operating in its passband so that $\left| H_{HP}(f) \right|^2 = 1$.

d. Postamplifier

The postamplifier is modelled as a single-section, low-pass filter with range frequency cutoff at 50 m. For example,

$$\left| H_{LP}(R) \right|^2 = \left(1 + \frac{R}{R_c} \right)^2 \tag{A-25}$$

$$R_c = 50 \text{ m}$$

3. Calculated Results

Figure A-5 shows contours of constant power as measured at the output of the detector of the tagged channel; no shaping was used. These results are in good agreement with the measured results shown in Figure 18, when letter E of Figure A-5 is compared with the -50 dB contour of Figure 18.

Figure A-6 shows the beam confinement when a postamplifier with a shape factor corresponding to a single-section, low-pass filter is used. The cutoff range is 50 m. The output is taken at the postamplifier. Even with the simple filter, the maximum range associated with the letter E is reduced from 68 m to 58 m. Measurements were not taken at the output of the postamplifier so that comparisons cannot be made.

A fortunate departure between the measured and calculated results is the extent and depth of the multipath null. The measured results indicate that the null is not as broad or as deep as the calculated results. This may be due to the nonideal nature of the tag; i.e., it is not a perfect reflector

```
100— .DDDDDDDDDDDDDDDDDDD                    CCCCCCCCCC
     .DDDDDDDDDDDDDDDDDDDDDDD                 CCCCCCCCCC
     .DDDDDDDDDDDDDDDDDDDDDDDD                CCCCCCCCCC
     .DDDDDDDDDDDDDDDDDDDDDDDDDD              CCCCCCCCCC
     .DDDDDDDDDDDDDDDDDDDDDDDDDDD             CCCCCCCCCC
 90— .DDDDDDDDDDDDDDDDDDDDDDDDDDDDD           CCCCCCCC
     .DDDDDDDDDDDDDDDDDDDDDDDDDDDDDDD         CCCCCCCC
     .        DDDDDDDDDDDDDDDDDDDDDDDD        CCCCCCCC
     .            DDDDDDDDDDDDDDDDDDD         CCCCCC
     .              DDDDDDDDDDDDDDD           CCCCCCC
 80— .                DDDDDDDDDDDDD           CCCCCCC
     .                 DDDDDDDDDDD            CCCCCCC
     .                  DDDDDDDDD             CCCCCCC
     .                   DDDDDDDD             CCCCC
     .                   DDDDDDDD             CCCCC       B
 70— .                   DDDDDDDD             CCCCC      BB
     .EEEEE               DDDDDDD             CCCCC      BB
     .EEEEEEEEE           DDDDDDD             CCCC       BBB
     .EEEEEEEEEEEE        DDDDDD              CCCCC      BBB
     .EEEEEEEEEEEEEE      DDDDDD              CCCC       BBB
 60— .EEEEEEEEEEEEEEEE    DDDDDD              CCCC       BBB
     .EEEEEEEEEEEEEEEEE   DDDDDD              CCCC       BBB   AA
     .EEEEEEEEEEEEEEEEEE  DDDDD               CCC        BB    AAA
     .EEEEEEEEEEEEEEEEEE  DDDDD               CCC        BB    AAAA
     .     EEEEEEEEEEEE   DDDDD               CCCC       BBB   AAAAAA
 50— .      EEEEEEEEEE    DDDDD    CCC        BBB   AAAAAA
     .        EEEEEEEE    DDDD     CCC        BB    AAAAAAAA
     .         EEEEEEE    DDDD     CC         BB    AAAAAAAAA
     .         EEEEEEE    DDD      CC         BB    AAAAAAAAAAA
     .          EEEEE     DDDD     CC         BB    AAAAAAAAAAAA
 40— .          EEEEE     DDD      CCC        B     AAAAAAAAAAAAAA
     .          EEEEE     DDD      CC         BB    AAAAAAAAAAAAAAAA
     .FFFF       EEEE     DDD      CC         B     AAAAAAAAAAAAAAAAAA
     .FFFFF      EEEEE    DDD      CC         BB    AAAAAAAAAAAAAAAAAAAA
     .FFFFF      EEEE     DD       CC         B     AAAAAAAAAAAAAAAAAAAAAA
 30— .FFFF       EEEE     DD       C          B     AAAAAAAAAAAAAAAAAAAAAA
     .           EEE      DD       CC         B     AAAAAAAAAAAAAAAAAAAAAAAA
     .           EEEE     DDD      CC         B     AAAAAAAAAAAAAAAAAAAAAAAAA
     .       EEEEE        DD       CC         B     AAAAAAAAAAAAAAAAAAAAAAAAAA
     .EEEEE              DDD  CC BB  AAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
 20— .DDDDD       CCC  BB  AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
     .BBB         AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
     .     DDD    C  B  AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
     .     EEE    D     B  AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
     .     EEE   D  C   AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
 10— .DD    C  B  AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
     .CCC   B  AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
     .AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
     .BAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
     .AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
  0— ............................................................
       |    |    |    |    |    |    |    |    |    |    |
       0         1         2         3         4         5
                            Offset, m
```

Axial Range, m

FIGURE A-5.   DETECTION PATTERN FOR COOPERATIVE RADAR
(OUTPUT OF DETECTOR).

FCL,N1,FCH,N2-50.,2,1,1

Axial Range, m

```
100— .        CCCCCCCCCCCCCCCCCCCCCCCCCCC                    BBBB
     .         CCCCCCCCCCCCCCCCCCCC                          BBB
     .          CCCCCCCCCCCCCCCCCC                           BBB
     .           CCCCCCCCCCCCCCCC                            BBB
     .            CCCCCCCCCCCCCC                             BBB
 90— .             CCCCCCCCCCCC                              BBB
     .              CCCCCCCCCCCC                             BBB
     .               CCCCCCCCCC                             BBB
     .DDDDDD          CCCCCCCCC                             BBB
     .DDDDDDDDDDDD     CCCCCCCC                             BBB
 80— .DDDDDDDDDDDDDD    CCCCCCC                             BBB
     .DDDDDDDDDDDDDDDDD  CCCCCCC                            BBBB
     .DDDDDDDDDDDDDDDDDDD CCCCCCC                           BBBB
     .DDDDDDDDDDDDDDDDDDDDD CCCCCC                          BBBBB
     .DDDDDDDDDDDDDDDDDDDDDD CCCCCC                         BBBBB
 70— .      DDDDDDDDDDDDDDDDD  CCCCCC                       BBBB
     .       DDDDDDDDDDDDDD     CCCCC                       BBBB
     .         DDDDDDDDDDD      CCCCCC                      BBBB
     .          DDDDDDDDDD      CCCCC                       BBBB
     .           DDDDDDDD       CCCCC       BBBB        A
 60— .           DDDDDDD        CCCCC       BBBB       AA
     .EEEEE        DDDDDDD       CCCCC      BBBB       AAA
     .EEEEEEEE      DDDDDDD      CCCC       BBB       AAAAA
     .EEEEEEEEEEEE   DDDDDD      CCCC       BBB       AAAAAA
     .EEEEEEEEEEEE    DDDDDD     CCCC     BB         AAAAAAA
 50— .EEEEEEEEEEEEEEE  DDDDD     CCCC     BB         AAAAAAAA
     .EEEEEEEEEEEEEEEE  DDDDD    CCC      BB        AAAAAAAAA
     .    EEEEEEEEEEEE   DDDD    CCC      BB        AAAAAAAAAA
     .      EEEEEEEEEE   DDDD    CCC     BBB       AAAAAAAAAAA
     .      EEEEEEEE     DDD     CCC     BB        AAAAAAAAAAAA
 40— .      EEEEEEE      DDDD    CCC     BB       AAAAAAAAAAAAAA
     .      EEEEE        DDD     CCC     B        AAAAAAAAAAAAAA
     .      EEEEE        DDD     CC      BB      AAAAAAAAAAAAAAAA
     .      EEEEE        DDD     CC      B       AAAAAAAAAAAAAAAA
     .      EEEEE        DDD     CC      BB     AAAAAAAAAAAAAAAAA
 30— .      EEEE         DD      CC      B      AAAAAAAAAAAAAAAAAA
     .      EEEE         DD      C       B      AAAAAAAAAAAAAAAAAAA
     .     EEEE          DD      CC      B     AAAAAAAAAAAAAAAAAAAA
     .    EEEEEE         DD      CC      B     AAAAAAAAAAAAAAAAAAAAA
     .EEEE              DD       CC      BB    AAAAAAAAAAAAAAAAAAAAAA
 20— .DDDD              CC       BB      AAAAAAAAAAAAAAAAAAAAAAAAAAAA
     .BB         AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
     .   DDDD CC  B  AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
     .   EEE   D C  BAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
     .   EEE D C   AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
 10— .DD   C B  AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
     .CCC B  AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
     .AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
     . BAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
     .AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
  0— .................................................................
        |     |     |     |     |     |     |     |     |     |
        0     1     2     3     4     5
                            Offset, m
```

FIGURE A-6.   DETECTION PATTERN OF COOPERATIVE RADAR
(OUTPUT OF POSTAMPLIFIER).

whose radiation pattern is unaltered by the modulator as a termination. Also, the nonideal nature of the road surface contributes to a flattening of the null.

C. MONOSTATIC NONCOOPERATIVE X-BAND (BASEBAND OPERATION)

The baseband channel of the X-band radar can be treated as a special case of the bistatic radar discussed in Section A, with $S_o=0$. The only other changes required are in the physical constants such as the number of antenna elements and side lobes and the amplifier cutoff ranges. From equation (A-4)

$$P_r' = \frac{G^2(\phi)\ P_m}{R^4} \tag{A-25}$$

where
$$\phi = \tan^{-1}\frac{x}{y}$$

R = distance from radar to target

Similarly, $P_r'' = P_r'\ \left|H_{HP}(f)\right|^2$

and $P_r''' = P_r''\ \left|H_{LP}(f)\right|^2$

where $\left|H_{HP}(f)\right|^2$ is modeled by equations (A-12) and (A-13). The conversion from frequency to range is different at X-band due to the different modulation parameters so that equation (A-14) becomes

$$R = \frac{f}{0.667}\ m \tag{A-26}$$

with f expressed in kHz. Similarly, the postamplifier is given by equations (A-15a) and (A-15b).

Contours of the power out of the preamplifier are shown in Figure A-7. The preamplifier was modeled as a single-section high-pass filter, with cutoff at 50 m. The antenna was modeled as a 20-dB side-lobe Chebyshev array with 16 x 8 elements. The contour represented by the letter E has a maximum range of 80 m and an axial offset of 2.7 m. The multipath null extends from 30 to 36 m. This contour approximates the -60 dB contour shown in Figure 11. The measured results show the maximum range to be about 90 m and the axial offset to be about 3 m. The measured multipath null extends from 31 to 41 m.

If one keeps in mind the large number of approximations and simplifying assumptions that have to be taken in the calculation of these antenna patterns,

FCL,N1,FCH,N2-1,1,50,2

FIGURE A-7. DETECTION PATTERN OF MONOSTATIC, X-BAND, NONCOOPERATIVE
RADAR (OUTPUT OF PREAMPLIFIER).

the agreement between theory and measured results is quite good. The computer solution presented here thus can be used to predict with reasonable accuracy other situations not treated here.

SOFTWARE LISTING FOR CMS ALGORITHM

```
        0000                          1  ..
        0000                          2  ..     >CMS3    M.I.    RCA LABS 10:16:79
        0000                          3  ..     CDP1802 MICROPROCESSOR VERSION
        0000                          4  ..     FOR RSV CAR
        0000                          5  ..     DEVIATION,SPEED,STEERING WHEEL ANGLE
        0000                          6  ..     CHECK
        0000                          7  ..
        0000                          8  ..     THIS VERSION IS EQUIVALENT TO CMS1
        0000                          9  ..     NO SWITCHES ARE USED
        0000                         10  ...
        0000                         11         STACK=#10FF
        0000                         12         UPBUF=#1000
        0000                         13         DNBUF=#1030
        0000                         14  ...
        0000                         15  ...
        0000                         16  ...
        0000                         17         VAR=#1060
        0000                         18         V=VAR
        0000                         19         UCOUNT=VAR+2
        0000                         20         DCOUNT=VAR+4
        0000                         21         NUP=VAR+6
        0000                         22         NDN=VAR+8
        0000                         23         TEMP1=VAR+10
        0000                         24         TEMP2=VAR+12
        0000                         25         TEMP3=VAR+14
        0000                         26         DOPRR=VAR+16
        0000                         27         DOPRR1=VAR+18
        0000                         28         DOPRR0=VAR+20
        0000                         29         RRDV2=VAR+22
        0000                         30         RANGE=VAR+24
        0000                         31         RANGE0=VAR+26
        0000                         32         TVAL=VAR+28
        0000                         33         AVGUCT=VAR+30
        0000                         34         AVGDCT=VAR+32
        0000                         35         FLAG=VAR+34
        0000                         36         FLAG1=VAR+35
        0000                         37         FLAG2=VAR+37
        0000                         38         FLAG3=VAR+39
        0000                         39         LOLIM=VAR+41
        0000                         40         UPLIM=VAR+43
        0000                         41  ...
        0000                         42  ...
        0000                         43  ...
        0000                         44  ...
        0000                         45         ORG 0
        0000                         46  ..
F       0000  F800B3                 47         A.1(NEWPC)->R3.1
F       0003  F800A3                 48         A.0(NEWPC)->R3.0
        0006  D3                     49         GO STATE R3    ..R3 IS PC
        0007  F810B2                 50  NEWPC: A.1(STACK)->SP.1
        000A  F8FFA2                 51         A.0(STACK)->SP.0
        000D  E2                     52         SEX SP
        000E  F80FB4                 53         A.1(CALLS)->R4.1
```

```
      0011  F85EA4         54          A.0(CALLS)->R4.0
      0014  F80FB5         55          A.1(RETR)->R5.1
      0017  F86EA5         56          A.0(RETR)->R5.0
      001A  6522           57          OUT 5; DEC SP ..TURN OFF MEAS. CIRCUIT
      001C                 58  ...
F     001C  F800BA         59  START:  A.1(SYSAC)->AR.1
F     001F  F800AA         60          A.0(SYSAC)->AR.0
F     0022  D40000         61          CALL DISP     ..DISPLAY "SYSTEM ACTIVE"
      0025  D40F8CFFFF     62          CALL DELAY;,#FFFF
      002A  D40F8CFFFF     63          CALL DELAY;,#FFFF ..ABOUT 3 SECS
      002F  F810BA         64  CLEAN:  A.1(FLAG3)->AR.1
      0032  F887AA         65          A.0(FLAG3)->AR.0
      0035  4A             66          LDA AR
F     0036  3200           67          BZ CLEN
      0038  F88052         68          #80->@SP
      003B  6122           69          OUT 1;DEC SP ..CLEAR DISPLAY
      003D  F80052         70  CLEN:   0->@SP
      0040  6622           71          OUT 6;DEC SP ..TURN OFF WARNING
      0042  F810BA         72          A.1(FLAG)->RA.1
      0045  F882AA         73          A.0(FLAG)->RA.0
      0048  F800           74          LDI 0
      004A  5A             75          STRA   ...FLAG=0
      004B  1A5A           76          INC AR;STRA ...FLAG1=0
      004D                 77  .......
      004D  D40F8C0001     78  FIRST:  CALL DELAY;,0,1
      0052  F810BA         79          A.1(FLAG3)->AR.1
      0055  F887AA         80          A.0(FLAG3)->AR.0
      0058  F8005A         81          #0->@AR
      005B  3C2F           82          BN1 CLEAN  ..EF1=1 SPEED<SPEED CUTOFF
      005D  7B             83          SEQ
F     005E  D40000         84  LOOK:CALL GETRAN    ...ACQ. DATA,DEVIATION CHECK
      0061  3B2F           85          BNF CLEAN
      0063  3D2F           86          BN2 CLEAN...EF2=1 S.W. ANGLE>NUM.NG
      0065  7A             87          REQ
      0066                 88          ...
      0066                 89          ...
      0066  D40E491070     90  CAON:CALL LOADOP;,A(DOPRR)
F     006B  D40C2D0000     91          CALL SMOP;,A(RRTHR)    ...RR>RRTHR
F     0070  9FFA80CA0000   92          AC.1.AND.#80;LBNZ NOALR1
      0076  F810BA         93          A.1(FLAG)->AR.1
      0079  F882AA         94          A.0(FLAG)->AR.0
      007C  F8805A         95          LDI #80;STR AR    ...FLAG=80
F     007F  1A4AC20000     96          INC AR;LDA AR;LBZ NOALAR    ...FLAG1=0->N
      0084  D40E491070     97          CALL LOADOP;,A(DOPRR)
      0089  D40C2D1072     98          CALL SMOP;,A(DOPRR1)
F     008E  D40000         99          CALL ABSAC    ..(DOPRR-DOPRR1]
F     0091  D40C2D0000     100         CALL SMOP;,A(DELRR)    ...-DELRR
F     0096  9FFA80C20000   101         AC.1.AND.#80; LBZ NOALAR    ...DIFF. RR>DE
      009C  D40E49107A     102         CALL LOADOP;,A(RANGE0)
      00A1  D40C2D1078     103         CALL SMOP;,A(RANGE)    ...PRESENT R<PREVIO
F     00A6  9FFA80CA0000   104         AC.1.AND.#80;LBNZ NOALAR
      00AC  9FB08FA0        105         AC.1->R0.1;AC.0->R0.0
      00B0  D40C2D108B     106         CALL SMOP;,A(UPLIM)    ...DIFF. RANGE<UPLI
F     00B5  9FFA80C20000   107         AC.1.AND.#80;LBZ NOALAR
```

```
        00BB  90BF80AF              108        R0.1->AC.1;R0.0->AC.0
        00BF  D40C2D1089            109        CALL SMOP;,A(LOLIM)      ...DIFF. RANGE>LOL1
F       00C4  9FFA80CA0000          110        AC.1.AND.#80;LBNZ NOALAR
        00CA  D40E491078            111        CALL LOADOP;,A(RANGE)
F       00CF  D40C2D0000            112        CALL SMOP;,A(RCUTOF)     ..RANGE<RCUTOF
F       00D4  9FFA80C20000          113        AC.1.AND.#80;LBZ NOALAR
        00DA  F801526622            114   ALARM:1->@SP;OUT 6;DEC SP     ...TURN ON ALARM
        00DF  D40E491078            115        CALL LOADOP;,A(RANGE)
        00E4  D40E57107A            116        CALL STOROP;,A(RANGE0)      ...RANGE->RANGE
        00E9  D40E491070            117        CALL LOADOP;,A(DOPRR)
        00EE  D40E571072            118        CALL STOROP;,A(DOPRR1)      ...DOPRR->DOPRR
        00F3  F810BA                119        A.1(FLAG)->AR.1
        00F6  F882AA                120        A.0(FLAG)->AR.0
        00F9  4A5A                  121        LDA AR; STR AR      ...FLAG->FLAG1
F       00FB  D40000                122        CALL RANUP          ...CALCULATE UPLIM
        00FE  D40E57108B            123        CALL STOROP;,A(UPLIM)   ...UPLIM=.078*DOP
        0103                        124        .....     DISPLAY SUBROUTINE
F       0103  D40F7A0000000020      125   FORMAT:CALL MOVB,A(MESOUT),A(OUTBF),32
F       010B  F800BA                126        A.1(OUTBF)->AR.1
F       010E  F802AA                127        A.0(OUTBF+2)->AR.0
        0111  D40E491078            128        CALL LOADOP;,A(RANGE)
        0116  D40FA20401            129        CALL CVT;,4,1
        011B  D40E491070            130        CALL LOADOP;,A(DOPRR)
F       0120  F80AAA                131        A.0(OUTBF+10)->AR.0
        0123  F82B5A                132        T'+'->@AR
F       0126  9FFA803200            133        AC.1.AND.#80; BZ CHSIGN
        012B  F82D5A                134        T'-'->@AR
F       012E  D40000                135        CALL ABSAC
        0131  1A                    136   CHSIGN: INC AR
        0132  D40FA20401            137        CALL CVT;,4,1
        0137  D40E491060            138        CALL LOADOP;,A(V)
F       013C  F813AA                139        A.0(OUTBF+19)->AR.0
        013F  D40FA20200            140        CALL CVT;,2,0
        0144  D40E491066            141        CALL LOADOP;,A(NUP)
F       0149  F81AAA                142        A.0(OUTBF+26)->AR.0
        014C  D40FA20300            143        CALL CVT;,3,0
F       0151  F800AA                144        A.0(OUTBF)->AR.0
F       0154  D40000                145        CALL DISP
        0157  C0004D                146        LBR FIRST   .... TO STORE R,RR PUT 3   NOP
        015A  D40E491083            147        CALL LOADOP;,A(FLAG1)
        015F  9FFD80                148        AC.1.XOR.#80
F       0162  C20000                149        LBZ CTD
        0165  C0004D                150        LBR FIRST
        0168  00                    151   CTD: IDLE      .... TO STORE R,RR PUT NOP (C4)
        0169                        152        ..... STORE R,RR SUBROUTINE
        0169  D40E491078            153     CALL LOADOP;,A(RANGE)
        016E  8FFD40                154        GLO AC;SDI #40
F       0171  C30000                155        LBDF ZIP
        0174  8FB0                  156        GLO AC;PHI R0
        0176  D40E491070            157        CALL LOADOP;,A(DOPRR)
        017B  8FA0                  158      GLO AC;PLO R0
        017D  D40E491085            159        CALL LOADOP;,A(FLAG2)
        0182  905F1F                160        GHI R0;STR AC; INC AC
        0185  805F1F                161        GLO R0;STR AC; INC AC
```

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```
0188 D40E571085    162          CALL STOROP;,A(FLAG2)
018D C0004D        163          LBR FIRST
0190 00            164    ZIP:  IDL
0191              165    ....
0191              166    ....   TURN OFF ALARM SUBRUTINE
0191              167    ....
0191 F810BA        168    NOALR1: A.1(FLAG)->AR.1
0194 F882AA        169          A.0(FLAG)->AR.0
0197 F8005A        170          LDI #0;STR AR      ...FLAG=0
019A F800526622    171    NOALAR: 0->@SP;OUT 6;DEC SP      ...TURN OFF ALA
019F D40E491078    172          CALL LOADOP;,A(RANGE)
01A4 D40E57107A    173          CALL STOROP;,A(RANGE0)     ..RANGE->RANGE0
01A9 D40E491070    174          CALL LOADOP;,A(DOPRR)
01AE D40E571072    175          CALL STOROP;,A(DOPRR1)     ...DOPRR->DOPRR
01B3 F810BA        176          A.1(FLAG)->AR.1
01B6 F882AA        177          A.0(FLAG)->AR.0
01B9 4A5A          178          LDA AR;STR AR       ...FLAG->FLAG1
F 01BB D40000       179          CALL RANUP          ... CALCULATE UPLIM
01BE D40E57108B    180          CALL STOROP;,A(UPLIM)   ..UPLIM=.078*DO
01C3 C00103        181          LBR FORMAT          ...BRANCH TO DISPLAY
01C6              182          ...
01C6              183          ...
01C6              184          ...RANGE DIFFERENCE UPER LIMIT CALCULATION
01C6              185          ... UPLIM=.078*DOPRR
01C6              186          ..
01C6 D40E491070    187    RANUP: CALL LOADOP;,A(DOPRR)
F 01CB D40C4F0000    188          CALL MPYOP;,A(DEC5)
F 01D0 F800BD        189          A.1(DEC40)->MA.1
F 01D3 F800AD        190          A.0(DEC40)->MA.0
01D6 D40D5F        191          CALL DIVQ   .. UPLIM=1.25*DOPRR
01D9 D5            192          EXIT
01DA              193    ..    >ABSAC      J.M.C.     RCA LABS
01DA              194    ..
01DA              195    ....    COMPUTE ABS VALUE OF AC
01DA              196    ..
F 01DA 9FFA80C20000   197    ABSAC: AC.1.AND.#80; LBZ ABSEX
01E0 8FFBFFFC01AF   198          AC.0.XOR.#FF+1->AC.0      ..WAS NEG
01E6 9FFBFF        199          AC.1.XOR.#FF  ..COMPLEMENT IT
01E9 3BEDFC01      200          BNF *+4;   +1
01ED BF            201          ->AC.1
01EE D5            202    ABSEX: EXIT
01EF              203    ...
01EF              204    ...
01EF              205          ...FAST VERSION-- OBTAIN VEHICLE SPEED
01EF              206    ...
01EF              207          ...
01EF              208          ...
01EF F88052        209    DISP:#80->@SP
01F2 6122          210          OUT 1; DEC SP ... CLEAR MEMORY
01F4 F808AC        211          8->CR.0
01F7 2C8C3AF7      212    CLP:  DEC CR; CR.0; BNZ CLP
01FB F820AC        213          32->CR.0
01FE EAEAEA        214    DGO:  SEX AR;SEX AR;SEX AR ..MORE SEX
0201 4A2A          215          LDA AR;DEC AR ..STALL A WHILE
```

```
      0203 61              216        OUT 1        ..ZING IT
      0204 8CFF01AC        217        CR.0-1->CR.0   ..SLOW DECREMENT
      0208 CA01FEE2        218        LBNZ DGO; SEX SP
      020C F80152          219        1->@SP
      020F 6222            220        OUT 2; DEC SP ..MAKE SURE IT IS ON
      0211 D5              221        EXIT
      0212                 222    ...
      0212                 223 ...
      0212                 224 ...
      0212                 225        W=1; X=3; Y=4; Z=5
      0212                 226 ..
      0212 69FA03FB03      227     GETRAN:INP W;.AND.3.XOR.3
      0217 CA0212          228        LBNZ GETRAN
      021A 6322            229        OUT 3; DEC SP  ..PRESET STROBE
      021C 69FA03FB01      230 GET1:   INP W;.AND.3.XOR.1
F     0221 CA0000          231        LBNZ GET11
      0224 6DFBFFFF02AF    232        INP Z;.XOR.#FF-2->AC.0
F     022A FC00C20000      233    CLRU:ADI 0;LBZ GETX
      022F 8FFA80          234        AC.0;.AND.#80
F     0232 CA0000          235        LBNZ GETX
      0235 F800BF          236        0->AC.1
      0238 D40E571066      237        CALL STOROP;,A(NUP)
F     023D C00000          238        LBR PKUP
      0240 FC0069FA04      239     GET 11:ADI #0;INP W;.AND.4
      0245 76              240        RSHR
      0246 CA021C          241        LBNZ GET1
      0249 6DFBFFFF02AF    242        INP Z;.XOR.#FF-2->AC.0
      024F C0022A          243        LBR CLRU
      0252 F810B0          244    PKUP:A.1(UPBUF)->R0.1
      0255 F800A0          245        A.0(UPBUF)->R0.0
      0258 1F              246        INC AC
      0259 6B50            247 GET2: INP ';->@R0   ..READ FIFO
      025B 10              248        INC \
      025C 6C50            249        INP ';->@R0
      025E 10              250        INC R0
      025F 2F8FCA0259      251        DEC AC; AC.0; LBNZ GET2
      0264                 252 ..
      0264                 253 ...
      0264                 254 ..
      0264 69FA03FB01      255 GET3: INP W;.AND.3.XOR.1
      0269 3A64            256        BNZ GET3
      026B 6322            257        OUT 3; DEC SP  ..PRESET STROBE
      026D 69FA03FB03      258 GET4:  INP W;.AND.3.XOR.3
F     0272 CA0000          259        LBNZ GET 44
      0275 6DFBFFFF02AF    260        INP Z;.XOR.#FF-2->AC.0
F     027B FC00C20000      261    CLRD:ADI 0;LBZ GETX
      0280 8FFA80          262        AC.0;.AND.#80
F     0283 CA0000          263        LBNZ GETX
      0286 F800BF          264        0->AC.1
      0289 D40E571068      265        CALL STOROP;,A(NDN)
F     028E C00000          266        LBR PKDN
      0291 FC0069FA04      267     GET 44: ADI #0;INP W;.AND.4
      0296 76              268        RSHR
      0297 CA026D          269        LBNZ GET4
```

```
  029A 6DFBFFFF02AF      270        INP Z;.XOR.#FF-2->AC.0
  02A0 C0027B            271        LBR CLRD
  02A3 F810B0            272   PKDN:A.1(DNBUF)->R0.1
  02A6 F830A0            273        A.0(DNBUF)->R0.0
  02A9 1F                274        INC AC
  02AA 6B50              275   GET5:INP X;->@R0   ..READ FIFO
  02AC 10                276        INC R0
  02AD 6C50              277        INP Y;->@R0
  02AF 10                278        INC R0
  02B0 2F8F3AAA          279        DEC AC; AC.0; BNZ GET5
  02B4 F810B0            280        A.1(UPBUF)->R0.1
  02B7 F800A0            281        A.0(UPBUF)->R0.0
  02BA D40E491066        282        CALL LOADOP;,A(NUP)
  02BF 2F                283        DEC AC
F 02C0 D40000            284        CALL AUPDN
  02C3 D40E571062        285        CALL STOROP;,A(UCOUNT)
  02C8 F800AEBE          286        0->MQ.0,MQ.1
  02CC D40CA11066        287        CALL DIVOP;,A(NUP)
  02D1 D40E57107E        288        CALL STOROP;,A(AVGUCT)
  02D6 F810B0            289        A.1(DNBUF)->R0.1
  02D9 F830A0            290        A.0(DNBUF)->R0.0
  02DC D40E491068        291        CALL LOADOP;,A(NDN)
  02E1 2F                292        DEC AC
F 02E2 D40000            293        CALL AUPDN
  02E5 D40E571064        294        CALL STOROP;,A(DCOUNT)
  02EA F800AEBE          295        0->MQ.0,MQ.1
  02EE D40CA11068        296        CALL DIVOP;,A(NDN)
  02F3 D40E571080        297        CALL STOROP;,A(AVGDCT)
  02F8 F800BC            298        0->CR.1
  02FB D40E491066        299        CALL LOADOP;,A(NUP)
  0300 8FAC              300        AC.0->CR.0
F 0302 D40E490000        301        CALL LOADOP;,A(DELRAN)
  0307 9F73              302        GHI AC;STXD
  0309 8F73              303        GLO AC;STXD
  030B D40E49107E        304        CALL LOADOP;,A(AVGUCT)
  0310 9F73              305        GHI AC;STXD
  0312 8F73              306        GLO AC;STXD
  0314 F810B0            307        A.1(UPBUF)->R0.1
  0317 F800A0            308        A.0(UPBUF)->R0.0
  031A 40AF              309        @R0!->AC.0
  031C 40FA0F73          310        @R0!.AND.15;STXD
  0320 8F7312            311        GLO AC;STXD; INC SP
  0323 40AF              312   CHKUP: @R0!->AC.0
  0325 F5AA              313        SD;->AR.0
  0327 12                314        INC SP
  0328 40FA0FBF          315        @R0!.AND.15->AC.1
  032C 75BA              316        SDB ;->AR.1
  032E 12                317        INC SP
  032F 8AF5AA            318        AR.0;SD;->AR.0
  0332 12                319        INC SP
  0333 9A75BA            320        AR.1;SDB ;->AR.1
F 0336 C30000            321        LBDF AH1
  0339 8AFBFFFC01AA      322        AR.0.XOR.#FF+1->AR.0
  033F 9AFBFFFA0F        323        AR.1.XOR.#FF.AND.15
```

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```
     0344 7C00BA          324         ADCI #0;->AR.1
     0347 12              325  AH1:   INC SP
     0348 8AF712          326         AR.0;SM; INC SP
     034B 9A77            327         AR.1;SMB
F    034D C30000          328         LBDF GEREX
F    0350 2C8CC20000      329         DEC CR;CR.0;LBZ DEVDN
     0355 22222222        330         DEC SP;DEC SP;DEC SP;DEC SP
     0359 9F738F7312      331         AC.1;STXD;AC.0;STXD;INC SP
     035E C00323          332         LBR CHKUP
     0361 F800BC          333  DEVDN: 0->CR.1
     0364 D40E491068      334      CALL LOADOP;,A(NDN)
     0369 8FAC            335         AC.0->CR.0
F    036B D40E490000      336      CALL LOADOP;,A(DELRAN)
     0370 9F73            337      GHI AC;STXD
     0372 8F73            338      GLO AC;STXD
     0374 D40E491080      339      CALL LOADOP;,A(AVGDCT)
     0379 9F73            340      GHI AC;STXD
     037B 8F73            341      GLO AC;STXD
     037D F810B0          342      A.1(DNBUF)->R0.1
     0380 F830A0          343      A.0(DNBUF)->R0.0
     0383 40AF            344      @R0!->AC.0
     0385 40FA0F73        345      @R0!.AND.15;STXD
     0389 8F7312          346      GLO AC;STXD;INC SP
     038C 40AF            347  CHKDN: @R0!->AC.0
     038E F5AA            348      SD;->AR.0
     0390 12              349      INC SP
     0391 40FA0FBF        350      @R0!.AND .15->AC.1
     0395 75BA            351      SDB ;->AR.1
     0397 12              352      INC SP
     0398 8AF5AA12        353      AR.0;SD;->AR.0;INC SP
     039C 9A75BA          354      AR.1;SDB;->AR.1
F    039F C30000          355      LBDF AH2
     03A2 8AFBFFFC01AA    356      AR.0.XOR.#FF+1->AR.0
     03A8 9AFBFFFA0F      357      AR.1.XOR.#FF.AND.15
     03AD 7C00BA          358      ADCI #0;->AR.1
     03B0 12              359  AH2:  INC SP
     03B1 8AF712          360      AR.0;SM; INC SP
     03B4 9A77            361      AR.1;SMB
F    03B6 C30000          362      LBDF GEREX
F    03B9 2C8CC20000      363      DEC CR;CR.0;LBZ DEVON
     03BE 22222222        364      DEC SP;DEC SP;DEC SP;DEC SP
     03C2 9F738F7312      365      AC.1;STXD;AC.0;STXD;INC SP
     03C7 C0038C          366      LBR CHKDN
     03CA D40E491066      367  DEVON:   CALL LOADOP;,A(NUP)
F    03CF 8FFF01C20000    368         GLO AC;SMI 1;LBZ CHK1
     03D5 D40E491068      369         CALL LOADOP;,A(NDN)
F    03DA 8FFF01C20000    370         GLO AC;SMI 1;LBZ CHK1
F    03E0 C00000          371         LBR COMPRA
     03E3 D40E49107E      372         CHK1:CALL LOADOP;,A(AVGUCT)
     03E8 D40C2D1080      373            CALL SMOP;,A(AVGDCT)
     03ED D401DA          374            CALL ABSAC
F    03F0 D40C2D0000      375               CALL SMOP;,A(DELRAN)
     03F5 9FFA80FC00      376            AC.1.AND.#80;ADI 0
F    03FA C20000          377            LBZ GEREX
```

```
      03FD  D40E491080    378   COMPRA:  CALL LOADOP;,A(AVGDCT)
      0402  8FA0          379            GLO AC;PLO R0
      0404  9FFC05B0      380            GHI AC;ADI #5;PHI R0
      0408  40AA          381            @R0!->AR.0
      040A  D40E49107E    382            CALL LOADOP;,A(AVGUCT)
      040F  8FA0          383            GLO AC;PLO R0
     ·0411  9FFC05B0      384            GHI AC;ADI #5;PHI R0
      0415  40528AF4AF    385            @R0!->@SP;AR.0;ADD;PLO AC
  F   041A  CB0000        386            LBNF DAV
  F   041D  F801BF        387            1->AC.1
      0420  C00000        388            LBR DAV1
      0423  F800BF        389   DAV:     0->AC.1
      0426  D40E571078    390   DAV1:    CALL STOROP;,A(RANGE)
      042B  D40E491080    391            CALL LOADOP;,A(AVGDCT)
      0430  8FFEA0        392            GLO AC;SHL;PLO R0
      0433  9F7EFC08B0    393            GHI AC;SHLC;ADI #8;PHI R0
      0438  40BF          394   AG3:     @R0!->AC.1
      043A  40AF          395            @R0!->AC.0
      043C  8FAA9FBA      396            AC.0->AR.0;AC.1->AR.1
      0440  D40E49107E    397            CALL LOADOP;,A(AVGUCT)
      0445  8FFEAD        398            GLO AC;SHL;PLO MA
      0448  9F7EFC08BD    399            GHI AC;SHLC;ADI #8;PHI MA
      044D  9ABF8AAF      400   AG1:     AR.1->AC.1;AR.0->AC.0
      0451  D40C31        401            CALL SM
      0454  D40E571070    402            CALL STOROP;,A(DOPRR)
      0459  F800BCF805AC  403            0->CR.1;#5->CR.0
      045F  9FFE9F76BF    404   RD2:     GHI AC;SHL;GHI AC;SHRC;PHI AC
      0464  8F76AF        405            GLO AC;SHRC;PLO AC
      0467  2C8CCA045F    406            DEC CR;CR.0;LBNZ RD2
      046C  D40E571089    407            CALL STOROP;,A(LOLIM)
      0471  FF00          408            SMI 0
      0473  D5            409   GETRX:   EXIT
      0474  FC00D5        410    GEREX:  ADI #0;EXIT
      0477  F810BA        411      GETX: A.1(FLAG3)->AR.1
      047A  F887AA        412            A.0(FLAG3)->AR.0
      047D  F8015A        413            #1->@AR
      0480  FC00D5        414            ADI #0;EXIT
      0483                415   ...
      0483                416   ...
      0483                417   .. AVERAGE UPAND DOWN COUNT
      0483  40AA          418   AUPDN:  @R0!->AR.0
      0485  4073          419           @R0!;STXD
      0487  8A7312        420           AR.0;STXD;INC SP
      048A  10102F        421   AVE:    INC R0;INC R0;DEC AC
      048D  8FCA048A      422           AC.0;LBNZ AVE
      0491  40F5AF12      423           @R0!;SD;->AC.0;INC SP
      0495  4075FA0FBF    424           @R0!;SDB;.AND.15->AC.1
      049A  D5            425           EXIT
      049B                426   ...
      049B                427   ... TABLE FOR RANGE CONSTANTS
      049B                428   ...>RTAB  8:27:1979
      049B                429   ...
      051E                430        ORG #51E
      051E                431   ..
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051E  FEF6EFE7E0DAD4CE    432  ,254,246,239,231,224,218,212,206,201,196,191
0530  9F9C989593908D8B    433  ,159,156,152,149,147,144,141,139,136,134,13
0542  7372706E6D6B6A68    434  ,115,114,112,110,109,107,106,104,103,101,1
0556  5857                435  ,88,87
0558  56555454535251650   436  ,86,85,84,84,83,82,81,80,79,78,78,77,76,75,
056F  4444434342414140    437  ,68,68,67,67,66,65,65,64,64,63,63,62,62,61,
0586  3938383737373636    438  ,57,56,56,55,55,55,54,54,53,53,53,52,52,52,
059D  3030302F2F2F2E2E    439  ,48,48,48,47,47,47,46,46,46,46,45,45,45,44,
05B3  2A2A2A2A29292929    440  ,42,42,42,42,41,41,41,41,40,40,40,40,40,39,
05CA  2525252525242424    441  ,37,37,37,37,37,36,36,36,36,36,36,35,35,35,
05E2  2121212121212020    442  ,33,33,33,33,33,33,32,32,32,32,32,32,32,32,
05FA  1E1E1E1E1E1E1D1D1D  443  ,30,30,30,30,30,29,29,29,29,29,29,29,29,29,
0611  1C1B1B1B1B1B1B1B1B  444  ,28,27,27,27,27,27,27,27,27,27,27,26,26,26,
0629  1919191919191919    445  ,25,25,25,25,25,25,25,25,25,24,24,24,24,24,
0641  1717171717171717    446  ,23,23,23,23,23,23,23,23,23,23,23,23,22,22,
0657  1616161616151515    447  ,22,22,22,22,22,21,21,21,21,21,21,21,21,21,
066F  1414141414141414    448  ,20,20,20,20,20,20,20,20,20,20,20,20,20,20,
0684  1313131313131313    449  ,19,19,19,19,19,19,19,19,19,19,19,19,19,19,
083C                      450  ORG #083C
083C  0AE10A870A3309E4    451  ,2785,2695,2611,2532,2457,2387,2321,2258,219
0858  076B0741071806F2    452  ,1899,1857,1816,1778,1741,1705,1671,1638,16
0874  05A005880570055A    453  ,1440,1416,1392,1370,1347,1326,1305,1285,12
0890  048804780469045A    454  ,1160,1144,1129,1114,1099,1085,1071,1057,10
08AC  03CB03C003B503AA    455  ,971,960,949,938,928,918,908,898,889,879,87
08CE  032B032303 1B0314   456  ,811,803,795,788,781,773,766,759,752,746,73
08F0  02B802B202AD02A7    457  ,696,690,685,679,673,668,663,658,652,647,64
0912  0262025D02590254    458  ,610,605,601,596,592,588,584,580,576,572,56
0936  021B021702140210    459  ,539,535,532,528,525,522,519,515,512,509,50
0958  01E501E301E001DD    460  ,485,483,480,477,474,472,469,466,464,461,45
097C  01B701B501B301B1    461  ,439,437,435,433,430,428,426,424,422,419,41
09A0  0191018F018D018C    462  ,401,399,397,396,394,392,390,388,386,385,38
09C4  01710170016E016C    463  ,369,368,366,364,363,361,360,358,357,355,35
09E6  0157015601550153    464  ,343,342,341,339,338,336,335,334,332,331,33
0A0A  0140013E013D013C    465  ,320,318,317,316,315,314,313,311,310,309,30
0A2E  012B012A01290128    466  ,299,298,297,296,295,294,293,292,291,290,28
0A52  0119011801170116    467  ,281,280,279,278,277,276,275,274,274,273,2
0A76  0109                468  ,265
0A78  0108010701060105    469  ,264,263,262,261,261,260,259,258,257,257,25
0A96  00FC00FB00FA00FA    470  ,0,252,0,251,0,250,0,250,0,249,0,248,0,247,
0AAC  00F400F300F200F2    471  ,0,244,0,243,0,242,0,242,0,241,0,240,0,240,
0AC4  00EC00EB00EA00EA    472  ,0,236,0,235,0,234,0,234,0,233,0,232,0,232,
0ADC  00E400E300E300E2    473  ,0,228,0,227,0,227,0,226,0,225,0,225,0,224,
0AF4  00DD00DC00DB00DB    474  ,0,221,0,220,0,219,0,219,0,218,0,218,0,217,
0B0C  00D600D500D500D4    475  ,0,214,0,213,0,213,0,212,0,212,0,211,0,211,
0B24  00CF00CF00CE00CE    476  ,0,207,0,207,0,206,0,206,0,205,0,205,0,204,
0B3C  00C900C900C800C8    477  ,0,201,0,201,0,200,0,200,0,199,0,199,0,198,
0B54  00C400C300C300C2    478  ,0,196,0,195,0,195,0,194,0,194,0,193,0,193,
0B6C  00BE00BE00BD00BD    479  ,0,190,0,190,0,189,0,189,0,189,0,188,0,188,
0B84  00B900B900B800B8    480  ,0,185,0,185,0,184,0,184,0,184,0,183,0,183,
0B9C  00B400B400B400B3    481  ,0,180,0,180,0,180,0,179,0,179,0,178,0,178,
0BB4  00B000AF00AF00AF    482  ,0,176,0,175,0,175,0,175,0,174,0,174,0,174,
0BCC  00AB00AB00AB00AA    483  ,0,171,0,171,0,171,0,170,0,170,0,170,0,169,
0BE4  00A700A700A700A6    484  ,0,167,0,167,0,167,0,166,0,166,0,166,0,165,
0BFC  00A300A3            485  ,0,163,0,163
```

```
0C00                          486  ...
0C00                          487  ...
0C00                          488          ...
0C00                          489          ...
0C00                          490      OUTBF=#1090
0C00                          491  ...
0700                          492      ORG  #0700
0700  2020202020             493  SYSAC:  ,32,32,32,32,32
0705  20202020               494          ,32,32,32,32
0709  53595354454D20         495          ,T'SYSTEM',32
0710  414354495645           496          ,T'ACTIVE'
0716  2020202020             497          ,32,32,32,32,32
071B  2020202020             498          ,32,32,32,32,32
0720                          499  ...
0720                          500  ...
0720  523D58582E5820         501  MESOUT:,T'R=XX.X',32
0727  52523D2D58582E58       502          ,T'RR=+XX.X',32,32
0731  533D585820             503          ,T'S=XX',32,32
0737  4E55503D585858         504          ,T'NUP=XXX'
073E  202020                 505          ,32,32,32
0741                          506  ...
0741  00A0                   507      RRTHR:,0,160
0743  003C                   508      DELRR:,0,60
0745  000A                   509      SCUTOF:,0,10
0747  00FA                   510      RCUTOF:,0,250
0749  0010                   511      DELCNT:,0,16
074B  000D                   512      DELRAN:,0,13
074D  0005                   513      DEC5:,0,5
074F  0028                   514      DEC40:,0,40
0751                          515      PEND:END
```

