



**NTNU – Trondheim**  
Norwegian University of  
Science and Technology

# Winterization of Railways

Issues and Effects



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## **SUMMARY**

Railways are an important mode of transportation all around the world. Inherent privileges of rail transportation, and increasing tendency of governments towards maximized utilization of railway systems, emphasize the importance of having high-quality train services.

Reliability of train services as an important quality factor, is evaluated through looking at various indicators, including the punctuality. Maintaining the services punctual, regardless of seasonal conditions has been a perennial concern for railways authorities. Though, it has become highlighted after many countries in Europe and Northern America, experienced widespread delays in train services, following the recent extreme weather patterns.

In order to address the issues with winter operation of trains , the current study (a) explores the expected consequences of various winter phenomena on railway operations, (b) reviews the technical and managerial problems that arose in the past winters, (c) gathers the existing countermeasures for addressing those issues, and (d) discusses the reasons why, despite many years of experience, railways are still being taken by surprise with occurrence of known winter phenomena. Furthermore, (e) development of a number of winterization measures in Norwegian railway infrastructure are studied, and (f) their impacts on winter performance of Norwegian railways in term of punctuality is reviewed. Finally, (f) the effects of low-temperature on occurrence and magnitude of delays for a selected number of trains are investigated.

In order to achieve the aforementioned goals, both qualitative and quantitative approaches have been followed through reviewing the literature, interviewing related individuals, and analyzing the punctuality and historical weather data.

By reviewing the performance of Norwegian railways in the recent years, an improvement trend for winter punctuality was observed. Comparing this with development of winterization measures in Norwegian railways infrastructure, proved that the level of winter-preparation affects the punctuality performance. Moreover, comparing the minimum daily temperature with probability of delayed services, revealed that the lower the temperature gets, the higher will be the probability of delays. Correspondingly, the higher number of regions with extremely low-temperature along the line, increases the probability and magnitude of delays.

Key Words: Railways, Winterization, Punctuality, Low-temperature.



## **PREFACE**

This thesis has been carried out as the final part of a two-year international program in Project Management at Norwegian University of Science and Technology (NTNU), at the department of production and quality engineering (IPK).

The study was initiated after a former thesis, “winter technologies for high speed rail” by Maxime Bettez (2011), attracted the interest of experts from South Korean national railroad (Korail) and Korea university of transportation, and brought them all the way to NTNU for ex-changing the knowledge of winter operation within the railway industry.

Preparation of railway systems for providing optimum services during the winter seasons, is an important and perpetual mission which is continuously evolving. These fact explains the importance of continual studies in this field for keeping the knowledge updated.

The initial intention of this work was set to compile and upgrade the existing knowledge and experiences in the field of winter operations. Furthermore, the effects of winter conditions and available countermeasures on performance of railway operations with special focus on the punctuality of services have been studied. To do so, historical weather data, as well as complementary information and data from Norwegian railway authorities through interviews, databases and annual reports have been utilised.

Hereby, I use this chance to express my special appreciation to my dear supervisor, Nils Olsson, for an endless stream of enthusiasm and great inspiration throughout this study. I would also like to declare my gratitude towards Per Magnus Heggland, and Jan Birger Almåsbro from Jernbaneverket, Andreas Dypvik Landmark from Sintef, and my dear friend Babak Moussakhani for their sincere contribution.



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## ABBREVIATIONS

ADD	Auto Drop Device
APU	Auxiliary Power Unit
ARISCC	Adaptation Of Railway Infrastructure To Climate Change
BO	Bodø
CWR	Continuous Welded Rail
DMU	Diesel Multiple Unit
EMU	Electric Multiple Unit
ERA	European Railway Agency
EWENT	Extreme Weather Impacts On European Networks Of Transport
GIS	Geographic Information System
HPF	High Positive Friction
IPK	Institutt For Produksjons Og Kvalitetsteknikk
JBV	Jernbaneverket
Korail	Korea Railroad Corporation
MDBF	Mean Distance Between Failures
MET	Norwegian Meteorological Institute
MTBF	Mean Time Between Failures
NGI	Norwegian Geotechnical Institute
NNRA	Norwegian National Railway Administration
NSB	Norges Statsbaner
NTNU	Norges Teknisk-Naturvitenskapelige Universitet
OOR	Out Of Round
PPM	Public Performance Measure
TAN	Minimum Temperature In A Day
TND	Trondheim
TSI	Technical Specification For Interoperability
UIC	International Union Of Railways
VHPF	Very High Positive Friction
WCM	Wheel Condition Monitor
WCM	Wheel Condition Monitor





**Part 1**  
**INTRODUCTION**





## CHAPTER 1 - INTRODUCTION

### **Background**

Transportation, as an essential constituent of daily life, contributes to the prosperity of nations by facilitating economic, industrial, social and cultural developments (Greene, Jones, & Delucchi, 1997).