SOFTWARE LISTING FOR ARITHMETIC SUBROUTINE GETRAN

FL LOC	COSMAC CODE	LNNO	SOURCE LINE
0000		1	..COPYRIGHT 1976 RCA CORPORATION
0000		2	.. COSMAC ARITHMETIC SUBROUTINE PACKAGE
0C00		3	ORG #C00 ..**FOR RADAR CRUISE CONTROL
0C00		4	..
0C00		5	.. VERSION 1.1 FOR CDP1802
0C00		6	..
0C00		7	.. EXTRACTED FOR BINARY ARITHMETIC
0C00		8	.. AND CONVERSIONS FOR DECIMAL
0C00		9	.. OCCUPIES 1K BYTES
0C00		10	..
0C00		11	..
0C00		12	.. DESIGNED FOR STANDARD CSDP SUBROUTINE CA
0C00		13	..
0C00		14	.. FOR STANDARD LINKAGE,
0C00		15	SP= #02 ...IT SHOULD BE THE STACK POINTER.
0C00		16	PC= #03 ...IT IS THE PROGRAM COUNTER
0C00		17	.. USED BY THESE SUBROUTINES.
0C00		18	CALL= #04 ...IT SHOULD POINT TO THE ROUTINE
0C00		19	.. WHICH EFFECTS SUBROUTINE CALLS.
0C00		20	RETN= #05 ...IT SHOULD POINT TO THE ROUTINE
0C00		21	.. WHICH EFFECTS SUBROUTINE RETURN.
0C00		22	LINK= #06 ...IT SHOULD POINT TO CALL PARAME
0C00		23	.. .. (USUALLY OPERAND ADDRESSES AND/OR CON
0C00		24	..THE FOLLOWING REGISTERS MUST BE ASSIGNED
0C00		25	AR= #0A ..(USED FOR RESULT ADDRESS)
0C00		26	NR= #0B ..(USED FOR RESULT DIGIT COUNT)
0C00		27	.. 16-BIT BINARY ARITHMETIC ROUTINES
0C00		28	.. THE FOLLOWING REGISTERS MUST BE ASSIGNED
0C00		29	AC =#0F ..16-BIT ACCUMULATOR=RF
0C00		30	MQ =#0E ..16-BIT ACCUMULATOR=RE EXTENSION
0C00		31	MA =#0D ..(TEMPORARY) OPERAND MEMORY ADDRESS.
0C00		32	CR =#0C .. (TEMPORARY) SCRATCHPAD AND COUNTER.
0C00		33	..
0C00		34	..
0C00		35	.. SWAP AC WITH MQ REGISTERS
0C00	9E	36	SWAPAQ: GHI MQ .. SAVE MQ.1
0C01	AC	37	PLO CR .. IN CR.0 (COULD HAVE PUSHED ON STA
0C02	9F	38	GHI AC .. NOW AC.1 TO MQ.1
0C03	BE	39	PHI MQ
0C04	8E	40	GLO MQ .. SAVE MQ.0
0C05	BF	41	PHI AC .. IN AC.1
0C06	8F	42	GLO AC .. THEN AC.0 TO MQ.0
0C07	AE	43	PLO MQ
0C08	9F	44	GHI AC .. NOW SAVED MQ.0 TO AC.0
0C09	AF	45	PLO AC
0C0A	8C	46	GLO CR .. FINALLY SAVED MQ.1
0C0B	BF	47	PHI AC .. TO AC.1
0C0C	D5	48	SEP RETN
0C0D		49	.. 16-BIT SUBTRACT AC FROM CONSTANT
0C0D		50	.. ****AC= CONSTANT-AC
0C0D		51	.. ************ (TO CALL, WRITE) **********
0C0D		52	.. ****CALL SDCON ; ,CONSTANT
0C0D	86	53	SDCON: GLO LINK .. (ESSENTIALLY SAME AS ADCON)

```
       0C0E AD       54        PLO MA
       0C0F 96       55        GHI LINK
       0C10 BD       56        PHI MA
       0C11 16       57        INC LINK
       0C12 16       58        INC LINK
F      0C13 3000     59        BR SD
       0C15          60        ..
       0C15          61        .. 16-BIT SUBTRACT AC FROM OPERAND
       0C15          62        .. ****AC=OPRN-AC
       0C15          63        .. ************ (TO CALL, WRITE) **********
       0C15          64        .. ****CALL SDOP ; ,A(OPRN)
       0C15          65        ..
       0C15 46       66  SDOP: LDA LINK .. FETCH OPERAND ADDRESS
       0C16 BD       67        PHI MA .. TO MA REGISTER
       0C17 46       68        LDA LINK
       0C18 AD       69        PLO MA .. FALL INTO SD
       0C19          70        .. 16-BIT SUB@TRACT AC FROM OPERAND.
       0C19          71        .. CALL HERE IF OPERAND
       0C19          72        .. ADDRESS IN REGISTER MA
       0C19          73        .. ****AC=M(R(MA))-AC
       0C19          74        .. ************ (TO CALL, WRITE) **********
       0C19          75        .. ****CALL SD
       0C19          76        ..
       0C19 ED       77  SD:   SEX MA .. SET X PTR TO MA
       0C1A 9F       78        GHI AC ..CHECK SIGN BIT OF AC
       0C1B F3       79        XOR  ..AND OPERAND @MA
       0C1C 52       80        STR SP  ..AND STORE ON STACK
       0C1D 1D       81        INC MA ..POINT TO LOW 8
       0C1E 8F       82        GLO AC .. FETCH AC LOW 8
       0C1F F5       83        SD .. SUBTRACT FROM LOW 8 IN MEMORY
       0C20 AF       84        PLO AC .. PUT IT BACK
       0C21 2D       85        DEC MA .. NOW HIGH 8
       0C22 9F       86        GHI AC
       0C23 75       87  SDNB: SDB .. SUBTRACT HIGH 8
       0C24 BF       88        PHI AC .. PUT IT BACK
       0C25 02       89        LDN SP   ..LOAD STORED COMPARING BIT OF OPE
       0C26 FE       90        SHL  ..CHECK STORED SIGN COMPARISION BIT
F      0C27 3B00     91        BNF SDFF  ..IF OPERAND'S SIGNS ARE SAME
       0C29 9F       92        GHI AC ..NO OVERFLOW POSSIBLE
       0C2A F3       93        XOR  ..OTHER WISE CHECK RESULT
       0C2B FE       94        SHL  ..SET DF=0  IF OK
       0C2C D5       95  SDFF:   SEP RETN   ..RETURN
       0C2D          96        .. 16-BIT SUBTRACT FROM AC (ADDRESS IN CALL
       0C2D          97        .. ****AC=AC-OPRN
       0C2D          98        .. ************ (TO CALL, WRITE) **********
       0C2D          99        .. ****CALL SMOP ; ,A(OPRN)
       0C2D          100       ..
       0C2D 46       101  SMOP: LDA LINK
       0C2E BD       102       PHI MA
       0C2F 46       103       LDA LINK
       0C30 AD       104       PLO MA
       0C31          105       .. 16-BIT SUBTRACT FROM AC (ADDRESS IN MA)
       0C31          106       .. CALL HERE IF OPERAND
       0C31          107       .. ADDRESS IN REGISTER MA
```

```
0C31              108        .. ****AC=AC-M(R(MA))
0C31              109        .. ************ (TO CALL, WRITE) **********
0C31              110        .. ****CALL SM
0C31              111        ..
0C31 ED           112  SM:   SEX MA  ..SET X PTR
0C32 9F           113        GHI AC  ..GET SIGN OF AC AND
0C33 F6           114         SHR    ..AND STORE IN 7TH BIT OF CR
0C34 52           115        STR SP  ..BUT PUT IN (SP) FIRST
0C35 9F           116        GHI AC  ..AND SEE IF OPERANDS SIGNS ARE THE
0C36 F3           117        XOR
0C37 FA80         118        ANI #80 ..TAKE OUT COMPARING SIGN BIT
0C39 E2           119        SEX SP  ..NOW STORE THAT BIT IN 8TH OF CR
0C3A F4           120        ADD  ..BY ADDING TO IT
0C3B 52           121        STR SP  ..AND STORE THESE TWO BITS ON STACK
0C3C 1D           122        INC MA  ..POINT TO LOW 8
0C3D ED           123        SEX MA  ..REMEMBER TO SET X TO OPERANDS
0C3E 8F           124        GLO AC .. FETCH AC LOW 8
0C3F F7           125        SM .. SUBTRACT MEMORY FROM IT
0C40 AF           126        PLO AC .. PUT IT BACK.
0C41 2D           127        DEC MA .. NOW HIGH 8
0C42 9F           128        GHI AC
0C43 77           129  SMNB: SMB .. HIGH 8 SUBTRACT, NO BORROW ACCROSS
0C44 BF           130        PHI AC .. PUT HIGH 8 BACK
0C45 E2           131        SEX SP  ..NOW CHECK IF  UNDERFLOWED
0C46 F0           132        LDX  ..LOAD THE STORED TWO BITS
0C47 FE           133        SHL  ..AND TAKE OUT THE COMPARING SIGN BIT
F 0C48 3B00       134        BNF SMRT ..THE SAME, UNDERFLOW NOT POSSIBLE
0C4A 52           135        STR SP  ..PUT IT BACK TO STACK
0C4B 9F           136        GHI AC   ..OTHERWISE HAVE TO COMPARE SIGN O
0C4C F3           137        XOR  ..SIGN BIT OF AC WAS STORED ON STACK
0C4D FE           138        SHL  ..TAKE OUT THAT 7TH BIT
0C4E D5           139  SMRT:  SEP RETN  ..DF=0 IF SUBTRACTION OK
0C4F              140        ..
0C4F              141        ..
0C4F              142        ..16X16 BIT SIGNED MULTIPLY(2'S COMPLEMENT)
0C4F              143        ..****AC=AC*OPRN
0C4F              144        ..***********(TO CALL, WRITE)***********
0C4F              145        ..****CALL MPYOP ; ,A(OPRN)
0C4F              146        ..
0C4F 46           147  MPYOP: LDA LINK  ..FETCH MULTIPLICAND ADDRS
0C50 BD           148        PHI MA  ..INTO REGISTER A
0C51 46           149        LDA LINK
0C52 AD           150        PLO MA  ..FALL INTO MPY
0C53              151        .. 16X16 BIT SIGNED MULTIPLY (2'S COMPLEMEN
0C53              152        .. CALL HERE IF OPERAND ADDRESS
0C53              153        .. IN REGISTER MA
0C53              154        .. ****AC=AC*M(R(MA))
0C53              155        .. ************ (TO CALL, WRITE) **********
0C53              156        .. ****CALL MPY
0C53              157        ..
0C53 ED           158  MPY: SEX MA .. SET X NOW
0C54 9F           159        GHI AC  ..CHECK IS THE SIGN OF MULTICAND
0C55 F3           160        XOR  ..THE SAME AS THE SIGN OF MULTIPR
0C56 FA80         161        ANI #80  ..AND STORE THAT BIT
```

```
0C58 BC        162        PHI CR   ..INTO CR.1
0C59 F810      163        LDI #10 .. SET COUNTER TO 16
0C5B AC        164        PLO CR
0C5C F800      165        LDI #00 ..  INITIALIZE MQ TO 0
0C5E BE        166        PHI MQ ... TO HOLD PRODUCT.
0C5F AE        167        PLO MQ
0C60 2C        168 MPL:    DEC CR  ..IF NOT, DECREMENT IT.
0C61 9F        169        GHI AC .. SHIFT AC (=MULTIPLIER) RIGHT
0C62 F6        170        SHR
0C63 BF        171        PHI AC
0C64 8F        172        GLO AC
0C65 76        173        SHRC .. SHIFT 0 ACCROSS BYTES ..
0C66 AF        174        PLO AC
0C67 9E        175        GHI MQ
0C68 3B00   F  176        BNF MPB  ..IF NO BIT OUT, DON'T ADD.
0C6A 1D        177        INC MA .. POINT TO LOW 8 OF MULTIPLICAND
0C6B 8C        178        GLO CR .. IF NOT LAST ITERATION,
0C6C 3A00   F  179        BNZ MPA .. GO ADD.
0C6E 8E        180        GLO MQ  ..LOAD MQ.0 INTO D
0C6F F7        181        SM   ..MQ.0-(MA.0)
0C70 AE        182        PLO MQ  ..AND STORE BACK INTO MQ.0
0C71 2D        183        DEC MA  ..NOW DO THE HIGH BYTE
0C72 9E        184        GHI MQ  ..
0C73 77        185        SMB     ..REMEMBER THE BORROW BIT
0C74 BE        186        PHI MQ  ..AND PUT BACK INTO MQ.1
0C75 9C        187        GHI CR  ..NOW ARE THE SIGNS OF OPERANDS THE
0C76 FE        188 MPB:    SHL  ..TEST FOR SIGN BIT
0C77 3003   F  189        BR MPS+#03  ..IF NEGATIVE, SIGN EXTEND
0C79 8E        190 MPA:    GLO MQ  ..DO MQ+(MA)
0C7A F4        191        ADD   ..MQ.0+(MA.0)
0C7B AE        192        PLO MQ  ..AND PUT BACK INTO MQ.0
0C7C 2D        193        DEC MA  ..SAME FOR HIGH BYTE
0C7D 9E        194        GHI MQ  ..
0C7E 74        195        ADC   ..ADD WITH CARRY
0C7F BE        196        PHI MQ  ..
0C80 CF        197 MPS:    LSDF
0C81 F0        198 ,      LDX
0C82 FE        199        SHL..IF OPERAND IS NEGATIVE,THEN
0C83 9E        200        GHI MQ  ..PUT MQ.1 INTO D
0C84 76        201        SHRC .. SHIFT IN CARRY
0C85 BE        202        PHI MQ
0C86 8E        203        GLO MQ .. CONTINUE TO LOW 8 OF MQ
0C87 76        204        SHRC
0C88 AE        205        PLO MQ
0C89 3B00   F  206        BNF MT ..  IF NO CARRY OUT, ITERATE.
0C8B 9F        207        GHI AC .. ADD CARRY OUT INTO AC MSB.
0C8C F980      208        ORI #80
0C8E BF        209        PHI AC
0C8F 8C        210 MT:     GLO CR   ..CHECK COUNTER
0C90 3A60      211        BNZ MPL    ..IF COUNTER IS NOT 0,GO BACK FOR
0C92 9F        212  MPX: GHI AC .. FINISHED;
0C93 FE        213        SHL .. CHECK FOR PRODUCT > 15 BITS.
0C94 8E        214        GLO MQ
0C95 C7        215        LSNF  ..THAT'S HIGH 17 BITS
```

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```
0C96  FBFF    216         XRI  #FF .. ALL 00 OR FF.
0C98  3A9E    217         BNZ  *+#06 .. NAW.
0C9A  9E      218         GHI  MQ
0C9B  C7      219         LSNF
0C9C  FBFF    220         XRI  #FF
0C9E  FCFF    221         ADI  #FF .. SET DF IF PRODUCT > 15 BITS
0CA0  D5      222         SEP  RETN .. RETURN.
0CA1          223         .. 32/16 BIT SIGNED DIVIDE (2'S COMPLEMENT)
0CA1          224         .. AC=MQ, AC/OPRN
0CA1          225         .. QUOTIENT IN AC , REMAINDER IN MQ
0CA1          226         .. *********** (TO CALL, WRITE) ***********
0CA1          227         .. CALL DIVOP ; ,A(OPRN)
0CA1          228         ..
0CA1  46      229  DIVOP: LDA  LINK .. FETCH OPERAND ADDRESS
0CA2  BD      230         PHI  MA .. TO REGISTER MA
0CA3  46      231         LDA  LINK
0CA4  AD      232         PLO  MA .. FALL INTO DIVO/DIV/DIVQ.
0CA5          233         .. 32/16 BIT SIGNED DIVIDE (2'S COMPLEMENT)
0CA5          234         ... OPTION #1: CLEAR MQ AND CHECK FOR ZERO
0CA5          235         .. ****AC=MQ, AC/M(R(MA))
0CA5          236         .. *********** (TO CALL, WRITE) ***********
0CA5          237         .. ****CALL DIVO
0CA5  ED      238  DIVO:  SEX  MA .. SET X TO POINT TO DIVISOR (0)
0CA6  9F      239         GHI  AC .. LOOK AT AC SIGN (0)
0CA7  FE      240         SHL  .. COPY IT TO DF (0)
0CA8  F800    241         LDI  #00 .. EXTEND #00 IF POSITIVE, (0)
0CAA  C7      242         LSNF .. (0)
0CAB  F8FF    243         LDI  #FF .. #FF IF NEGATIVE. (0)
0CAD  BE      244         PHI  MQ .. GIVING +0 OR -0 IN MQ (0)
0CAE  AE      245         PLO  MQ .. (0)
0CAF  4D      246         LDA  MA .. CHECK FOR ZERO DIVISOR (0)
0CB0  F1      247         OR   .. (0)
0CB1  2D      248         DEC  MA .. (DON'T FORGET TO FIX POINTER)(0)
0CB2  FD00    249         SDI  #00 .. IF ZERO, CALL IT DIVIDE CHECK(0)
0CB4  3B00    250         BNF  DIV ..GO ON IF NO DIVIDE CHECK ERR
0CB6  D5      251         SEP  RETN ..AND RETURN WITH DF=1 (0)
0CB7          252         ... OPTION #2: PERMIT 32-BIT DIVIDEND; (/)
0CB7          253         ..
0CB7          254         ..MAKE SURE QUOTIENT DOES NOT EXCEED 16 BIT
0CB7          255         .. ****** (TO CALL, WRITE) ******(/)
0CB7          256         .. ***** CALL DIV *****(/)
0CB7  9E      257  DIV:   GHI  MQ  ..SAVE PARTIAL DIVIDEND(/)
0CB8  BC      258         PHI  CR  ..INTO CR.1(/)
0CB9  8E      259         GLO  MQ  ..(/)
0CBA  AC      260         PLO  CR  ..AND CR.0(/)
0CBB  FE      261         SHL  ..(/)
0CBC  AE      262         PLO  MQ  ..(/)
0CBD  9E      263         GHI  MQ  ..DO THE SAME FOR HIGH BYTE(/)
0CBE  7E      264         SHLC ..REMEMBER CARRY(/)
0CBF  BE      265         PHI  MQ  ..(/)
0CC0  9F      266         GHI  AC  ..ALSO SHIFT IN AC HIGH(/)
0CC1  FE      267         SHL  ..(/)
0CC2  33FF    268         BDF  D2-#01  ..(/)
0CC4  8C      269         GLO  CR  ..SEE IF MQ.0 =0(/)
```

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```
F  0CC5  3A00      270        BNZ D2    ..IF NOT GO THROUGH CHECKING STEPS
   0CC7  9C        271        GHI CR    ..SEE IF MQ.1 IS #40(/)
   0CC8  FD40      272        XRI #40   ..WHICH SHOULD RESULT 0 IF TRUE(/)
F  0CCA  3200      273        BZ D4     ..IF TRUE,SKIP NORMAL CHECKING(/)
   0CCC  38        274        ,#38
   0CCD  1E        275        INC MQ    ..IF 1, SHIFT INTO MQ(/)
   0CCE  9C        276  D2:   GHI CR    ..CHECK IF HIGH 2 BITS OF MQ AR
   0CCF  FAC0      277        ANI #C0   ..TAKE OUT 2 HIGH BITS(/)
   0CD1  FD00      278        SDI #00   ..SEE IF THEY ARE THE SAME(/)
   0CD3  FE        279        SHL       ..SHIFT OUT COMPARISION (/)
F  0CD4  C30000    280        LBDF DVXX ..SET DF AND RETURN(/)
   0CD7  9C        281  D4:   GHI CR    ..LOOK AT THE SIGNS OF DIVND AND D
   0CD8  ED        282        SEX MA    ..POINT X TO DIVISOR(/)
   0CD9  F3        283        XOR       ..(/)
   0CDA  FE        284        SHL       ..SET DF IF THE SAME(/)
   0CDB  1D        285        INC MA    ..MQ.0-(MA)(/)
   0CDC  8E        286        GLO MQ    ..MQ.0 TO D(/)
F  0CDD  3300      287        BDF DVA   ..IF FLAG ,MQ.0+(MA)(/)
   0CDF  F7        288        SM        ..MQ.0-(MA.0)(/)
   0CE0  AE        289        PLO MQ    ..AND STORE BACK INTO MQ.0(/)
   0CE1  2D        290        DEC MA    ..DO THE SAME FOR HIGH BYTE(/)
   0CE2  9E        291        GHI MQ    ..LOAD MQ.1 INTO D(/)
   0CE3  77        292        SMB       ..MQ.1-(MA.1) WITH CARRY(/)
F  0CE4  3600      293        BR DVB    ..SKIP OVER ADD STEP(/)
   0CE6  F4        294  DVA:  ADD       ..MQ+(MA)(/)
   0CE7  AE        295        PLO MQ    ..STORE BACK TO MQ.0(/)
   0CE8  2D        296        DEC MA    ..SAME FOR HIGH BYTE(/)
   0CE9  9E        297        GHI MQ    ..MQ.1+(MA.1)(/)
   0CEA  74        298        ADC       ..ADD MQ.1 AND (MA.1) WITH CARRY(/)
   0CEB  BE        299  DVB:  PHI MQ    ..AND STORE BACK INTO MQ.1(/)
   0CEC  9C        300        GHI CR    ..LOOK AT THE SIGN OF DIVIND(/)
   0CED  FE        301        SHL       ..SET DF IF DIVIND IS NEGATIVE
F  0CEE  CB0000    302        LBNF DV2  ..IF NOT, DON'T COMPLEMENT DIFF(/
   0CF1  9E        303        GHI MQ    ..COMPLEMENT MQ(/)
   0CF2  FBFF      304        XRI #FF   ..BY XOR TO #FF(/)
   0CF4  BE        305        PHI MQ    ..(/)
   0CF5  8E        306        GLO MQ    ..(DO THE SAME FOR LOW BYTE)(/)
   0CF6  FBFF      307        XRI #FF   ..(/)
   0CF8  AE        308        PLO MQ    ..(/)
   0CF9  1E        309        INC MQ    ..REMEMBER TO ADD 1 (/)
   0CFA  9E        310  DV2:  GHI MQ    ..NOW LOOK AT THE DIFF OF MQ&(M
F  0CFB  C20000    311        LBZ D10   ..IF 0,CHECK MQ=0(/)
   0CFE  FE        312        SHL       ..CHECK IF MQ IS NEGATIVE(/)
F  0CFF  3300      313        BDF DDQ   ..IF YES, NO PROBLEM(/)
F  0D01  3000      314        BR D9     ..IF NOT 0 NOR NEG,DIVND IS TOO LARG
   0D03  8E        315  D10:  GLO MQ    ..HERE WE CHECK DIFF=0 CASES(/)
   0D04  FCFE      316        ADI #FE   ..IF MQ.0 IS NOT EITHER 0 OR 1(/)
F  0D06  3300      317        BDF DVXX  ..THEN DIVND IS STILL TOO LARGE(
   0D08  FBFF      318        XRI #FF   ..RESULT 0 IF MQ.0 WAS 1(/)
F  0D0A  3A00      319        BNZ DVH   ..IF NOT, MUST BE 0, GO TO DVH(/)
   0D0C  9C        320        GHI CR    ..SEE IF DIVND IS NEGATIVE(/)
   0D0D  FA80      321        ANI #80   ..RESULT 80 IF YES(/)
F  0D0F  3200      322        BZ D9     ..IF DIVND POSITIVE, IT CANNOT DIV
   0D11  F4        323        ADD       ..SEE IF DIVISOR IS POSITIVE(/)
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```
F  0D12 3300     324 DVH:  BDF DVXX   ..IF NEGATIVE, DIVND CANNOT DIVI
   0D14 1D       325       INC MA    ..AC+(MA) TO MQ(/)
   0D15 8F       326       GLO AC    ..DO AC LOW FIRST(/)
   0D16 F4       327       ADD   ..(/)
   0D17 AE       328       PLO MQ    ..STORE BACK TO LOW MQ(/)@
   0D18 2D       329       DEC MA   ..DO THE SAME FOR HIGH BYTE(/)
   0D19 9F       330       GHI AC   ..(/)
   0D1A 74       331       ADC   ..ADD WITH CARRY(/)
   0D1B BE       332       PHI MQ   ..(/)
   0D1C 1D       333       INC MA ..LEAVE MA POINTING TO LOW DIVISOR(/
   0D1D F0       334       LDX   ..NOW HECK LOW BIT (MA) IS 0 OR 1(/)
   0D1E F6       335       SHR   ..SHIFT THAT LOW BIT OUT(/)
   0D1F 2D       336       DEC MA   ..REMEMBER TO RESET MA(/)
   0D20 9E       337       GHI MQ   ..READY TO ADD #80(/)
   0D21 C7       338       LSNF   ..IF LOW BIT OF AC IS 1(/)
   0D22 FC80     339       ADI #80   ..TO MQ.1(/)
   0D24 BE       340       PHI MQ   ..STORE STATUS(/)
   0D25 FE       341       SHL   ..SEE IF MQ >0(/)
   0D26 9C       342       GHI CR   ..SEE IF DIVND POSTIVE(/)
   0D27 FA80     343       ANI #80   ..BY TAKE OUT SIGN(/)
   0D29 3A2F     344       BNZ *+#06   ..(/)
F  0D2B 3B00     345       BNF D9   ..EXIT WITH DF=1(/)
F  0D2D 3000     346       BR DDQ   ..OK(/)
F  0D2F 3300     347       BDF DVXX   ..IF NEGATIVE, THEN OUT(/)
   0D31 9E       348       GHI MQ   ..SEE IF MQ=0?(/)
F  0D32 3A00     349       BNZ DDQ   ..IF NOT, THEN NO PROBLEM(/)
   0D34 8E       350       GLO MQ   ..MAKE SURE MQ.0 IS 0 TOO(/)
F  0D35 3200     351       BZ D9   ..IF YES, THEN RETURN WITH DF=1(/)
F  0D37 3000     352       BR DDQ   ..OR ELSE GO TO DIVIDE(/)
   0D39 9C       353 DVH:  GHI CR   ..SEE IF THE OPERANDS SIGNS DIF
   0D3A F3       354       XOR   ..BY COMPARING SIGN BITS(/)
   0D3B FE       355       SHL   ..AND TAKE OUT THAT BIT(/)
   0D3C 3314     356       BDF D10+#11   ..IF SINGS DIFF, IT'S OK(/)
   0D3E 9C       357       GHI CR   ..OTHERWISE TEST SIGN OF DIVND(/)
   0D3F FE       358       SHL   ..IF POSITIVE, RETURN WITH DF=1(/)
F  0D40 3B00     359       BNF D9   ..RETURN WITH DF=1(/)
   0D42 1D       360       INC MA   ..SEE IF LOW BIT OF AC IS 0 OR 1(/
   0D43 F0       361       LDX   ..LOAD THAT IN D(/)
   0D44 2D       362       DEC MA   ..REMEMBER TO RESET MA(/)
   0D45 F6       363       SHR   ..SHIFT THAT BIT OUT(/)
   0D46 8F       364       GLO AC   ..IF AC IS NOT 0 ,NOT PROBLEM(/)
F  0D47 3A00     365       BNZ DDQ   ..GO TO DIVIDE(/)
   0D49 9F       366       GHI AC   ..READY TO CHECK #80 IF LOW BIT AC
   0D4A 3350     367       BDF *+#06   ..(/)
F  0D4C 3200     368       BZ D9   ..NO GOOD, RETURN WITH DF=1(/)
F  0D4E 3000     369       BR DDQ   ..ANY THING ELSE IS OK(/)
   0D50 FB80     370       XRI #80   ..IF AC.1 IS'NT #80(/)
F  0D52 3A00     371       BNZ DDQ   ..IT'S OK(/)
   0D54 FF00     372 D9:   SMI #00   ..DF IS SET TO 1(/)
   0D56 9C       373 DVXX: GHI CR   ..PUT ORGINAL DIVND(/)
   0D57 BE       374       PHI MQ   ..INTO MQ(/)
   0D58 8C       375       GLO CR ..(/)
   0D59 AE       376       PLO MQ   ..(/)
   0D5A D5       377       SEP RETN   ..AND RETURN WITH DF=1(/)
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```
0D5B 9C          378 DDQ:   GHI CR  ...PUT ORGINAL DIVND(/)
0D5C BE          379        PHI MQ  ..BACK INTO MQ(/)
0D5D 8C          380        GLO CR  ..(/)
0D5E AE          381        PLO MQ  ..(/)
0D5F             382        ... OPTION #3: ASSUME BENIGN PROGRAM; NOCHE
0D5F             383        .. ************ (TO CALL, WRITE) **********
0D5F             384        .. ****CALL DIVQ
0D5F 9E          385 DIVQ:  GHI MQ  ..LOOK AT DIVIDEND SIGN
0D60 FE          386        SHL  .. IF POSITIVE,
0D61 F890        387        LDI #90 .. PLAN TO BEGIN WITH SUBTRACT,
0D63 C7          388        LSNF .. (ALSO SAVE SIGN OF DIVIDEND)
0D64 F850        389        LDI #50 .. OTHER WISE BEGIN WITH ADD.
0D66 AC          390        PLO CR .. SET ITERATION COUNT IN CR.0
0D67 8E          391 DVL:   GLO MQ  ..SHIFT MQ LEFT 1 BIT
0D68 FE          392        SHL  ..SHIFT LEFT MQ.0
0D69 AE          393        PLO MQ  ..
0D6A 9E          394        GHI MQ  ..SAME FOR HIGH BYTE
0D6B 7E          395        SHLC ..SHIFT LEFT WITH CARRY
0D6C BE          396        PHI MQ ..
0D6D 8F          397        GLO AC  ..SHIFT AC LEFT 1 BIT
0D6E FE          398        SHL  ..SHIFT AC.0
0D6F AF          399        PLO AC  ..
0D70 9F          400        GHI AC  ..
0D71 7E          401        SHLC  ..SHIFT WITH CARRY
0D72 BF          402        PHI AC
0D73 3B76        403        BNF *+#03 .. BIT SHIFTED OUT OF AC.1,
0D75 1E          404        INC MQ .. GOES INTO MQ.0
0D76 ED          405        SEX MA ..
0D77 8C          406        GLO CR .. NOW, WAS THAT ADD, OR SUBTRACT?
0D78 F3          407        XOR .. IT DEPENDS ON SAVED FLAG,
0D79 FE          408        SHL  ..AND SIGN OF DIVISOR
0D7A 1D          409        INC MA  ..MQ.0-(MA.0)
0D7B 8E          410        GLO MQ  ..
F 0D7C 3B00      411        BNF DSA  ..IF NO FLAG,MQ.0+(MA.0)
0D7E F7          412        SM  ..
0D7F AE          413        PLO MQ  ..
0D80 2D          414        DEC MA  ..FIX X PTR
0D81 9E          415        GHI MQ  ..DO THE SAME FOR HIGH BYTE
0D82 77          416        SMB  ..REMEMBER THAT BORROW BIT
F 0D83 3000      417        BR DSM  ..SKIP OVER ADD STEPS
0D85 F4          418 DSA:   ADD  ..MQ+(MA)
0D86 AE          419        PLO MQ  ..
0D87 2D          420        DEC MA ..DO THE SAME FOR HIGH BYTE
0D88 9E          421        GHI MQ  ..
0D89 74          422        ADC  ..ADD WITH CARRY
0D8A BE          423 DSM:   PHI MQ  ..STORE BACK TO MQ.1
0D8B 2C          424        DEC CR .. COUNT DOWN ITERATION COUNTER
0D8C 8C          425        GLO CR
0D8D FA7F        426        ANI #7F
0D8F 3B94        427        BNF *+#05 .. TEST CARRY OUT OF ADD/SUBTRACT
0D91 1F          428        INC AC .. IF 1, SHIFT INTO QUOTIENT,
0D92 F980        429        ORI #80 .. AND FLAG NEXT OP AS SUBTRACT.
0D94 AC          430        PLO CR .. OTHERWISE IT'S ADD.
0D95 FA3F        431        ANI #3F .. LOOK AT COUNTER:
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       0D97  3A67     432         BNZ DVL .. IF NOT 0, LOOP BACK;
F      0D99  3300     433         BDF DVR .. AT END, CHECK REMAINDER ADJUST.
       0D9B  38       434             ,#38
       0D9C  1F       435     DVC: INC AC .. (FINAL DIVIDE STEP)
       0D9D  F3       436         XOR .. BE SURE TO GET POLARITY
       0D9E  FE       437         SHL .. OF ADJUSTMENT RIGHT...
       0D9F  1D       438         INC MA .. YES, ADD DIVISOR BACK ON,
       0DA0  8E       439         GLO MQ .. TO CORRECT FOR FINAL SUBTRACT,
F      0DA1  3300     440         BNF DVM .. (ADDING NEGATIVE IS SUBT.)
       0DA3  F4       441         ADD .. WHICH SHOULDN'T HAVE.
       0DA4  AE       442         PLO MQ
       0DA5  2D       443         DEC MA
       0DA6  9E       444         GHI MQ
       0DA7  74       445         ADC  ..ADD WITH CARRY
F      0DA8  00FF     446         BR DVR-#01
       0DAA  F7       447     DVM: SM .. SAME THING,
       0DAB  AE       448         PLO MQ .. EXCEPT, FOR NEGATIVE DIVISOR.
       0DAC  2D       449         DEC MA
       0DAD  9E       450         GHI MQ
       0DAE  77       451         SMB
       0DAF  BE       452         PHI MQ
       0DB0  9E       453     DVR: GHI MQ .. IF REMAINDER IS NOT ZERO,
       0DB1  3AB6     454         BNZ *+#05
       0DB3  8E       455         GLO MQ
F      0DB4  3200     456         BZ DVN .. BUT IT IS; NO PROBLEM.
       0DB6  8C       457         GLO CR .. IF NOT ZERO,
       0DB7  FE       458         SHL .. IT SHOULD BE SAME SIGN
       0DB8  FE       459         SHL .. AS ORIGINAL DIVIDEND.
       0DB9  9E       460         GHI MQ
       0DBA  CF       461         LSDF
       0DBB  FB80     462         XRI #80
       0DBD  FC80     463         ADI #80 .. IF NOT, WE NEED
       0DBF  3B9C     464         BNF DVC .. ONE MORE DIVIDE ITERATION.
       0DC1  F0       465     DVN: LDX .. FINALLY, IF DIVISOR NEGATIVE,
       0DC2  FE       466         SHL
F      0DC3  3B00     467         BNF DVX   ..(IT'S NOT; WE ARE DONE)
       0DC5  8F       468         GLO AC .. COMPLEMENT QUOTIENT,
       0DC6  FBFF     469         XRI #FF .. BY INVERTING IT,
       0DC8  AF       470         PLO AC
       0DC9  9F       471         GHI AC
       0DCA  FBFF     472         XRI #FF
       0DCC  BF       473         PHI AC
       0DCD  1F       474         INC AC .. THEN INCREMENTING
       0DCE  FC00     475         ADI #00 .. ALSO CLEAR DF.
       0DD0  D5       476     DVX: SEP RETN .. DF=0 IF DIVIDE SUCCESSFUL.
       0DD1           477         ..
       0DD1           478         .. 16-BIT ADD TO AC, OPERAND ADDRESS IN CAL
       0DD1           479         .. ****AC=AC+OPRN .. OPRN=2 BYTE OPERAND
       0DD1           480         .. ************ (TO CALL, WRITE) *********
       0DD1           481         .. ****CALL ADDOP ; ,A(OPRN)
       0DD1           482         ..
       0DD1           483         ..
       0DD1  46       484     ADDOP: LDA LINK .. FETCH OPERAND ADDRESS
       0DD2  BD       485         PHI MA .. TO REGISTER MA
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0DD3  46        486          LDA  LINK
0DD4  AD        487          PLO  MA  ..  FALL  INTO  ADD
0DD5           488          ..  16-BIT  ADD  TO  AC,  OPERAND  ADDRESS  IN  REG
0DD5           489          ..  CALL  HERE  IF  OPRN  ADDRESS
0DD5           490          ..  IS  IN  REGISTER  MA
0DD5           491          ..  ****AC=AC+M(R(MA))
0DD5           492          ..  ************  (TO  CALL,  WRITE)  **********
0DD5           493          ..  ****CALL  ADD
0DD5           494          ..
0DD5  LD       495   ADD:   SEX  MA  ..CHECK  SIGN  BIT  OF  AC
0DD6  9F       496          GHI  AC  ..GET  THE  OPERAND
0DD7  F3       497          XOR  ..AND  OPERAND  @MA
0DD8  FB80     498          XRI  #80  ..RESULT  A  1  IF  DIFF
0DDA  52       499          STR  SP  ..STORE  ON  STACK
0DDB  1D       500          INC  MA  ..POINT  TO  LOW  8  BITS
0DDC  8F       501          GLO  AC  ..  FETCH  AC  LOW  8
0DDD  F4       502          ADD  ..  ADD  LOW  8  FROM  MEMORY
0DDE  AF       503          PLO  AC  ..  PUT  IT  BACK
0DDF  2D       504          DEC  MA  ..  POINT  TO  HIGH  8  MEMORY  LOCATION
0DE0  9F       505          GHI  AC
0DE1  74       506          ADC  ..ADD  HIGH  BYTE  WITH  CARRY
0DE2  BF       507          PHI  AC  ..  PUT  IN  AC.
0DE3  62       508          LDN  SP  ..LOAD  THE  STORED  COMPARING  SIGN  BI
0DE4  FE       509          SHL  ..RESET  STACK  PTR
F    0DE5  3B01     510          BNF  ADDRT+#01  ..NOT  POSSIBLE
0DE7  9F       511          GHI  AC  ..OTHERWISE  SEE  IF  SUM  IS  RIGHT
0DE8  F3       512          XOR  ..BY  COMPARING  SIGN  BITS
0DE9  FE       513   ADDRT:    SHL    ..SHIFT  OUT  0  INTO  DF
0DEA  D5       514          SEP  RETN  ..RETURN  TO  MAIN
0DEB          515          ..
0DEB          516          ..  16-BIT  CONSTANT  ADD  TO  AC.
0DEB          517          ..  CALL  HERE  FOR  ADD  CONSTANT  TO  AC
0DEB          518          ..  ****AC=AC+CONSTANT
0DEB          519          ..  ************  (TO  CALL,  WRITE)  **********
0DEB          520          ..  ****CALL  ADDCON  ;  ,CONSTANT
0DEB          521          ..
0DEB  86       522   . ADDCON:  GLO  LINK  ..  COPY  LINK  TO  MA
0DEC  AD       523          PLO  MA
0DED  96       524          GHI  LINK
0DEE  BD       525          PHI  MA
0DEF  16       526          INC  LINK  ..  INCREMENT  PAST  DATUM
0DF0  16       527          INC  LINK
0DF1  30D5     528          BR  ADD  ..  GO  ADD.
0DF3          529          ..
0DF3          530          ..  16-BIT  ADD  FROM  TOP  OF  STACK
0DF3  92       531   'ADDST:  GHI  SP  ..  COPY  STACK  POINTER
0DF4  BD       532          PHI  MA  ..  TO  MA  REGISTER
0DF5  82       533          GLO  SP
0DF6  AD       534          PLO  MA
0DF7  1D       535          INC  MA  ..  ADVANCE  TO  SUB-TOP  (@)
0DF8  1D       536          INC  MA  ..  (@)
0DF9  1D       537          INC  MA  ..  (@)
0DFA  30D5     538          BR  ADD  ..  GO  DO  IT
0DFC          539          ..
```

```
0DFC           540      ..
0DFC           541      ..
0DFC           542      .. PUSH AC INTO STACK
0DFC           543      .. STACK POINTER = SP
0DFC           544      .. *********** (TO CALL, WRITE) ********
0DFC           545      .. ****CALL PUSHAC
0DFC           546      .. PUSH AC (UNDER TOP OF STACK)
0DFC 92        547  PUSHAC: GHI SP .. COPY STACK POINTER TO MA
0DFD BD        548      PHI MA
0DFE 82        549      GLO SP
0DFF AD        550      PLO MA
0E00 1D        551      INC MA .. NOW SLICE OFF TOP 2 BYTES,
0E01 1D        552      INC MA
0E02 E2        553      SEX SP
0E03 0D        554      LDN MA .. TO MAKE A 2-BYTE HOLE.
0E04 73        555      STXD
0E05 2D        556      DEC MA
0E06 0D        557      LDN MA
0E07 73        558      STXD
0E08 9F        559      GHI AC .. NOW STUFF AC INTO THE HOLE.
0E09 5D        560      STR MA
0E0A 8F        561      GLO AC
0E0B 1D        562      INC MA
0E0C 5D        563      STR MA
0E0D 2D        564      DEC MA .. LEAVE MA POINTING TO IT.
0E0E D5        565      SEP RETN .. (AC UNCHANGED)
0E0F           566      .. PUSH CR, MA, MQ (UNDER TOP OF STACK)
0E0F 8D        567  PUSHCQ: GLO MA .. FIRST PUSH MA ONTO TOP
0E10 E2        568      SEX SP
0E11 73        569      STXD
0E12 9D        570      GHI MA
0E13 52        571      STR SP
0E14 92        572      GHI SP .. NOW COPY SP TO MA
0E15 BD        573      PHI MA
0E16 62        574      GLO SP
0E17 AD        575      PLO MA
0E18 22        576      DEC SP
0E19 1D        577      INC MA .. THEN ADJUST IT
0E1A 1D        578      INC MA
0E1B 1D        579      INC MA .. TO POINT INTO OLD TOP
0E1C 8E        580      GLO MQ .. CONTINUE PUSHING, MQ
0E1D 73        581      STXD
0E1E 9E        582      GHI MQ
0E1F 73        583      STXD
0E20 0D        584      LDN MA
0E21 73        585      STXD
0E22 2D        586      DEC MA
0E23 0D        587      LDN MA
0E24 73        588      STXD
0E25 9C        589      GHI CR .. FINALY INSERT CR IN HOLE
0E26 5D        590      STR MA
0E27 1D        591      INC MA
0E28 8C        592      GLO CR
0E29 5D        593      STR MA
```

```
0E2A  D5       594       SEP RETN .. (MA IS GARBAGE OUT)
0E2B           595       ..
0E2B           596       .. POP STACK INTO MQ, MA, CR (UNDER TOP OF
0E2B  12       597   POPCQ: INC SP
0E2C  92       598       GHI SP .. COPY STACK POINTER TO MA
0E2D  BD       599       PHI MA
0E2E  82       600       GLO SP
0E2F  AD       601       PLO MA
0E30  1D       602       INC MA .. ADJUST POINTER TO CR DATUM
0E31  1D       603       INC MA
0E32  1D       604       INC MA
0E33  1D       605       INC MA
0E34  1D       606       INC MA
0E35  1D       607       INC MA
0E36  4D       608       LDA MA .. FETCH IT
0E37  BC       609       PHI CR
0E38  0D       610       LDN MA
0E39  AC       611       PLO CR
0E3A  2D       612       DEC MA .. COPY TOP OF STACK INTO GAP
0E3B  42       613       LDA SP
0E3C  5D       614       STR MA
0E3D  1D       615       INC MA
0E3E  42       616       LDA SP
0E3F  5D       617       STR MA
0E40  42       618       LDA SP .. THEN POP MQ
0E41  BE       619       PHI MQ
0E42  42       620       LDA SP
0E43  AE       621       PLO MQ
0E44  42       622       LDA SP .. FINALLY POP MA
0E45  BD       623       PHI MA
0E46  02       624       LDN SP
0E47  AD       625       PLO MA
0E48  D5       626       SEP RETN
0E49           627       .. 16-BIT ACCUMULATOR LOAD (ADDRESS IN CALL
0E49           628       .. ****AC=OPRN
0E49           629       .. *********** (TO CALL, WRITE) ***********
0E49           630       .. ****CALL LOADOP ; ,A(OPRN)
0E49           631       ..
0E49  46       632   LOADOP: LDA LINK .. FETCH ADDRESS
0E4A  BD       633       PHI MA .. TO MA REGISTER
0E4B  46       634       LDA LINK
0E4C  AD       635       PLO MA .. FALL INTO LOAD
0E4D           636       .. 16-BIT ACCUMULATOR LOAD (ADDRESS IN MA)
0E4D           637       .. CALL HERE IF OPERAND
0E4D           638       .. ADDRESS IN REGISTER MA
0E4D           639       .. ****AC=M(R(MA))
0E4D           640       .. *********** (TO CALL, WRITE) ***********
0E4D           641       .. ****CALL LOAD
0E4D           642       ..
0E4D  4D       643   LOAD: LDA MA .. FETCH HIGH 8
0E4E  BF       644       PHI AC
0E4F  4D       645       LDA MA .. NOW LOW 8
0E50  AF       646       PLO AC .. LEAVE MA AT NEXT DOUBLE-BYTE
0E51  D5       647       SEP RETN .. GEE, THAT WAS QUICK.
```