Among all the possible modes of transportation, railways have always been a popular preference since the 19<sup>th</sup> century. However, today's global tendency towards an economic, fast, safe and eco-friendly response to transportation needs, explains the growing interests in development of railway services and the gradual movement towards more reliance on railways (Espinosa-Aranda & García-Ródenas, 2013; Stenström, Parida, & Galar, 2014).

In order to ensure that the railways can continue to be a competitive alternative for other transportation modes, the railway companies will need to strive for achieving higher levels of customer satisfaction. Additionally, the ambitions of the governments and international unions for increasing the interoperability (e.g. building of a trans-European railway network) emphasizes the importance of achieving higher operational performance standards in an international level (Gudmundsson, Hall, Marsden, & Zietsman, 2016).

Punctuality of railway services, which in brief means on-time departure and arrival of trains according to the time tables, is broadly considered as a key performance indicator when evaluating the quality of services by both the customers and decision makers. Therefore, improving the punctuality of services, is one of the main steps ahead of the railway companies toward preserving their competitive advantages.

A point to be considered is that, such objectives can be realized through achieving high quality services which last throughout the year, regardless of seasonal conditions. In other words, some measures are needed to be considered in order to maintain the railway systems functional, and to guarantee the optimal quality of operations, which are unaffected by the variations of weather conditions.



### Current Situation

Winter and its consequential phenomena are known, and operation of trains during the winters have continually been practiced since the invention of first locomotives. However, although it is generally accepted that winter arrives every year (at least in many countries), it still catches transportation networks by surprise (Jackson, 2011; Kloow, 2011). It is while occurrence of any failures in the railway networks and disturbed services, has the potential to cause huge problems for the whole society (Ip & Wang, 2011).

Winter and its inherent phenomena can still be the root causes of disruptions in services, as they might cause malfunctions in rolling stock and infrastructures' systems, or simply can close the tracks or force the operators to slow down the trains or prolong the stays at stations.

Some of the most recent examples are the winters of 2009-10 and 2010-11 in Europe and 2013-14 in northern America and Western Canada, when unusual weather patterns and associated snow, ice and subzero temperatures disturbed the transportations, and truly put the railways in many countries to the test (Doll et al., 2014; economist, 2011; Guss, 2014; Jackson, 2011; Johnston, 2014; Juga & Vajda, 2012; Juntti, 2011; Kelly, 2015; Kloow, 2011; Merkert & Mangia, 2012; Smith, 2011; Trap, Huisman, & Goverde, 2015; Wanek-Libman, 2012, 2014).

Reviewing the literature and following the news archives, reveals that disturbed punctuality performance due to delayed or canceled services, followed by unforeseen winter-events, or as a consequence of insufficient preparation has still been a prevailing winter-issue.

Even Norway, as a cold country which is expected to have high preparedness level and well established procedures to deal with winter situation was not an exemption. The punctuality records by Jernbaneverket (2016a) demonstrate a noticeable slippage between 2009 and 2011 (Figure 1).

One might say that the records presents the average annual punctuality which cannot be perceived as a proof for low winter performance. Though, after looking into winter and summer punctuality independently, it can be seen that although the punctuality level has been lower in those summers as well, but unprecedented low winter-punctuality performance during the winter of 2009-10 has had a considerable impact on recording such a low punctuality performance (Figure 2).

## CHAPTER 1 – INTRODUCTION

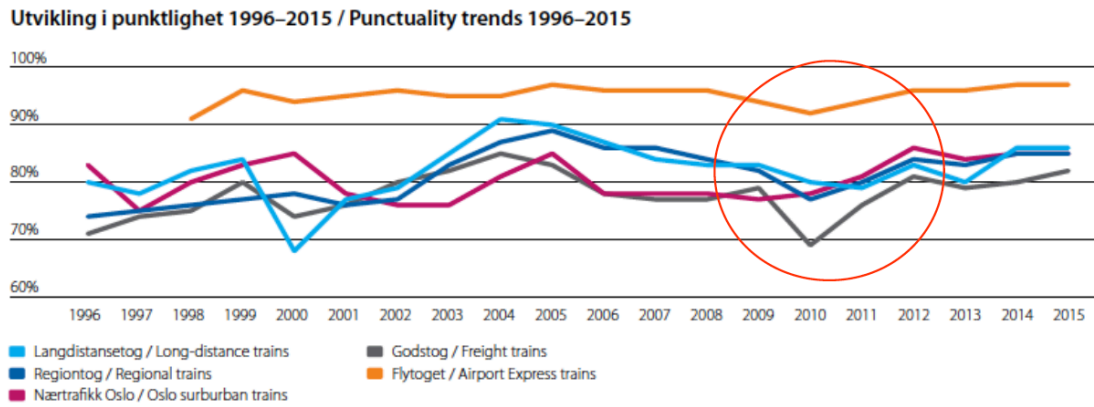


Figure 1- Punctuality trends in Norwegian railways 1996-2015 (Jernbaneverket,2016)