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```
0E52          648     ..
0E52          649     .. 16-BIT ACCUMULATOR LOAD FROM CONSTANT IN
0E52          650     .. ****AC=CONSTANT
0E52          651     .. ********** (TO CALL, WRITE) **********
0E52          652     .. ****CALL LODCON ; ,CONSTANT
0E52          653     ..
0E52 46       654     LODCON: LDA LINK .. FETCH HIGH 8
0E53 BF       655         PHI AC
0E54 46       656         LDA LINK .. THEN LOW 8
0E55 AF       657         PLO AC
0E56 D5       658         SEP RETN
0E57          659     ..
0E57          660     .. 16-BIT ACCUMULATOR STORE (ADDRESS IN CAL
0E57          661     .. ****OPRN=AC
0E57          662     .. ********** (TO CALL, WRITE) **********
0E57          663     .. ****CALL STOROP ; ,A(OPRN)
0E57          664     ..
0E57 46       665     STOROP: LDA LINK .. FETCH ADDRESS INTO MA
0E58 BD       666         PHI MA
0E59 46       667         LDA LINK
0E5A AD       668         PLO MA .. THEN FALL INTO STORE
0E5B          669     .. 16-BIT ACCUMULATOR STORE (ADDRESS IN MA)
0E5B          670     .. ****M(R(MA))=AC
0E5B          671     .. ********** (TO CALL, WRITE) **********
0E5B          672     .. ****CALL STORE
0E5B          673     ..
0E5B 9F       674     STORE: GHI AC .. FIRST HIGH 8
0E5C 5D       675         STR MA
0E5D 1D       676         INC MA .. INCREMENT MA, SINCE STR DOESN'T
0E5E 8F       677         GLO AC .. NOW LOW 8
0E5F 5D       678         STR MA
0E60 1D       679         INC MA .. LEAVE MA POINTING TO NEXT WORD
0E61 D5       680         SEP RETN .. QUIT
0E62          681     ..
0E62          682     ..
0E62          683     .. 16-BIT COMPARE, OPERAND ADDRESS IN CALL
0E62          684     .. ****AC-OPRN  (DF SET IF 0 OR +)
0E62          685     .. ********** (TO CALL, WRITE) **********
0E62          686     .. ****CALL COMOP ; ,A(OPRN)
0E62          687     ..
0E62 46       688     COMPOP: LDA LINK .. FETCH ADDRESS
0E63 BD       689         PHI MA .. TO MA REGISTER
0E64 46       690         LDA LINK
0E65 AD       691         PLO MA
0E66          692     .. 16-BIT COMPARE, OPERAND ADDRESS IN REGIS
0E66          693     .. CALL HERE IF OPERAND
0E66          694     .. ADDRESS IN REGISTER MA
0E66          695     .. ****AC-M(R(MA))  (DF SET IF 0 OR +)
0E66          696     .. ********** (TO CALL, WRITE) **********
0E66          697     .. ****CALL COMP
0E66          698     ..
0E66 ED       699     COMP: SEX MA .. COMPARE HIGH 8 FRST
0E67 9F       700         GHI  AC ..CHECK IF SIGN OF OPERANDS ARE SA
0E68 F3       701         XOR  ..BY LOOKING AT THE HIGHEST SIGN BIT
```

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```
     0E69 FA80     702        ANI  #80   ..RESULT A '1' IF NEGATIVE
F    0E6B 3A00     703        BNZ  CNE   ..IF NOT, THEN GO TO CNE
     0E6D 9F       704        GHI  AC
     0E6E F7       705        SM
F    0E6F 3A00     706        BNZ  CMPX ..  NOT EQUAL QUITS
     0E71 1D       707        INC  MA ..  TRY LOW 8
     0E72 8F       708        GLO  AC
     0E73 F7       709        SM
     0E74 2D       710        DEC  MA .. LEAVE MA POINTING TO IT
     0E75 38       711        ,#38
     0E76 F4       712 CNE:       ADD  ..SEE IF OPERAND IS NEGATIVE
     0E77 D5       713 CMPX:      SEP  RETN  ..DF=1 IF AC>=(MA)
     0E78          714        ..
     0E78          715        ..
     0E78          716        ..
     0E78          717        ..
     0E78          718        ..TEST 16-BIT ACCUMULATOR SIGN/ZERO ......
     0E78 16       719     .  INC  LINK  ..SKIP OVER NON ZERO RETURN
     0E79 16       720        INC  LINK  ..
     0E7A D5       721        SEP  RETN
     0E7B 9F       722 TEST:  GHI  AC ..  FIRST LOOK AT SIGN
     0E7C FE       723        SHL  ..SET DF IF MINUS
     0E7D 9F       724        GHI  AC .. NOW CHECK FOR 0
     0E7E 3A78     725        BNZ  TEST-#03 .. NO.
     0E80 8F       726        GLO  AC
     0E81 327A     727        BZ   TEST-#01 .. GO TAKE ZERO EXIT.
     0E83 3078     728        BR   TEST-#03 .. GO TAKE NON-ZERO EXIT.
     0E85          729        .. POP STACK (INTO AC) (UNDER TOP)
     0E85          730        .. POPS 2 BYTES FROM STACK INTO AC
     0E85          731        .. ************ (TO CALL, WRITE) ********
     0E85          732        .. ****CALL POPAC
     0E85 FF00     733 POPAC: SMI  #00 .. SET DF TO REMEMBER THIS ENTRY
     0E87 C8       734        LSKP
     0E88 FC00     735 POP:   ADI  #00 .. CLEAR DF FOR THIS ENTRY
     0E8A 12       736        INC  SP
     0E8B 92       737        GHI  SP .. COPY SP TO MA
     0E8C BD       738 ,      PHI  MA
     0E8D 82       739        GLO  SP
     0E8E AD       740        PLO  MA
     0E8F 1D       741        INC  MA .. ADJUST TO SUB-TOP OF STACK
     0E90 1D       742        INC  MA
     0E91 3B98     743        BNF  *+#07
     0E93 4D       744        LDA  MA .. POPPING INTO AC. GET DATUM
     0E94 BF       745        PHI  AC
     0E95 0D       746        LDN  MA
     0E96 AF       747        PLO  AC
     0E97 2D       748        DEC  MA
     0E98 42       749        LDA  SP .. NOW CLOSE UP THE GAP
     0E99 5D       750        STR  MA
     0E9A 1D       751        INC  MA
     0E9B 02       752        LDN  SP
     0E9C 5D       753        STR  MA
     0E9D 1D       754        INC  MA
     0E9E D5       755        SEP  RETN .. MA POINTS TO NEW SUB-TOP
```

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```
OE9F                 756        ..
OE9F                 757        ..  DECIMAL TO BINARY CONVERSION
OE9F                 758        ..  ***** AC=DECIMAL NUMBER OF N BYTES
OE9F                 759        ..  DECIMAL NUMBER = SIGN,NN,.....,N1,N0
OE9F                 760        ..  SIGN=#0B +
OE9F                 761        ..  SIGN=#0D -
OE9F                 762        ..  N0=10**0 DIGIT
OE9F                 763        ..  N1=10**1 DIGIT
OE9F                 764        ..  ********** (TO CALL, WRITE) *******
OE9F                 765        ..  **** CALL CDB; ,A(NUMBER); ,LENGTH
OE9F 46              766  CDB:   LDA LINK   ..GET NUM ADDRESS
OEA0 BA              767        PHI AR    ..AND STORE IN RA.
OEA1 46              768        LDA LINK
OEA2 AA              769        PLO AR
OEA3 46              770        LDA LINK   ..GET LENGTH
OEA4 FF01            771        SMI #01    ..MINUS SIGN BYTE
OEA6 AB              772        PLO NR    ..AND STORE IN RB.
OEA7 F800            773        LDI #00    ..CLEAR RF
OEA9 AF              774        PLO AC
OEAA BF              775        PHI AC
OEAB 0A              776        LDN AR      ..CHECK SIGN BYTE
OEAC FB0D            777        XRI #0D    ..MINUS?
OEAE BB              778        PHI NR   ..INTO NR.1
OEAF 1A              779  LOOP:  INC AR    ..GRAB THE FIRST DIGIT
OEB0 E2              780        SEX SP    ..FIX X PNTR
OEB1 0A              781        LDN AR    ..CLEAR HIGH BYTE (FOR ASCII)
OEB2 FA0F            782        ANI #0F
OEB4 52              783        STR SP    ..PUT IT BACK
OEB5 8F              784        GLO AC   ..ADD THAT DIGIT TO ACCUM
OEB6 F4              785        ADD
OEB7 AF              786        PLO AC
OEB8 9F              787        GHI AC
OEB9 7C00            788        ADCI #00   ..REMEMBER CARRY OVER
OEBB BF              789        PHI AC
F    OEBC 3300       790        BDF OVFLW   ..EXCEEDS ACCUM LIMIT?
OEBE 2B              791        DEC NR   ..DEC DIGIT COUNTER
OEBF 8B              792        GLO NR   ..SEE IF IT IS 0?
F    OEC0 3200       793        BZ FINAL   ..YES, THEN DONE
OEC2 8F              794        GLO AC   ..OTHERWISE MULTIPLTY THE ACC BY 10
OEC3 FE              795        SHL
OEC4 73              796        STXD
OEC5 9F              797        GHI AC
OEC6 7E              798        SHLC    ..CARRY OVER
OEC7 73              799        STXD
F    OEC8 33FE       800        BDF OVFLW-#02  ..EXCEEDED ACC LIMIT
OECA F802            801        LDI #02
OECC 52              802  MPY3:  STR SP   ..LOOP COUNT
OECD 8F              803        GLO AC
OECE FE              804        SHL   ..NOW SHIFT AC OVER 4 TIMES MORE
OECF AF              805        PLO AC
OED0 9F              806        GHI AC    ..SAME FOR AC.1
OED1 7E              807        SHLC
OED2 BF              808        PHI AC
F    OED3 33FE       809        BDF OVFLW-#02   ..IF OVFLOW, RESET STACK
```

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```
                          810         LDN SP   ..CHECK LOOP COUNT
  0ED5 02                 811         BZ MPY10    ..AFTER MULPLY BY 8
F 0ED6 3200               812         SMI #01  ..OR ELSE DEC LOOP COUNT
  0ED8 FF01               813         BR MPY3  ..BACK FOR MORE ADDITION
  0EDA 30CC               814 MPY10:    INC SP  ..RECOVER LOOP COUNT
  0EDC 12                 815         GHI AC   ..ADD HIGH BYTE
  0EDD 9F                 816         ADD    ..ADD 8ACC TO 2ACC
  0EDE F4                 817         PHI AC
  0EDF BF                 818         BDF OVFLW-#01  ..RESULT DF IF OVFLOW
F 0EE0 33FF               819         INC SP   ..RESET STACK PNTR
  0EE2 12                 820         GLO AC    ..SAME FOR AC.0
  0EE3 8F                 821         ADD
  0EE4 F4                 822         PLO AC
  0EE5 AF                 823         GHI AC   ..FOR CARRY OUT
  0EE6 9F                 824         ADCI #00
  0EE7 7C00               825         PHI AC
  0EE9 BF                 826         BNF LOOP   ..IF NOT OVFLW, GO BACK FOR MORE
  0EEA 3BAF               827         LSKP   ..SKIP STACK RESET
  0EEC C8                 828         INC SP   ..RESET STACK PTR
  0EED 12                 829         INC SP
  0EEE 12                 830 OVFLW:   SEP RETN   ..DF=1
  0EEF D5                 831 FINAL:   GHI AC   ..CHECK IF EXCEED MAX POS NUM L
  0EF0 9F                 832         ADI #80
  0EF1 FC80               833         BNZ CP   ..IF NOT POSSIBLE, SKIP
F 0EF3 3A00               834         GLO AC
  0EF5 8F                 835         BNZ CP   ..IF NOT, GO TO COMP
F 0EF6 3A00               836         GHI NR   ..SEE IF IT IS POSITIVE
  0EF8 9B                 837         ADI #FF  ..SET DF ACCORDINGLY
  0EF9 FCFF               838         SEP RETN
  0EFB D5                 839 CP:      BDF *-#01  ..OVERFLOWED!
  0EFC 33FB               840         GHI NR   ..TEST FOR SIGN
  0EFE 9B                 841         BNZ EXIT  ..IF POS, DONE
F 0EFF 3A00               842         GLO AC   ..IF NEG, SUBTRACT FROM 0
  0F01 8F                 843         SDI #00
  0F02 FD00               844         PLO AC
  0F04 AF                 845         GHI AC
  0F05 9F                 846         SDBI #00
  0F06 7D00               847         PHI AC
  0F08 BF                 848           ..
  0F09                    849           .. BINARY TO DECIMAL CONVERSION
  0F09                    850           .. ****DECIMAL NUMBER = AC
  0F09                    851           .. DECIMAL NUMBER = SIGN,NN,......,N1,N0
  0F09                    852           .. SIGN=#0B +
  0F09                    853           .. SIGN=#0D -
  0F09                    854           .. N0=10**0 DIGIT
  0F09                    855           .. N1=10**1 DIGIT, ETC
  0F09                    856           .. ******** (TO CALL, WRITE) ********
  0F09                    857           .. ****** CALL CBD; ,A(NUMBER); ,LENGTH
  0F09 D5                 858 EXIT:    SEP RETN
  0F0A 46                 859 CBD:     LDA LINK  ..GET THE ADDRESS
  0F0B BA                 860         PHI AR   ..AND STORE IN RA
  0F0C 46                 861         LDA LINK  ..SAME FOR LOW BYTE
  0F0D AA                 862         PLO AR
  0F0E 46                 863         LDA LINK  ..GET LENGTH
```

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```
0F0F  FF01              864         SMI  #01    ..SUBTRAC FOR SIGN BYTE
0F11  AB                865         PLO  NR     ..STORE IN NR.0
0F12  BB                866         PHI  NR     ..AND NR.1
0F13  F80F              867         LDI  #0F    ..NUM OF ITERATIONS
0F15  AD                868         PLO  MA     ..STORE IN MA.0
0F16  9F                869         GHI  AC     ..TEST FOR SIGN
0F17  FE                870         SHL
0F18  F80B              871         LDI  #0B    ..IF DF=0, IT IS POS
F  0F1A  3B00           872         BNF  POS    ..
0F1C  8F                873         GLO  AC     ..OTHERWISE CONVERT IT TO POS
0F1D  FD00              874         SDI  #00
0F1F  AF                875         PLO  AC
0F20  9F                876         GHI  AC
0F21  7D00              877         SDBI #00
0F23  BF                878         PHI  AC
0F24  F80D              879         LDI  #0D    ..MINUS SIGN
0F26  C8                880         LSKP ..
0F27  F800              881         LDI  #00
0F29  5A                882  POS:       STR  AR  ..PUT IT IN SIGN BYT
0F2A  8B                883         GLO  NR     ..CHECK DIGIT COUNTER
F  0F2B  32FE           884         BZ LOOP1-#02  ..GO BACK FOR MORE ITERATION
0F2D  1A                885         INC  AR     ..GO TO NEXT DIGIT
0F2E  2B                886         DEC  NR     ..DEC DIGIT CNTR
0F2F  3027              887         BR POS-#02    ..GO BACK FOR MORE CLEAR
0F31  E2                888         SEX  SP
0F32  9B                889         GHI  NR     ..RESET DIGIT CNTR
0F33  AB                890         PLO  NR     ..
0F34  8F                891  LOOP1:     GLO  AC  ..SHIFT BIT OF AC OUT
0F35  FE                892         SHL  ..
0F36  AF                893         PLO  AC
0F37  9F                894         GHI  AC
0F38  7E                895         SHLC ..  SAME FOR AC.1
0F39  BF                896         PHI  AC
0F3A  0A                897         LDN  AR
0F3B  7C00              898         ADCI #00     ..ADD TO LOWEST DIGIT
0F3D  5A                899         STR  AR
0F3E  8D                900         GLO  MA     ..FOR MORE ITERATION?
0F3F  3A42              901         BNZ *+#03    ..CONTINUE IF MORE ITERATION
0F41  D5                902  END:     SEP RETN
0F42  0A                903  NEXT:  LDN  AR   ..LOAD DIGIT
0F43  7E                904         SHLC  ..SHIFT LEFT OVER ONCE
0F44  5A                905         STR  AR    ..PUT IT BACK
0F45  FF0A              906         SMI  #0A    ..NEED TO INC NEXT DIGIT?
0F47  3B4A              907         BNF *+#03    ..SKIP IF NOT>10
0F49  5A                908         STR  AR    ..ELSE UPDATE DIGIT
0F4A  2A                909         DEC  AR    ..GO TO NEXT DIGIT
0F4B  2B                910         DEC  NR    ..DEC DIGIT COUNT
0F4C  8B                911         GLO  NR    ..CHECK IF 0?
0F4D  3A42              912         BNZ  NEXT   ..IF NOT, DO THE SAME FOR NEXT DI
0F4F  3341              913         BDF  END   ..OVERFLOWED
0F51  2D                914         DEC  MA    ..DEC NO OF SHIFTS
0F52  9B                915         GHI  NR    ..RESET ADDRESS PTR
0F53  52                916         STR  SP    ..PUT DIGIT ON STACK
0F54  8A                917         GLO  AR
```

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```
0F55 F4        918        ADD
0F56 AA        919          PLO  AR
0F57 9A        920          GHI  AR
0F58 7C00      921          ADCI #00
0F5A BA        922          PHI  AR
0F5B C032      923          BR  LOOP1-#02     ...
0F5D           924          ..
0F5D           925          .. *****SUBROUTINE CALL (CDP1802 VERSION)***
0F5D           926          ..
0F5D D3        927  CALLR:   SEP  PC  ..TO SUBROUTINE...
0F5E E2        928  CALLS:   SEX  SP  ..POINT TO STACK
0F5F 96        929          GHI  LINK  ..SAVE LINK ON STACK.
0F60 73        930          STXD
0F61 86        931          GLO  LINK
0F62 73        932          STXD
0F63 93        933          GHI  PC
0F64 B6        934          PHI  LINK
0F65 83        935          GLO  PC
0F66 A6        936          PLO  LINK
0F67 46        937          LDA  LINK
0F68 B3        938          PHI  PC
0F69 46        939          LDA  LINK
0F6A A3        940          PLO  PC
0F6B 305D      941          BR  CALLR   ..JUMP TO SUBROUTINE.
0F6D           942          ..
0F6D           943          .. *****SUBROUTINE RETURN (CDP1802 VERSION)*
0F6D           944          ..
0F6D D3        945  RETNR:   SEP  PC  ..RETURN TO MAIN ...
0F6E 96        946  RETR:    GHI  LINK  ..RESTORE RETURN ADDRESS
0F6F B3        947          PHI  PC  ..INTO PC.
0F70 86        948          GLO  LINK
0F71 A3        949          PLO  PC
0F72 E2        950          SEX  SP
0F73 12        951          INC  SP   ..ON STACK INTO LINK.
0F74 72        952          LDXA
0F75 A6        953          PLO  LINK
0F76 F0        954          LDX
0F77 B6        955          PHI  LINK
0F78 306D      956          BR  RETNR    ..RETURN.
0F7A           957          ...
0F7A           958          ...ADDITIONS BY J.M.C.
0F7A           959          ...NOT SUPPORTED!!!!!
0F7A           960          ...
0F7A           961  ..       MOVB -- ROUTINE TO MOVE N BYTES
0F7A           962  ..       OF MEMORY FROM ONE LOCATION TO ANOTHER
0F7A           963          ..CALLING SEQUENCE:
0F7A           964  ..       CALL MOVB; ,A(SOURCE) ,A(DEST) ,NBYTES
0F7A           965  ..
0F7A 46BD      966  MOVB:   @R6!-> MA.1
0F7C 46AD      967          @R6!-> MA.0
0F7E 46BA      968          @R6!-> AR.1
0F80 46AA      969          @R6!-> AR.0
0F82 46AB      970          @R6!-> NR.0
0F84 4D5A1A    971  MOVB01: @MA!->@AR;  INC AR
```

```
0F87 2B8B3A84     972  DEC NR; NR.0; BNZ MOVB01
0F8B D5           973       EXIT          ..DONE
0F8C             974  ...
0F8C             975  ...
0F8C             976  ...
0F8C             977  .. CALLING SEQ.: CALL DELAY;,DCON
0F8C             978  ..    WHERE DCON IS A 2 BYTE CONSTANT.
0F8C             979  ..    DCON=(TIME-400)/24
0F8C             980  ..    TIME IN MICROSECONDS
0F8C             981  ...
0F8C 8C5222      982  DELAY: CR.0->@SP; DEC SP
0F8F 9C52        983       CR.1->@SP     ..COPY CR TO STACK
0F91 46BC        984       @R6!->CR.1
0F93 46AC        985       @R6!->CR.0
0F95 38          986       SKIP
0F96 2C8C3A96    987  DEL1: DEC CR; CR.0; BNZ DEL1
0F9A 9C3A96      988       CR.1; BNZ DEL1
0F9D 42BC        989       @SP!->CR.1
0F9F F0AC        990       @->CR.0       ..RESTORE CR
0FA1 D5          991       EXIT
0FA2             992       ..
0FA2             993  ... >CVT   CONVERT BINARY (16 BIT)  TO ASCII
0FA2             994       ...CALL CVT;,(NO. CHARS).(CHARS AFTER ".")
0FA2             995       ...
0FA2 46BC52      996  CVT:  @LINK!->CR.1,@SP
0FA5 46AC        997       @LINK!->CR.0
0FA7 8AF4AA      998       AR.0+@->AR.0
0FAA 3BB0        999       BNF *+6
0FAC 9AFC01BA    1000      AR.1+1->AR.1   ..ADJUST AR
0FB0 2A          1001      DEC AR
0FB1 F800BEAE    1002 DIV10: 0->MQ.1,MQ.0
0FB5 8FFF0AAF    1003 DLOOP: AC.0-10->AC.0
0FB9 1E          1004      INC MQ        ..BUMP QUOTIENT COUNTER
0FBA 33B5        1005      BDF DLOOP
0FBC 9FFF01BF    1006      AC.1-1->AC.1   ..PROCESS HI BYTE BORROW
0FC0 33B5        1007      BDF DLOOP
0FC2 2E          1008      DEC MQ        ..AR HAS ROLLED OVER NEG
0FC3 8FFC3A5A    1009      AC.0+#3A->@AR ..CONVERT REMAIN TO ASCII
0FC7 2A          1010      DEC AR
0FC8 9EBF        1011      MQ.1->AC.1    ..COPY MQ TO AC
0FCA 9EAF        1012      MQ.0->AC.0
0FCC 8CFF01AC    1013      CR.0-1->CR.0
F 0FD0 3A00      1014      IF >0 GOTO CVT01
0FD2 F82E5A      1015      T'.'->@AR      ..OUTPUT DEC POINT
0FD5 2A          1016      DEC AR
0FD6 9CFF01BC    1017      CR.1-1->CR.1
F 0FDA 3A00      1018      IF >0 GOTO CVT01
F 0FDC 3000      1019      GOTO CVT03
0FDE 9CFF01BC    1020 CVT01: CR.1-1->CR.1
0FE2 3AB1        1021      IF >0 GOTO DIV10
0FE4 1A          1022 CVT03: INC AR
0FE5 D5          1023      EXIT           ..DONE
0FE6             1024      ...
0FE6             1025      END
```

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APPENDIX D

SOFTWARE LISTING FOR ELECTRONIC DASHBOARD DISPLAY

```
0000        1 ..     >DASH    J.M.C.  RCA LABS   9:3:76
0000        2 ...
0000        3 ..       REGISTER ALLOCATION
0000        4 ...
0000        5        SP  =R2 ...IT SHOULD BE THE STACK POINTER.
0000        6        PC  =R3 ...IT IS THE PROGRAM COUNTER
0000        7        .. USED BY THESE SUBROUTINES.
0000        8        CALL =R4 ...IT SHOULD POINT TO THE ROUTINE
0000        9        .. WHICH EFFECTS SUBROUTINE CALLS.
0000       10        RETN =R5 ...IT SHOULD POINT TO THE ROUTINE
0000       11        .. WHICH EFFECTS SUBROUTINE RETURN.
0000       12        LINK=R6          ..USED FOR SUBROUTINE PARAM
0000       13        ..
0000       14      MS=R9   .. (MESSAGE POINTER/COUNTER)
0000       15      AR=RA   ..(USED FOR RESULT ADDRESS)
0000       16      AC=RF   .. 16-BIT ACCUMULATOR=RF.
0000       17      MQ=RE   .. 16-BIT ACCUMULATOR=RE EXTENSION.
0000       18      MA=RD   .. (TEMPORARY) OPERAND MEMORY ADDRESS.
0000       19      CR=RC   ... (TEMPORARY) SCRATCHPAD AND COUNTER.
0000       20        ...
0000       21        MESSL=#10FE;STACK=#1080
0000       22        ...
0000       23        ...   INPUT--OUTPUT INSTRUCTION ALLOCATION
0000       24        ...
0000       25 ..   OUT 1   ENTER DATA IN DISPLAY MEMORY
0000       26 ..   OUT 2   TURN DISPLAY ON OR OFF
0000       27 ..   OUT 3   STROBE FOR A TO D CONVERSION
0000       28 ..   OUT 4   GROUP SELECT FOR A TO D CONVERSION
0000       29 ..   OUT 5   CLOCK SHIFT REGISTERS
0000       30 ..   OUT 6   SHIFT REGISTER LOAD (STROBE)
0000       31 ..   OUT 7   FREE
0000       32 ..
0000       33 ..   INP 1   READ BINARY DEVICES (CHANNEL 1)
0000       34 ..   INP 2   READ BINARY DEVICES (CHANNEL 2)
0000       35 ..   INP 3   READ BINARY DEVICES (CHANNEL 3)
0000       36 ..   INP 4   READ 8 BIT A TO D CONVERTED DATA
0000       37 ..   INP 5   READ TACH(4-7)/FUEL(0-3) COUNTERS
0000       38 ..   INP 6   READ SPEED COUNTER
0000       39 ..   INP 7   FREE
0000       40 ..
0000       41 ..   EF1     A TO D CONVERSION COMPLETE
0000       42 ..   EF2     ODOMETER SERIAL INPUT
0000       43 ..   EF3     CLOCK SERIAL INPUT
0000       44 ..   EF4     READ TELEPRINTER (UT2 UTILITY)
0000       45 ...
0000       46 ...   IMMEDIATE BYTE DATA VALUES
0000       47 ...
0000       48    ACT1=#7F; ACT2=0  ; ACT3=0
0000       49    INV1=#FE; INV2=#FF; INV3=#FF ..12V -> DANGER!
0000       50    OV2=237; OV3=217; OV4=196 ..OIL PRESSURE DATA
0000       51    OV5=176; OV6=156; OV7=135
0000       52 ..
0000       53 ...
```

```
       0000                  54          ORG 0
       0000  EO               55          SEX 0
       0001  EO               56          SEX 0
       0002  7100             57          DISABLE;,0       ..TURN INTERRUPTS OFF!
F      0004  F800B3           58          A.1(PC3)->R3.1
F      0007  F800A3           59          A.0(PC3)->R3.0
       000A  D3               60          GO STATE R3      ..FREE R0
       000B  F810B2F880A2     61  PC3:    A.1(STACK)->SP.1; A.0(STACK)->SP.0
       0011  F810BDF8FEADB9   62          A.1(MESSL)->MA.1; A.0(MESSL)->MA.0,MS.1
       0018  F8F05D2DF8FF5D   63          #F0->@MA; DEC MA; #FF->@MA   ..SET MESS ARE
       001F  F8F0A9           64          240->MS.0        ..MESSAGE COUNTER
       0022  F800A0           65          0->R0.0          ..INTERRUPT COUNTER
       0025  F80EAC           66          14->CR.0  ..ZERO RAM CONSTANT AREA
F      0028  F800BDF800AD     67          A.1(RAM)->MA.1; A.0(RAM)->MA.0
       002E  F8005D1D         68  ZLOOP:  0->@MA;  INC MA
       0032  2C8C3A2E         69          DEC CR; CR.0; BNZ ZLOOP
F      0036  FF00B4F800A4     70          A.1(CALLS)->R4.1; A.0(CALLS)->R4.0
F      003C  F800B5F800A5     71          A.1(RET)->R5.1; A.0(RET)->R5.0
F      0042  F800B1           72          A.1(INTCD)->R1.1 ..PREPARE FOR 'INTERRUPTS
F      0045  F800A1           73          A.0(INTCD)->R1.0
       0048  E37023           74          SEX R3; RETURN;,#23   ..ENABLE INTERRUPTS
       004B                   75          ...
       004B                   76  ...
       004B                   77  ..      WAIT FOR INTERRUPT
       004B                   78  ...
       004B  304B             79  INTWT:  GO TO INTWT
       004D                   80          ...
       004D  F800B3F84BA3     81  EXIT:   A.1(INTWT)->R3.1; A.0(INTWT)->R3.0
       0053  70               82          RETURN
       0054                   83  ...
       0054                   84  ..      INTERRUPT SERVICE STARTS HERE
       0054                   85  ...
       0054  2278             86  INTCD:  DEC SP; SAVE
       0056  22               87          DEC SP        ..POINT TO FREE
F      0057  F800B3           88          A.1(NEWPC)->R3.1
F      005A  F800A3           89          A.0(NEWPC)->R3.0
       005D  D3               90          GO STATE R3      ..R3 IS PC
       005E  1080FB08         91  NEWPC:  INC R0; R0.0.XOR.8 ..CHECK FOR RESET
       0062  3A65A0           92          BNZ *+3; -> R0.0
       0065  F820AC           93          32->CR.0
F      0068  F800BA           94          A.1(OUTBF+#400)->AR.1
F      006B  F800AA           95          A.0(OUTBF+#400)->AR.0
       006E  F8205A1A         96  CLEAN:  32->@AR; INC AR    ..PUT SPACES IN
       0072  2C8C3A6E         97          DEC CR; CR.0; BNZ CLEAN   ..DISPLAY BUFFER
       0076                   98  ...
       0076                   99  ..      UPDATE ECONOMY/TACH RAW VALUES
       0076                  100  ...
       0076  6D22            101  ECOTAC: INP 5; DEC SP
       0078  6DF012F3        102          INP 5; LDX; INC SP; XOR  ..READ AND COMPAR
       007C  3A76            103          BNZ ECOTAC       ..SHOULD BE SAME OR REPEAT
       007E  F0FBFFA7        104          @.XOR.#FF->R7.0
       0082                  105  ...
       0082                  106  ..      UPDATE FUEL COUNTER
       0082                  107  ...
```

```
F   0082  D400000400      108          CALL LOADOP;,A(FCNT+#400)
    0087  8752            109          R7.0->@SP
    0089  9BF5FA0FA852    110          RB.1-+@.AND.#F->R8.0,@SP ..NEW MINUS OLD
    008F  8FF4AF3B98      111          AC.0+@->AC.0; BNF *+6
    0094  9FFC01BF        112          AC.1+1->AC.1  ..ADD WITH CARRY
F   0098  D400000400      113          CALL STOROP;,A(FCNT+#400)
    009D                  114  ...
    009D                  115  ..     UPDATE TACH COUNTER
    009D                  116  ...
F   009D  F800BDF800AD    117          A.1(TCNT+#400)->MA.1; A.0(TCNT+#400)->MA.0
    00A3  4DAF2D          118          @MA!->AC.0; DEC MA
    00A6  87FAF052        119          R7.0.AND.#F0->@SP
    00AA  9BFAF0F5FAF0B8  120          RB.1.AND.#F0-+@.AND.#F0->R8.1   ..NEW-OLD
    00B1  F6F6F6F652      121          /2/2/2/2->@SP
    00B6  8FF45D          122          AC.0+@->@MA   ..CUMULATIVE TCNT
    00B9  87BB            123          R7.0->RB.1   .. NEW PREVIOUS VALUE
    00BB  80FA07          124          R0.0.AND.7    ..LOOK FOR 3 LSB=0
F   00BE  3A00            125          BNZ EPAG1  ..=>POWER OF 8 (EVERY SECOND)
    00C0  F800BFAFBEAE    126          0->AC.1,AC.0,MQ.1,MQ.0
    00C6  F806ACED        127          6->CR.0; SEX MA  ..COMPUTE R.P.M.
    00CA  8FF4AF3BD3      128  MPY6:   AC.0+@->AC.0; BNF *+6
    00CF  9FFC01BF        129          AC.1+1->AC.1
    00D3  2C8C3ACA        130          DEC CR; CR.0; BNZ MPY6
    00D7  E2F8005D        131          SEX SP; 0->@MA ..ZERO TCNT
    00DB  8FFF13AF        132  DIVTEN:AC.0-19->AC.0
    00DF  1E33DB          133          INC MQ; BDF DIVTEN
    00E2  9FFF01BF        134          AC.1-1->AC.1   ..SUBTRACT WITH BORROW
    00E6  33DB2E          135          BDF DIVTEN; DEC MQ
F   00E9  F800BDF800AD    136          A.1(RPM+#400)->MA.1; A.0(RPM+#400)->MA.0
    00EF  8E5D            137          MQ.0->@MA    ..SAVE RPM
F   00F1  D400000000      138  EPAG1: CALL JUMP;,A(PACE1)
    00F6                  139          ...
    0100                  140          PAGE
    0100                  141          ...
    0100                  142  ...
    0100                  143  ..     READ VELOCITY --CONVERT TO KM/H.
    0100                  144  ...
F   0100  80F63300        145  PACE1:R0.0/2; BDF SPEED   ..EVERY OTHER TIME
F   0104  D400000000      146          CALL JUMP;,A(PML)
    0109                  147  ...
    0109  6E22            148  SPEED:INP 6; DEC SP    ..READ A BYTE
    010B  6EF012F3        149          INP 6; LDX; INC SP; XOR ..READ AND COMPARE
    010F  3A09            150          BNZ SPEED    ..SHOULD BE SAME OR REPEAT
    0111  F0FBFF52        151          @.XOR.#FF->@SP
    0115  8BF5A7          152          RB.0-+@->R7.0..NEW MINUS OLD
    0118  F0AB            153          @->RB.0  ..NEW BECOMES OLD
F   011A  F800BDF800AD    154          A.1(KPH+#400)->MA.1; A.0(KPH+#400)->MA.0
    0120  875D            155          R7.0->@MA
    0122                  156  ...
    0122                  157  ..     UPDATE ODOMETER COUNT AND REGISTER
    0122                  158  ...
F   0122  D400000400      159          CALL LOADOP;,A(OCNT+#400)
    0127  8752            160          R7.0->@SP      ..SPEED DIFFERENCE
    0129  8FF4AF3B32      161          AC.0+@->AC.0; BNF *+6
```

```
      012E 9FFC01BF          162          AC.1+1->AC.1  ..ADD WITH CARRY
F     0132 D400000400        163          CALL STOROP;,A(OCNT+#400)
F     0137 D400000000        164          CALL SMOP;,A(TENTH)
F     013C 9FFA803200        165          AC.1.AND.#80; BZ 0D02
F     0141 D400000000        166          CALL JUMP;,A(PML)
      0146 F800BFAF          167 0D02:    0->AC.1,AC.0
F     014A D400000400        168          CALL STOROP;,A(OCNT+#400)
      014F F808FBFF52        169          8.XOR.#FF->@SP  ..HAVE GONE 0.1 KM.
      0154 6422              170          OUT 4; DEC SP ..STROBE ODOMETER REGISTER
      0156                   171 ...
      0156                   172 ..       COMPUTE FUEL ECONOMY EVERY 0.1 KM.
      0156                   173 ...
      0156 F800AF            174          0->MQ.0
F     0159 D400000400        175          CALL LOADOP;,A(FCNT+#400)    ..DIVIDE BY ZER
F     015E 8F3A009F3A00      176          AC.0; BNZ KP; AC.1; BNZ KP ..FCNT=0?
F     0164 F800BDF800AD      177          A.1(KMPL+#400)->MA.1; A.0(KMPL+#400)->MA.0
      016A 8F5D              178          AC.0->@MA    ..KMPL=0
F     016C 3000              179          GO TO KPLEX
F     016E D400000000        180 KP:      CALL LOADOP;,A(KPLCON)
F     0173 D400000400        181 KPLDIV:  CALL SMOP,A(FCNT+#400)
      0178 1E                182          INC MQ
      0179 9FFA803273        183          AC.1.AND.#80; BZ KPLDIV
      017E 2E                184          DEC MQ        ..ROLLED NEGATIVE
F     017F F800BDF800AD      185          A.1(KMPL+#400)->MA.1; A.0(KMPL+#400)->MA.0
      0185 8E5D              186          MQ.0->@MA
      0187 F800BFAF          187          0->AC.1,AC.0
F     018B D400000400        188 KPLEX:CALL STOROP;,A(OCNT+#400)  ..ZERO ODOMETER
F     0190 D400000400        189          CALL STOROP;,A(FCNT+#400)  ..FUEL COUNTERS
F     0195 D400000000        190          CALL JUMP;,A(PML)
      019A                   191 ...
      019A                   192 ..       ...
      019A                   193 ...
      019A                   194 ..       PROCESS MESSAGE LIST
      019A                   195 ...
      019A                   196          ...MESSAGE PROCESSING STATUS IS MAINTAINED
      019A                   197          ...LIST AREA OF MEMORY WHICH HAS THE
      019A                   198          ..FOLLOWING FORMAT:
      019A                   199          ...
      019A                   200          ...     #FF    ..END OF LIST MARKER
      019A                   201          ...    (MESSAGE #)  ..2ND MESSAGE OUTPUT
      019A                   202          ...    (MESSAGE #)  ..1ST MESSAGE OUTPUT
      019A                   203          ...MESSL: #F0   ...DOING A 30 SECOND WAIT
      019A                   204          ...
      019A 99ADF810BD        205 PML:  MS.1->MA.0; A.1(MESSL)->MA.1  ..LIST POINT
      019F 2989              206          DEC MS; MS.0  ..DECREMENT MESSAGE COUNTER
F     01A1 3A00              207          BNZ MSTAT    ..COUNTER AT ZERO?
      01A3 2D99FF01B9        208          DEC MA; R9.1-1->R9.1  ..DECR LIST POINTER
      01A8 4D522DFBFF        209          @MA!->@SP; DEC MA; .XOR.#FF ..END OF LIST?
F     01AD 3A00              210          BNZ NOTEOL
      01AF F8FEADB9          211          A.0(MESSL)->MA.0,MS.1  ..MESS ALL OUTPUT
      01B3 F8F0A9            212          240->MS.0    ..SET UP 30 SEC WAIT
F     01B6 3000              213          GO TO MSTAT
      01B8 F800BAF805ACF0AA  214 NOTEOL:0->AR.1; 5->CR.0; @->AR.0  ..NEXT MESSAGE
      01C0 9A52F4BA          215 SHL5: AR.1->@SP; 8+@->AR.1 ..COMPUTE MESS ADDR
```

```
01C8  3BCE           217        BNF *+6    ..16 BIT SHIFT LEFT
01CA  9AFC01BA       218        AR.1+1->AR.1  ..PROCESS CARRY
01CE  2C8C3AC0       219        DEC CR;  CR.0;  BNZ SHL5
01D2  9AFC07DA       220        AR.1+A.1(MES0)->AR.1 ..ADD OFFSET
F  01D6  D40000       221        CALL DISP     ..OUTPUT THE MESSAGE
01D9  F818A9         222        24->MS.0    ..SET UP 3 SEC WAIT
F  01DC  4DFBF03200   223  MSTAT: @MA!.XOR.#F0;  BZ BIP  ..NOW ON DISPLAY?
F  01E1  D400000000   224        CALL JUMP;,A(INTEX)
01E6                  225  ...
01E6                  226  ..     LOOK FOR NEW BINARY PROBLEMS
01E6                  227  ...
F  01E6  80F63B00     228  BIP:  R0.0/2;  BNF BEZEL   ..ODD COUNTS ONLY
F  01EA  D40000       229        CALL BSCAN
01ED                  230  ...
01ED                  231  ..     UPPER OR LOWER BEZEL ACTIVE?
01ED                  232  ...
F  01ED  69F0FA803200 233  BEZEL: INP 1;  @.AND.#80;  BZ LOBEZ
F  01F3  D400000000   234        CALL JUMP;,A(UPBEZ)
01F8                  235  ...
01F8                  236  ..     LOWER BEZEL PROCESSING:
01F8                  237  ...
01F8  80FA03         238  LOBEZ: R0.0.AND.3   ..LOOK FOR 2 LSB=0
F  01FB  C20000       239        LBZ TANK ..  =>POWER OF 4(EVERY 0.5 SEC)
F  01FE  D400000000   240        CALL JUMP;,A(INTEX) ..SKIP DISPLAY
0203                  241  ...
0203                  242  ..     FORMAT DISPLAY IN 1/6 TANK INCREMENTS
0203                  243  ...
0203  F801FBFF52      244  TANK: 1.XOR.#FF->@SP
0208  6422            245        OUT 4;  DEC SP ..GROUP SELECT
020A  6322            246        OUT 3;  DEC SP    ..CONVERT
020C  3C0C            247        BN1 *      ..WAIT FOR CONVERSION
020E  6CF0FF05AF      248        INP 4;  @-5->AC.0  ..ACCOUNT FOR OFFSET
F  0213  F800BAF800AA 249        A.1(OUTBF+#400)->AR.1;  A.0(OUTBF+#400)->AR
0219                  250        ...
0219  F807AC          251        7->CR.0 ..MAX 6 BARS ON FUEL DISPLAY
021C  8FFF10AF        252  FUEL: AC.0-16->AC.0
0220  F8405A1A        253        T'@'->@AR;  INC AR ..FILL IN FUEL BAR
F  0224  2C8C3200     254        DEC CR;  CR.0;  BZ FUEL1
0228  331C            255        BDF FUEL
022A  2AF8205A        256  FUEL1: DEC AR;  32->@AR ..BLANK ROLLOVER
022E                  257  ...
022E                  258  ..     FORMAT DISPLAY IN TACH REVS (TWO DIGITS)
022E                  259  ...
F  022E  F800BDF800AD 260  TACH: A.1(RPM+#400)->MA.1;  A.0(RPM+#400)->MA.0
0234  4DAF            261        @MA!->AC.0
F  0236  D400000407   262        CALL FMT2;,A(OUTBF+#400+7)
023B  4AFB303A44      263        @AR!.XOR.#30;  BNZ *+6  ..LEADING ZERO?
0240  2AF8205A        264        DEC AR;  32->@AR  ..BLANK IT
0244                  265  ...
0244                  266  ..     FORMAT DISPLAY IN KM/H (SPEED)
0244                  267  ...
0244  F800A7B7        268        0->R7.0,R7.1
F  0248  F800BDF800AD 269        A.1(KPH+#400)->MA.1;  A.0(KPH+#400)->MA.0
```

```
      024E 4DAF          270        @MA!->AC.0
F     0250 F80AAA        271        A.0(OUTBF+#400+10)->AR.0
      0253 8FFF07AF      272   DIV11:AC.0-7->AC.0  ..DIVIDE BY 7
      0257 F8405A1A      273        T'@'->@AR;  INC AR  ..AND FILL IN SPEED BAR
      025B 178752        274        INC R7;R7.0->@SP
      025E 3353          275        BDF DIV11      ..POSITIVE REMAINDER?
      0260 2AF8205A      276        DEC AR; 32->@AR    ..BLANK IT
F     0264 F809F53300    277        9;SD;BDF RESQL
      0269 7B38          278        SEQ;SKP
      026B 7A            279   RESQL:REQ
F     026C D400000000    280        CALL JUMP;,A(DISALL)
      0271              281        ...
      0300              282        PAGE
      0300              283        ...
      0300              284   ...
      0300              285   ..      UPPER BEZEL PROCESSING:
      0300              286   ...
F     0300 803200        287   UPBEZ: R0.0; BZ TIME  ..ONCE A SEC
F     0303 D400000000    288        CALL JUMP;,A(INTEX) ..ELSE WE ARE DONE.
      0308 F800A7B7BF    289      TIME:0->R7.0,R7.1,AC.1
F     030D F800BDF800AD  290        A.1(KPH+#400)->MA.1;A.0(KPH+#400)->MA.0
      0313 4DAF          291        @MA!->AC.0
      0315 8FFF07AF      292   DIV8:AC.0-7->AC.0
      0319 178752        293        INC R7;R7.0->@SP
      031C 3315          294        BDF DIV8
F     031E F809F53300    295        9;SD;BDF RESQ1
      0323 7B38          296        SEQ;SKP
      0325 7A            297     RESQ1:REQ
      0326              298   ...
      0326              299   ..      READ IN SERIAL TIME AND CONVERT
      0326              300   ...
      0326 F800B7A7F810AC 301       0->R7.1,R7.0;16->CR.0
      032D 6622          302        OUT 6; DEC SP ..LOAD SHIFT REGISTER
      032F 87F6A7        303   CLOSH: R7.0/2->R7.0  ..SHIFT LO BYTE
      0332 97F63638F980B7 304       R7.1/2; B3*+4;  .OR.#80->R7.1
      0339 3B3F87F980A7  305        BNF *+6;  R7.0.OR.#80->R7.0
      033F 6522          306        OUT 5; DEC SP  ..CLOCK SHIFT REGISTER
      0341 2C8C3A2F      307        DEC CR; CR.0; BNZ CLOSH
      0345              308        ...
      0345              309        ... BIT 15 IS MSB.  BIT 0 IS LSB.
      0345              310        ... BITS 15-8 CONTAIN MINUTES
      0345              311        ... BITS 7-4 CONTAIN HOURS
      0345              312        ...
      0345 F800BF        313        0->AC.1
      0348 87F6F6F6F6AF  314        R7.0/2/2/2/2->AC.0 ..SHIFT RIGHT 4
F     034E D400000400    315        CALL FMT2;,A(OUTBF+#400)  ..FORMAT HOURS
      0353 4A2AFB303A5C  316        @AR!; DEC AR;  .XOR.T'0'; BNZ *+5
      0359 F8205A        317        32->@AR       ..SUPPRESS LEADING ZERO
F     035C F802AA        318        A.0(OUTBF+#400+2)->AR.0
      035F F83A5A        319        T':'->@AR  ..PUT OUT A COLON
      0362 97AF          320        R7.1->AC.0      ..GET MINUTES
F     0364 D400000403    321        CALL FMT2;,A(OUTBF+#400+3)
      0369              322   ...
      0369              323   ...
```

```
0369                            324  ..           READ IN SERIAL ODOMETER AND CONVERT
0369                            325  ...
0369  F800BFAFF810AC            326            0->AC.1,AC.0;  16->CR.0
0370  6622                      327            OUT 6; DEC SP  ..LOAD SHIFT REGISTER
0372  8FF6AF                    328  ODOSH:   AC.0/2->AC.0   ..SHIFT LO BYTE
0375  9FF6357BF980BF            329            AC.1/2; B2*+4;  .OR.#80->AC.1
037C  3B82BFF980AF             330            BNF*+6; AC.0.OR.#80->AC.0
0382  6522                      331            OUT 5; DEC SP..CLOCK SHIFT REGISTER
0384  2C8C3A72                  332            DEC CR; CR.0; BNZ ODOSH
0388                            333  ...
0388                            334  ..        ODOMETER RANGE IS 0 TO 999.9 KM.
0388                            335  ..        REGISTER AC CONTAINS 4 BCD DIGITS.
0388                            336  ...
F     0388  F806AA              337            A.0(OUTBF+#400+6)->AR.0
      038B  9FF6F6F6F6FC305A    338            AC.1/2/2/2/2+#30->@AR; INC AR  ..1ST DIGIT
      0394  9FFA0FFC305A1A      339            AC.1.AND.#F+#30->@AR; INC AR ..2ND DIGIT
      039B  8FF6F6F6F6FC305A    340            AC.0/2/2/2/2+#30->@AR; INC AR ..3RD DIGIT
      03A4  F82F5A1A            341            T'.'->@AR; INC AR  ..DECIMAL POINT
      03A8  8FFA0FFC305A        342            AC.0.AND.#F+#30->@AR ..4TH DIGIT
      03AE                      343  ...
      03AE                      344  ..        SUPPRESS LEADING ZEROES
      03AE                      345  ...
F     03AE  F806AAEA            346            A.0(OUTBF+#400+6)->AR.0; SEX AR
F     03B2  F0FB303A00          347            @.XOR.#30; BNZ ESUP
      03B7  F8205A1A            348            #20->@AR; INC AR
F     03BB  F0FB303A00          349            @.XOR.#30; BNZ ESUP
      03C0  F8205A1A            350            #20->@AR; INC AR
F     03C4  F0FB303A00          351            @.XOR.#30; BNZ ESUP
      03C9  F8205A              352            #20->@AR
      03CC  E2                  353  ESUP:    SEX SP
      03CD                      354  ...
      03CD                      355  ..        DO A TO D ON WATER TEMPERATURE.  FORMAT.
      03CD                      356  ...
      03CD  F802FBFF52          357            2.XOR.#FF->@SP
      03D2  6422                358            OUT 4; DEC SP ..GROUP SELECT
      03D4  6322                359            OUT 3; DEC SP   ..CONVERT
      03D6  3CD6                360            BN1 *         ..WAIT FOR CONVERSION
      03D8  6CF0AF              361            INP 4; @->AC.0
F     03DB  D400000000          362            CALL JUMP;,A(SCALW)
      03E0                      363            ...
      0400                      364            PAGE
      0400                      365            ...
      0400                      366  ...
      0400                      367  ..        SCALE THRU 0-99
      0400                      368  ...
F     0400  F80FAA              369  SCALW:  A.0(OUTBF+#400+15)->AR.0
      0403  F84F5A1A            370            T'O'->@AR; INC AR ..PUT IN OK
      0407  F84B5A              371            T'K'->@AR
F     040A  8FFFF43300          372            AC.0-244; BGE FLW  ..TEMP < 60?
      040F  8FF652              373            AC.0/2->@SP ..USE LINEAR APPROX.
      0412  F8B6F7AFA7          374            182-@->AC.0,R7.0  ...TO COMPUTE TEMP
F     0417  D40000040C          375            CALL FMT2;,A(OUTBF+#400+12)  ..NO. FORMAT
F     041C  87FF613B00          376            R7.0-97;IF LESS GO TO FLW
      0421  F800BCF807AC        377            0->CR.1; 7->CR.0  ..MESSAGE #7
```