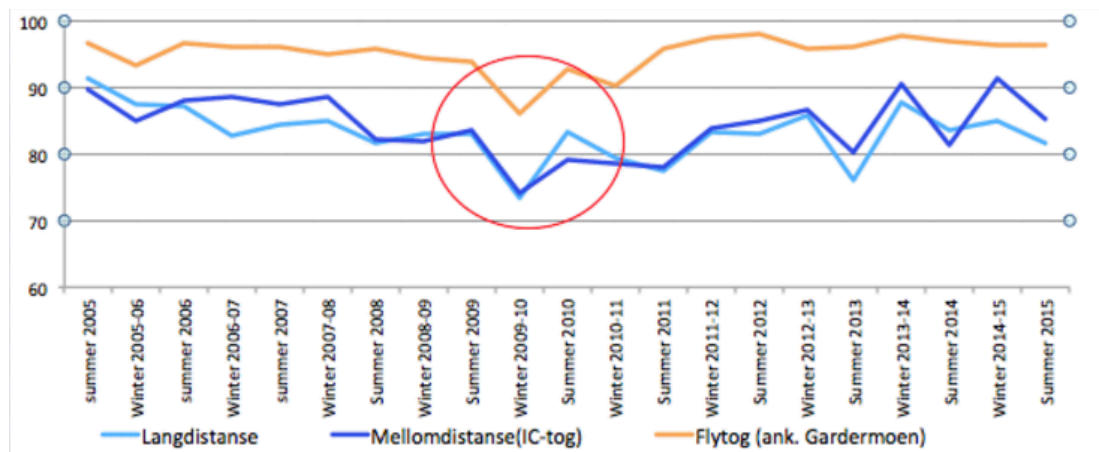


Figure 2- Separated winter and summer punctuality 2005-15 (Jernbaneverket)

Following the troublesome winter of 2009, Wiebe (2010a) conducted a survey to find out the root causes of experiencing such a challenging winter. The result of surveying the railway practitioners are presented in the table 1. From the results of that survey, it can be found that Norwegian railways still face technical problems in both rolling stock and infrastructure systems in case of extreme winter conditions; and there is some room for improving the managerial considerations as well.

Table 1- Root causes of challenging winter of 2009 (Wiebe,2010a)

Rolling Stocks	Couplers	Under frame
	Motor –Alternator sets	Detached ice blocks off the trains
	Sliding doors	Broken windows
	Electrical connectors	
Infrastructure	Rail breaks	Switch and crossings Heating systems
	Welding of the rails	Performance of switches and crossings
	Snow clearance of switches	
Management of winter equipment	Lack of proper snow clearance equipment	
	Low performance of existing snow-clearance equipment	
	Improper logistics of snow-clearance equipment	



### **Motivation of Choice**

Aforementioned winter-related problems as an initiation, urged the governments, international railways unions, and railway companies in many countries to perform some serious investigations on developing solutions for enhancing the reliability of winter services, so the same problems would not repeat in the future (Kloow, 2011; Smith, 2011; Wanek-Libman, 2012).

#### **Why this topic is important?**

Being aware of winter phenomena, and having many years of experience with operation of trains during the winters, and still facing disruptions due to winter-related problems is not acceptable. Still, railway companies fail to meet their aspirations and targets regarding the winter-punctuality, which is a big concern for customers and the other stakeholders. So more efforts are required for minimizing the negative impacts of external weather conditions on optimal operations.

#### **Why the Norwegian railways in particular?**

Due to the specific geographical situation and frequent long and harsh winters in Nordic countries, coping with snow and cold is an inseparable part of railways design and operations in these regions. This makes Nordic countries, including Norway, to be looked at as role-models and experts by other countries when searching for winter solutions. Therefore, results from studying the Norwegian railways can be used and adapted to serve many other countries with unique characteristics.

#### **Why did the author choose this topic?**

Personal interest of the author in all kind of land transportation modes has been the main drive for choosing railways as a theme. Moreover, living in Norway and being amazed by how the systems shall remain functional during the harsh winters doubled the curiosity and triggered the idea of working on winter operations of trains.



### Research Questions

By accepting the inevitability of experiencing extreme winter conditions in the future, and by knowing the importance of having reliable railway services all year round, the ultimate goal from conducting this thesis is to help improving the performance of railway operations during the winter season.