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F  0427  D40000            378         CALL MESADD .."WATER TEMP HIGH"
F  042A  F80FAA            379         A.0(OUTBF+#400+15)->AR.0
   042D  F8485A1A          380         T'H'->@AR; INC AR ..IT IS HIGH
   0431  F8495A            381         T'I'->@AR
F  0434  3000              382         GO TO OIL
   0436  F800BCF807AC      383  FLW:   0->CR.1; 7->CR.0  ..MESSAGE #7
F  043C  D40C00            384         CALL MESSUB
   043F                    385  ...
   043F                    386  ..      DO A TO D ON OIL PRESSURE. FORMAT.
   043F                    387  ...
   043F  F803FBFF52        388  OIL:   3.XOR.#FF->@SP
   0444  6422              389         OUT 4; DEC SP ..GROUP SELECT
   0446  6322              390         OUT 3; DEC SP   ..CONVERT
   0448  3C48              391         BN1 *      ..WAIT FOR CONVERSION
   044A  6CF0AF            392         INP 4;@->AC.0
   044D                    393         ...
   044D                    394  ...    SCALE 0-7
   044D                    395         ...
   044D  F802AE            396         2->MQ.0
F  0450  8FFFED3300        397         AC.0-OV2; IF GE GO TO OILEX
F  0455  1E8FFFD93300      398         INC MQ; AC.0-OV3; IF GE GO TO OILEX
F  045B  1E8FFFC43300      399         INC MQ; AC.0-OV4; IF GE GO TO OILEX
F  0461  1E8FFFB03300      400         INC MQ; AC.0-OV5; IF GE GO TO OILEX
F  0467  1E8FFF9C3300      401         INC MQ; AC.0-OV6; IF GE GO TO OILEX
F  046D  1E8FFF873300      402         INC MQ; AC.0-OV7; IF GE GO TO OILEX
   0473  1E                403         INC MQ      ..MQ NOW UP TO 7
F  0474  F813AA            404    OILEX:A.0(OUTBF+#400+19)->AR.0
   0477  8EF6AFFC305A      405         MQ.0;SHR;->AC.0;+#30->@AR
   047D  F808BCF800AC      406         8->CR.1; 0->CR.0 ..MESSAGE #8
   0483  1A1A              407         INC AR; INC AR
F  0485  8FFF023300        408         AC.0-2; IF GE GO TO OILOK
   048A  F84C5A1A          409         T'L'->@AR; INC AR
   048E  F84F5A            410         T'O'->@AR
F  0491  D40000            411         CALL MESADD .."OIL PRESSURE LOW"
F  0494  3000              412         GO TO FUELEC
   0496  F84F5A1A          413  OILOK:T'O'->@AR; INC AR
   049A  F84B5A            414         T'K'->@AR
F  049D  D40000            415         CALL MESSUB
   04A0                    416  ...
   04A0                    417  ..      FORMAT FUEL ECONOMY
   04A0                    418  ...
   04A0                    419
F  04A0  F800BDF800AD      420  FUELEC: A.1(KMPL+#400)->MA.1; A.0(KMPL+#400)->MA
   04A6  4DAF              421         @MA!->AC.0
F  04A8  8FA73200          422         AC.0->R7.0; BZ AMPS1
F  04AC  D400000418        423         CALL FMT2;,A(OUTBF+#400+24)
   04B1  4AFB303ABA        424         @AR!.XOR.#30; BNZ *+6 ..LEADING ZERO?
   04B6  2AF8205A          425         DEC AR; 32->@AR    ..BLANK IT
   04BA  87AF              426         R7.0->AC.0
F  04BC  F81BAA            427         A.0(OUTBF+#400+27)->AR.0
F  04BF  8FFF093300        428         AC.0-9; IF GE GO TO TRYOK
   04C4  F84C5A1A          429         T'L'->@AR; INC AR
   04C8  F84F5A            430         T'O'->@AR
F  04CB  3000              431         GO TO AMPS1
```

```
F    04CD  CFFF0D3300    432  TRYOK: AC.0-13;  IF GE GO TO TRYHI
     04D2  F84F5A1A      433         T'O'->@AR;  INC AR
     04D6  F14B5A        434         T'K'->@AR
F    04D9  3000          435         GO TO AMPS1
     04DB  F385A1A       436  TRYHI: T'H'->@AR;  INC AR
     04DF  FB495A        437         T'I'->@AR
     04E2                438         ...
F    04E2  D400000000    439  AMPS1: CALL JUMP;, A(AMPS)
     0500                440         PAGE
     0500                441         ...
     0500                442  ...
     0500                443  ..      DO "LO" OR "OK" INDICATION FOR AMPS
     0500                444  ...
F    0500  F81EAA        445  AMPS:  A.0(OUTBF+#400+30)->AR.0
     0503  F84F5A1A      446         T'O'->@AR;  INC AR
     0507  F84B5A        447         T'K'->@AR
F    050A  6AF0FA013200  448         INP 2;@.AND.1;BZ DISALL..UNUSED BINARY
     0510  2AF84C5A1A    449         DEC AR; T'L'->@AR;  INC AR
     0515  F84F5A        450         T'O'->@AR
     0518                451  ...
     0518                452  ...
F    0518  F800BAF800AA  453  DISALL:  A.1(OUTBF+#400)->AR.1;  A.0(OUTBF+#400)->
F    051E  D40000        454         CALL DISP
     0521                455  ...
     0521                456  ..      EXIT FROM INTERRUPT
     0521                457  ...
     0521  12            458  INTEX: INC SP
     0522  F800B1        459         A.1(EXIT)->R1.1
     0525  F84DA1        460         A.0(EXIT)->R1.0
     0528  D1            461         GO STATE R1
     0529                462         ...
     0529                463  ...
     0529                464  ..      SCAN AND PROCESS ALL BINARY INPUTS
     0529                465  ...
F    0529  F800BDF800AD  466  BSCAN: A.1(OST1+#400)->MA.1;  A.0(OST1+#400)->MA.0
     052F  4DAF          467         @MA!->AC.0
     0531  8F5222        468         AC.0->@SP;  DEC SP
     0534  69            469         INP 1      ..LEAST SIGNIF. (DEV 7-0)
     0535  F0FBFEFA7F    470         @.XOR.INV1.AND.ACT1
     053A  52AF          471         ->@SP,AC.0
     053C  12F3          472         INC SP;  XOR  ..XOR OLD,NEW STATUS
     053E  A7            473         ->R7.0     ..SAVE FOR LATER
     053F  22            474         DEC SP     ..POINT BACK TO NEW STATUS
     0540  F2B7          475         AND;->R7.1 ..DETECT 0->1 TRANSITION
F    0542  F800BDF800AD  476         A.1(OST1+#400)->MA.1;  A.0(OST1+#400)->MA.0
     0548  8F5D          477         AC.0->@MA   ..STORE IT
     054A  F800BC        478         0->CR.1    ..DEVICE OFFSET
F    054D  D4000012      479         CALL BINDET;  INC SP
F    0551  F800BDF800AD  480         A.1(OST2+#400)->MA.1;  A.0(OST2+#400)->MA.0
     0557  4DAF          481         @MA!->AC.0
     0559  8F5222        482         AC.0->@SP;  DEC SP
     055C  6A            483         INP 2      ..DEVICES 15-8
     055D  F0FBFFFA00    484         @.XOR.INV2.AND.ACT2   ..PROCESS SAME WAY
     0562  52AF          485         ->@SP,AC.0
```

```
        0564  12F3A7          486         INC SP; XOR; ->R7.0
        0567  22F2B7          487         DEC SP; AND; ->R7.1
    F   056A  F800BDF800AD    488         A.1(OST2+#400)->MA.1; A.0(OST2+#400)->MA.0
        0570  8F5D            489         AC.0->@MA
        0572  F808BC          490         8->CR.1             ..DEVICE OFFSET
    F   0575  D4000012        491         CALL BINDET; INC SP
    F   0579  F800BDF800AD    492         A.1(OST3+#400)->MA.1; A.0(OST3+#400)->MA.0
        057F  +DAF            493         @MA1->AC.0
        0581  8F5222          494         AC.0->@SP; DEC SP
        0584  6B              495         INP 3           ..DEVICES 23-16
        0585  F0FBFFFA00      496         @.XOR.INV3.AND.ACT3
        058A  52AF            497         ->@SP,AC.0
        058C  12F3A7          498         INC SP; XOR; ->R7.0
        058F  22F2B7          499         DEC SP; AND; ->R7.1
    F   0592  F800BDF800AD    500         A.1(OST3+#400)->MA.1; A.0(OST3+#400)->MA.0
        0598  8F5D            501         AC.0->@MA
        059A  F810BC          502         16->CR.1            ..DEVICE OFFSET
    F   059D  D4000012        503         CALL BINDET; INC SP
        05A1  D5              504         EXIT                ..DONE
        05A2                  505         ...
        05A2                  506         ...
        05A2                  507  ...
        05A2                  508  ..        DETECT DEVICE TRANSITIONS
        05A2                  509  ...
        05A2  F800ACAF        510  BINDET: 0->CR.0,AC.0
        05A6  97F6B7          511  BIND01: R7.1/2->R7.1 ..SHIFT OUT LOW BIT
    F   05A9  3B00            512         IF NDF GOTO CONT0  ..NO CHANGE DETECTED?
    F   05AB  D40000          513         CALL MESADD     ..GO ADD DEVICE MESSAGE
        05AE  1C8CFB083AA6    514  CONT0: INC CR; CR.0.XOR.8; BNZ BIND01
        05B4  F800AC          515         0->CR.0             ..RESET
        05B7  121212          516         INC SP; INC SP; INC SP ..POINT TO OLD STAT
        05BA  87F2B7          517         R7.0.AND.@->R7.1    ..1->0 TRANSITION
        05BD  222222          518         DEC SP; DEC SP; DEC SP  ..RESTORE STACK
        05C0  97F6B7          519  LOOP1: R7.1/2->R7.1  ..SHIFT OUT LOW BIT
    F   05C3  3B00            520         IF NDF GOTO CONT1 ..NO CHANGE DETECTED?
    F   05C5  D40000          521         CALL MESSUB     ..GO REMOVE DEVICE MESSAGE
        05C8  1C8CFB083AC0    522  CONT1: INC CR; CR.0.XOR.8; BNZ LOOP1
        05CE  D5              523         EXIT            ..END OF BINARY DETECT
        05CF                  524         ...
        0600                  525         PAGE
        0600                  526         ...
        0600                  527  ...
        0600                  528  ...
        0600                  529  ..        ADD MESSAGE TO DISPLAY LIST
        0600                  530  ...
        0600  9C528CF4A8      531  MESADD: CR.1->@SP; CR.0+@->R8.0 ..DEVICE NUM
        0605  F810BD          532         A.1(MESSL)->MA.1   ..ADD MESSAGE
        0608  F8FEAD          533         A.0(MESSL)->MA.0
        060B  ED              534         SEX MA
        060C  88F3            535  MESA01: R8.0;XOR        ..ITEM TO BE ADDED?
    F   060E  3A00            536         BNZ MESA02
    F   0610  3000            537         BR MESA99       ..REJECT
        0612  F0FBFF          538  MESA02: @; XRI #FF ..EOL MARKER?
        0615  2D              539         DEC MA
```

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```
0616  3A0C            540         BNZ MESA01
0618  1D885D          541         INC MA; R8.0->@MA    ..PUSH ON MESSAGE STAC
061B  2D              542         DEC MA
061C  F8FF5D          543         #FF->@MA         ..MARK NEW EOL
061F  F810BD99AD      544         A.1(MESSL)->MA.1; MS.1->MA.0
F 0624 4DFBF03A00     545         @MA!.XOR.#F0; BNZ MESA99 ..MESS ON DISPLAY
0629  F801A9          546         1->MS.0 ..FORCE DISPLAY OF MESSAGES
062C  E2D5            547 MESA99: SEX SP;EXIT  ..GOOD RETURN
062E                  548 ...
062E                  549 ..     REMOVE MESSAGE FROM DISPLAY LIST
062E                  550 ...
062E  9C528CF4A8      551 MESSUB: CR.1->@SP; CR.0+@->R8.0  ..DEVICE NUM
0633  F810BDF8FEADED  552         A.1(MESSL)->MA.1; A.0(MESSL)->MA.0; SEX MA
063A  F800B0          553         0->R0.1  ..CLEAR FOUND FLAG
063D  F052            554 MESS01: @->@SP     ..PUSH MESSAGE LIST ON SP
063F  88F3            555         R8.0;XOR      ..ITEM TO REMOVE?
F 0641 3A00           556         BNZ NOTIT
0643  12F801B0        557         INC SP; 1->R0.1    ..KNOCK IT OFF SP
0647  F0FBFF          558 NOTIT:  @.XOR.#FF  ..EOL?
064A  2D22            559         DEC MA;DEC SP
064C  3A3D            560         BNZ MESS01
064E  121D            561         INC SP;INC MA
F 0650 903200         562         R0.1; BZ MESS02
0653  1D              563         INC MA        ..COMPRESS LIST IF FOUND
0654  425D1D          564 MESS02: @SP!->@MA;INC MA ..PUT BACK MESSAGE LIST
0657  FBF0            565         XRI #F0        ..FRAME MARKER?
0659  3A54            566         BNZ MESS02
065B  22E2D5          567         DEC SP;SEX SP;EXIT
065E                  568 ...
065E  F88052          569 DISP:#80->@SP
0661  6122            570         OUT 1; DEC SP ... CLEAR MEMORY
0663  F808AC          571         8->CR.0
0666  2C8C3A66        572 CLP:    DEC CR; CR.0; BNZ CLP
066A  F820AC          573         32->CR.0
066D  EAEAEA          574 DGO:    SEX AR;SEX AR;SEX AR ..MORE SEX
0670  4A2A            575         LDA AR;DEC AR ..STALL A WHILE
0672  61              576         OUT 1      ..ZING IT
0673  8CFF01AC        577         CR.0-1->CR.0  ..SLOW DECREMENT
0677  3A6DE2          578         BNZ DGO; SEX SP
067A  F80152          579         1->@SP
067D  6222            580         OUT 2; DEC SP ..MAKE SURE IT IS ON
067F  D5              581         EXIT
0680                  582 ...
0680  46BA            583 FMT2:   @R6!->AR.1   ..FORMAT 2 DIGIT ASCII
0682  46AA            584         @R6!->AR.0   ..GET DESTINATION ADDRESS
0684  F800AE          585 D10:    0->MQ.0
0687  8FFF0AAF        586 DLP:    AC.0-10->AC.0
068B  1E3387          587         INC MQ; BDF DLP
068E  2E8EFC305A      588         DEC MQ; MQ.0+#30->@AR
0693  1A8FFC3A5A2A    589         INC AR; AC.0+#3A->@AR; DEC AR
0699  D5              590         EXIT ..REGISTER AR IS UNCHANGED
069A                  591 ...
069A  E2              592 JUMP:   SEX SP       ..MAKE SURE
069B  4652            593         @R6!->@SP ..SAVE HIGH BYTE
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069D  46A6      594          @R6!->R6.0  ..PUT IN LOW
069F  F0B6      595          @->R6.1     ..PUT IN HIGH
06A1  D5        596          EXIT            ..RETURN ADJUSTED
06A2            597      ...
06A2  46        598  LOADOP: LDA LINK .. FETCH ADDRESS
06A3  BD        599          PHI MA .. TO MA REGISTER
06A4  46        600          LDA LINK
06A5  AD        601          PLO MA .. FALL INTO LOAD
06A6  4D        602    LOAD: LDA MA .. FETCH HIGH 8
06A7  BF        603          PHI AC
06A8  4D        604          LDA MA .. NOW LOW 8
06A9  AF        605          PLO AC .. LEAVE MA AT NEXT DOUBLE-BYTE
06AA  D5        606          SEP RETN .. GEE, THAT WAS QUICK.
06AB            607      ..
06AB  46        608  STOROP: LDA LINK .. FETCH ADDRESS INTO MA
06AC  BD        609          PHI MA
06AD  46        610          LDA LINK
06AE  AD        611          PLO MA .. THEN FALL INTO STORE
06AF  9F        612   STORE: GHI AC .. FIRST HIGH 8
06B0  5D        613          STR MA
06B1  1D        614          INC MA .. INCREMENT MA, SINCE STR DOESN'T
06B2  8F        615          GLO AC .. NOW LOW 8
06B3  5D        616          STR MA
06B4  1D        617          INC MA .. LEAVE MA POINTING TO NEXT WORD
06B5  D5        618          SEP RETN .. QUIT
06B6            619      ..
06B6  46        620   SMOP: LDA LINK
06B7  BD        621          PHI MA
06B8  46        622          LDA LINK
06B9  AD        623          PLO MA
06BA  1D        624     SM:  INC MA .. POINT TO LOW 8
06BB  ED        625          SEX MA .. SET X TO MA
06BC  8F        626          GLO AC .. FETCH AC LOW 8
06BD  F7        627          SM .. SUBTRACT MEMORY FROM IT
06BE  AF        628          PLO AC .. PUT IT BACK.
06BF  2D        629          DEC MA .. NOW HIGH 8
06C0  9F        630          GHI AC
F  06C1  3300   631          BDF SMNB
06C3  FF01      632          SMI #1 .. PROPAGATE BORROW OF LOW 8
F  06C5  3300   633          BDF SMNB
06C7  F3        634          XOR .. SECOND BORROW; FORCE BORROW OUT,
06C8  38        635          ,#38 .. WHILE SUBTRACTING HIGH 8.
06C9  F7        636   SMNB: SM .. HIGH 8 SUBTRACT, NO BORROW ACCROSS.
06CA  BF        637          PHI AC .. PUT HIGH 8 BACK
06CB  E2        638          SEX SP         ...
06CC  D5        639          SEP RETN .. RETURN. DF=NO BORROW OUT
06CD            640   ...
06CD  D3        641          SEP R3         ... RETURN TO MAIN
06CE  9652      642  CALLS:  R6.1->@R2
06D0  22        643          DEC R2         ... STACK LEFT POINTING AT
06D1  8652      644          R6.0->@R2      ... NEXT FREE LOCATION
06D3  22        645          DEC R2
06D4  93B6      646          R3.1->R6.1     ... COPY R3 TO R6
06D6  83A6      647          R3.0->R6.0
```

```
06D8 46B3    648          @R6!->R3.1
06DA 46A3    649          @R6!->R3.0
06DC 30CD    650          GOTO CALLS-1
06DE         651 ...
06DE D3      652          SEP R3           ... RETURN TO MAIN
06DF 96B3    653 RET:     R6.1->R3.1       ...COPY R6 TO R3
06E1 86A3    654          R6.0->R3.0
06E3 12      655          INC R2
06E4 42A6    656          @R2!->R6.0       ... POP R6 FROM STACK
06E6 42B6    657          @R2!->R6.1
06E8 22      658          DEC R2
06E9 30DE    659          GOTO RET-1
06EB         660 ...
06EB         661 ..       ROM CONSTANTS
06EB         662 ...
06F0         663          ORG #6F0
06F0 0BB8    664          KPLCON:,3000 ..TO COMPUTE KM/LITER
06F2 0F4E    665          TENTH:,3918 ..TENTH OF A KILOMETER
06F4         666          ...
06F4         667 ...
06F4         668          .. RAM STORAGE REQUIRED
06F4         669 ...
0C00         670          ORG #C00
0C00         671 ...
0C00         672 RAM:     ..RAM START ADDRESS
0C00 00      673 KPH:     ,0          ..PROPORTIONAL TO KM. PER HR.
0C01 00      674 RPM:     ,0
0C02 00      675 OST1:,0
0C03 00      676 OST2:,0
0C04 00      677 OST3:,0
0C05 0000    678 OCNT:,0,0              ..ODOMETER COUNT
0C07 00      679 TCNT:,0
0C08 0000    680 FCNT:,0,0             ..FUEL COUNT
0C0A 00      681 KMPL:,0              ..CURRENT FUEL ECONOMY
0C0B         682          ...
0C0B         683 OUTBF:      ..WORKING RAM BUFFER FOR DISPLAY
0C0B         684          ...
0C0B         685          ...
0C0B         686 END:     END
```

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FL LOC  COSMAC CODE        LNNO SOURCE LINE
FL LOC  COSMAC CODE        LNNO SOURCE LINE
   00C0                      1  ..    >MESS     J.M.C.  RCA LABS    8:16:76
   0000                      2  ...
   0000                      3  ..       ELECTRONIC DASHBOARD MESSAGES
   0000                      4  ...
   0700                      5         ORG  #700
   0700                      6  ...
   0700  2020202020202020    7  MES0:  ,32,32,32,32,32,32,32,32
   0708  5345525649434520    8         ,T'SERVICE',32
   0710  4252414B45204F4E    9         ,T'BRAKE',32,T'ON'
   0718  2020202020202020   10         ,32,32,32,32,32,32,32,32
   0720                     11  ...
   0720  2020202020202020   12  MES1:  ,32,32,32,32,32,32,32,32
   0728  202020444F4F5253   13         ,32,32,32,T'DOORS'
   0730  204F50454E20       14         ,32,T'OPEN',32
   0736  2020202020202020   15         ,32,32,32,32,32,32,32,32
   073E  2020               16         ,32,32
   0740                     17  ...
   0740  2020202020202020   18  MES2:  ,32,32,32,32,32,32,32,32
   0748  2020202020         19         ,32,32,32,32,32
   074D  48415A415244       20         ,T'HAZARD'
   0753  2020202020202020   21         ,32,32,32,32,32,32,32,32
   075B  2020202020         22         ,32,32,32,32,32
   0760                     23  ...
   0760  2020202020202020   24  MES3:  ,32,32,32,32,32,32,32,32
   0768  4252414B4520       25         ,T'BRAKE',32
   076E  464C5549442        0 26         ,T'FLUID',32
   0774  4C4F5720           27         ,T'LOW',32
   0778  2020202020202020   28         ,32,32,32,32,32,32,32,32
   0780                     29  ...
   0780  202020202020       30  MES4:  ,32,32,32,32,32,32
   0786  2020               31         ,32,32
   0788  44414E4745522 0    32         ,T'DANGER',32
   078F  534C4F5720         33         ,T'SLOW',32
   0794  444F574E           34         ,T'DOWN'
   0798  2020               35         ,32,32
   079A  202020202020       36         ,32,32,32,32,32,32
   07A0                     37  ...
   07A0  202020202020       38  MES5:  ,32,32,32,32,32,32
   07A6  524553545241494E   39         ,T'RESTRAIN'
   07AE  542053595354454D   40         ,T'T',32,T'SYSTEM'
   07B6  204F5554           41         ,32,T'OUT'
   07BA  202020202020       42         ,32,32,32,32,32,32
   07C0                     43  ...
   07C0  2020202020202020   44  MES6:  ,32,32,32,32,32,32,32,32
   07C8  20414E54492D       45         ,32,T'ANTI-'
   07CE  534B494420         46         ,T'SKID',32
   07D3  4F55542020         47         ,T'OUT',32,32,32
   07D9  202020202020       48         ,32,32,32,32,32,32,32
   07E0                     49  ...
   07E0                     50  ...     ANALOG SENSORS
   07E0                     51         ...
   07E0  2020202020         52  MES7:  ,32,32,32,32,32
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07E5  574154455220        53            ,T'WATER',32
07EB  54454D5045524154    54            ,T'TEMPERAT'
07F3  5552452048494748    55            ,T'URE',32,T'HIGH'
07FB  2020202020          56            ,32,32,32,32,32
0800                      57            ...
0800  2020202020202020    58  MES8:     ,32,32,32,32,32,32,32,32
0808  4F494C20            59            ,T'OIL',32
080C  5052455353555245    60            ,T'PRESSURE'
0814  204C4F57            61            ,32,T'LOW'
0818  2020202020202020    62            ,32,32,32,32,32,32,32,32
0820                      63            ...
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APPENDIX B

VOLVO OF AMERICA CORPORATION FINAL REPORT

LARGE RESEARCH SAFETY VEHICLE (LRSV)
ENGINE DEVELOPMENT

LARGE RESEARCH SAFETY VEHICLE (LRSV)

ENGINE DEVELOPMENT FINAL REPORT

February, 1981

Minicars, Inc. Subcontract Purchase Order #5185

Prepared by:

Product Planning & Development Department
Volvo of America Corporation
Rockleigh, New Jersey 07647

Volvo of America Corporation, Rockleigh, New Jersey 07647

ABSTRACT:

The intent of the Large Research Safety Vehicle (LRSV) program is to research passenger car technology for the purpose of meeting the discussed safety, fuel economy and emission standards for the mid 1980s. It is also the goal of that program to be able to meet these standards while still retaining the comfort and size of an automobile typical to the U. S. motoring public.

Volvo of America Corp., (VAC) under contract to Minicars, Inc. of Goleta, California, and subcontract to the LRSV program, agreed to provide an engine capable of meeting the defined fuel economy, performance and emission goals of that program.

This report describes the procedure and results by which a refined spark ignition engine was developed, constructed, tested and provided for that program.

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INTRODUCTION AND SUMMARY:

The need for clean running and fuel efficient vehicles combined with passenger comfort and safety are major concerns for car manufacturers.

Aware of the need to research such technology, the U. S. Government through U.S. DOT/NHTSA implemented the Large Research Safety Vehicle (LRSV) program.

Volvo of America Corp. (VAC), under contract to Minicars, Inc. of Goleta, California, and subcontract to the LRSV program, agreed to supply a refined spark ignition engine capable of meeting the program objectives. The program commenced with Issuance of Subcontract January 20, 1978 and was concluded Summer, 1979.

The program's intentions, as set by NHTSA, specified development of technology which may be translated into a feasible, affordable, mass-produced product for the mid-eighties but did not necessarily require the provided engine to be an actual production engine.

The engine program had the following goals to be met:

EXHAUST EMISSIONS

Objective	Maximum Acceptable
HC - .41 g/mi	HC - .41 g/mi
CO - 3.4 g/mi	CO - 3.4 g/mi
NOx - .4 g/mi	NOx - 1.0 g/mi

FUEL ECONOMY

Objective

27.5 mi/gal. combined EPA cycle

ACCELERATION

Objective	Maximum Acceptable
0-60 mph - 13.5 secs.	0-60 mph - 20.0 secs.

The general specification and performance objectives are further detailed in Appendix A.

To this end, DM Engineering, Inc. of Brookfield, Conn., under VAC direction, was contracted to complete the hardware development and construction of the LRSV engine.

With their assistance, a methodology was developed for considering what technical features would be incorporated and the means by which they

would be tested.

As an overview, technical modifications to be developed would be centered around: improving cycle and thermal efficiency, reducing internal frictional losses and rotational mass, and improving combustion characteristics within established emission levels.

The basic engine selected for the program was the Volvo B-21F 2.1 in-line 4 cylinder engine. To stay within the intent of the program, a serious effort was made to retain as much of the present engine as possible. It was further realized that the Lambda-Sond® feedback control system, would form a vital part of the program. A detailed description of the system is presented in Appendix B.

The program for the engine was outlined to follow this course of development: initially candidate technical modifications were to be evaluated with the engine on a dynamometer and run under a predetermined steady state condition. All the modifications which were found to improve either the fuel efficiency or emission characteristics would be explored further with the aim to be incorporated into the final refined engine. Subsequently, the refined engine would be installed in a Volvo 244 DL with over-drive transmission and developed on DM's chassis dynamometer. Once completed, the LRSV-Volvo chassis would undergo final development and fine-tuning at an approved EPA lab. Results would then be verified on the FTP cycle.

During the approved EPA lab testing the dyno horsepower would be set to the PAU (Power Absorption Unit) setting for the actual LRSV chassis, as determined by Minicars. Upon completion of this course of development, a duplicate EPA test cycle would be run to verify the repeatability of the results. The Volvo test chassis would serve the dual purpose of investigating and determining specific gear ratios and proving acceleration times and driveability.

From this work the following refinements were found to be beneficial: reduced engine displacement, elevated coolant temperature, synthetic engine lubricants, reduction of accessory drive speed, multi-spark capacitive discharge system, reduced rotational mass, and matched fuel injectors.

As a result of these technical features and tuning the program goals were met. They account for an approximate 15% increase in fuel economy over the stock production engine while remaining within the emission and acceleration objectives.

* The name Lambda-Sond is a registered trademark of A.B. Volvo.

It should be noted that the engine, including turbocharger as developed in the program and tested in the Volvo chassis, met the test goals. However, when the engine was fitted to the LRSV the turbo was removed to ease installation. It was found that all the program goals could be met with the engine in its normally aspirated version, and therefore this vehicle configuration was pursued.

Following January, 1980, the initial LRSV program was extended to facilitate replacement of original engine and further fitting and testing. For this, DM Engineering was named as the prime contractor with Volvo of America Corporation, again, named as a subcontractor.

The final results stated below were acquired with DM as the prime contractor.

To clarify and conclude, this is a special research engine that was carefully prepared for the needs of this program. Therefore, it should be realized that application of all the refinements would not necessarily yield the same results in a production car or in a production environment. Rather, it should be concluded that gains in fuel economy can be attained with the utilization of a similar engine development program.

Results: LRSV

Emissions:

    HC   0.19 gpm
    CO   2.38 gpm
    NOx   0.57 gpm

MPG:

    EPA City (Est.)   22.8 mpg
    EPA Highway   36.5 mpg
    EPA Combined   27.43 mpg

Dyno Setting: 10.8 hp @ 50 mph
Inertia Weight: 3250 lbs.

PROCEDURE:

The goal of the LRSV engine development program was to arrive at a Volvo B-21 based power plant which would meet established emissions and fuel economy levels as measured by the 1978 FTP emission/fuel economy cycle and 0-60 mph acceleration times.

To expedite development, a modeling "tool" was devised to approximate the transient conditions of the FTP test cycle. Therefore, it was desired to find a steady state condition which would, on a "first cut" basis, resemble the driving cycle. In this way, the effect of technical features or modifications could be assessed to determine the contribution to the program. The exact effect of all the technical additions would later be verified by the testing on the FTP cycle.

To determine this steady state condition, a 1978 B-21F Lambda-Sond engine was fitted with a vacuum transducer to monitor intake manifold pressure. The obtained vacuum trace, along with a speed trace of the driving cycle, allowed an average engine load schedule to be developed.

Calculating the N/V ratio (engine RPM in 4th. gear/mph) of the test Volvo led to an rpm range which the engine operated during the EPA cycle. This rpm range was later corrected for the actual LRSV drivetrain N/V ratio. Subsequently, an engine dynamometer testing schedule was structured to record various engine performance and operating conditions under partial and wide-open throttle.

These recorded engine parameters are:

1. Engine RPM

2. Engine Torque

3. Engine Air-inlet Temperature, Dry Bulb

4. Engine Air-inlet Temperature, Wet Bulb

5. Barometric Pressure

6. Engine Oil Pressure

7. Engine Water Temperature

8.   Engine Inlet Oil Temperature

9.   Engine Fuel Flow Rate, Pounds per Hour

10. Exhaust gas %CO

11. Exhaust gas HC, ppm

12. Exhaust gas NOx, ppm

13. Manifold Vacuum/pressure

14. Ignition Patterns/RPM

For reference, a description of equipment used and its application is presented in Appendix C.

A list of technical modifications were compiled for evaluation and, as stated earlier, these modifications include:

1.   Reduction in displacement (2.1 liter to 2.0 liter)

2.   Substitution of synthetic engine oil

3.   Reduction of accessory drive speed

4.   Addition of a multi-spark capacitive discharge ignition system

5.   Elevated engine coolant temperature

6.   Turbocharging

7.   Reduction of engine lubricant pumping losses

8.   Reduction of crankcase pressure

It was anticipated, from the onset, that a reduction in engine displacement from 2.1 L to 2.0 L would be beneficial to the program. This would be accomplished by utilizing a B-19 engine block with a B-21 Lambda-Sond cylinder head. Therefore, initial break-in and running would be done with a B-19 block.

Engine development began with three B-19 engines being broken in and baselined. The engine break-in was accomplished by operating these engines on the engine dynamometer over a predetermined vacuum and RPM schedule. The schedule was arrived through the use of factory recommended break-in schedules. (The total break-in time for each engine was 30 hours.) All three engines, at completion of their break-in, were baselined to determine their relative horsepower, torque and brake specific fuel consumption (BSFC).

The third engine remained on the dynamometer to begin evaluation of the candidate modifications previously mentioned.

Simultaneously, engines #1 and #2 were disassembled to determine their dimensional consistency. After measuring, #1 engine was blueprinted and balanced. It should be noted that the machining of these internal engine parts were maintained within production tolerances but brought to a finer degree of precision than normally found in factory production.

For reference, the following describes some of the tolerances incorporated into the LRSV engine:

	B-21	LRSV
Cylinder Bores	+/- .0004"	+/- .0001"
Piston Diameter	+/- .002'	+0/-.002'
Piston Weight Variation	+/- .220 oz.	+0/-.010 oz.
Connecting Rod Weight	+/- .180 oz.	+0/-.004 oz.

Engine #1 was reassembled according to recommended Volvo procedure and subsequently broken in and baselined.

Concurrently, engine #2 was reassembled to serve as an installation mock-up for the turbocharging system. This turbocharging layout was then re-installed on engine number one.

The turbo air delivery pressure capability of the turbocharging system was matched according to operational requirements of the B-19 engine. Similarly, boost levels and knock suppression system (water injection) were matched and installed.

At conclusion of the testing program those modifications which were significant or necessary were incorporated onto #1. This engine was then installed into a 1978 244DL Volvo for final testing.

In addition to the engine modifications, a series of power train modifications were assessed and included into the final test chassis. These modifications include:

1. Reduction of engine rotating mass by reducing the flywheel, clutch and pressure plate size and weight.

2. Addition of synthetic lubricants in the transmission and rear axle.

3. Optimization of transmission and rear axle ratios with available ratio.

This engine and chassis were then tested at New York City Department of Environmental Protection, Air Resources Lab in Brooklyn, New York to optimize and confirm results on the EPA cycle.

To facilitate the final stages of development and tuning a series of hot starts, using the 1972 Federal Driving Cycle, were run. During these tests, the performance of the Lambda-Sond system, catalytic converter and engine were monitored by continuous reading of the HC and CO reading before the catalyst and HC, CO, CO_2 and NOx levels at the tailpipe. Analysis of these results returned sufficient data to reasonably predict performance of both emission and fuel economy on the FTP composite and highway cycle.

Final test verification was run on the 1978 EPA Test Procedure which required a 12 hour cold soak prior to the city and highway cycle.

RESULTS:

(All figures referenced are included immediately following the result section of this report).

As stated from the Procedure Section of this report, it was desired to establish a steady state condition which could serve as a "modeling tool" to expedite technical trend analysis during initial stages of development.

The installed manifold vacuum transducer yielded a trace, a section of which is described on Figure 1, which when integrated manually, indicated a load corresponding to 13" Hg would approximate the transient conditions of the test cycle. Further, a speed trace of engine speed range yielded a test range of 1600 to 2800 Rpm.

Engines were broken in and baselined according to the "break-in" schedule described on Figures 2 and 3. The total break-in time was 30 hours each engine.

Using this modeling "tool", it was possible to evaluate a number of anticipated modifications in a fairly rapid manner. As stated in the previous section, the list of test modifications included:

1. Reduction in displacement (2.1 liter to 2.0 liter)

2. Addition of synthetic engine oil

3. Reduction of accessory drive speed

4. Addition of a multi-spark capacitive discharge ignition system

5. Elevated engine coolant temperature

The below modifications were tested but for reasons noted later in the report were not included into the final engine.

1. Turbocharging

2. Reduction of engine lubricant pumping losses

3. Reduction of crankcase pressure

Using the stated procedure in evaluating the above items, the following results were obtained:

Before continuing it should be emphasized that each candidate modification was in turn evaluated and compared against the baseline data from the stock B-19 engine. It should be understood that the results

of all the tests are <u>not</u> additive and the presence or effect of one modification will, in most circumstances, influence the results of the other modifications. Therefore, the combined effect of all these modifications will be diminished by the effect or change of engine operating characteristics caused by the other modifications.

To determine the effect of reduction of displacement from 2.1 L to 2.0 L under wide open throttle conditions (WOT), BSFC curves were generated for both engines. From these curves, Figure 4, it can be seen that there is a decrease in fuel consumption that varies from 3% at 1700 rpm to a maximum decrease of 8% at 4000 rpm.

The baselined B-19 BSFC curve is depicted in Figure 5; this curve is provided as a reference for comparison of following modifications.

Figure 6 is a graphical representation of the B-19 Lambda Sond engine emissions before and after the catalyst. For the remainder of this section, if emission levels are discussed, only emission levels before the catalyst will be considered.

The effect of the substitution of low viscosity synthetic lubricants was studied. Figure 7 shows the results of this test at 13" Hg manifold pressure. From the graph it can be seen that there was reduction in BSFC with a maximum decrease of 4% at 2200 rpm. This effect has been attributed to the reduced pumping loss from a lower viscosity oil and to a lesser extent, reduced friction in the main bearing, rod bearings and cylinder wall surfaces.

The alternator and water pump constituted the only engine driven accessories. Customarily, during the FTP cycle, the alternator would be driving no accessories and, therefore, at low load. However, it was anticipated that there would be a decrease in BSFC if the accessory drive speed was reduced.

This was accomplished with the installation of 3.75" diameter crank pulley as opposed to the stock pulley diameter of 5.50" diameter. This accounted for a 30% reduction of accessory drive speed. The largest decrease in BSFC, as shown on Figure 8, was 7% at 2200 rpm.

A commercially available multi-spark ignition system was installed and tested. This system is designed to spark repetitively over $30°$ of crank-shaft rotation. Referring to Figure 9, there was a decrease in BSFC over the range of 1600 to 2500 rpm.

It was believed that emissions could be attenuated particularly during certain parts of the FTP (Bag 1), if the cooling system was modified to raise the coolant temperature above the standard $195°F$. The two test temperatures were selected at $210°F$ and $220°F$. The cooling system was modified by: removing the engine driven fan and replacing it with an electric fan activated by a temperature switch sensing coolant temperature, and the installation of a thermostat of the correct opening temperature.

By increasing the coolant temperature, it was speculated that there would also be a simultaneous improvement in cycle efficiency which would return correspondingly lower BSFC. However, only when the 220°F coolant temperature was used was there a noticed decrease in BSFC over the test range of 1600 to 2800 Rpm. Due to the risk of thermal degradation to the engine, the lower test temperature of 210°F was used. When evaluating the 210°F coolant temperature over the same test range, the change in fuel efficiency was only marginal.

The final system, as installed on the LRSV, utilized the mentioned electric fan with a thermostatic temperature setpoint of 210°F on, 200°F off.

Finally, fuel injectors were flowed to obtain matched sets of injectors ensuring consistent cylinder to cylinder A/F ratios. Eight sets of nozzles were flowed at A/F meter control arm openings of 1/4, 1/2, 3/4 and full open to determine flow rate consistency. Of all eight sets, one set would flow to within 2% variation up to a 1/2 control arm opening, and one more set would hold up to 3% variation in flow rates up to 3/4 A/F ratio control arm opening. In the other cases, variations of up to 4% were encountered.

Earlier exploration of BSFC curves and engine maps revealed that there would be a need to decrease the N/V ratio. It was further speculated that reduced rotational mass would reduce inertial losses and enhance fuel economy. This was accomplished via the following methods:

N/V ratio was lowered by utilization of overdrive ratio on 1st, 2nd as well as engaged 5th overdrive ratio on the highway cycle above 45 mph. The rear axle ratio was lower (numerically) to a 3.54 ratio as opposed to the standard 3.91 axle. Utilizing this, the N/V ratio was lowered to 51.8 at 4th. or 41.3 in 5th. (O.D.) compared to the stock N/V ratio of 57.2 in 4th. and 45.5 in 5th. (O.D.).

Inertial losses were reduced during acceleration through utilization of a lighten flywheel, clutch and pressure plate. To accomplish this, the stock flywheel was machined to reduce the flywheel weight to 11 lbs. A Borg Beck pressure plate and clutch was added, bringing the entire installed weight of the assembly to 23lbs. This compares to a stock flywheel, clutch, and pressure plate weight of 34 lbs.

As mentioned earlier, special attention was given to the control of the Lambda-Sond system. Before continuing, it is necessary to briefly describe the system. The system centers itself around controlling the HC, CO, NOx levels from the engine to a degree of accuracy so as to accommodate the very narrow operating conditions needed for the three-way catalyst to be effective in reducing the three pollutants. This is accomplished by sensing the oxygen present in the exhaust system and altering air/fuel ratio to make the appropriate change. A more detailed description of the system operation is presented in Appendix B.

During the EPA testing, it became evident that tighter and better control of the Lambda-Sond controller would be necessary for this application.

Initial findings indicated that it would be advantageous for emission reduction to lean the mixture during the cold start portion of the composite cycle.

To accommodate this, the sensor voltage was lowered according to coolant temperature. This was accomplished with a thermostat set to the correct temperature level making the appropriate change in the controller internally. The best results were achieved with a 400 mv sensor voltage during cold condition changing to 550 mv as coolant temperature reached $180^\circ F$.

During testing it was found helpful in reducing exhaust emission to insulate the exhaust header and catalytic converter. The insulation required a thermal conductivity of .55 BTU/hr/sqft/$^\circ$F/in. and thickness of 1/2".

The specific results of the FTP testing which commenced 9/18/78 and was concluded on 8/2/79 are presented in Appendix D. The development program was concluded with a repeated cycle for verification of results.

As noted earlier, certain modifications were tested but for reasons described below were not included into the final engine. As these modifications were part of the initial program, the results obtained are discussed below.

When the program was initially proposed, it was felt that the additional hp and torque provided by turbocharge boosting would be necessary for meeting acceleration objectives. As stated previously, it was later found that the naturally aspirated version would meet the program objectives.

Initially when the turbocharger was fitted, it was fitted to an exhaust manifold with similar primaries, but no secondary exhaust head pipe.

The turbo and manifold were then installed and tested, but provided actually lower hp. at high manifold vacuum than the stock engine. The manifold was then redesigned to include the secondary exhaust head pipe. After investigation of the manifolding system, the best configuration was found to be the stock exhaust head pipe coupled with a fabricated "J" pipe which duplicates the secondaries of the stock engine.

The turbo was then matched to the engine such that positive pressure boost from the compressor was not utilized below 2500 rpm. This was accomplished by testing of various capacity exhaust housings. The engine was then dynamometer tested under load to determine the knock limited boost, which under these circumstances is 4 PSIG boost.

The maximum horsepower output was then tested and recorded under WOT conditions. The results are shown on Figure 11. Referring to this figure, maximum boosted turbo power is 122 hp. at 5000 rpm compared to the naturally aspirated version with 100 hp at 5000 rpm.

Knocking was suppressed via a modulated water injection system which would introduce water into the turbo compressor inlet according to engine load as determined by manifold pressure. Additionally, an independent manifold fuel injector was installed to both deter knocking and introduce additional fuel required for boost conditions.

Knocking was further deterred by a vacuum ignition retard system as described on Figure 12. Under boost conditions, the in-line check valve closes and supplies positive pressure to the diaphragm retarding the system. At a maximum boost of 4 PSIG, ignition can be retarded up to 8°.

Reducing engine lubricant pumping losses was next investigated. Most engine oil pressure levels are somewhat higher than necessary to maintain bearing life. Therefore, it was felt that if the oil pressure could be lowered to a level somewhat above a critical level, the oil pumping horsepower could be reduced increasing BSFC. This was accomplished by modifying the existing oil pump to output 35 PSI instead of 65 PSI.

After evaluation of oil pressure reduction, it was found there was only a marginal improvement in horsepower output and in lieu of the possible reduced bearing life, it was felt that this modification did not warrant installation onto the final LRSV engine.

Positive crankcase pressure increases the pumping losses induced by the piston movement. In certain instances, output horsepower increases if this pressure is reduced. This reduction in crankcase pressure is usually accomplished by "syphoning" the engine's crankcase into the intake manifold. In most cases, this type of system is working well if zero crankcase pressure is maintained. Referring to the Figure 12 which correlates crankcase pressure of a production Volvo B-19, operating at 13.0 inches Hg manifold vacuum and at wide open throttle full load, it can be seen that the production system functions extremely well. Therefore, crankcase pressure reduction was considered of marginal benefit and not included in the final engine.
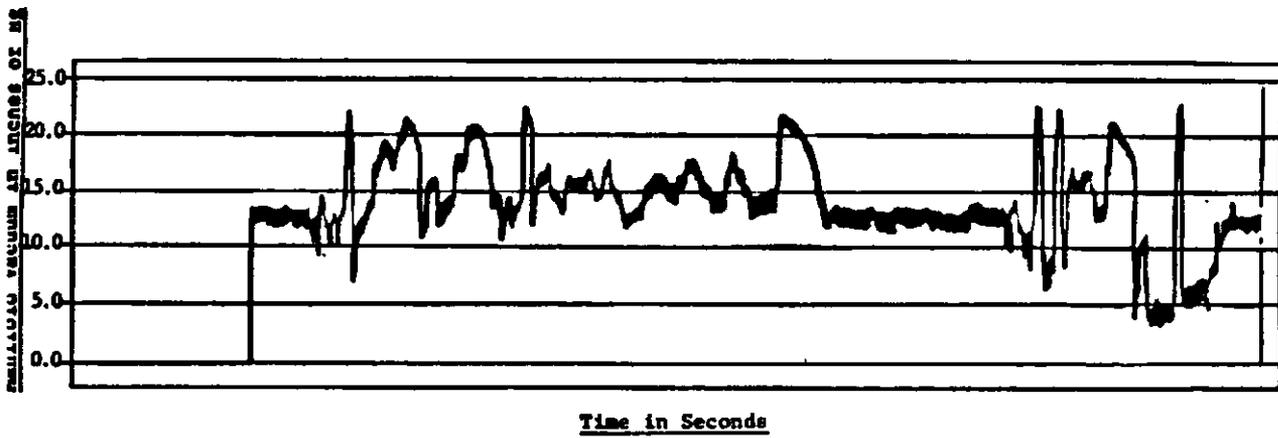
Figure No. 1. Manifold Vacuum vs. Time - 1978 B-21 Volvo Manifold

Vacuum During 1978 FTP Driving Cycle
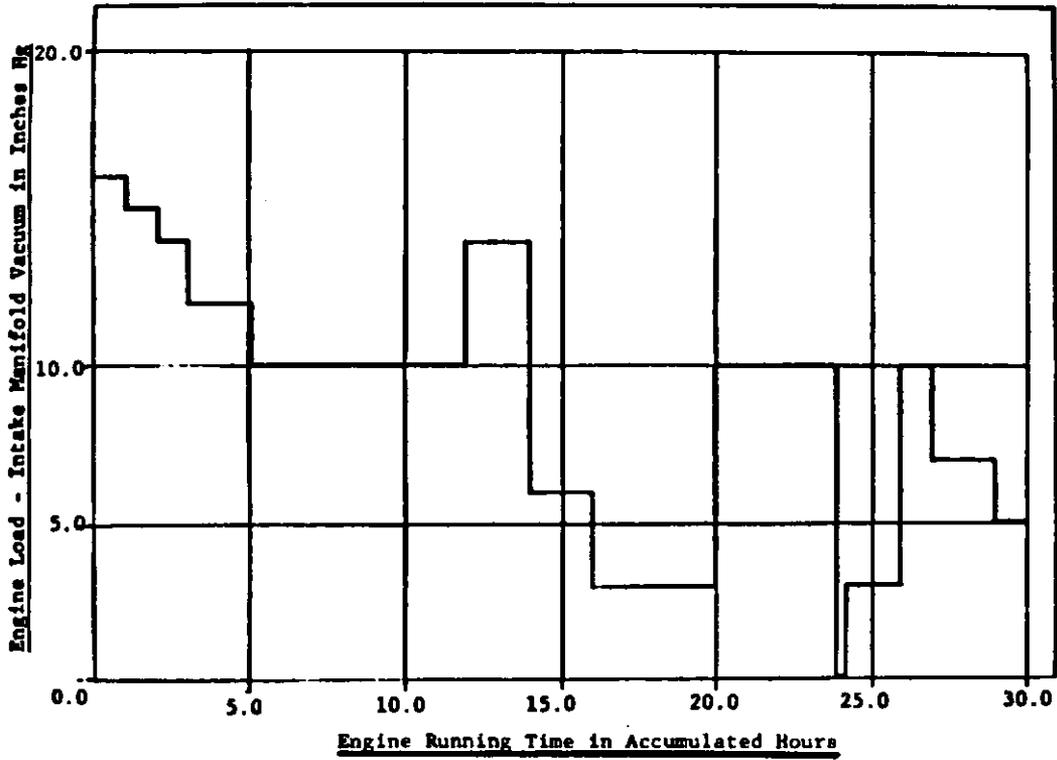
Figure No. 2. Engine break-in Schedule - Manifold Vacuum vs. Total Time
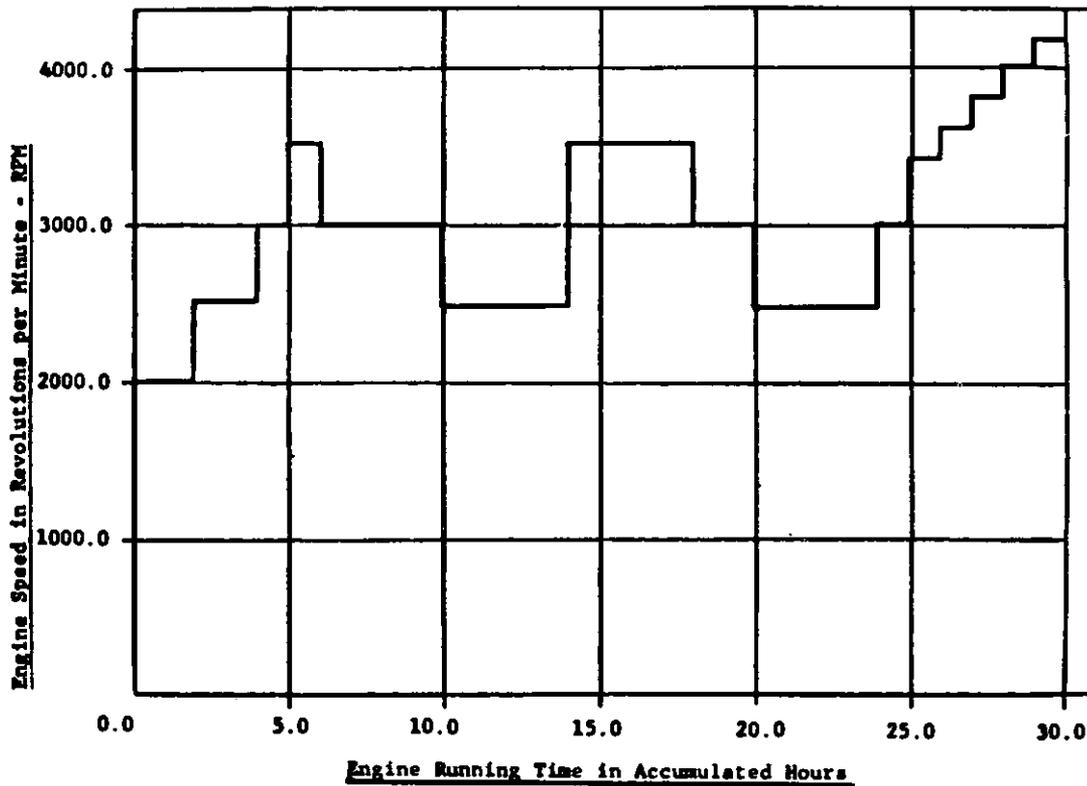
Figure No. 3. Engine Break-in Schedule - Engine Speed vs. Total Time

B-14.

Brake Specific Fuel Consumption in Pounds per Horsepower Hour - #/HP-HR

Engine Speed in Revolutions per Minute - RPM
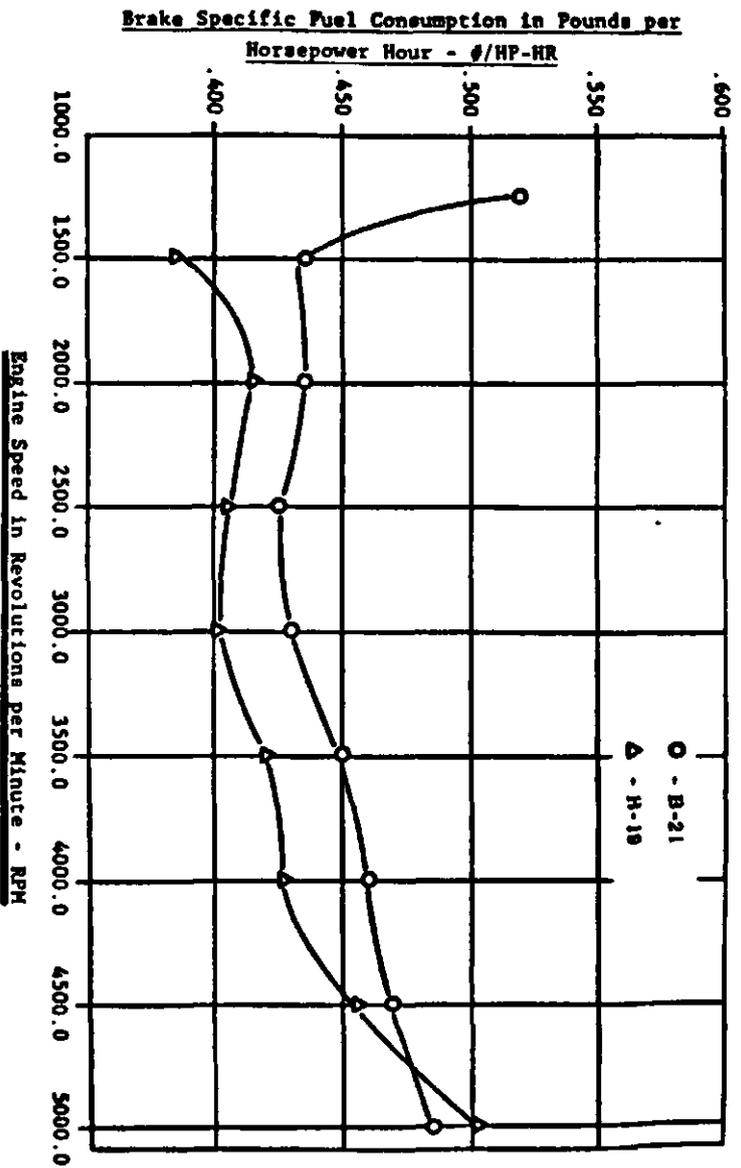
O - B-21
Δ - B-19

Figure No. 4 . Graph of Brake Specific Fuel Consumption vs. Engine Speed for Volvo B-21 & B-19 Engines Evaluated at Wide Open Throttle

. Brake Specific Fuel Consumption in Pounds per Horsepower Hours - #/HP-HR

Engine Speed in Revolutions per Minute - RPM
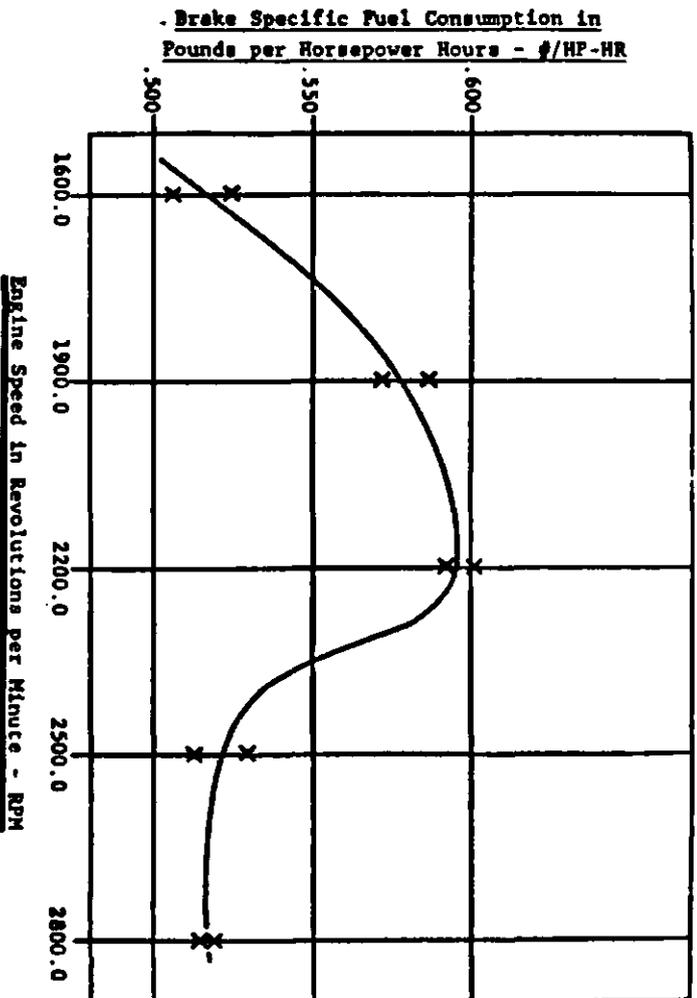
Figure No. 5 . Graph of Brake Specific Fuel Consumption vs. Engine Speed - Volvo B-19 Operated at 13.0 Inches (Hg) Intake Manifold Vacuum
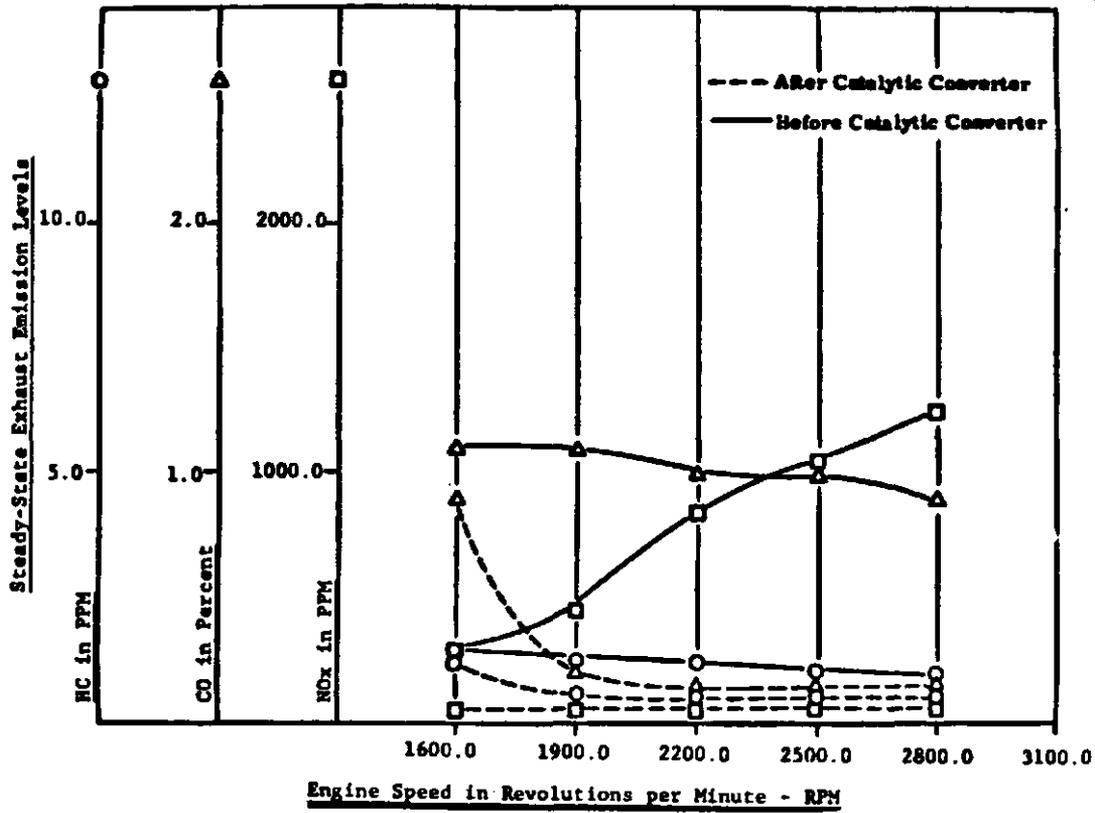
Figure No. 6 . Graph of Steady-State Exhaust Emission Levels vs. Engine Speed –
Volvo B-19 Engine Operated at 13.0 Inches Hg Intake Manifold Vacuum
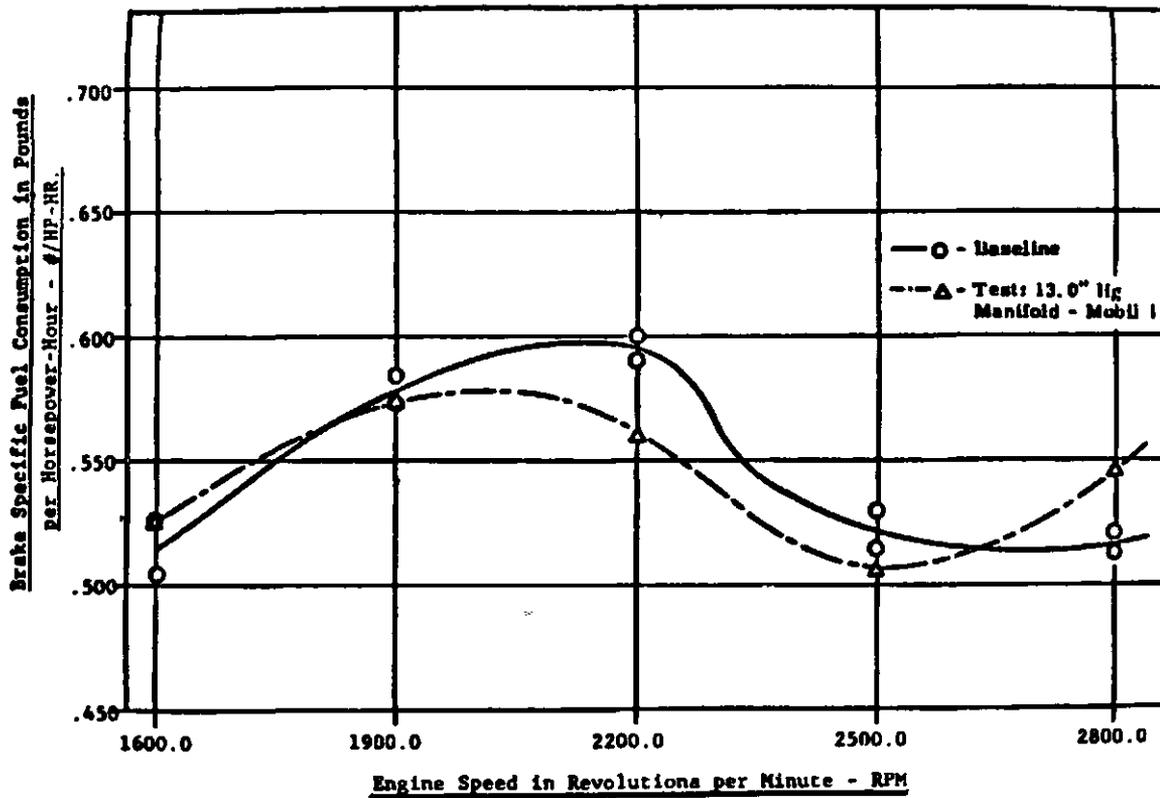
Figure No. 7 . Graph of Brake Specific Fuel Consumption vs. Engine Speed – Volvo B-19
Engine Operated at 13.0 Inches Hg Intake Manifold Vacuum with Synthetic Engine Oil

B-16.
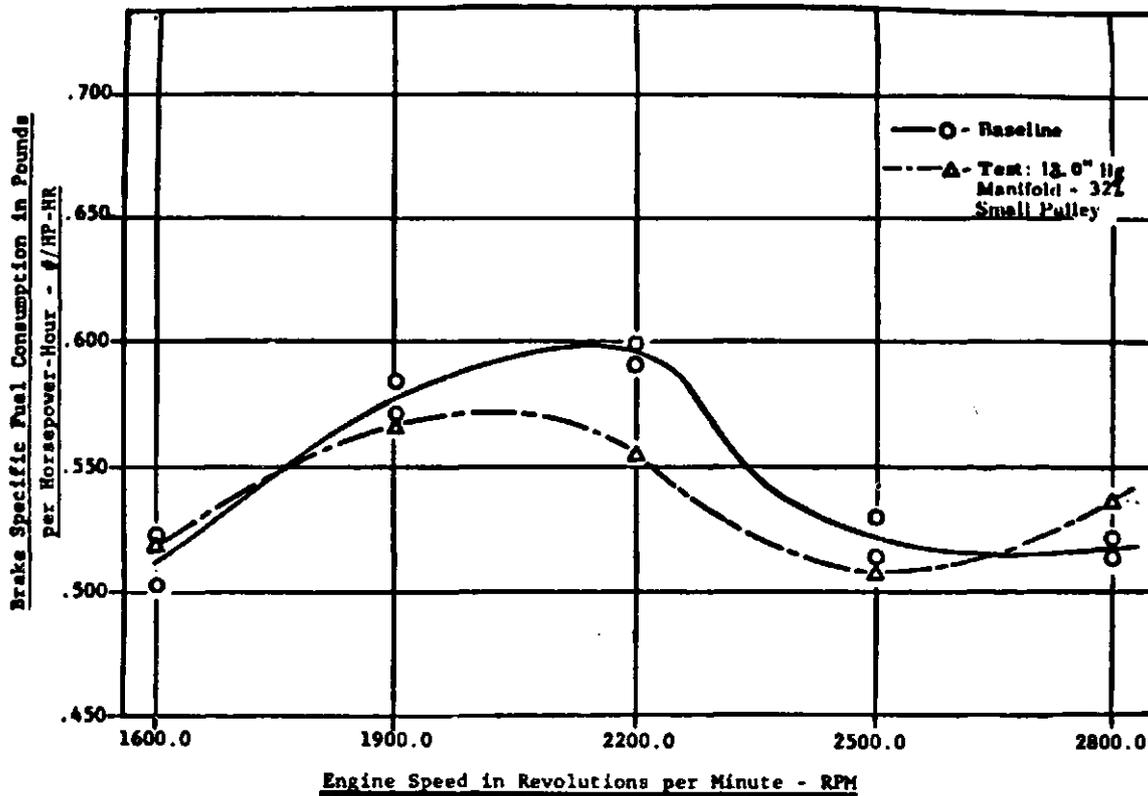
Figure No. 8 Graph of Brake Specific Fuel Consumption vs. Engine Speed - Volvo B-19

Operated at 13.0 Inches Hg Intake Manifold Vacuum with a 32% Reduced Diameter Crankshaft Pulley
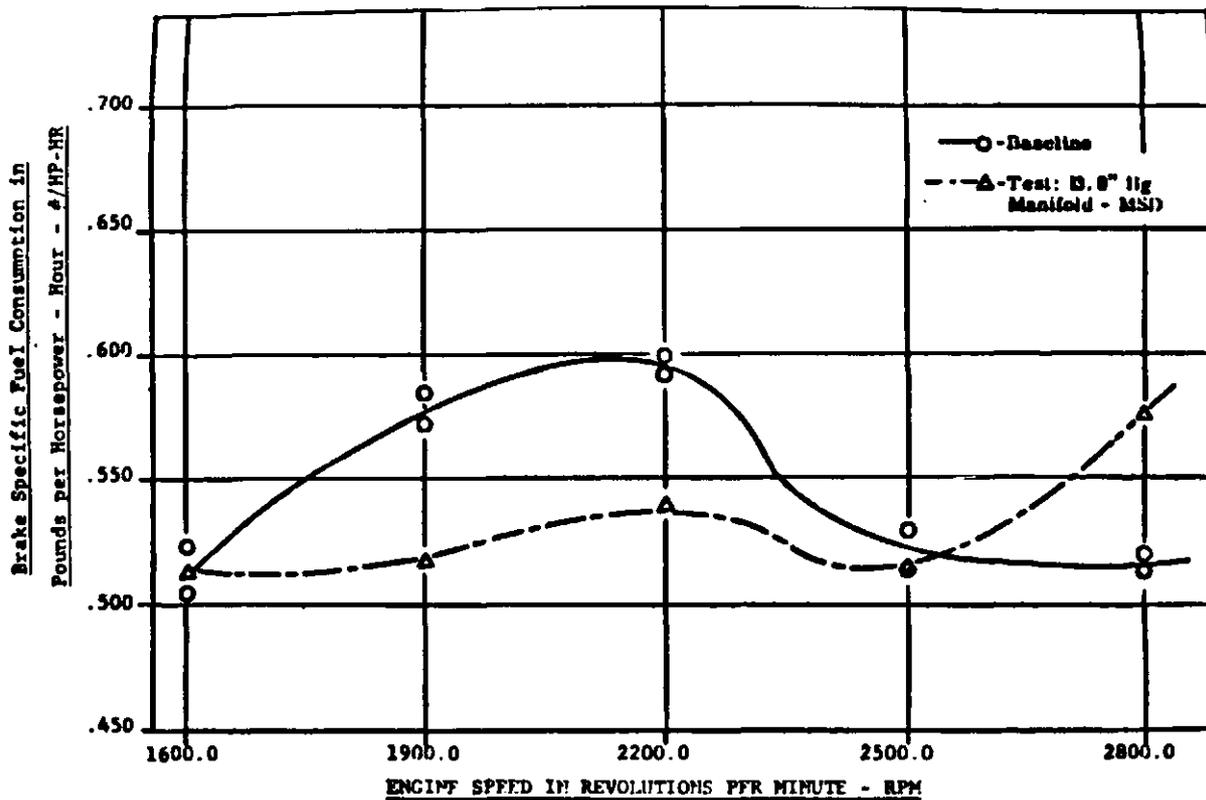
FIGURE NO. 9 Graph of Brake Specific Fuel Consumption vs. Engine Speed

Volvo B-19 Operated at 13.0 Inches Intake Manifold Vacuum With Multi-Spark

Discharge Ignition

B-17.
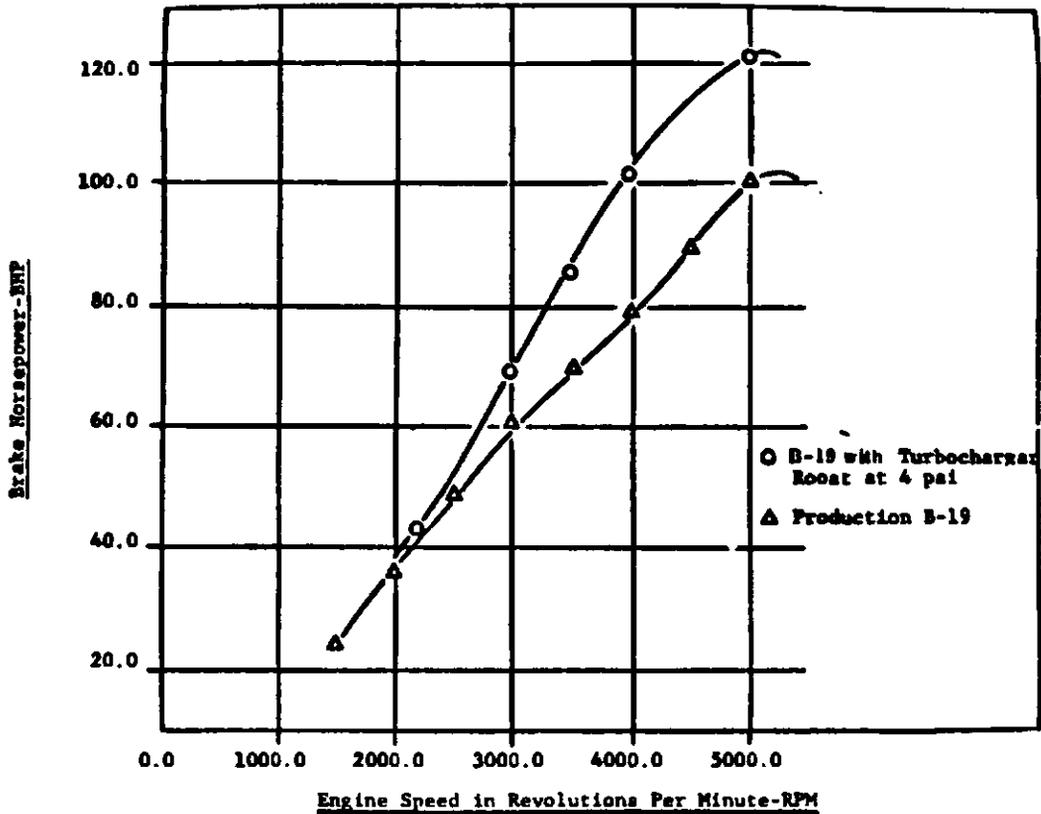
Figure No. 10 Graph of Brake Horsepower vs. Engine Speed - Production Volvo B19 and Balanced-Blueprinted- Turbocharged Volvo B-19
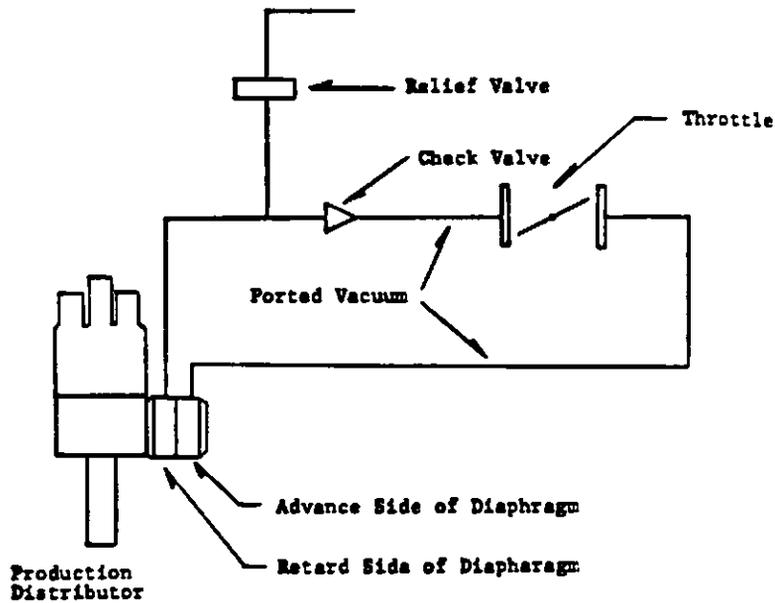
Figure No. 11 Boost Pressure Retard System

Figure 12	Crankcase Pressure as Recorded Against Engine Speed at 13" Manifold Vacuum and Wide Open Throttle

Engine Speed-RPM	Load-Speed	Crankcase Pressure
1600.0	13.0 in. Hg	0.0 in H_2O
1900.0	"	"
2200.0	"	"
2500.0	"	"
2800.0	"	-.2 in
1500.0	WOT	1.2 in
2000.0	"	1.0 in
2500.0	"	.8 in
3000.0	"	.3 in
3500.0	"	.2 in
4000.0	"	0.0 in
5000.0	"	0.0 in

APPENDIX A   GENERAL SPECIFICATIONS AND PERFORMANCE OBJECTIVES

This section defines 1) the preliminary design specifications for the LRSV; 2) the performance specification for the LRSV when powered by the Engine to be furnished by VAC, and 3) the general specifications for that Engine when it is configured for installation and operation in the large RSV.

I.   LRSV SPECIFICATIONS

The specifications that follow describe the preliminary configuration of the LRSV. These specifications will be updated as the engine/vehicle interface and LRSV designs evolve into their final forms.

Vehicle Type

4-door, 6-passenger sedan; front engine, front wheel drive

Inertia Weight Class:	3,000 lbs.
Weight Distribution Front/Rear (with driver)	52/48
Wheelbase:	115.0" Width 76.0"
Length:	213.0" Height 59.3"
Track, Front/Rear:	63"/63"
Ground Clearance:	6.0"
Fuel Capacity:	10 U.S. gallons

II.   LRSV PROGRAM GOALS

The LRSV Engine shall provide the following performance:

Exhaust Emissions

As an objective, the levels of exhaust emissions shall be:

HC 0.41g/mi; CO 3.4g/mi; NOx 0.4g/mi. The maximum acceptable emissions levels shall be: HC .41g/mi; CO 3.4g/mi; NOx 1.0g/mi. Exhaust emissions performance is to be determined according to test procedures used for 1978 EPA Certification. Data based on sound engineering practice shall be provided to show that the LRSV can be reasonable expected at low emissions levels throughout a projected 50,000 miles of normal use.

Fuel Economy

The minimum acceptable fuel economy of the LRSV shall be 27.5 miles/gallon for combined EPA city and highway driving. The fuel economy performance is to be determined according to 1978 EPA Fuel Economy Test Procedures.

Acceleration

As an objective, the LRSV shall accelerate from 0 to 60 mph in not more than 13.5 seconds. The maximum acceptable time for this acceleration shall not exceed 20.0 seconds.

III.   ENGINE SPECIFICATIONS

The Engine to be furnished for the LRSV shall be based on a modified design of the 1977 Volvo B21 engine. The specifications that follow describe the preliminary Volvo B21 engine configuration revised for LRSV use.

Type	Liquid cooled 4 cylinder in-line with cast iron block, light-alloy cylinder head of cross flow design; belt driven overhead camshaft
Displacement	2017cc
Bore	3.53" (89 mm)
Stroke	3.15" (80 mm)
Compression Ratio	10.4:1
Maximum Output	Estimated SAE net H.P.: 122 @ 5,000 rpm
Fuel Requirements	91 RON unleaded gasoline
Fuel Induction	Bosch K Jetronic continuously manifold injected system with exhaust oxygen sensing mixture correction and three-way catalyst
Ignition System	Autotronic Controls Corporation High energy multi spark capacitive Discharge system

Standard engine driven accessory equipment	770 watt (55 amp) alternator
Starter	810 watt, 1.1 HP
Cooling system	Positive pressure, closed system with cross flow radiator and separate expansion tank. Radiator fan and fan drive to be supplied by Minicars. System capacity: 10 qts. (9.5 liters) 50% water/glycol solution
	Temperature activated electric fan, set point $210^{\circ}F$
Clutch	Borg and Beck pressure plate and flywheel with lighter flywheel. Cable operated Borg and Beck dry plate type
Miscellaneous	Lubrication system adopted to synthetic oil plus other friction reduction modifications.
	A three-way catalytic converter and an appropriately configured exhaust head pipe to connect it to the turbo charger discharge connection shall be provided.
Engine Weight	Estimated net, including engine mounted accessories and components as indicated excluding fluids, 380 lbs. max.

The following description has been excerpted from a Volvo Publication:

The Lambda-Sond oxygen sensor feedback system, described in the flow
chart below, is a self-tuning engine control system designed to reduce
emissions and improve fuel economy. An exhaust gas sensor, (oxygen
sensor, also called Lambda Sensor) monitors the composition of the
exhaust gases leaving the engine. The exhaust gas analysis is fed into a
closed loop feedback system. This continuously adjusts the air/fuel ratio
to provide optimum conditions for combustion and efficient elimination of
all three of the major pollutants (HC, CO, NOx) by a 3-way catalytic
converter.

OXYGEN SENSOR FEEDBACK SYSTEM
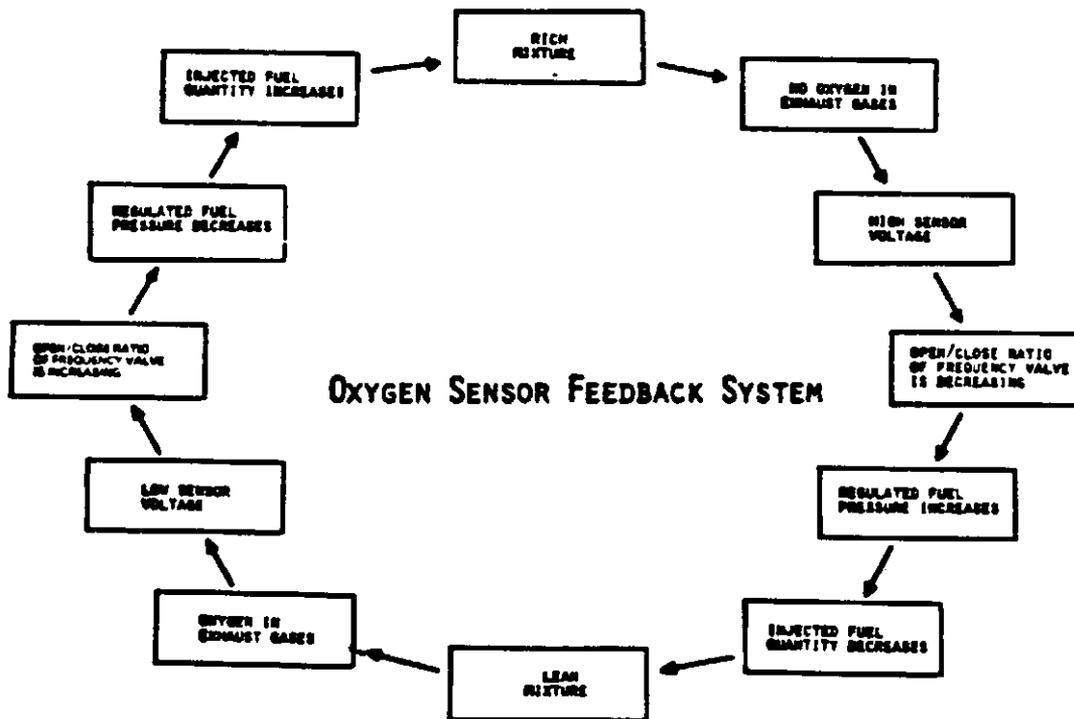
Fuel system – B21F with oxygen sensor system

control pressure regulator

return to tank

injectors

cold start injector

frequency valve

line pressure regulator

return to tank

air and fuel control unit

fuel filter

return to tank

fuel accumulator

fuel pump

oxygen sensor

electronic module
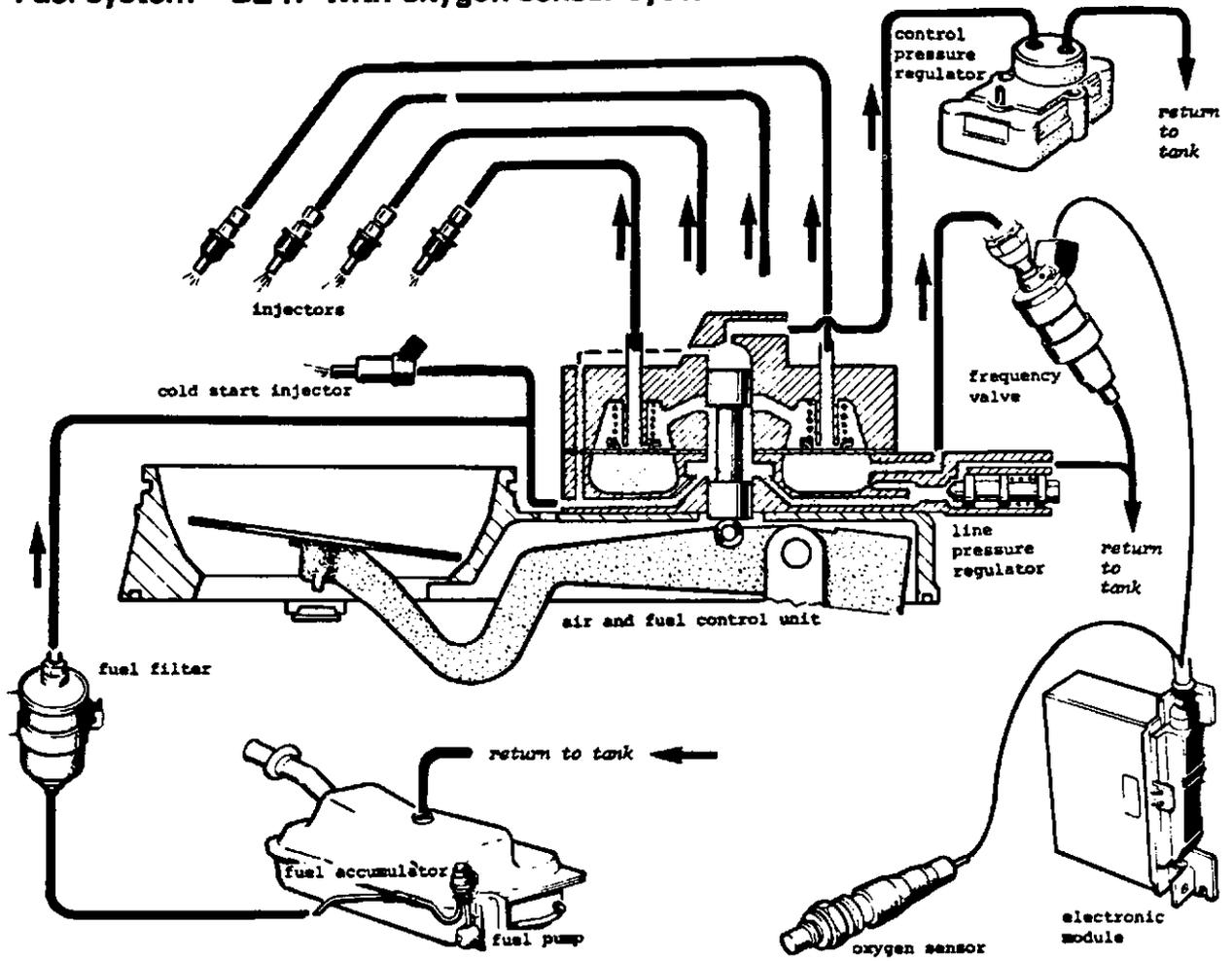
Description of
Oxygen Sensor Feedback System

General idea

.... ELECTRONIC MODULE
which converts the signal
and supplies a control
current to the . . .

....FREQUENCY VALVE
which influences the
fuel flow and thereby
the ratio of oxygen
in the exhaust gases

frequency
valve

fuel distributor

The ratio of oxygen
in the exhaust gases
determines the strength
of the output signal
from the

OXYGEN SENSOR
This signal is fed into
the . . . .
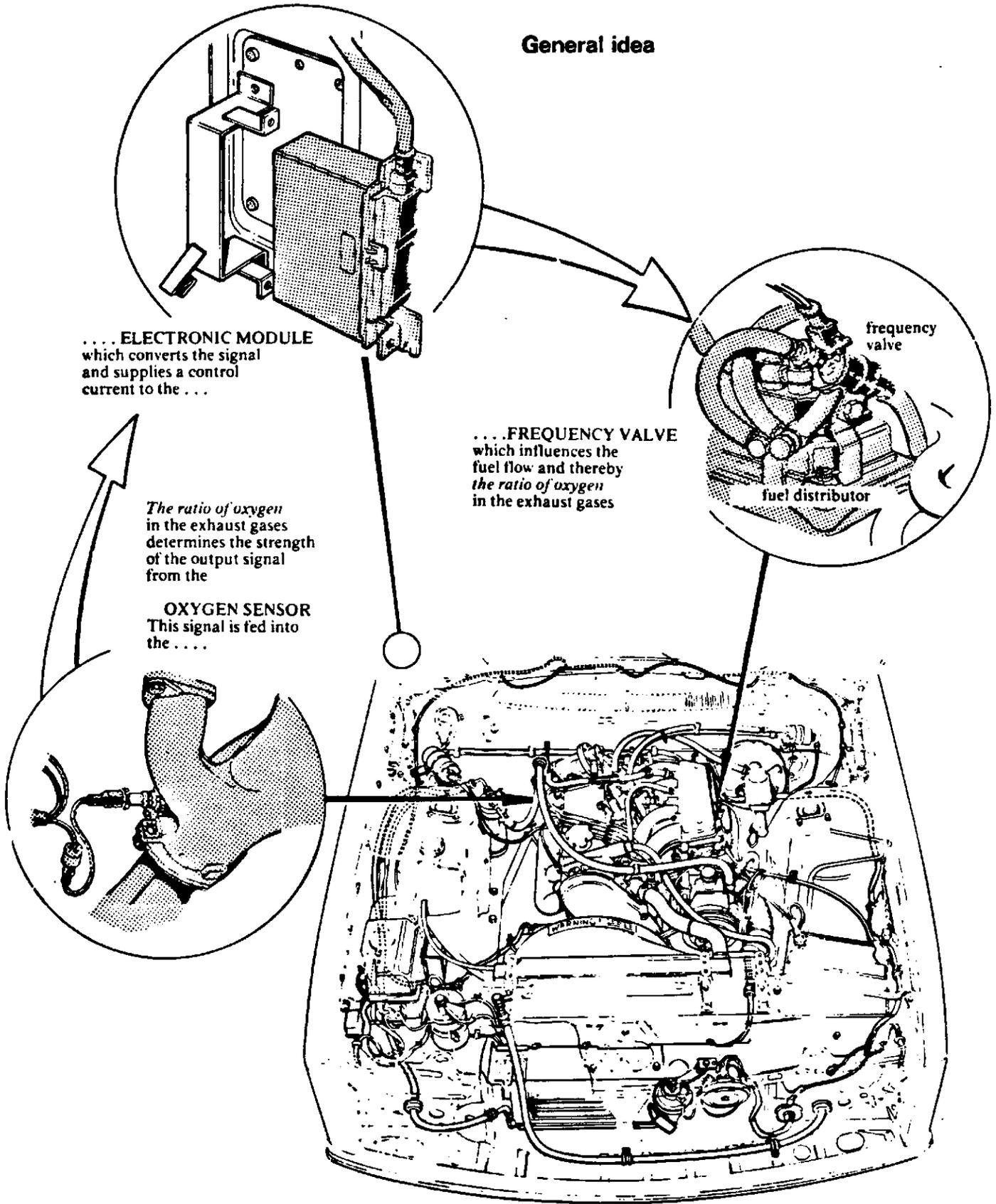
OXYGEN SENSOR

The exhaust gas sensor, called oxygen sensor, is located in the exhaust manifold. It consists of a platinum coated ceramic tube. The inside is connected to atmosphere, while the outside extends into the exhaust gases.

An electrical potential is built up according to air/fuel ratio. There is a steep transition just at the point where the air/fuel ratio is ideal.

The electrical potential is high (approx. 1 volt) with low content of oxygen in the exhaust gases (= rich mixture) and low (approaching 0 volt) when the mixture is lean (= oxygen surplus).
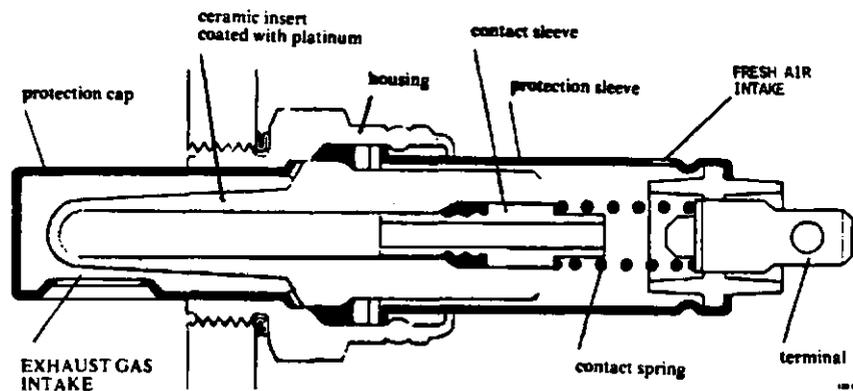
ELECTRONIC MODULE

The output from the oxygen sensor is fed into an electronic unit, called the electronic module. This device supplies a control current to the frequency valve. The control current has a set frequency and operates by varying the duty cycle.

The electronic module is located inside the vehicle, at the right side in front of the right door. In this position it is protected and is close to the oxygen sensor and the electrical system.
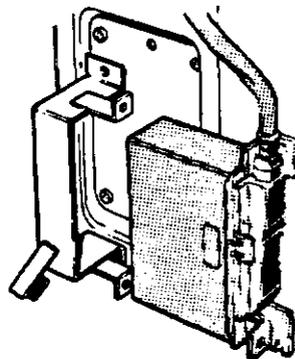
FREQUENCY VALVE

This device influences the fuel flow by influencing the pressure on the underside of the diaphragm in the pressure regulating valves in the C1 System.

It is located on a bracket behind the fuel distributor on the left side of the engine.

The frequency valve operates on a set frequency and by varying the duty cycle (ratio of closed/open circuit).
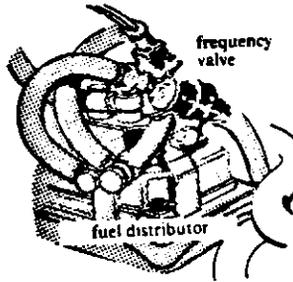
APPENDIX C   DESCRIPTION ENGINE DEVELOPMENT APPARATUS

The testing apparatus as used in the engine dynamometer engine development can be divided into three basic systems:

1. . Engine performance measurement

2. Engine fuel consumption measurement, and

3. Engine emission measurement.

Because direct correlation between FTP cycle results and engine dynamometer fuel economy and emission data is very difficult to obtain, the engine dynamometer measurement systems were used only for trend analysis of the effects of select modifications. This offered the ability to weigh the relative value of each modification. Considering the preceding, the following is a partial description of the test apparatus for information purposes.

The engine performance measuring system is shown in diagrammatic form in Figure No. 13. The engine parameters measured in this system are as follows:

1. Engine rpm

2. Engine torque

3. Engine air inlet temperature, dry bulb

4. Engine air inlet temperature, wet bulb

5. Barometric pressure

6. Engine oil pressure

7. Engine water temperature

8. Engine inlet oil temperature

9. Manifold vacuum/pressure

This system centers around a water absorption type dynamometer unit and is controlled by varying the flow of water through the unit using an analog pneumatic valve arriving at the engine's output horsepower. The absorption dynamometer's water supply consists of a 3,000 gallon capacity reservoir. The water is maintained at a constant temperature using an external water cooling tower. Engine torque was measured using a pressure transducer as a load cell. The torque measurement system was calibrated daily using a detachable arm and calibrated weights. Engine rpm was measured using a mechanical tachometer calibrated in place.

Oil pressure, manifold vacuum, and fuel pressure were measured using Bourdon Tube mechanical gauges. Oil and water temperatures were measured using resistance type electric gauges. Air inlet wet and dry bulb temperatures were continuously monitored throughout the testing series using thermistors. Finally, barometric pressure was measured using a temperature compensated Taylor aneroid barometer.
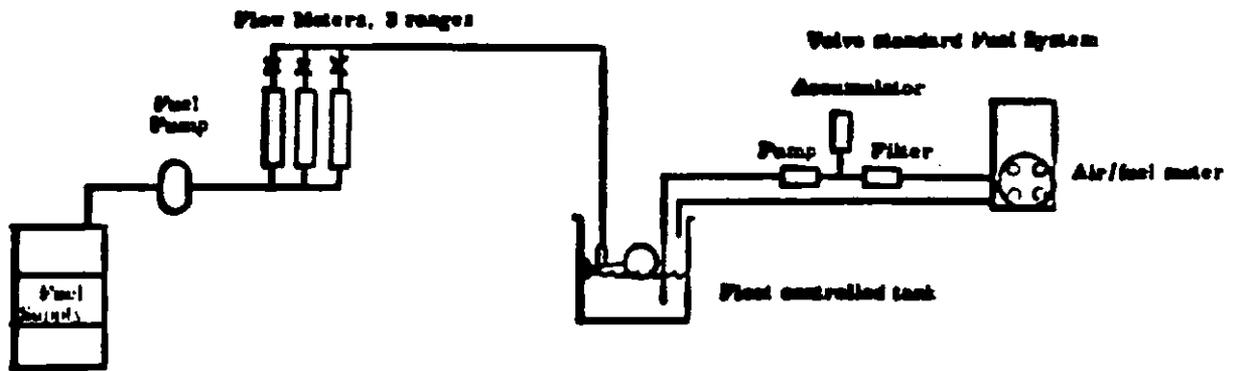
The fuel measurement system, shown in Figure No. 14, is calibrated to read engine fuel flow rate in pounds per hour. The system consisted of the following: An aircraft type fuel pump supplying fuel to one of three Rotometer type flow meters ranging: 3-30 lbs/hr, 20-190 lbs/hr and 50-350 lbs/hr. The use of any one of the flow meters was determined by opening and closing the appropriate valves. Fuel continues into a level controlled tank which acts as the fuel reservoir for the Volvo system.

The exhaust emission measurement system equipment was chosen to be of the infrared type. This measurement system, shown in Figure No. 15 is explained as follows: Exhaust gas, sampled from before and after the catalytic converter enters discreet stainless steel lines into an ice bath cooler. From the cooler the gases enter two inline 0.6 micron filters and into the systems' pump. From the pump, gases flow into two discreet flow meters and one line enters a NOx oven and the NOx cell, while the other enters a condenser, a HC cell, and CO cell.

This type of measurement allowed direct comparison of emission being produced from a Volvo engine with a select modification to the production Volvo engine.
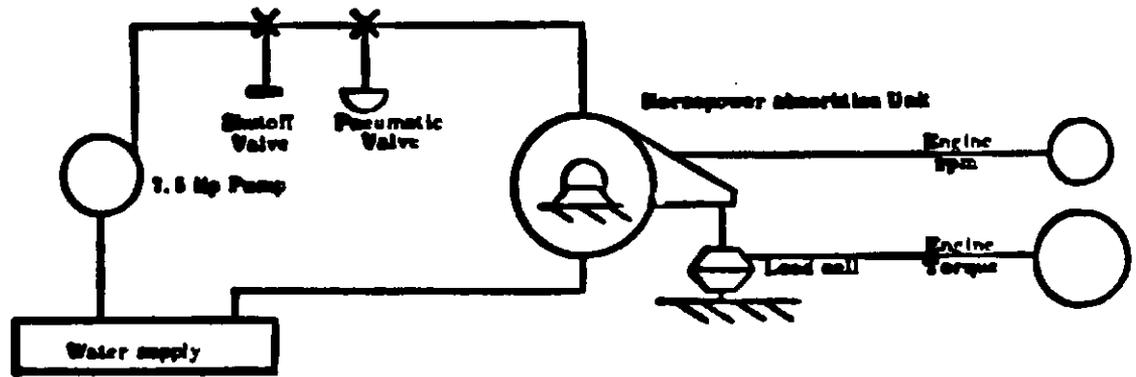
Figure No. 13 Engine Performance Measurement System

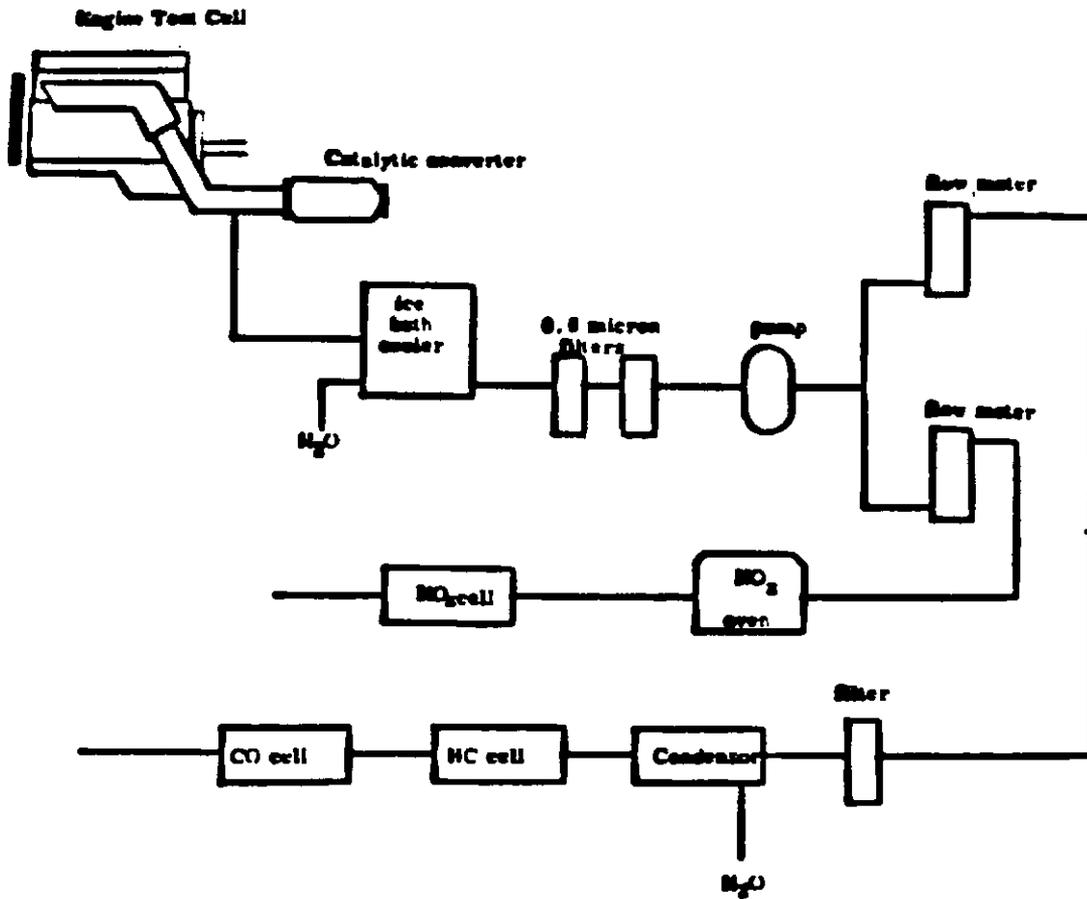

Figure No. 14 Engine Dynamometer Fuel Measurement System

Figure No. 15. Engine Dynamometer Exhaust Emissions Measurement

APPENDIX D

VOLVO B19 LRS.

Brooklyn Air Resources Lab Test Results

Date	Run #	HC	CO	CO_2	NO_x	MPG	Notes
9/18	2871c	.56	11.16	437.	.12	19.3	As delivered
	2971c	.37	8.98	259.1	.10	32.0	
9/18	2872c	.39	9.27	366.4	.01	23.0	Trans & rear end
	2872h	.44	9.75	251.4	.10	32.8	lube installed
9/19	2873c	.51	10.83	375.3	.10	22.3	Run leaner
9/19	2874c	.53	4.79	373.5	.12	23.0	Lambda Sond
	2874h	.28	8.17	241.9	.08	34.8	Problems
	2974h	.35	8.43	231.8	.14	35.8	Overdrive used
9/29	Englehard	1.48	11.50	462.8	1.86	18.4	
10/23	2883c	.48	8.48	365.7	1.05	23.3	New cat. Engine
	2883h	.20	4.29	214.2	1.01	39.7	as per Englehard
	2884c	.24	3.69	364.4	.07	23.7	Remove warm-up
	2884h	.20	2.56	214.0	.06	40.2	regulator/install ol
	2885c	.53	7.17	364.5	.26	23.3	cat. Fuel meter wi large air meter
10/30	2891c	.37	4.47	373.2	.20	23.1	
	2891h	.20	2.27	222.4	.04	38.8	CO high-repeat hot
	2892c	.24	3.68	373.2	.07	23.2	
	2892h	.16	2.53	218.8	.03	39.4	
	2893c	.22	3.98	373.4	.07	23.1	
	2893h	.14	2.28	219.0	.02	39.4	
10/31	2894comp	.57	8.42	392.0	.44	21.8	Cold start
	2894i	1.67	16.14	---	1.22	---	
	2894il	.19	3.67	---	.05	---	Average 27.22
	2894iii	.45	4.30	---	.58	---	
	2894c	.32	3.97	387.1	.30	22.3	
	2894h	.17	1.99	221.4	.12	30.1	

VOLVO B19 LRSV Brooklyn Air Resources Lab Test Results Continued

Date	Run #	HC	CO	CO$_2$	NO$_x$	MPG	Notes
11/20	2902c	.20	2.11	394.0	.34	22.1	Weighted fuel meter
	2902h	.13	1.04	225.9	.06	38.6	
	2903c	.56	9.34	384.8	.49	21.9	Rich sensor/retard
	2904c	.51	5.43	369.5	.96	23.2	Rich sensor/no retard
	2905c	.38	4.09	382.9	.73	22.5	Good sensor/retard
11/21	2906comp	.68	3.58	425.6	.32	20.3	Cold start test/
	2906i	2.39	8.56	---	1.14	---	raised air meter disc.
	2906ii	.15	2.21	---	.08	---	Too lean on start.
	2906iii	.31	2.42	---	.15	---	Average 25.83
	2906h	.09	.84	225.6	.12	38.7	
12/18	2910c	.14	2.80	370.5	.71	23.4	New Lambda Sond
	2911c	.24	3.77	364.6	.49	23.7	computer set lower
	2912c	.12	2.61	364.8	.20	23.8	500mv nom. added
	2913c	.19	3.38	364.4	.51	23.7	2 oz wgt. fuel meter
	2913h	.04	.62	214.0	.09	40.8	
	2914	.10	2.99	385.7	.07	22.5	#2913 same as 2918
12/19	2915comp	.47	4.77	398.5	.44	21.8	Set volt richer/600mv
	2915i	1.50	13.08	---	1.44	---	500mv
	2915ii	.13	2.72	---	.14	---	
	2915iii	.33	2.41	---	.25	---	
	2915h	.08	1.11	218.0	.08	40.0	
	2916c	.46	3.84	371.5	.09	23.2	Same as 2915/fuel
	2917c	.12	2.29	377.8	.31	23.0	shutoff hookup 600mv
	2918c	.10	2.67	365.6	.12	23.8	OD in all gears
	2919c	.12	3.45	377.8	.05	22.9	No OD 550mv 50ms
12/20	2920comp	.45	5.22	383.2	.37	22.3	550 mv 16ms
	2920i	1.53	12.75	---	1.33	---	OD all gears
	2920ii	.13	3.69	---	.08	---	
	2920iii	.25	2.44	---	.19	---	
	2920h	.07	1.14	230.5	.08	37.8	

VOLVO H 19 Brooklyn Air Resources Lab Test Results Continued

Date	Run	HC	CO	CO_2	NO_x	MPG	Notes
12/27	SATRA comp	.27	4.33	---	.36	22.51	400 - 4 min.
	SATRA ih	.29	4.75	---	.49	21.62	
	iih	.29	4.46	---	.55	22.35	
	iiih	.27	4.34	---	.46	22.06	
	ivh	.28	4.23	---	.40	21.90	
1/10	2921comp	.28	1.78	361.5	.55	24.1	Turbo charger
	2921i	1.14	7.44	---	.89	---	removed
	2921ii	.04	.23	---	.26	---	
	2921iii	.08	.36	---	.83	---	
	2921h	.06	.37	225.8	.15	38.8	
1/15	2924c	.05	.51	360	.11	24.4	Vac. retard
	2925c	.09	1.19	350.7	.11	24.9	No vac. retard
	2926c	.05	.51	366.1	.09	24.0	3250 inertia wheel
1/16	2927comp	.28	2.42	367.8	.17	23.8	
	2927i	1.07	10.08	---	.51	---	
	2927ii	.04	.38	---	.04	---	
	2927iii	.08	.53	---	.17	---	
	2927h	.06	.26	222.8	.04	39.4	

B-34

APPENDIX E--TASK RESULTS:

TASK 1 -   Predict performance of an LRSV powered by the engine
and an estimate of the maintenance required to preserve
the performance levels over 50,000 miles.

A)   LRSV engine output
          (Based on actual dynamometer data)

Engine:	B-19 derived Lambda-sond emission control system
Displacement:	2017 cc
Compression Ratio:	10.4:1
Max Turbo Boost:	4 Psig

Figure 16

RPM	LRSV Turbo		LRSV (N.A.)	
	hp	Torque (ft.-lbs.)	hp	Torque (ft.-lbs.)
1000	15.0	78.8	15.0	78.8
1500	25.4	88.9	25.4	88.9
2000	35.9	94.3	37.3	98.1
2500	52.0	109.2	49.0	102.9
3000	70.2	122.9	62.3	109.1
3500	86.2	129.3	71.5	107.2
4000	103.3	135.7	81.3	106.7
4500	115.0	134.2	91.9	107.2
5000	122.1	128.2	102.6	107.7

TASK 1 (cont'd)

B)   **LRSV Preliminary Performance Prediction**
     Determined from following data:

1   Engine torque: turbo and normally aspirated from figure 16.

2   Maximum engine rpm 5000

3   Gear Box Ratio:

1st.	3.53
2nd.	1.45
3rd.	1.24
4th.	0.81
Final Drive	3.34

4   Assume transmission efficiency 96%

5   Wheel dimension P175/14 tire

     Rolling radius 11.5 in.

6   Coefficient of Drag = .42

     Frontal Area = 25 ft.^{2}

7   Rolling Resistance = 36 lbs.

8   Curb weight = 3004 lbs.

     Test weight = 3304 lbs.
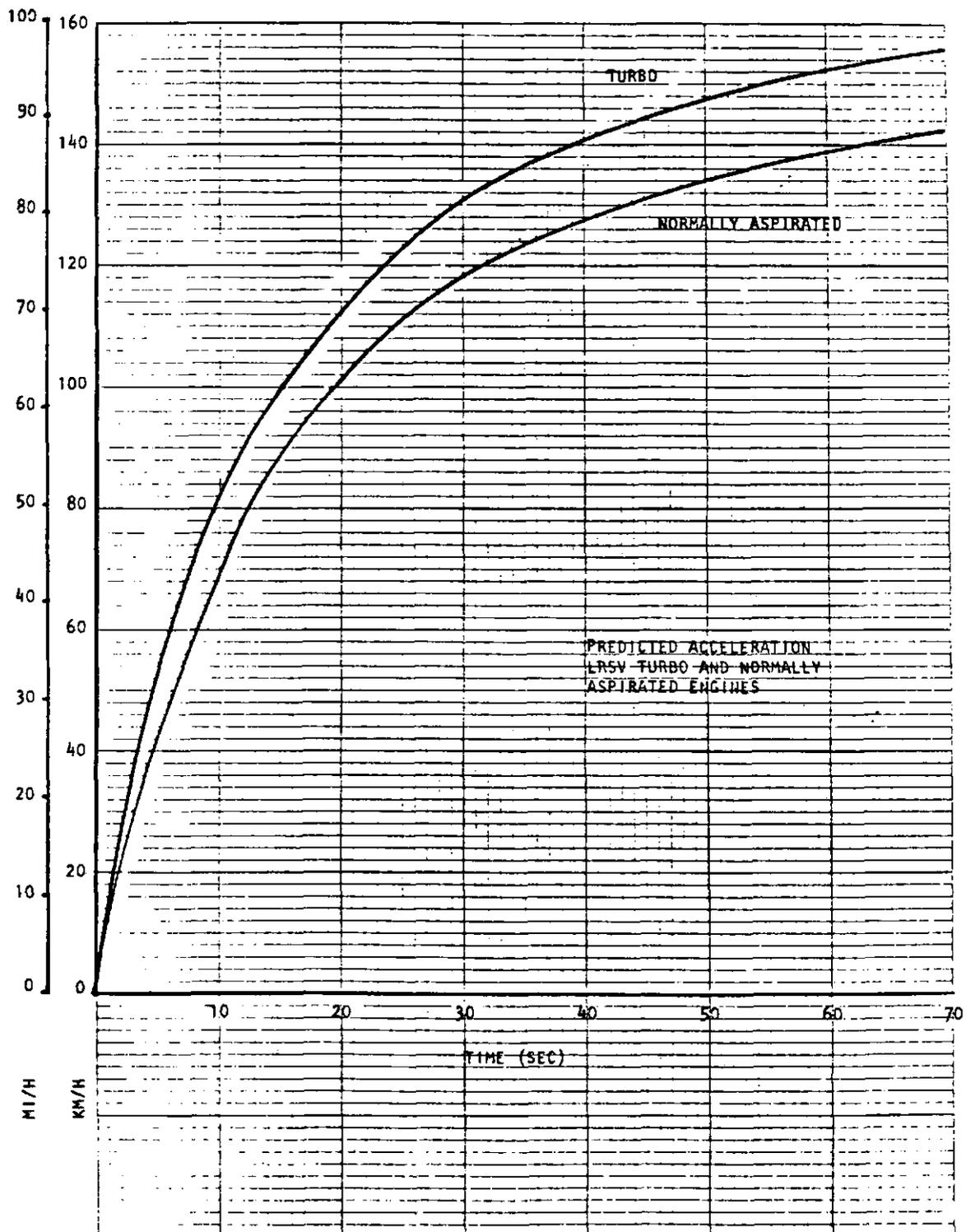
TASK 1 (cont'd)

Figure 17 LRSV Acceleration Prediction

Turbocharged engine:

MPH	TIME (Sec.)	DISTANCE (Ft.)
10	1.20	6.01
20	2.46	36.20
30	4.25	115.73
40	7.50	246.70
50	9.50	417.48
60	13.80	793.74
70	19.75	1280.64
80	28.00	2302.26
90	44.50	5024.16

Normally aspirated engine:

MPH	TIME (Sec.)	DISTANCE (Ft.)
10	1.50	11.30
20	3.30	47.52
30	6.00	137.54
40	9.00	300.79
50	12.40	521.57
60	17.75	1003.24
70	25.50	1702.02
80	40.50	3964.56
90	-----	------

Figure 18   Predicted Acceleration Curve

B-38.

TASK 1 (cont'd)

C) LRSV Maintenance Schedule

Replace	Initially (miles)	Interval (miles)
Engine oil and oil filter	600-1200	3,750
Oxygen sensor		30,000
Spark plug		30,000
Transmission oil	600-1200	
Rear axle oil	600-1200	
Air cleaner filter		30,000
Engine coolant		30,000
Camshaft belt (if required)		45,000

Adjust		
Engine drive belts	600-1200	
Torque manifold bolts	600-1200	
Camshaft drive belt	600-1200	
Oxygen sensor	600-1200	10,000
Catalytic converter mounting bolts	600-1200	

Inspect		
Cooling system and connection	600-1200	30,000
Engine drive belts		30,000
Valve clearance		30,000
Vacuum fitting	600-1200	30,000
Idle rpm	600-1200	10,000
Fuel system cap, tank, lines and connections	600-1200	30,000

TASK 2   Furnish a description of procedure that will be followed
           in the tests and the type of test data to be acquired.
           Fabricate engine according to this procedure.

Test Procedure for LRSV Engine

1) a)   outfit 1978 244DL with vacuum transducer

    b)   run a 1978 FTP

    c)   determine steady state "modelling tool"

2) a)   construct B-19 Lambda-Sond engine

    b)   break in (three engines) 30 hours each according to load/engine
         speed schedule

    c)   baseline engine WOT test B-19 and production B-21

3) a)   test engine at steady state modelling tool conditions

    b)   record engine parameters for following:

         1)   synthetic oil

         2)   reduced accessory drive speed

         3)   multi-spark capacitive discharge ignition system

         4)   reduced oil pump pressure

         5)   reduced crankcase pressure

         6)   elevated coolant temperature

    c)   determine BSFC's of above modifications

4) a)   blueprint and balance engine

    b)   break in on dyno

    c)   baseline engine

5) a)   install turbocharging system from mock-up

    b)   break in, baseline

    c)   WOT test turbo engine

    d)   install boost retard system

    e)   match and install injectors

6)   a)   assemble final engine with selected modifications from above test

     b)   install in 244DL test chassis

7)   a)   test on FTP

     b)   drivetrain modifications

     c)   Lambda-Sond modifications

TASK 3   Engine specifications shall be revised by the findings of TASK 2. Where revisions influence performance, trade off studies shall be conducted to assure that revisions do not unnecessarily compromise performance objectives.

Updated Engine Specifications - None at TASK 3, as actual dynamometer values were utilized for performance predictions, the need to revise the engine specifications are at TASK 3 not necessary. This is evidenced by the satisfactory acceleration data computed during TASK 1, Page 37, Figure 17.

TASK 4   Follow up testing, tests shall be conducted to determine acceleration performance of TASK 3 engine.

Actual Acceleration Times for LRSV - Volvo Chassis

A   Data:

    1   Engine torque: turbo and normally aspirated torque, see Figure 16 Page 35

    2   Maximum engine speed 5,000

    3   Gear Box Ratio

1st.	3.17
2nd.	2.16
3rd.	1.37
4th.	1.00
5th.	0.80
Final drive	3.54

    4   Transmission efficiency 96%

    5   Wheel dimensions 185/70 SR14
       Rolling radius 11.1 in.

    6   Coefficient of drag = 0.51
       Frontal area = 22.6 ft.^{2}

    7   Rolling resistance = 37 lbs.

    8   Curb weight = 3040 lbs.
       Test weight = 3340 lbs. (assumed)

Note: 1980 GL acceleration times are provided for comparison.

TASK 4 (cont'd)

Figure 19

Actual acceleration times:

Engine: LRSV-turbo

Chassis: Volvo 1978 244DL

Zero to mph	Time to Speed LRSV-turbo	1980 Volvo GL
20	2.23	2.15
30	3.40	3.56
40	5.09	5.60
50	6.80	8.10
60	9.50	12.03
70	13.00	16.46
80	16.60	24.03
90	22.10	-----

Note: This data reprinted with permission from Motor Trend Magazine,
April 1980, Petersen Publishing Co., Los Angeles, California

TASK 5   The durability of the engine in maintaining the specified emission and fuel economy levels shall be extrapolated to 50,000 miles, using actual data and appropriate engineering data.

Figure·20

Predicted Emission Levels and Fuel Economy at 50,000 Miles

	Initial Level		Predicted Levels 50,000 miles	
	Turbo	Non-turbo	Turbo[1]	Non-turbo[2]
Emission Data:				
HC	0.37	0.19	0.49	0.19
CO	2.96	2.38	4.80	2.54
NOx	0.48	0.57	0.56	0.57
Fuel Economy (Combined):				
MPG	29.65	27.43	30.1	28.04

1) Based on "deterioration factors" for 1980 GLT Turbo,
   Chassis: Volvo LRSV
   Transmission: Volvo 5 Sp. Manual

2) Based on "deterioration factors" for 1978 244 DL Lambda-Sond engine,
   Chassis: LRSV
   Transmission: GM X-body 4 Sp. Manual

TASK 6   Zero mile test, final drawing, final maintenance schedule, and raw data collected during dynamometer.

A)   Zero mile test:

1976 Federal Urban Driving Cycle conducted at Air Resources Lab, Brooklyn, N.Y., August 2, 1979

Test #3021

Figure 21

	HC	CO	CO_2	NOx	MPG
Bag 1	1.24	10.08	---	1.93	---
Bag 2	0.13	1.23	---	0.06	---
Bag 3	0.18	0.94	---	0.22	---
Composite	0.37	2.96	363.2	0.48	24.0
Highway	0.06	0.32	225.8	0.17	39.1

Inertia weight: 3,000 lbs.

Dyno setting: 10.3 hp @ 50 mph.

Chassis: LRSV-Volvo

B)   Final drawing - see separate General Arrangement Drawing

C)   Final maintenance schedule - unchanged from preliminary specification, Page 39

D)   Raw data - see Appendix F, G

Appendix F. Observed and Calculated Data Recorded During Dynamometer Study

VAC. = in. Hg
Torque = lbs.-ft.

Temp. = Dry Bulb, °F
Fuel Flow = lbs./hr.

Test 1:   Baseline
VAC: WOT

RPM	TORQUE	FUEL FLOW	TEMP.	Hp	CORRECTED Hp	BSFC
1600	82.72	9.10	84	23.62	24.38	0.385
2000	91.91	14.60	84	35.00	36.12	0.417
2500	97.68	18.90	85	46.50	48.03	0.406
3000	100.05	22.80	86	57.15	59.09	0.399
3500	99.79	28.00	85	66.50	68.69	0.421
4000	98.46	32.00	86	75.00	77.55	0.427
4500	99.79	39.00	87	85.50	88.49	0.456
5000	99.79	48.00	86	95.00	98.23	0.505
5200	98.21	47.00	87	97.20	100.64	0.483

Test 2:   Baseline
VAC: 13.0"
Baro: 30.27"

RPM	TORQUE	FUEL FLOW	TEMP.	Hp	CORRECTED Hp	BSFC
1600	29.15	4.50	83	8.80	9.21	0.507
1900	30.46	6.30	83	11.02	11.02	0.572
2200	28.68	8.40	83	14.19	14.72	0.592
2500	34.14	8.60	83	16.25	16.86	0.529
2800	35.45	9.80	84	18.90	19.63	0.519

Test 3:   Baseline
VAC: 13"
Baro: 30.28

RPM	TORQUE	FUEL FLOW	TEMP.	Hp	CORRECTED Hp	BSFC
1600	31.25	5.00	86	9.52	9.90	0.525
1900	29.67	6.30	86	10.73	11.16	0.587
2200	33.35	8.40	86	13.97	14.52	0.601
2500	35.19	8.60	86	16.75	17.42	0.513
2800	35.71	9.80	86	19.04	19.80	0.515

Test 4: Multi-Spark Ignition
VAC: 13"
Baro: 30.4

RPM	TORQUE	FUEL FLOW	TEMP.	Hp	CORRECTED Hp	BSFC
1600	31.25	4.90	83	9.52	9.81	0.515
1900	32.56	6.10	83	11.78	12.23	0.518
2200	35.45	8.00	83	14.85	15.29	0.539
2500	35.19	8.60	84	16.75	17.26	0.513
2800	36.50	11.20	84	19.46	20.06	0.576

Test 5: Reduced Diameter Crank Pulley
VAC: 13"
Baro: 30.45

RPM	TORQUE	FUEL FLOW	TEMP.	Hp	CORRECTED Hp	BSFC
1600	32.03	5.10	81	9.76	10.01	0.523
1900	33.09	6.80	81	11.97	12.28	0.568
2200	35.19	8.20	81	14.74	18.12	0.556
2500	35.98	8.70	80	17.12	17.55	0.508
2800	36.76	10.50	80	19.60	20.09	0.536

Test 6: Synthetic Lubricant
VAC: 13"
Baro: 30.43"

RPM	TORQUE	FUEL FLOW	TEMP.	Hp	CORRECTED Hp	BSFC
1600	32.03	5.10	91	9.76	10.15	0.523
1900	32.83	6.80	91	11.87	12.35	0.573
2200	35.71	8.40	91	14.96	15.55	0.561
2500	35.97	8.70	91	17.12	17.81	0.508
2800	36.87	10.80	91	19.65	20.44	0.549

Test 7: Elevated Coolant 210°F Temp.
VAC: 13"
Baro: 30.80"

RPM	TORQUE	FUEL FLOW	TEMP.	Hp	CORRECTED Hp	BSFC
1600	28.36	4.70	82	8.64	8.85	0.544
1900	29.15	5.40	82	10.54	10.79	0.512
2200	34.14	6.80	82	14.08	14.41	0.438
2500	34.40	10.20	82	16.37	16.76	0.623
2800	35.19	10.50	82	18.76	19.21	0.560

Test 8:   Elevated Coolant 220°F Temp.
VAC: 13"
Baro: 30.8

RPM	TORQUE	FUEL FLOW	TEMP.	Hp	CORRECTED Hp	BSFC
1600	29.94	4.20	83	9.12	9.34	0.461
1900	29.94	5.80	83	10.83	11.10	0.536
2200	33.09	7.80	83	13.86	14.20	0.563
2500	34.14	8.60	83	16.25	16.65	0.529
2800	35.45	11.00	83	18.90	19.37	0.582

Test 9:   Turbocharged
VAC: 13"

RPM	TORQUE	FUEL FLOW	TEMP.	Hp	CORRECTED Hp	BSFC
1600	26.19	5.30	–.	7.68	7.77	0.690
1900	29.41	6.30	–	10.64	10.77	0.592
2200	30.99	7.80	–	12.98	13.13	0.601
2500	34.66	8.50	–	16.50	16.70	0.515
2800	37.29	11.09	–	19.88	20.12	0.558

Test 10:   Turbocharged
VAC: WOT (positive pressure)

RPM	TORQUE	FUEL FLOW	TEMP.	Hp	CORRECTED Hp	BSFC
2000	93.49	15.59	–	35.60	35.92	0.435
2200	101.70	17.97	–	42.60	43.06	0.422
2400	105.04	19.68	–	48.00	48.43	0.410
3000	121.85	28.81	–	69.60	70.22	0.414
3500	128.15	36.04	–	85.40	86.17	0.422
4000	134.45	25.60	–	102.40	103.32	0.250

Test 11:   Blueprinted Engine
VAC: 13"

RPM	TORQUE	FUEL FLOW	TEMP.	Hp	CORRECTED Hp	BSFC
1600	21.00	5.00	–	6.40	6.56	0.781
1900	25.72	6.50	–	9.31	9.55	0.698
2200	30.46	7.90	–	12.76	13.09	0.619
2500	32.81	9.40	–	15.62	16.03	0.602
2800	35.19	11.11	–	18.76	19.24	0.592

Test 12:   Blueprinted Engine
VAC: WOT

RPM	TORQUE	FUEL FLOW	TEMP.	Hp	CORRECTED Hp	BSFC
1500	86.67	9.99	-	24.75	25.39	0.404
2000	95.59	14.60	-	36.40	37.34	0.401
2500	102.41	19.80	-	48.75	38.31	0.406
3000	106.35	24.00	-	60.75	62.33	0.395
3500	104.97	28.12	-	69.95	71.46	0.402
4000	103.99	38.42	-	79.20	81.26	0.429
4500	104.51	38.00	-	89.55	91.87	0.424
5000	105.04	44.00	-	100.00	102.60	0.440
5200	101.10	45.04	-	100.10	102.70	0.450

Test 13:
VAC: 13" Hg

RPM	TORQUE	FUEL FLOW	TEMP.	Hp	CORRECTED Hp	BSFC
1600	24.94	6.75	-	7.60	7.78	0.888
1900	28.08	7.00	-	10.16	10.40	0.689
2200	31.25	8.19	-	13.09	13.40	0.626
2500	32.56	9.60	-	15.50	15.87	0.619
2800	35.71	11.25	-	19.04	19.49	0.591

Test 14:   Blueprinted Engine
VAC: WOT

RPM	TORQUE	FUEL FLOW	TEMP.	Hp	CORRECTED Hp	BSFC
1500	87.18	10.51	-	24.90	25.49	0.422
2000	96.37	14.68	-	36.70	37.58	0.409
2500	103.72	19.70	-	49.37	50.56	0.399
3000	105.04	22.02	-	60.00	61.44	0.367
3500	105.56	36.02	-	70.35	72.03	0.512
4000	104.78	33.99	-	79.80	81.71	0.426
4500	103.20	38.02	-	88.42	90.54	0.430
5000	99.79	45.03	-	95.00	97.28	0.474
5200	102.94	44.03	-	101.92	104.36	0.432

Test 15: Blueprinted Engine
VAC: 13"

RPM	TORQUE	FUEL FLOW	TEMP.	Hp	CORRECTED Hp	BSFC
1600	19.95	4.90	-	6.08	6.28	0.806
1900	24.93	6.59	-	9.02	9.32	0.731
2200	29.41	8.30	-	12.32	12.72	0.674
2500	32.46	9.30	-	15.45	15.96	0.602
2800	35.19	11.34	-	18.76	19.38	0.605

Test 16: Blueprinted Engine
VAC: WOT

RPM	TORQUE	FUEL FLOW	TEMP.	Hp	CORRECTED Hp	BSFC
1500	86.38	11.20	-	24.67	25.48	0.454
2000	96.11	15.48	-	36.60	37.80	0.423
2500	102.14	19.59	-	48.62	50.23	0.403
3000	103.99	22.99	-	59.40	61.36	0.387
3500	103.99	28.00	-	69.30	71.58	0.404
4000	104.51	32.00	-	79.60	82.83	0.402
4500	103.46	38.03	-	88.65	91.57	0.429
5000	102.41	43.00	-	97.50	100.71	0.441
5200	100.05	45.96	-	99.06	102.32	0.464

Appendix G <u>Steady State Emission Data Recorded During Dynamometer Study</u>

VAC 13" Hg

Test 1:   Baseline Before Catalytic Converter

<u>RPM</u>	<u>% CO</u>	<u>PPM/HC</u>	<u>PPM/NOx</u>
1600	1.10	1.55	300
1900	1.10	1.30	400
2200	0.98	1.39	840
2500	1.00	1.35	1020
2800	0.90	1.18	1220

Test 2:   Baseline After Catalytic Converter

1600	0.90	1.30	75
1900	0.20	0.63	65
2200	0.17	0.65	80
2500	0.15	0.62	80
2800	0.13	0.61	20

Test 3:   Reduced Diameter Crankshaft Pulley Before Catalytic Converter

1600	2.13	1.53	320
1900	1.60	1.10	520
2200	1.30	1.10	840
2500	1.05	1.00	1160
2800	0.90	0.80	1400

Test 4:   Elevated Coolant Temp. - 210°F Before Catalytic Converter

1600	0.72	0.85	380
1900	0.70	0.60	560
2200	0.64	0.60	920
2500	0.70	0.61	1380
2800	0.78	0.44	1380

Test 5: Elevated Coolant Temp. - 220°F Before Catalytic Converter

RPM	% CO	PPM/HC	PPM/NOx
1600	1.23	1.15	430
1900	0.80	0.75	460
2200	0.65	0.79	940
2500	0.73	0.72	1240
2800	0.79	0.65	1380

Test 6: Multi-Spark Ignition System Before Catalytic Converter

RPM	% CO	PPM/HC	PPM/NOx
1600	2.23	1.80	320
1900	1.85	1.50	500
2200	1.70	1.55	740
2500	1.40	1.40	1020
2800	1.27	1.29	1300

APPENDIX C

BENDIX AUTOMOTIVE CONTROL SYSTEMS GROUP FINAL REPORT

Final Test Report

Bendix Adaptive Braking
System Installations on

Minicars'
Research Safety Vehicles

March 1980

<u>Final Test Report</u>

Bendix Adaptive Braking System
Installations on
Minicars' Research Safety Vehicles

SUMMARY

This report summarizes test activities associated with the installation of four-wheel adaptive braking system (ABS) on Minicars' Ride and Handling Test Bed and High Technology Research Safety Vehicle (RSV). A recurring problem associated with insufficient front brake pressure consumed an inordinate amount of activity. However, this problem did not prevent the acquisition of substantial data and satisfactory demonstration of major test objectives.

Briefly, the Ride and Handling Test Bed was initially tested to a portion of MVSS-105 procedures; then, the ABS was installed and system function verified on a number of test surfaces. The system was then transferred to the High Technology RSV which was fitted with new Dunlop run-flat tire / wheel assemblies. Pre-and-post burnish effectiveness data was obtained. System function was verified and demonstrated via an eight-to-ten minute color movie. The balance of this report will discuss testing, results, and related events in more detail. Appendix "A" discusses the brake pressure problem.

DISCUSSION

Ride and Handling Test Bed

Prior to any vehicle testing, the four Chapman / McPherson strut assemblies were replaced with Minicars' supplied items to accommodate a higher GVW. The vehicle front and rear axles were realigned by a local chassis specialist. New brake pads (procured from local Fiat dealer) were installed with thermocouples per SAE J-46. The vehicle was equipped with a fifth wheel and instrumentation to monitor rear brake pressure, pedal effort, and vehicle deceleration.

The vehicle was loaded to GVW and MVSS-105 test procedures were followed through the second effectiveness portion. Figures 1 and 2 show results of these tests. As requested, a measurement of vehicle deceleration versus brake pressure was then conducted. Figure 3 shows the results.

DISCUSSION   (Continued)

Ride and Handling Test Bed (Continued)

The four-wheel adaptive braking system was then installed.
In preparation for initial system tests, difficulties were
experienced in obtaining sufficiently high front brake pres-
sure to assure wheel lock prior to primary master cylinder
runout. Many different solutions were attempted with only
fair success. Appendix "A" (attached) will provide more
details on these efforts.

In order to demonstrate ABS performance, all ballast was
removed from the vehicle to reduce high brake pressure
requirements. The vehicle was then tested periodically
over a six week period at curb weight, plus two occupants,
plus approximately 100 pounds of instrumentation.

In a typical test sequence, several alternate system ON and
system OFF stops are made under the same test surface / speed
condition. SAE J-46 procedures were used including rapid brake
application to a high level of effort. Initial speed (0.1 ft./
sec. resolution) and stopping distance (0.1 ft. resolution) were
recorded. The data was reduced by correcting stopping distance
for minor initial speed variations, and then averaging the
groups of system ON and system OFF stops. Figure 4 summarizes
the results of these ABS performance measurements. Please note
the test surfaces changed over the time period due to wear,
climate, and, in some cases, resurfacing; thus, no attempt
should be made to dwell on absolute distances. In fact, it is
for this type of reason that J-46 seeks to compare the system
equipped vehicle only with itself in a locked wheel stop at the
same surface / speed condition.

High Technology RSV

With satisfactory system function demonstrable on the Ride and
Handling Test Bed, transfer to the High Technology RSV was
accomplished. The vehicle was also equipped with new brake pads
and thermocouples, instrumentation, and weighed with the following
results:

	Weight (Lbs.)	
	Front	Rear
Left	576	765
Right	560	760
Totals	1,136	1,525

2,661

DISCUSSION   (Continued)

High Technology (RSV)   (Continued)

Pre-burnish effectiveness was measured at 30 and 60 mph (two
occupants) and the results are plotted in Figures 5 and 6.
The vehicle was then subjected to the 200 stop burnish schedule
of SAE J-46 and 30 and 60 mph brake effectiveness again measured.
See Figures 7 and 8.

A short movie was made of the High Technology RSV on a variety
of surfaces. The movie sought to visually demonstrate the ABS
contribution to vehicle performance, much like SAE J-46, by
comparing vehicle behavior with and without the system in operation.

Attachments

Figure 1

Ride and Handling Test Bed
MVSS-105 Test Results

<u>Conditions</u>:

- Fuel tank 75 - 100% full.
- Tire inflation pressure correct.
- Weight: Front Axle - 1,440 Lbs.
          Rear Axle - 1,782 Lbs.

First Effectiveness - 30 MPH

Stop Number	Maximum Line Pressure (psi)	Corrected Distance (Ft.) [1]	Maximum Pedal Effort (Lbs.)
1	1,470	41.7	128
2	1,510	41.0	137
3	1,550	40.7	142
4	1,440	42.1	139
5	1,500	40.1	137
6	1,470	42.7	135

(1) Corrected distance, $D_c = D_A \left(\dfrac{V_0^2}{V_A^2} \right)$

Where: D_A = actual distance, feet.

V_A = actual velocity, feet/second.

V_0 = desired velocity, feet/second.

First Effectiveness - 60 MPH

Stop Number	Maximum Line Pressure (psi)	Corrected Distance (Ft.)	Maximum Pedal Effort (Lbs.)
1	1,400	184.9	128
2	1,500	171.5	131
3	1,300	176.4	125
4	1,460	182.4	128
5	1,470	176.0	128
6	1,490	183.6	125

C-6

FIGURE 2

Ride and Handling Test Bed
MVSS-105 Test Results

Second Effectiveness - 30 MPH

Stop Number	Maximum Line Pressure (psi)	Corrected Distance (Ft.)	Maximum Pedal Effort (Lbs.)
1	1,550	44 6	133
2	1,580	41.5	136
3	1,600	40.6	142
4 *			
5	1,500	46.3	135
6	1,525	44.6	140

* Both front wheels slide, midway.

Second Effectiveness - 60 MPH

Stop Number	Maximum Line Pressure (psi)	Corrected Distance (Ft.)	Maximum Pedal Effort (Lbs.)
1	1,560	176.0	133
2	1,650	170.1	145
3	1,600	174.9	132
4	1,510	175.5	115
5	1,530	181.3	107
6	1,550	179.5	102

Figure 3

Ride and Handling Test Bed
Brake Effectiveness

(Vehicle Weight: 3,220 lbs.)
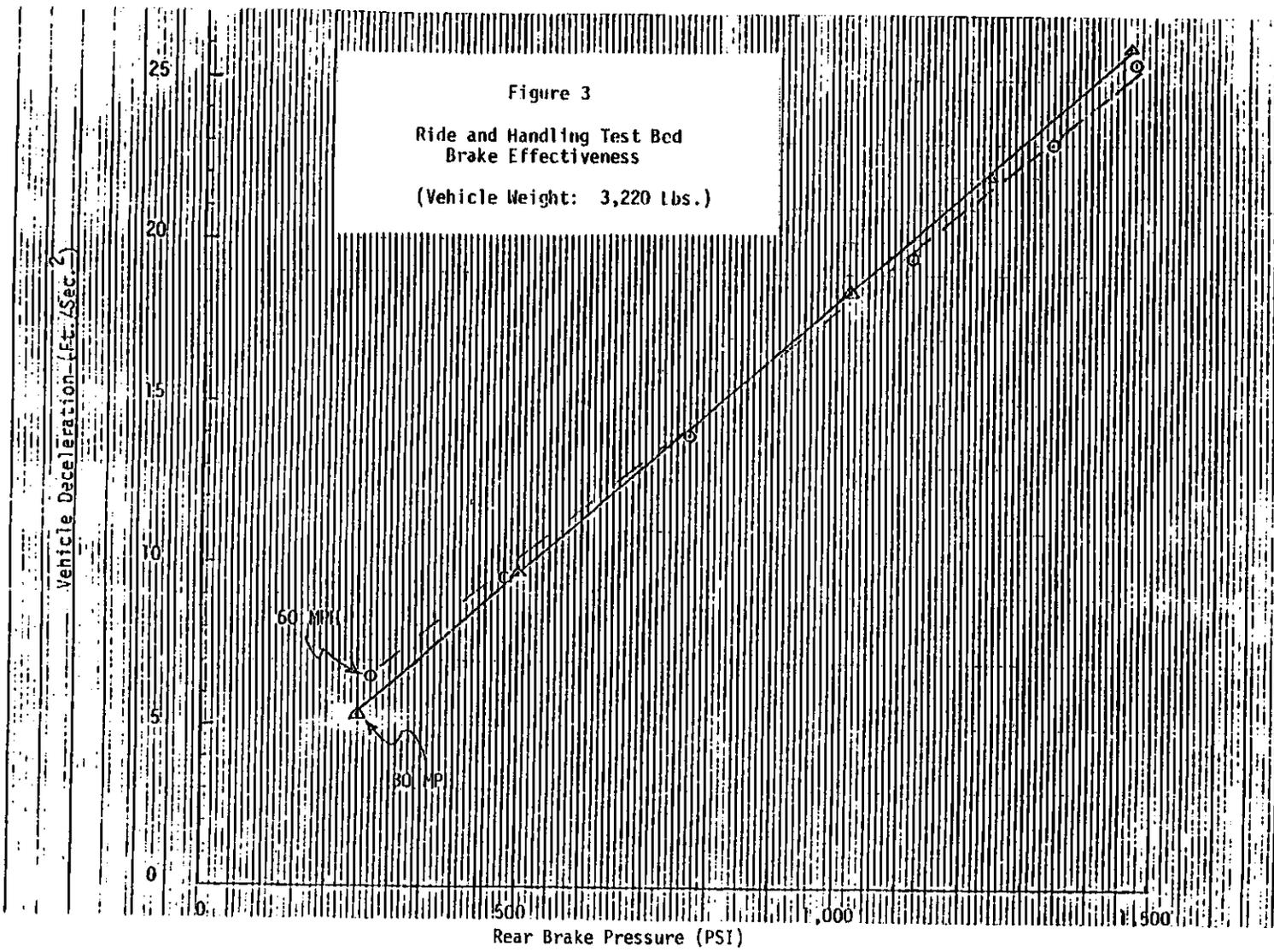
Figure 4

Ride and Handling Test Bed
ABS Performance Summary

Surface (Skid Number Range)	Speed (MPH)	Corrected Stopping Distance System ON (Ft.)	System OFF (Ft.)	Improvement (Percent) [1]
Wet X-10 (18 - 35)	30	76.1	92.6	+18.0
	30	76.8	90.6	+15.2
	30	75.3	90.6	+16.9
	30	117.8	158.7	+25.8
Wet Jennite (28 - 48)	30	73.5	90.0	+15.3
	30	68.3	85.6	+20.2
	40	137.9	177.9	+22.6
	45	118.7	150.6	+21.2
Wet Asphalt (55 - 65)	30	52.0	49.4	- 5.3
Dry Asphalt[2] (70 - 85)	30	41.0	38.5	- 6.5
	60	159.9	156.0	- 2.1

1. Percent improvement of system ON over system OFF.

2. Locking of both front wheels sometimes erratic.

Figure 5

Minicars' High Technology RSV
30 MPH Pre-Burnish Brake Effectiveness
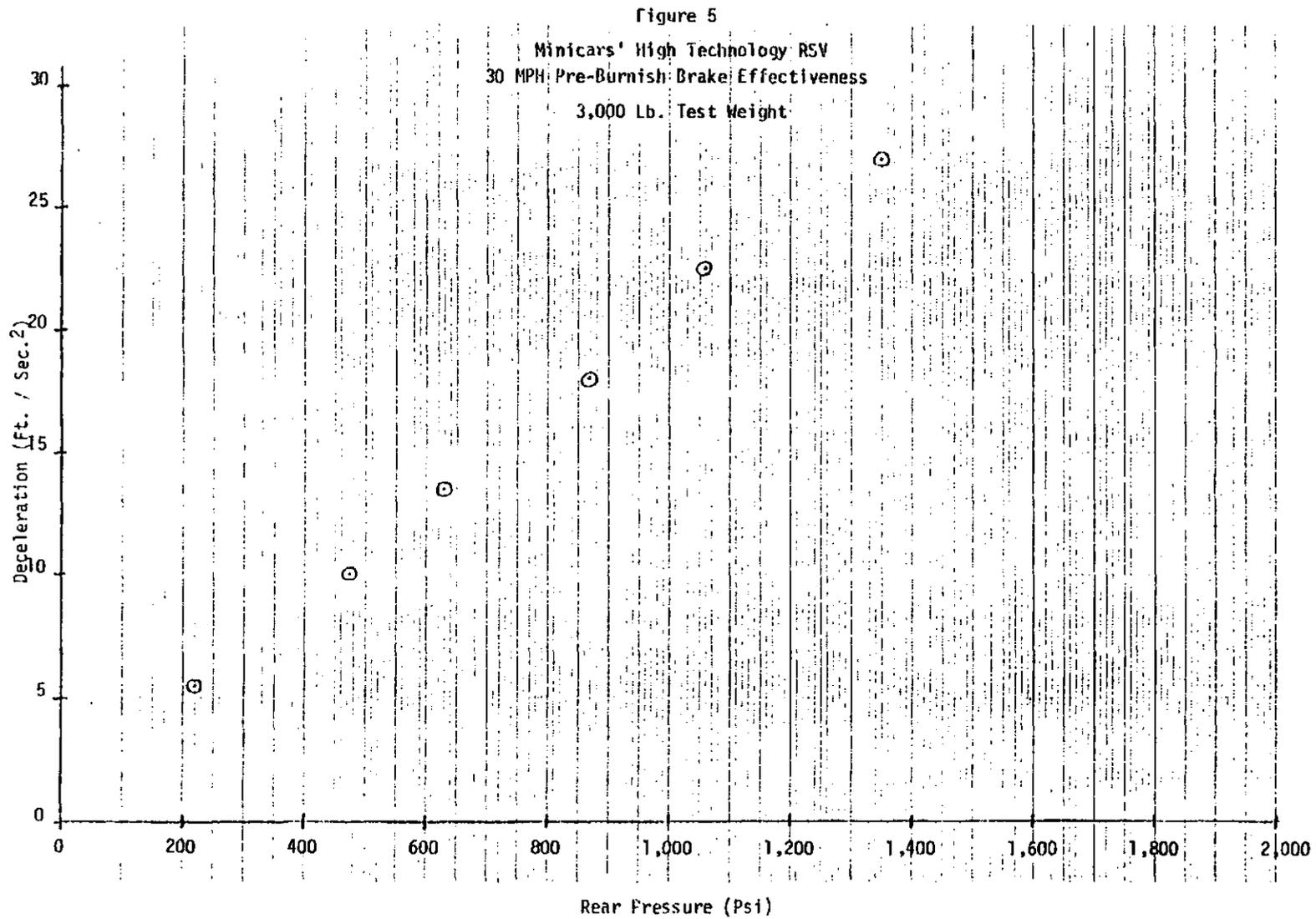
3,000 Lb. Test Weight

Figure 6

Minicars' High Technology RSV
60 MPH Pre-Burnish Brake Effectiveness
3,000 lb. Test Weight

Figure 7
Minicars' High Technology RSV
30 MPH Post-Burnish Brake Effectiveness
3,000 Lb. Test Weight

Figure 8

Minicars' High Technology RSV
60 MPH Post-Burnish Brake Effectiveness
3,000 Lb. Test Weight
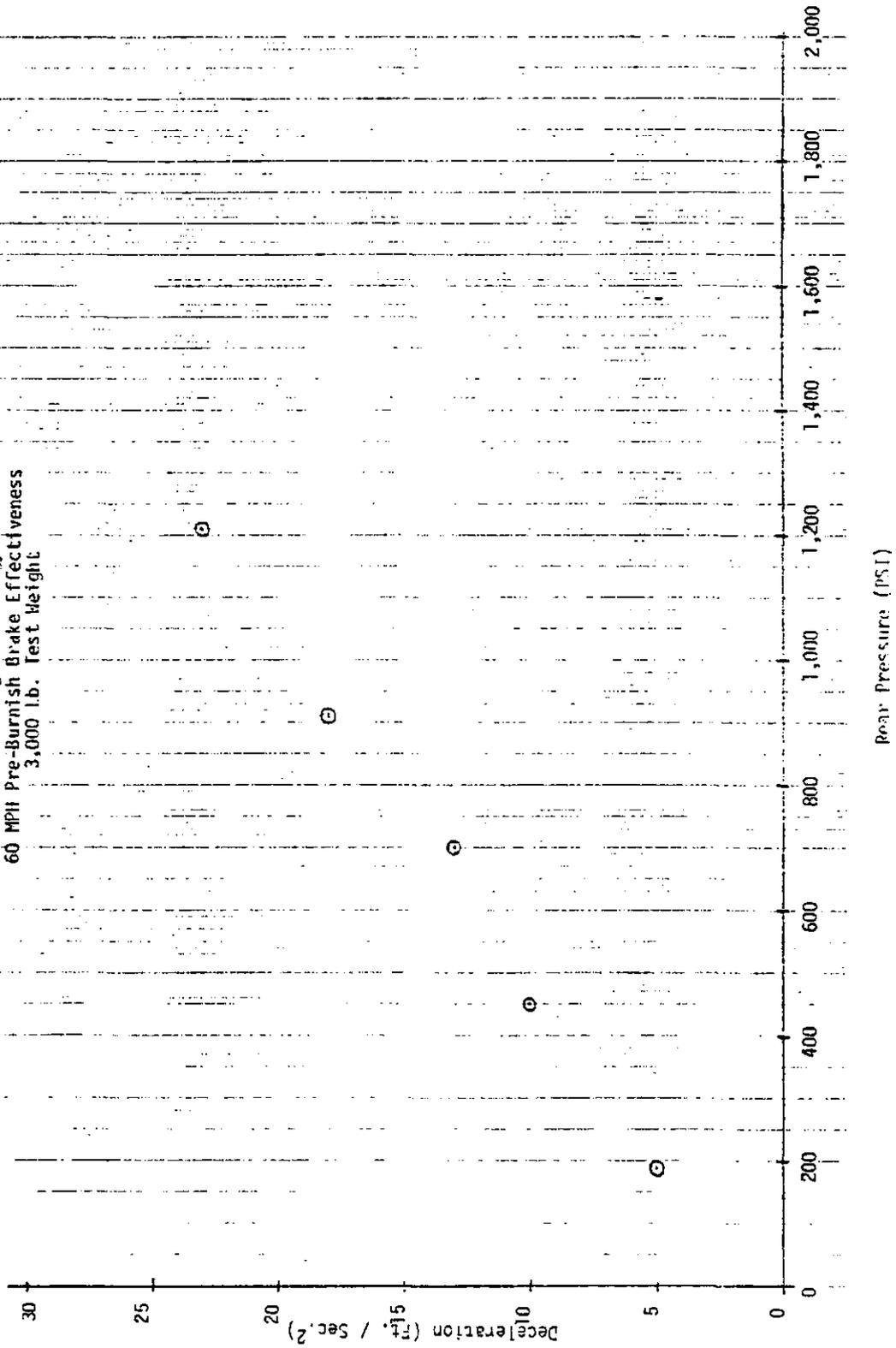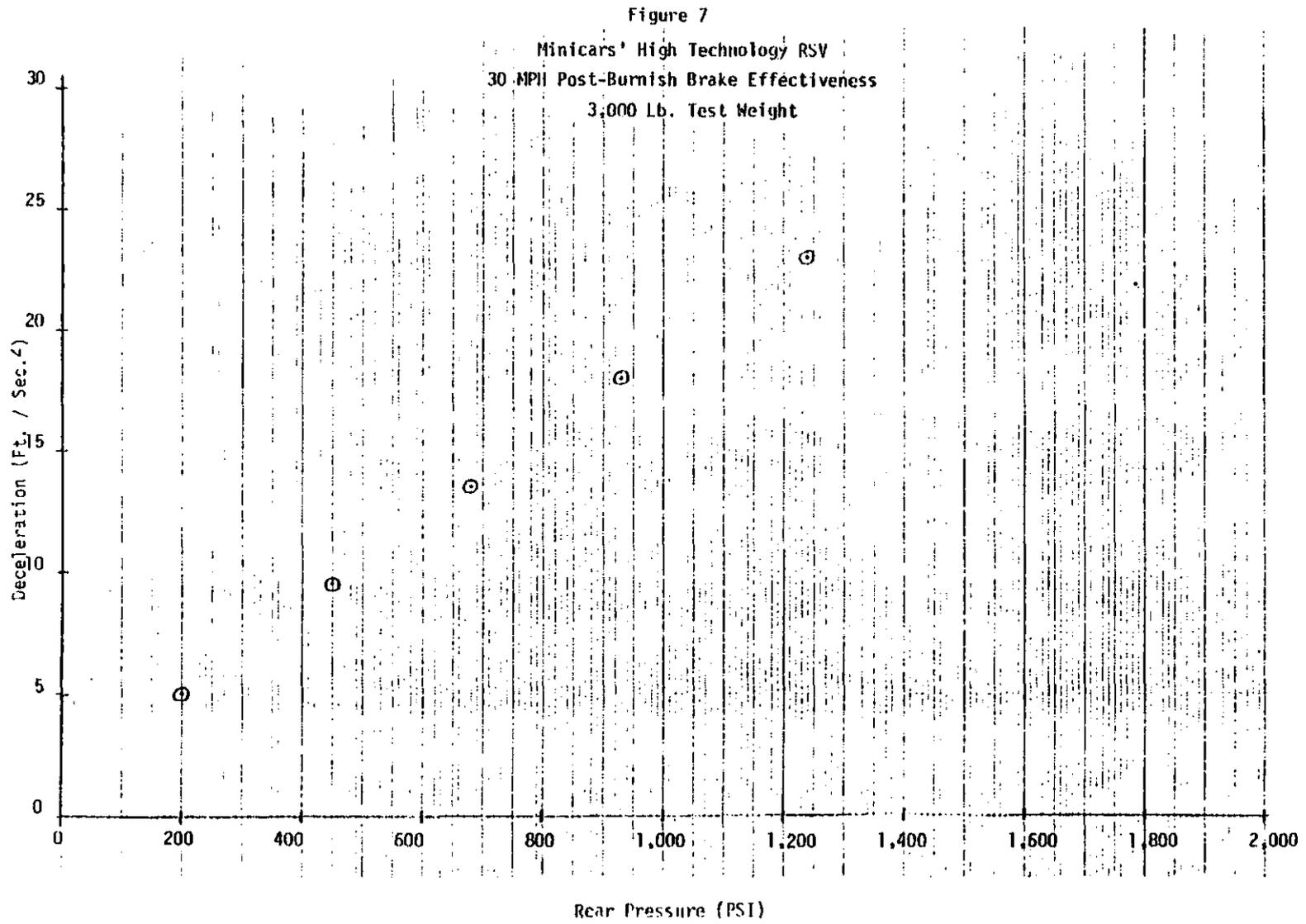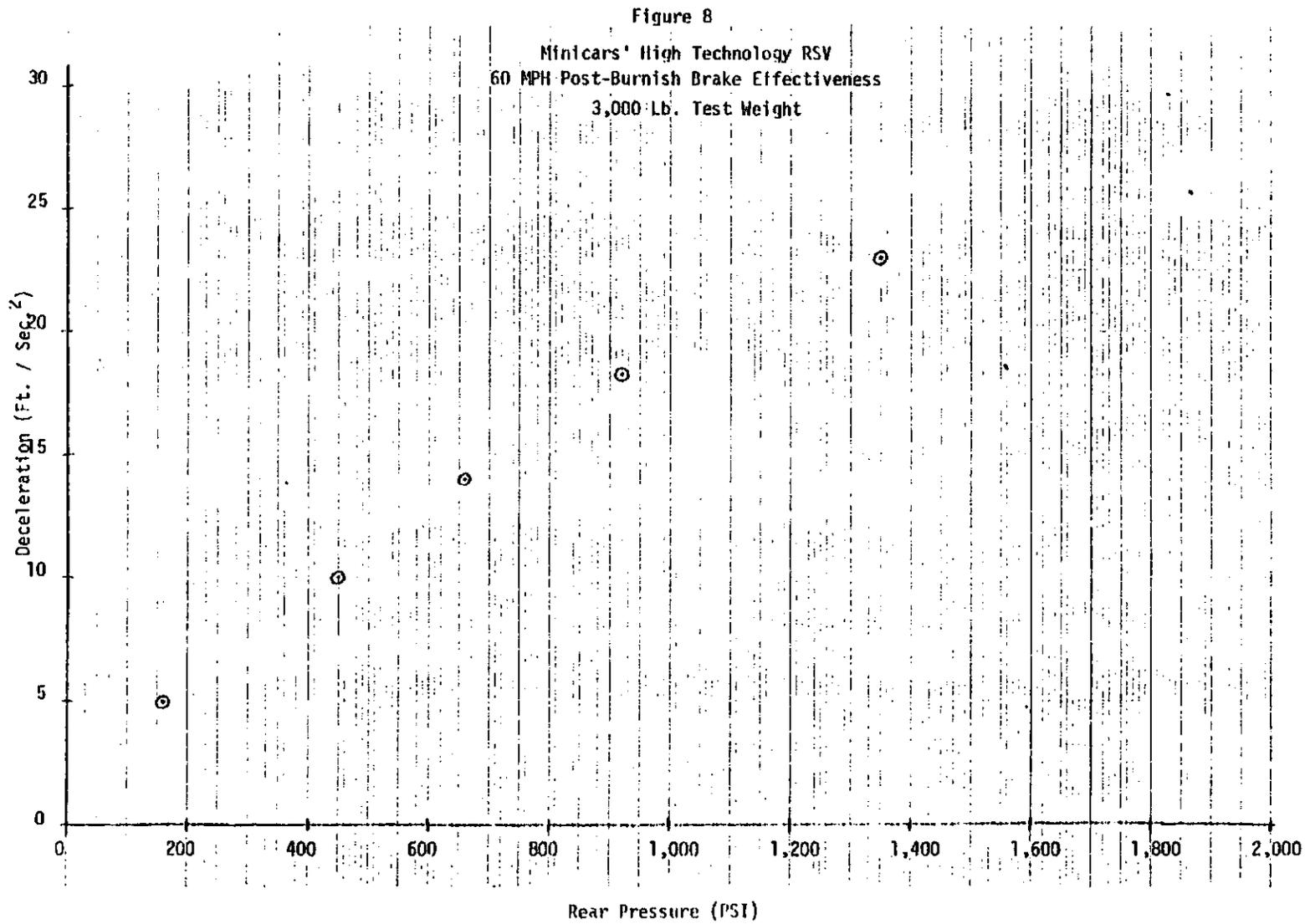
Appendix A

High Brake Pressure Limitation

SUMMARY

The ability to develop a given level of brake pressure in the foundation brake system for a given pedal stroke diminished in both vehicles. Thus, for full pedal stroke, peak brake pressure available diminished. No conclusive reason was identified although some attempted changes were helpful in mitigating the problem. This Appendix summarizes activities associated with this phenomena.

DISCUSSION

Figures A-1 and A-2 illustrate the changes observed in the stroke / pressure relationship. Figure A-1 demonstrates the relationship of travel and pressure versus pedal effort before any test activity had been conducted on the High Technology RSV. Note that with a pedal travel of four inches, both front and rear pressures in excess of 2,000 psi were demonstrable. Figure A-2 represents data from the same vehicle at a later time. Note here that pedal travel of almost five inches provides pressures of 1,500 psi or less. This reduced maximum pressure produced two effects:

A. On high coefficients, sufficient torque to quickly lock the front wheels was marginal; thus, a meaningful comparison of OFF versus ON stopping distances was difficult.

B. With the pedal fully stroked, the primary master cylinder piston (front axle) was also fully stroked. In ABS operation, desired pressure balance in the front regulator was uncertain since even minute motion of the regulator piston could have a substantial effect on front master cylinder pressure in the full stroked situation.

Examination of Figures A-1 and A-2 reveal a difference which suggested an insight into cause of the phenomena. Note on Figure A-1, the initial knee of the pedal stroke application curve occurs at around 0.9" of stroke with an application force of around 12 pounds. By contrast, Figure A-2 shows that 12 pounds of force results in approximately two inches of pedal travel. Thus, this "loss" of an inch of stroke is thought to be a direct casual factor of the diminished high pressure capability.

DISCUSSION   (Continued)

Although the bulk of activity investigating this phenomena was
directed at the Ride and Handling Test Bed, both vehicles demon-
strated quite similar behavior; therefore, it is concluded that
differences between the two vehicles were insignificant. (This
dispells the earlier hypothesis that the pressure differential
switch, which was only present on the Ride and Handling Test Bed,
was a major contributor.)

Presence of ABS was widely examined as a factor on the Ride and
Handling Test Bed even though the same system had been installed
on several earlier vehicles without incident. However, this
hypothesis was ruled out when the phenomena continued to manifest
itself on the Ride and Handling Test Bed after the vehicle was
returned to standard in preparation for return.

Speculations on the principle cause and subsequent investigations
can be grouped broadly into two categories: air in the brake system
and some added source of hydraulic compliance.

Air

Various bleeding techniques were utilized on many different occasions
including those suggested by the local Fiat Service Manager and those
used by Minicars during vehicle assembly. None of these techniques
proved superior. In all cases, pumping the brakes rapidly produced
higher peak pressure. The following summarizes these techniques:

> Standard Pressure Bleeding - This technique is widely used by
> Bendix test vehicle support personnel and with only minor
> variations was suggested by both Minicars and the local Fiat
> representative. A source of brake fluid, under pressure of
> 30 - 50 psi, is connected to the master cylinder remote reservoir
> or to the reservoir lines. A transparent tube is attached to the
> individual caliper bleed screws; the screw is turned and flow out
> of the caliper is continued until the flow is free of bubbles or
> foam. An alternative was used on many occasions where, during
> the time that flow was under way, the pedal was exercised to
> promote higher flow rates, intended to dislodge air in the lines
> which might be stationary due to high surface adhesion.

> Reverse Pressure Bleeding - In this technique, flow through the
> brake system is reversed by connecting the brake fluid pressure
> source to the caliper bleed screw port and monitoring flow out of
> the reservoir lines.

DISCUSSION   (Continued)

Vacuum Bleeding - In this technique, a vacuum pump capable
of producing approximately 29 In. Hg. is connected to the
master cylinder reservoir. After the brake system is thor-
oughly evacuated, reservoir pressure is returned toward
atmospheric. By intent, air removed during evacuation is
replaced by fluid from the reservoir.

Manual Bleeding - Mild pressure is applied to the pedal and
maintained while the caliper bleed screw is opened and closed.
The pedal is then released allowing the master cylinder to be
recharged with fluid from the reservoir. The process is con-
tinued until the flow out of the bleed screw port is free of
bubbles or foam.

Service Bleeding - This technique from the Fiat X-1/9 Service
Manual is a variation of manual bleeding. A transparent hose
is attached to the bleed screw and the other end is immersed
in clean brake fluid. After the bleed screw is opened, the
brake pedal is rapidly depressed, then allowed to return
slowly. This process is continued until bubble and foam-free
fluid is obtained; then, while the pedal is depressed, the
bleed screw is tightened.

Other - The master cylinder has two outlet ports in the primary
bore, which normally are connected to individual front brake
lines. Because only one line was necessary from the master
cylinder to the front regulator / modulators assembly, one of
the primary ports was plugged. During activities directed at
the High Technology RSV, the master cylinder was removed and
the two primary outlet ports were plumbed together. The master
cylinder was bled in the laboratory and reinstalled. This change
made no detectable difference in high pressure capability.

As installed, the master cylinder bore axis is not horizontal;
the outlet ports are higher than the reservoir ports. To test
the hypothesis that air could be trapped in the top of the master
cylinder bore, the front of the High Technology RSV was raised
to reverse the inclination of the bore axis with the horizontal.
The brake pedal was actuated repeatedly in an effort to flow any
air trapped in the master cylinder back into the reservoir. No
benefits were detected from this exercise.

Additional Hydraulic Compliance

This hypothesis came into being because of the apparent diminishment
of high pressure capability after the vehicles had been exercised
and was strengthened when bypassing of the ABS showed no improvement
in pressure capability.

DISCUSSION   (Continued)

Master Cylinder Replacement - From vehicle instrumentation,
it was sometimes observed that the master cylinder front
piston would reach a limiting pressure before the pedal had
full stroked. This situation allowed rear master cylinder
pressure to continue to increase with stroke. This phenomena
was not visible during the initial testing (MVSS-105) of the
Ride and Handling Test Bed since only rear pressure was moni-
.tored. Thus, it was hypothesized that an anomoly might exist
with the primary piston seal and / or compensating arrangement.
Disassembly of the master cylinder did not reveal any problems.
A new master cylinder was procured and installed with no benefits
detectable.

Pedal Linkage Hinge Pin - After noting that the hinge pin was
made of Delrin tubing, it was hypothesized that high stresses
had caused it to yield. A new solid pin was fabricated from
aluminum. However, no improvements were noted after instal-
lation on the High Technology RSV.

Caliper Mounting Influence - Since the calipers had been removed
during speed sensor installation, it was suggested that they had
been remounted in a fashion that caused the pads to not be paral-
lel with the contact surface of the new rotors. The calipers
were removed from the High Technology RSV hub assemblies and pie
shaped sections of a spare rotor were inserted between the pads.
However, no change in high pressure capability was observed.

Front Brake Hoses - Under pressure, a slight swelling of the
front brake hoses was observed. New hoses were provided by
Minicars. However, after installation, no significant improve-
ment was detected.

Master Cylinder Modification - The Fiat X-1/9 brake system
includes 48mm front calipers and 34mm rear calipers, meaning
that the fronts require essentially twice the fluid displacement
as the rears for a given amount of piston travel. The X-1/9
master cylinder has a 50 / 50 split, i.e., front and rear sections
displace the same amount of fluid, which is measured as 0.186 cubic
inches on the original master cylinder from the Ride and Handling
Test Bed. Data from another program indicated that a pair of 48mm
calipers would require 0.223 cubic inches at 2,000 psi. As an
experiment, the primary piston stroke on the Ride and Handling
Test Bed was increased by cutting .122 inches off the piston
snout. Thic change provided an increase in maximum pressure on
the front axle sufficient to reliably lock the front wheels. How-
ever, this change was not pursued on the High Technology RSV because
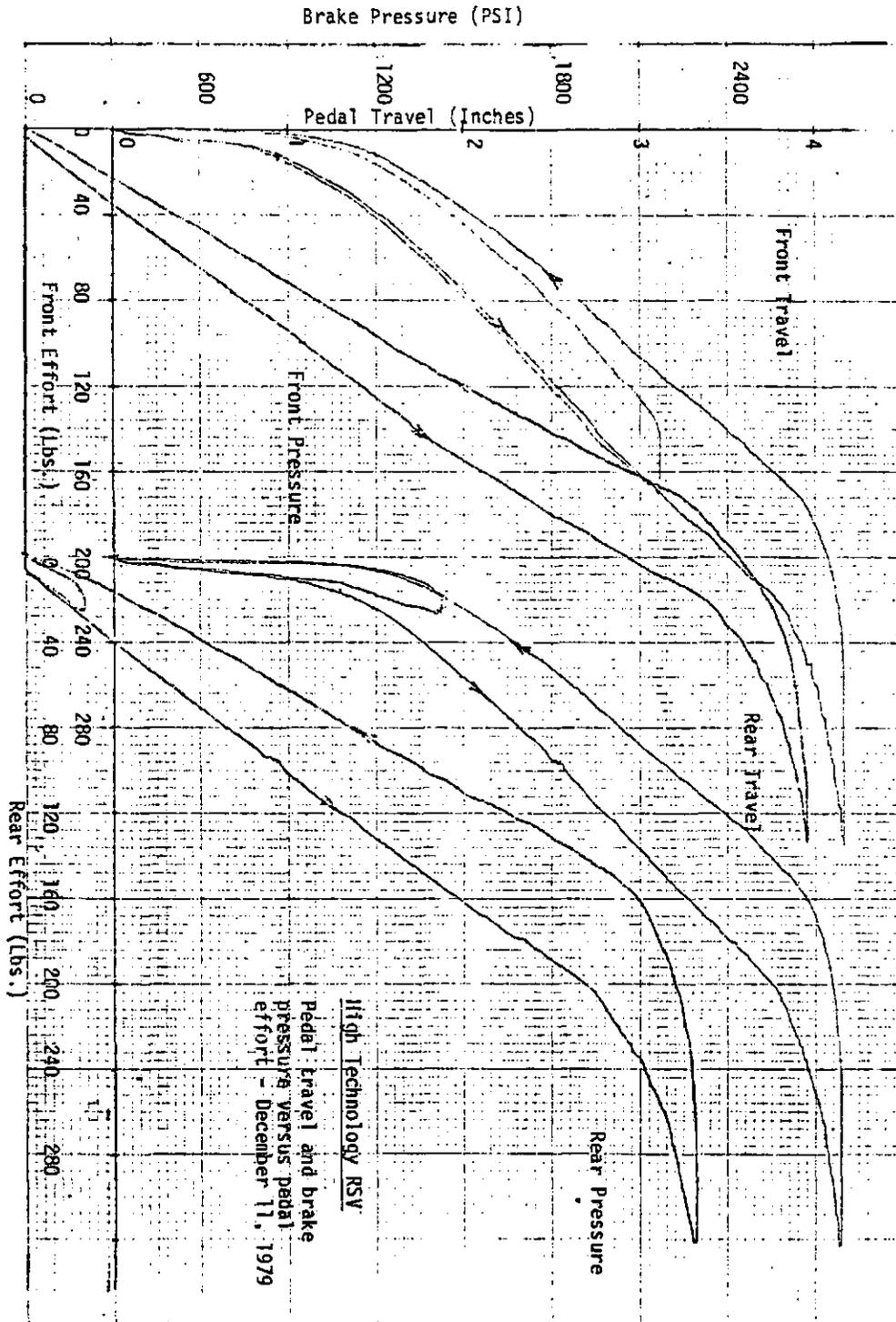of MVSS-105 split system implications.

Figure A-1

High Technology RSV
Pedal travel and brake
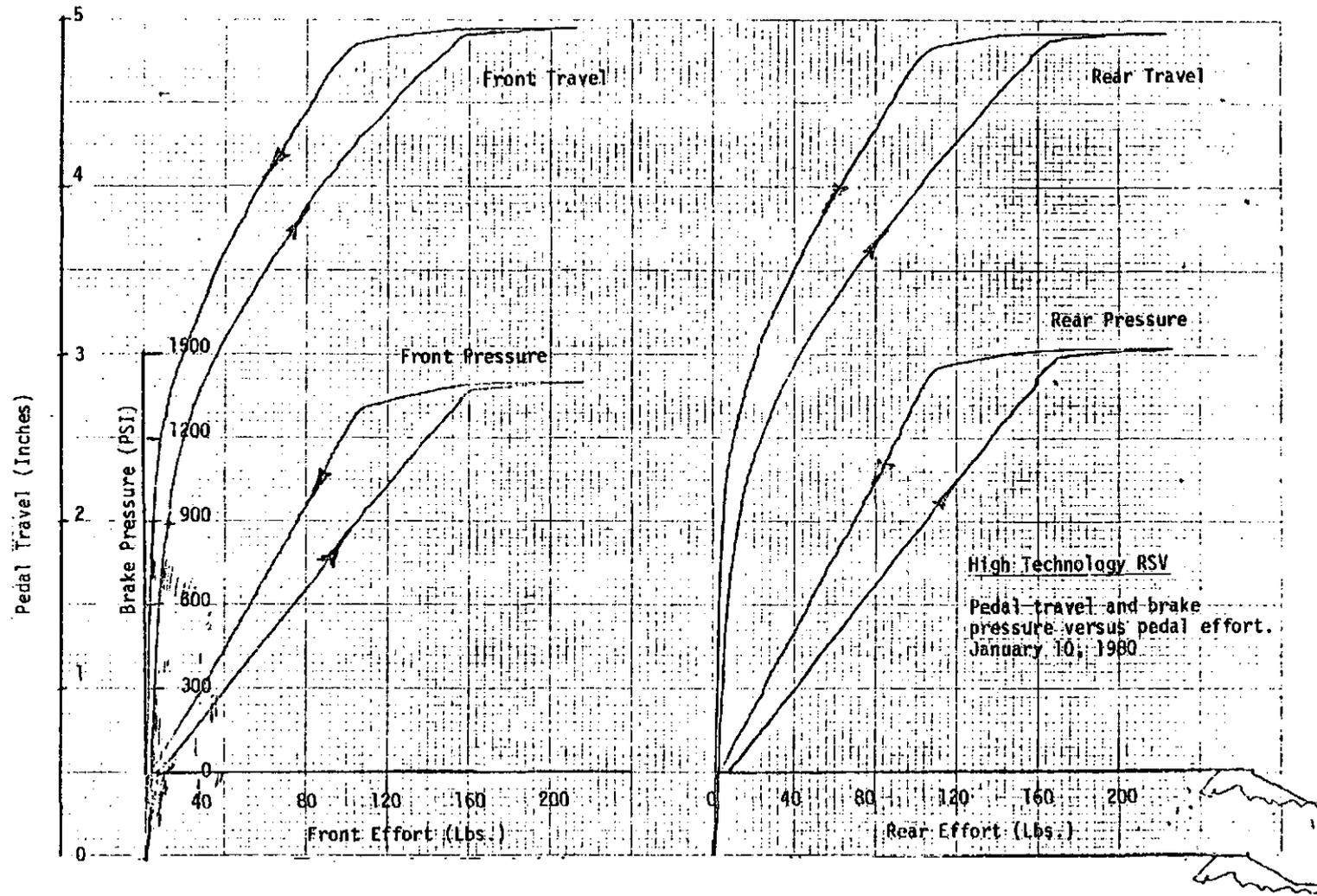pressure versus pedal
effort — December 11, 1979

Figure A-2

Adaptive Braking
System

for

MINICARS
HIGH TECHNOLOGY
RESEARCH SAFETY
VEHICLE

Description

and

Operating Instructions

March, 1980

INTRODUCTION

This booklet provides operating instructions and describes the four-wheel Adaptive Braking System (ABS) installed in Minicars' High Technology Research Safety Vehicle, DOT License Number 80141. The system is quite similar to other systems installed by Bendix Automotive Control Systems Group (ACSG) in an earlier feasibility program for commercial application, and is also similar to the system utilized in another RSV application.

Briefly, the system consists of wheel speed sensors in each wheel, an electronic control unit, a brake pressure modulator for each front wheel and the rear axle, and a hydraulic power supply which consists of an electric motor driven brake fluid pump and two brake fluid accumulators. Except for the speed sensors, Figure 1, all components are mounted on a common bracket in the right rear corner of the trunk, Figure 2.

The system has no effect on routine braking and requires no participative action by the operator. However, because of the prototype nature of this system and, as well, to allow vehicle evaluation without the system, an ON / OFF switch has been provided. In the OFF position, electrical power to the system pump and solenoid valves is denied by a specially installed relay. When the switch is in the ON position, it is internally illuminated while the ignition key is ON. With the system switch in the ON position and with a brake light signal present, the system continuously monitors for imminent wheel lock. Should this be detected, brake pressure to the affected wheel(s) is decreased and reapplied in order to maximize braking performance and avoidance of wheel lockup at all speeds above approximately five miles per hour. Avoidance of wheel lockup allows for significant vehicle steerability and stability characteristics not otherwise possible.

A red warning light on the instrument panel is connected to the system. This light will illuminate (with the ignition key ON) should the system detect any of several undesirable conditions or if the system switch is in the OFF position. When the warning light is illuminated, the system is inoperable.

Since the system does not require any servicing or periodic maintance, no special tools or equipment are necessary for support.

The remaining sections of this booklet will describe the system components and function in greater detail.

SYSTEM COMPONENT DESCRIPTION

General

The four-wheel Adaptive Braking System (ABS) is designed to prevent
any wheel from locking due to excessive brake pressure above a speed
of approximately five miles per hour. The system reduces the skid
potential of a locked wheel but still maintains brake pressure for
maximum stopping effort available with the existing tire / road con-
dition. The end result is to improve the directional control and
steerability of the vehicle and, in many cases, to reduce the
distance required to bring the vehicle to a stop.

The major components of the ABS are:

1. A speed sensor at each front and rear wheel.

2. An electronic control unit (ECU) located inside the
   trunk right side adjacent to the fuse panel.

3. An electric motor driven brake fluid pump located
   in the trunk below the ECU.

4. Two accumulators which are located on the forward
   side of the ABS mounting bracket inside the right
   side of the trunk, along the firewall.

5. Two regulators which are attached to the modulators
   inside the right rear of the vehicle trunk.

6. Three pressure modulators mounted inside the right
   rear of the vehicle trunk. They are attached to
   the aft side of the ABS mounting bracket.

Figure 3 illustrates the basic plumbing arrangement of the ABS
components.

Speed
Sensors

Each wheel speed sensor consists of a variable reluctance pickup
placed in close proximity to a rotating toothed wheel. The pickup
includes a permanent magnet and coil in a case which is attached
to the mounting bracket. In this installation, the toothed wheel
is formed by teeth cut on the outside diameter of the brake rotor.
Clearance between the pickup and toothed wheel is adjustable and
is nominally set for .020-inch air gap.

Electronic
Control
Unit

The electronic control unit (ECU) is essentially a small computer
and contains various electronic components. The unit is encased
in a container and includes the necessary cables and connectors.
Electronically, the ECU contains three channels, one for each of
the three pressure modulators, as well as failure detection logic.

Wiring
System

The wiring system consists of one major wiring harness plus the leads
from the speed sensors and the pressure modulators. Figure 4 shows a
schematic of the harness and the other electrical leads that make up
the wiring system.

Brake
Fluid
Pump

This assembly is an electric motor driven single piston pump. The
motor is activated by the pump relay. The pump relay coil is powered
by ignition voltage; coil current flows when the pump switch provides
a ground (low pressure). The pump accepts fluid from the master
cylinder reservoir and provides brake fluid under pressure to the two
system accumulators. The accumulators are maintained at about 1,700
psi by the pressure sensitive pump switch which turns the pump motor
ON and OFF via the pump relay.

SYSTEM COMPONENT DESCRIPTION

Accumulators

The two accumulators are spring loaded devices which store pump output fluid under pressure for replenishment of caliper fluid during ABS function. One accumulator is provided for each half of the brake system to preserve the hydraulically split brake system. The accumulators have a check valve at their pump inlets and a filter is provided at their output to the regulators. Also, internal to the accumulators is a relief valve which vents the accumulator to master cylinder reservoir, should the internal pressure exceed approximately 2,700 psi. Attached to the top of the accumulators are low pressure switches which provide an electrical signal (ground) to the ECU when stored pressure is greater than 1,000 psi. This signal is used for failsafe purposes described later.

Regulators

The regulators receive fluid from the accumulators and provide the modulators with a fluid pressure source equivalent to master cylinder pressure for use during ABS cycling. There are two regulators, a front and a rear, to maintain the brake system split.

Pressure Modulators

The system includes three pressure modulators. There is a pressure modulator for each front brake and one pressure modulator for the two rear brakes.

The hydraulic brake tubes are routed as follows: (See Figure 3.)

    a.   <u>Front Wheels</u> - From the master cylinder primary outlet port to both front brake modulators; from each modulator to an individual front disc brake caliper.

    b.   <u>Rear Wheels</u> - From the master cylinder secondary outlet port to the rear brake modulator; from the modulator to the disc brake calipers of both rear brakes.

Pressure
Modulators
(Continued)

The pressure modulators are simply an assembly of two two-way
electrically operated solenoids and two flow rate control
orifices. The two valves are called "isolation" and "decay"
and function as follows: (Refer to Figure 5.)

Isolation Valve - As the name implies, this valve can,
when energized, isolate the master cylinder from commu-
nicating with the wheel caliper. Normally, the valve is
de-energized and master cylinder pressure comes in and
passes the open ball seat and passes on to the decay valve.
The regulator supply pressure is sealed off by the closed
ball seat of this valve.

Decay Valve - Again, as the name implies, this valve can,
when energized, allow wheel caliper fluid to bleed to
reservoir, decreasing caliper fluid pressure. Normally,
the valve is de-energized and master cylinder pressure
comes in the top center of the valve seat, passes the open
ball seat, and out to the caliper.

The two orifices, build and decay, control the flow rate of the
brake fluid during pressure build and decay. Their function will
be described in the ABS Function section of this document.

Speed sensor layout drawings, AEXD-10540 and 10541, were provided
earlier. Remaining major packaging drawings are attached.

Warning
System
(Continued)

If the ABS OFF / ON switch is illuminated and the ABS failure lamp is illuminated, then a failure is being detected by the ECU. The conditions under which the ECU will cause the ABS failure lamp to illuminate are as follows:

1. No low I (e.g. fuse blown) - five millisecond delay - non-latching.*

2. Low pressure switch open (e.g. low accumulator pressure) - 35 millisecond delay - non-latching.*

3. Any isolation or decay valve continuously energized (e.g. solenoid driver transistor shorted) - 6.8 seconds delay - latching.** Fail only if no brake signal present.

4. Any isolation or decay valve or its conductive path to the ECU open (e.g. connector unplugged) - 6.8 second delay - latching.** Fail only if no brake signal present.

5. Any processed speed sensor signal 15 MPH less than other speed sensor signals (e.g. connector unplugged) - differential must exist for 7.0 seconds - latching.** Fail only if no brake signal present.

* Non-latching: ABS warning lamp lit only for duration of failure.

** Latching: If failure is detected, ABS warning lamp is lit continuously until ignition switch is turned off.

ABS FUNCTION

Ignition OFF

With the ignition switch in the OFF position, the system relay is de-energized and, therefore, no voltage is supplied to the motor / pump or to the ECU for powering solenoids. If the brakes are applied, master cylinder pressure is applied to the calipers as shown in Figure 5, passed the two normally open ports of the solenoid valves.

Ignition ON

When the ignition is turned ON and the system OFF / ON switch is in the ON position, the system relay is energized providing voltage to the ECU for solenoid power and to the motor / pump. If the vehicle has been sitting for any length of time, the accumulators may have lost some fluid charge; therefore, the ABS warning lamp may be lit, due to low pressure, and the motor will run to charge the accumulators. Within approximately ten seconds, the pump motor will normally have recharged the accumulators, causing the ABS warning lamp to extinguish.

Engine Running - Vehicle Stationary

The speed sensors do not generate any signals while the vehicle is stationary. In the absence of speed signals, the ECU does not send any commands to the pressure modulators.

If the brake pedal is depressed, master cylinder pressure is applied to the calipers as shown in Figure 5, passed the two normally open solenoid valve ports in each modulator.

Engine Running - Vehicle in Motion

When the vehicle is in motion, an alternating voltage (AC) is generated at each speed sensor and is sent to the ECU. The frequency of the AC voltage is directly proportional to the speed of the wheel.

The ECU converts the signals received from the speed sensors to a DC voltage which is proportional to wheel speed. If the brakes are not applied, or if they are applied lightly, the ECU sends no commands to the pressure modulators.

Engine Running -
Vehicle in Motion
(Continued)

When the brakes are applied with greater force, the ECU, based on the signals received from the speed sensors, determines the rate at which each wheel is decelerating. If the rate of deceleration is great enough to produce excess wheel slippage or wheel lockup and a brake light signal is present, the ECU sends commands to the pressure modulator of the slipping wheel(s).

The command from the ECU initially performs two functions at the pressure modulators: (Refer to Figure 6.)

1. It energizes the isolation valve. This shuts off the fluid communication path from the master cylinder to wheel caliper.

2. It energizes the decay valve. This provides a path for now trapped wheel caliper fluid to flow to master cylinder reservoir. The rate of pressure drop is controlled by the decay orifice.

As the caliper pressure decreases, and brake torque consequently reduces, the wheel speed stops decreasing and starts to increase back toward vehicle speed. The ECU, which is continuously monitoring wheel speeds, detects the increase in wheel speed. At the appropriate time, the ECU de-energizes the decay valve. The isolation valve is maintained in an energized condition for a pre-determined fixed period of time. This action results in the following:

1. Isolation Valve Energized - Communication is denied to master cylinder. However, a path is now provided across the lower isolation valve seat to regulator supply. Regulator fluid is supplied from the accumulator at master cylinder pressure.

2. Decay Valve De-energized - Regulator supply is now communicated to the wheel caliper (see Figure 7). The rate of flow from the regulator supply, and therefore the rate of pressure increase at the caliper, is controlled by the build orifice.

• Engine Running -
  Vehicle in Motion
  (Continued)

This controlled resupply of brake fluid to the caliper increases
hydraulic pressure to reapply the brakes at a controlled rate.

The cycle described above is repeated during a hard brake appli-
cation until the vehicle has stopped or the driver reduces force
on the brake pedal below a level which will cause wheel(s) lock.
Pressure decay may not occur below five miles per hour due to
wheel speed signal resolution.

Under some conditions, the ECU timed isolation valve command,
which is set by a decay command, may expire causing the isolation
valve to de-energize. If this happens, the driver may notice a
slight drop in the brake pedal as the master cylinder is again
able to provide fluid to the caliper.

After the ABS stop, when the isolation valve timer in the ECU times
out, the isolation valve will de-energize. When this happens, the
brake pedal may drop slightly as noted above.

If either accumulator pressure drops below approximately 1,500 psi
during ABS cycling, the pump switch will detect this event and
provide a ground to the pump relay, causing the electric motor to
start and continue to run until the low accumulator is replenished.

Warning
System

The ABS includes a warning sub-system to warn the driver of certain
types of failures or undesired conditions in the system. The warning
system illuminates the ABS warning lamp to warn the driver that an
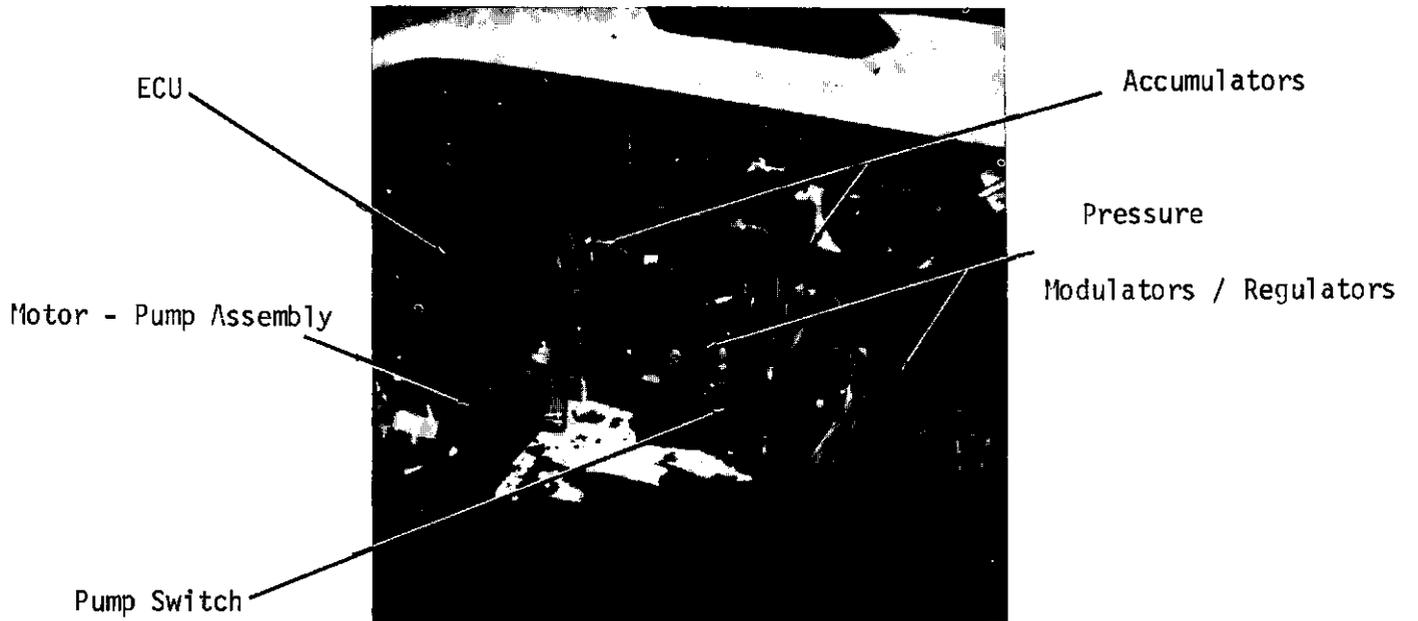anomaly exists and inhibits system cycling for the duration of the
warning.

Note that on the wiring diagram, Figure 4, there is an ABS OFF / ON
switch. When the switch is ON, the switch's internal lamp is illu-
minated and the ABS is active. When the switch is OFF, the switch's
internal lamp is extinguished and the ABS warning lamp is illuminated.
Also when the switch is OFF, the system relay is de-energized, which
denies power to the electric motor driven pump and all power required
to energize solenoid valves in the pressure modulators (Hi I conductor).

Figure 1

Sensor Pickup

Teeth on Rotor OD
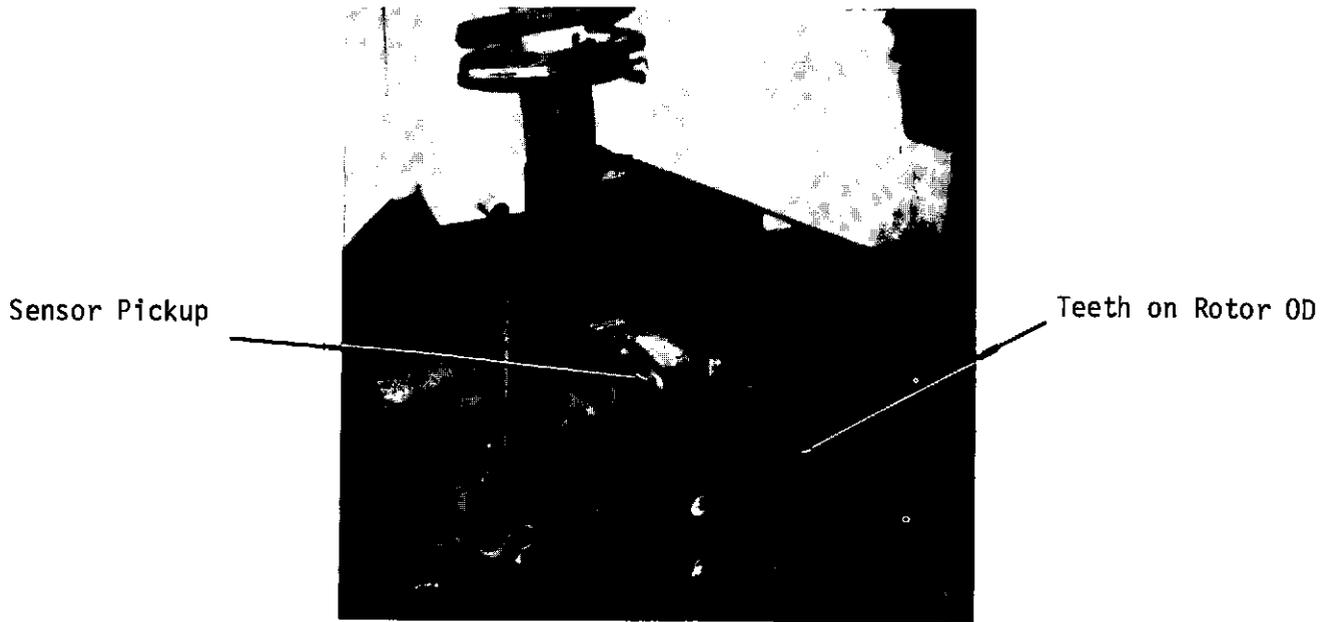
TYPICAL WHEEL SPEED SENSOR

Figure 2

ECU

Accumulators

Pressure

Modulators / Regulators

Motor - Pump Assembly

Pump Switch

ABS TRUNK LAYOUT
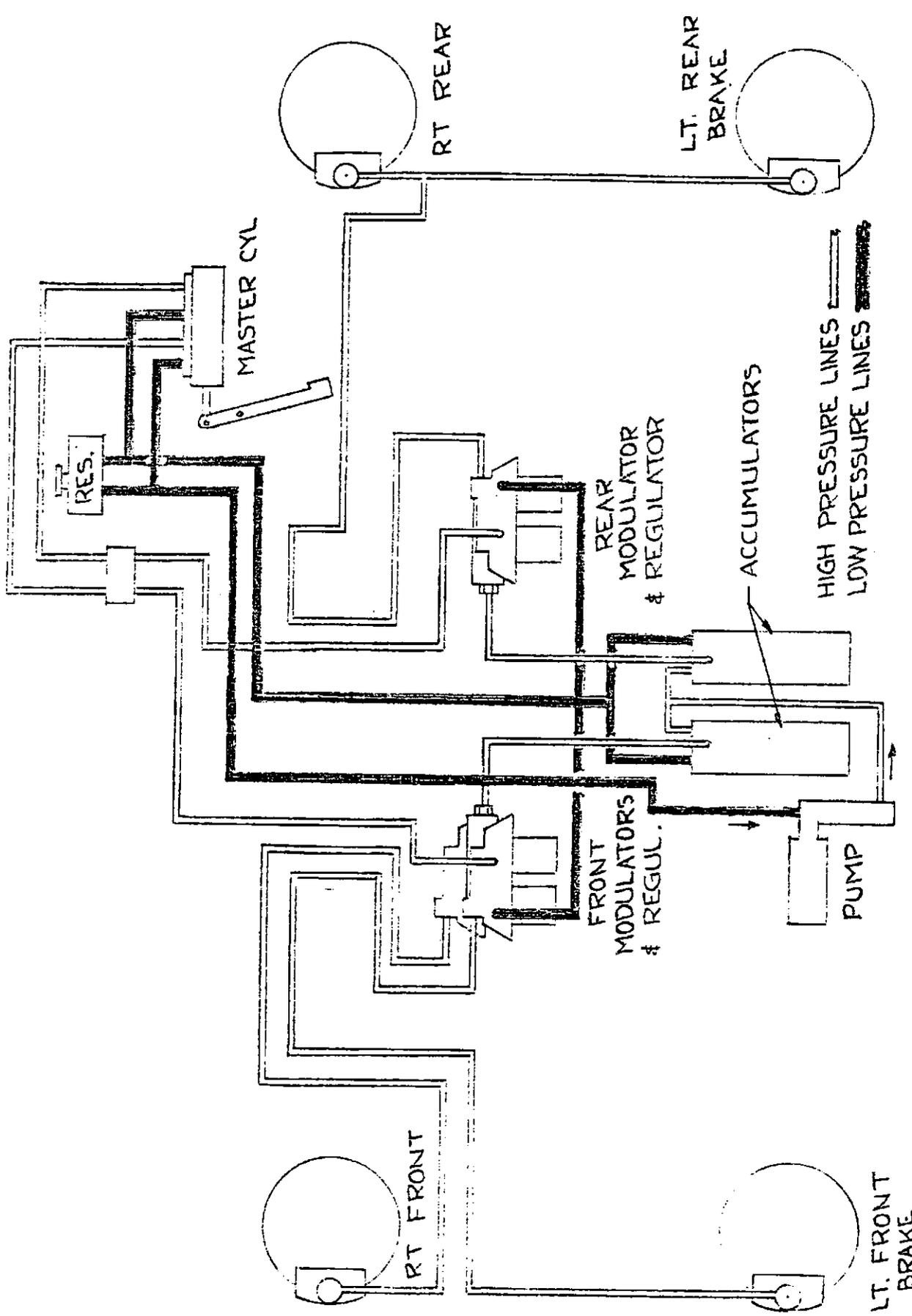
MINICAR RSV HYDRAULIC DIAGRAM

FIGURE 3

RT REAR

LT. REAR BRAKE

Bendix

MASTER CYL

RES.

REAR MODULATOR & REGULATOR

ACCUMULATORS

HIGH PRESSURE LINES
LOW PRESSURE LINES

FRONT MODULATORS & REGUL.

PUMP

RT FRONT

LT. FRONT BRAKE

MINICAR RSV WIRING DIAGRAM

PRESSURE MODULATORS

REAR — ISOLATION VALVE / DECAY VALVE
LEFT FRONT — ISO / DEC
RT. FRONT — ISO / DEC

WHITE/GREEN
GREEN
WHITE/BLUE
BLUE
WHITE
YELLOW

6 PIN FEM.
6 PIN MALE

ELECTRONIC CONTROL UNIT

7 PIN FEM.
7 PIN MALE

8 PIN MALE
8 PIN FEM.

TO SPEED SENSORS

LF
RF
LR
RR

BLACK #6
SYSTEM RELAY
RED

BLACK

BROWN
BROWN

2 PIN FEMALE
2 PIN MALE

ACCUMULATORS WITH LOW PRESSURE SWITCHES

BLACK #10
MOTOR/PUMP

PUMP SWITCH

PUMP RELAY
RED
RED
BLACK #10

RED
HI I
#12 WHITE

ORANGE
#22 RED
ABS FAILURE LAMP

HI 2
RED
5 AMP FUSE

ACC OFF
RUN START
IGNITION SWITCH

BRAKE LITE SWITCH

RED
BLACK

#22 ORANGE

SYSTEM SWITCH

PURPLE → TO STOP LIGHTS

BATTERY − +

#18 WIRE UNLESS OTHERWISE NOTED

FIG. 4

Bendix

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WHEEL CALIPER

REGULATOR SUPPLY

MASTER CYLINDER INPUT

RESERVOIR

BUILD ORIFICE

DECAY ORIFICE

FIG. 5

ISOLATION VALVE DE-ENERGIZED

DECAY VALVE DE-ENERGIZED

WC

REG

MC

RES

DECAY ORIFICE

FIG. 6

ISO. ENERGIZED

DEC. ENERGIZED

WC

REG

MC

RES

BUILD ORIFICE

FIG. 7

ISO. ENERGIZED

DEC. DE-ENERGIZED

Bendix

C-35

Ø2.00
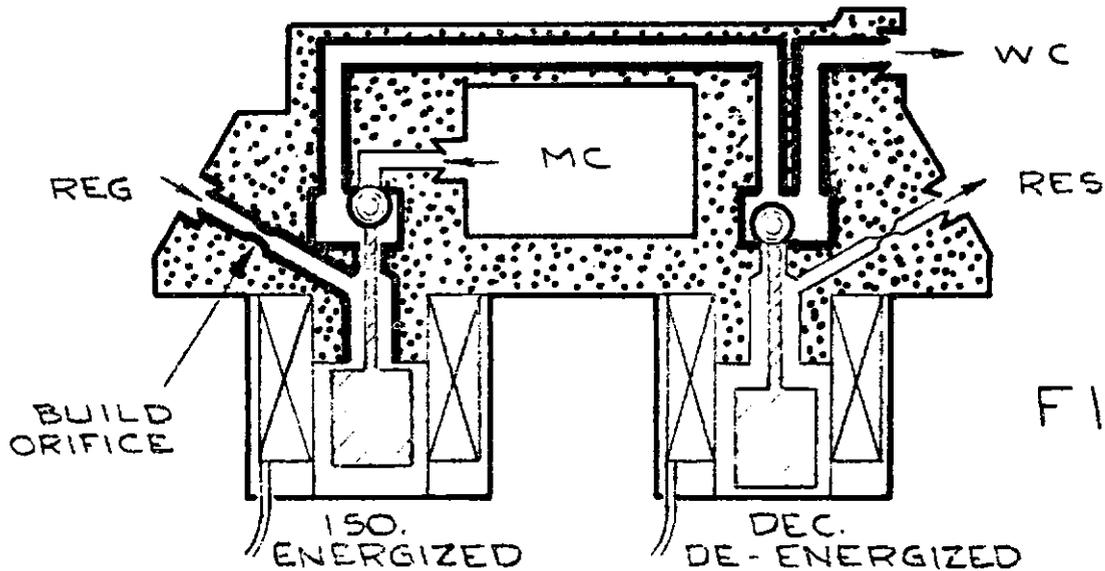
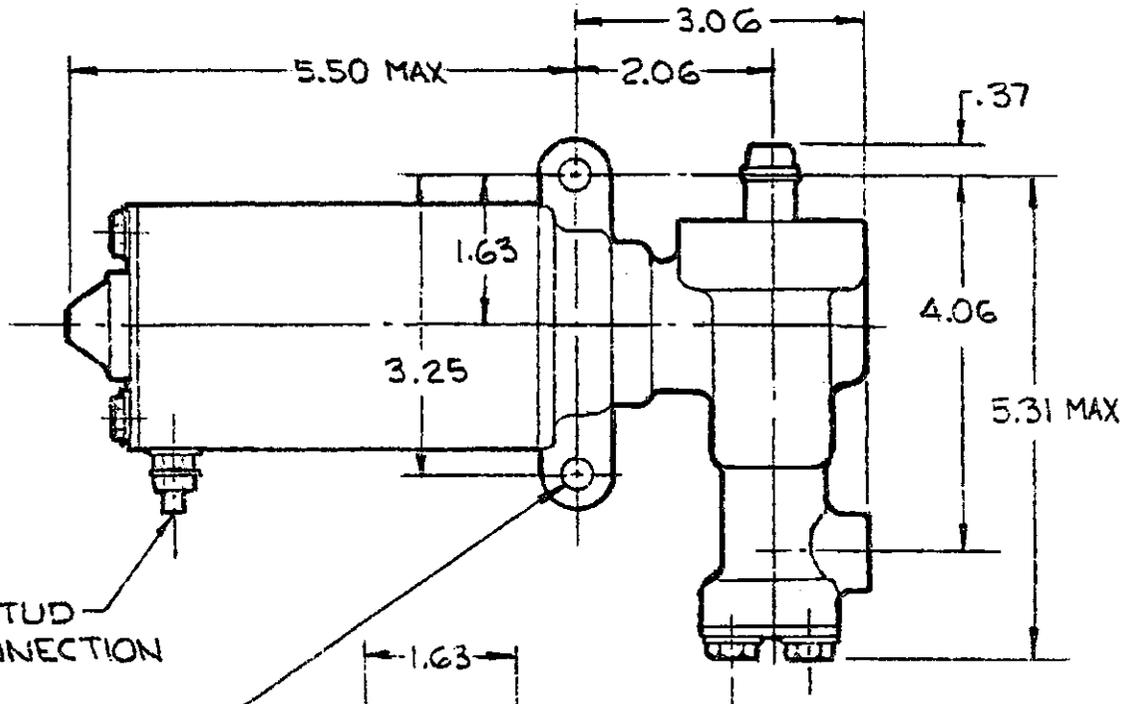Ø2.63

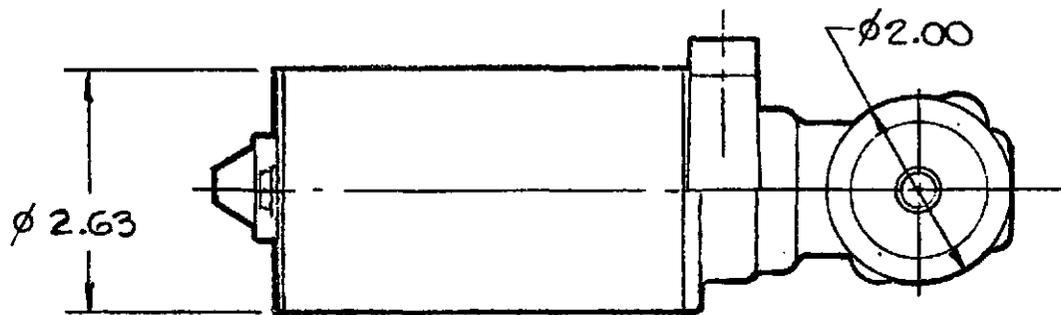3.06

5.50 MAX

2.06

.37

1.63

4.06

3.25

5.31 MAX
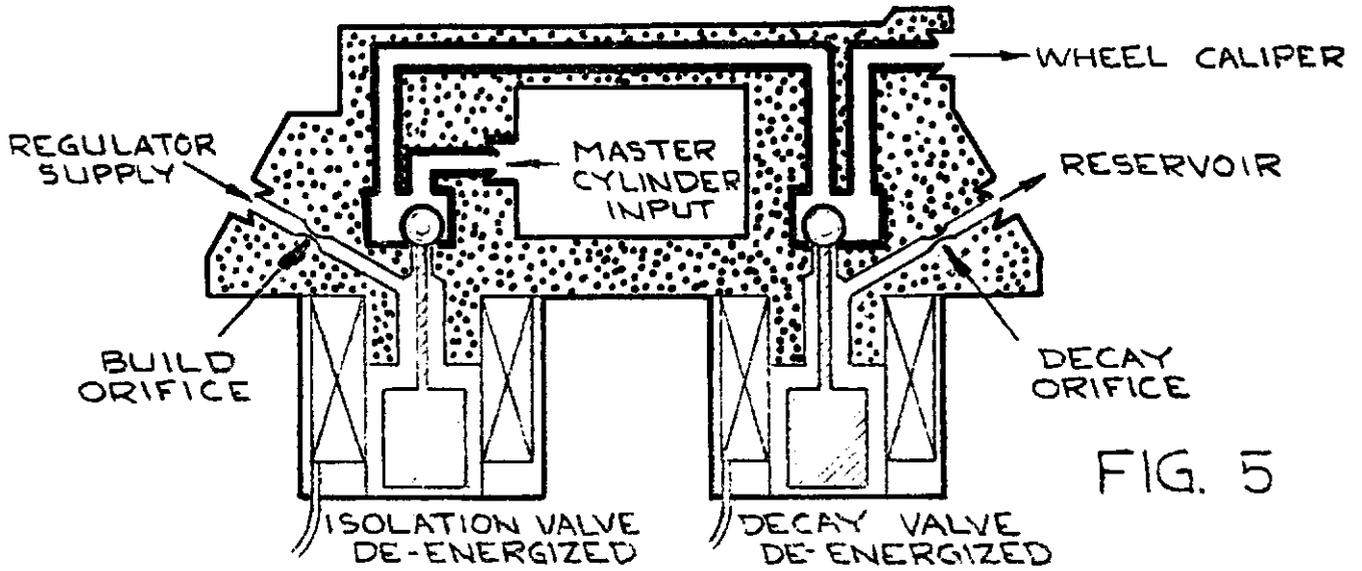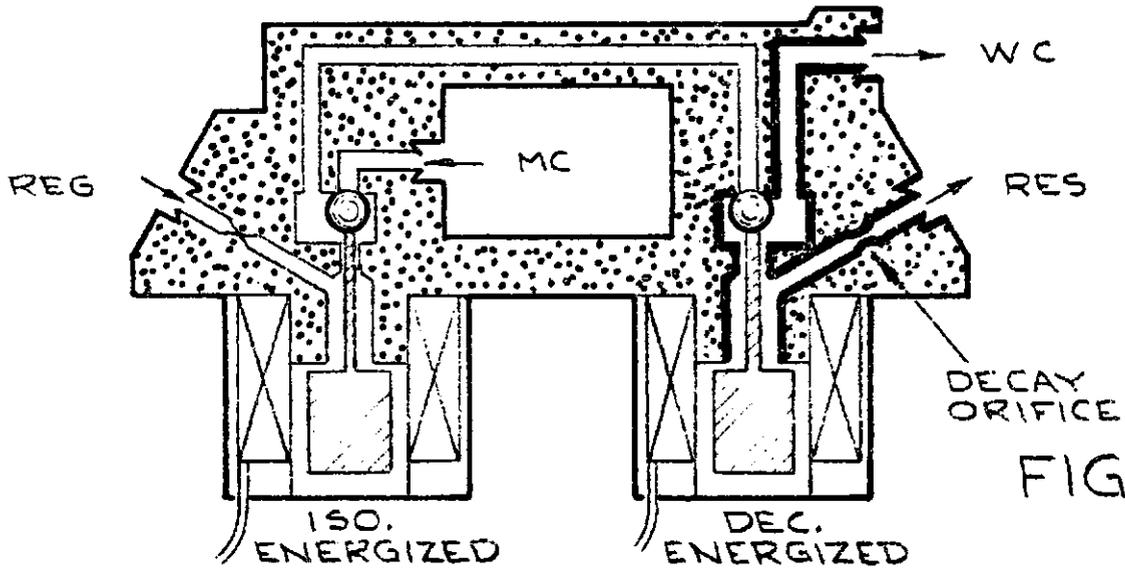
#IC-32 STUD
12 V. CONNECTION

1.63

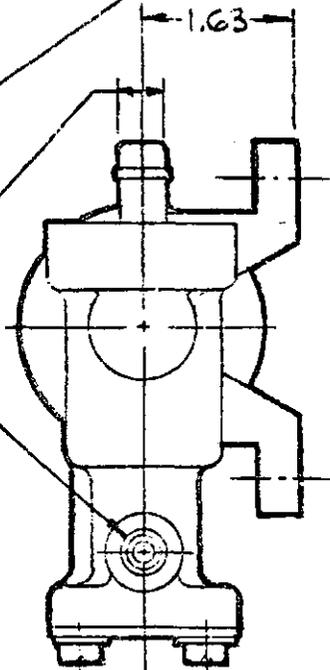.34 DIA - 2 HOLES
FOR MOUNTING

INLET FITTING
FOR ½" I.D.
FLEXIBLE HOSE

OUTLET PORT
#4 JIC
7/16-20 THREAD

ABS   MOTOR/PUMP ASSEMBLY

C-36

PUMP SUPPLY PORT
#4 JIC 7/16-20 THREAD

Ø.34 THRU FOR
MOUNTING BOLT

.88

OUTLET PORT TO
ACCUMULATOR
FOR 3/16 INVERTED
FLARE TUBING
3/8 -24 THREAD

1.44

.56

.31

.31

.63

PUMP   ACC

SW

1.38

3.12 MAX

2.12

Ø.125
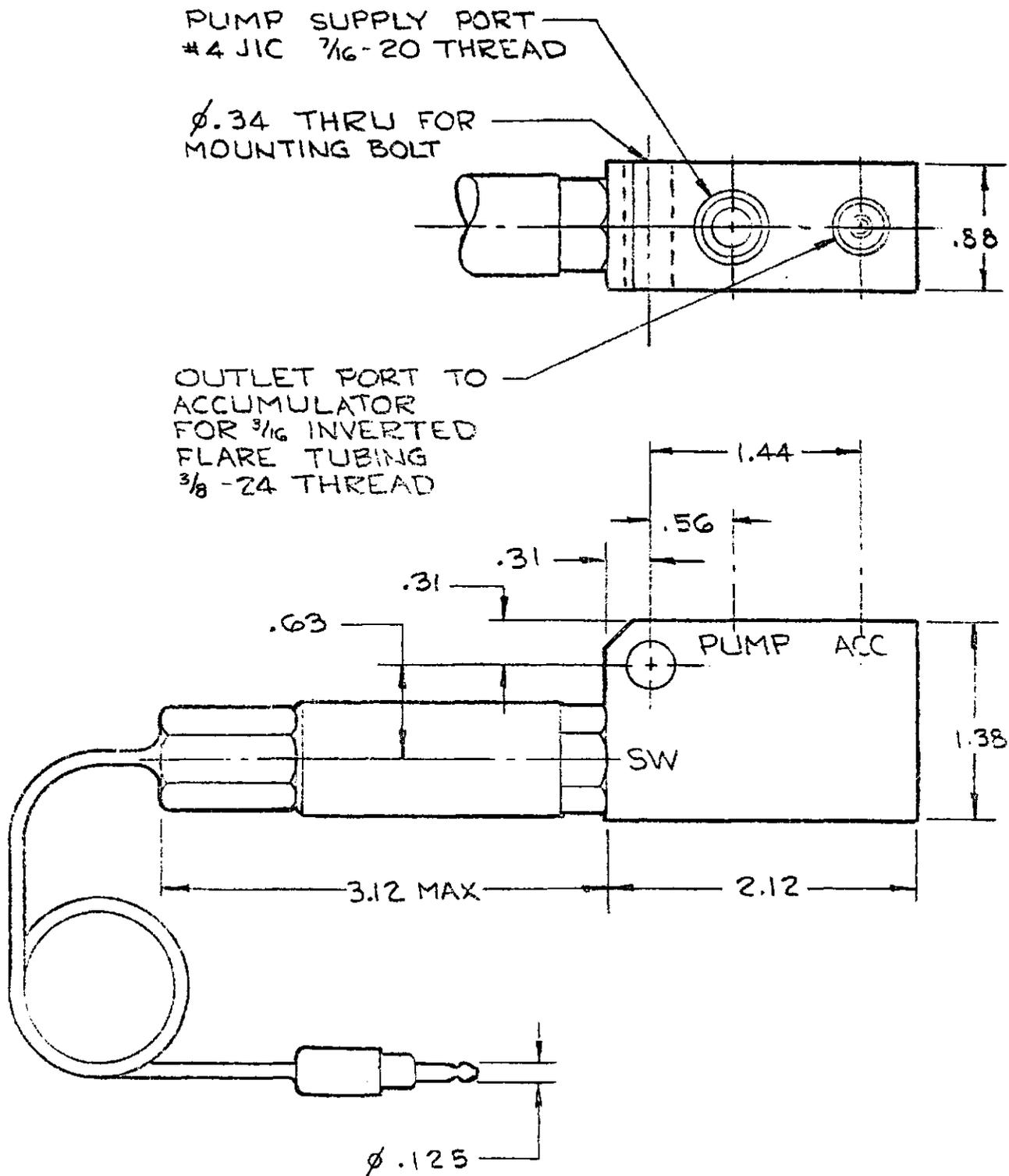
ABS PUMP SWITCH ASSEMBLY

Bendix

ALL PORTS FOR
3/16 INVERTED FLARE
TUBING 3/8 - 24 THREAD

4.54

2.98

1.42

5/16-18 MOUNTING STUDS

WHEEL CALIPERS

RESERVOIR

1.28

3.94 MAX

.50

4.37

4.63

.62

4.18

MASTER CYLINDER

1.88

2.59

6.28

.88

.64

4.00 MAX

.36

.69

TANDEM UNIT FRONT BRAKES

SINGLE UNIT REAR BRAKES

ACCUMULATOR SUPPLY

5.88 MAX

ABS MODULATOR / REGULATOR ASSEMBLY

C-38

SUPPLY FROM PUMP
FOR 3/16 DOUBLE
FLARE TUBING
3/8-24 THREAD

.48

.61

OUTLET TO RESERVOIR
FOR 1/4 DOUBLE FLARE
TUBING 1/2-20 THREAD

.38

.52

.30

.30

1/8 BULLET CONNECTOR

LOW PRESSURE SWITCH

OUTLET TO REGULATOR
FOR 3/16 DOUBLE FLARE
TUBING 3/8-24 THREAD

.53

12.30 MAX

9.13

.36

Ø3.38

8.50

Ø2.00

Bendix

ABS ACCUMULATOR ASSEMELY

C-39