The initial aim has been to assimilate and organize the knowledge and experiences obtained to date, and to present an updated reference for serving the railway practitioners and other interested individuals.

Punctuality of railway services has been the topic of several previous academic researches, both in master's and PhD level. However, punctuality of railways during the winter seasons has not been specifically studied. Hence, this research aims to follow its objectives with specific focus on punctuality of services.

In order to achieve the abovementioned main objectives, this research aims to:

- 1- Investigate the expected consequences of various winter phenomena on railway operations,
- 2- Conduct a research on the problems arising in the railways industry due to winter conditions,
- 3- Review the existing countermeasures, solutions and technologies,
- 4- List the reasons for frequent disruptions of services during the winters,
- 5- Review the recent winter performance of Norwegian railway in terms of punctuality,
- 6- Trace the development of winter solutions in Norwegian railways; and evaluate their impacts on improvements in punctuality,
- 7- Analyse the impacts of low-temperature, on occurrence and magnitude of delays.



### General Limitations

- It is assumed that the readers of this work are familiar with the basic operational and technical concepts within the railway industry. Thus, introduction of fundamental concepts is avoided.
- Characteristics of this topic bounds the resources to official and unofficial reports, fact sheets and datasets. This fact makes the quality of results and discussions to be dependent upon accuracy and compatibility of available resources.
- Another issue in such studies is that, usually there are complicated collection of different factors which affect the overall performance of services. Therefore, not all the improvements and declines in performance can be related solely to winter conditions or to the level of winter-preparation. In other words, a weak performance during certain winters can have its roots in many other reasons, than just the winter-related aspects. Hence, as previously mentioned, service punctuality is the core of the comparisons, so the other aspects and indicators (E.g. cost) might be simply overlooked.
- Railway systems as a whole, consists mutual interactions between the sub-systems of rolling stock and infrastructure. In some cases, categorising a single winter-issue firmly into a specific group might not look ideal.
- Available material in this field mostly focus either on passenger trains or freight trains. This makes it a bit challenging when comparing and combining the previous results to cover all kinds of train services.
- Due to the limited connections and access to information, and by considering the other existing constraints, the attention has been given to Nordic countries with special emphasis on Norway.
- The most significant fact about winterization of railways is that there is no right solution which fits all the situations. Each country and region, based on local weather features, characteristics of the railway networks, and national policies, might require tailored solutions to address its winter-problems.
- In the part two of the report, the punctuality analysis is limited to low-temperature effects, on specific trains, in a certain line and within a predefined time period. More details regarding the limitations in this part has been clearly explained in the methodology section.





### Structure of Report

The report is designed in 4 main parts, and the research questions are addressed throughout the chapters. The main parts of the report are:

#### Part 1-Introduction

The first part, covers the fundamentals and essentials, and does not answer any of the research questions. This part contains:

Chapter 1. Introduction:

- Describes why this topic is important, and why it is chosen to be studied,
- Reviews the current situation and demands,
- List the research questions and general limitations,
- Presents the way the report is structured to address its research questions.

Chapter 2. Methodology:

- In this chapter, the approaches for conducting the literature review and interviews are explained.
- A brief description over how has the data-analysis been proceeded is given.

#### Part 2- Literature Review

The second part of report is based on reviewing the literatures and interviewing railway practitioners. The answers to the first 4 research questions can be found here. This part contains:

Chapter 3. Theoretical concepts

- This chapter clarifies the characteristics of transportation systems, and gives an in depth description of performance indicators. Knowing these concepts is a prerequisite for understanding the discussions.

Chapter 4. Winter phenomena and their impact thresholds

- In this chapter the winter phenomena and the expected consequences are studied from the railways perspective. **The 1st research problem is addressed here.**

Chapters 5, 6, 7. Winter problems and solutions

- Chapters 5, 6 & 7 are dedicated to gathering the experiences from previous winters and reviews the existing solutions. Therefore, **these chapters fulfill the 2nd and the 3rd research questions.**

Chapter 8. the reasons for experiencing troubles in winters

- In this chapters, the main reasons for experiencing difficulties despite having years of experience are presented which is **a direct answer to the research question number 4.**

### Part 3. Case studies

This part is specifically about studying the Norwegian railway, and “Nordlansbanen” in particular.

#### Case 1. Winterization of Norwegian railway

- This case gives an introduction to geographical and climatic characteristics of Norway, and reviews the punctuality performance of Norwegian railways in recent years which **fulfills the 5<sup>th</sup> research question.**
- Reviews the development of a number of winter solutions in Norwegian infrastructure, based on the registered data in Bane Data. Later, their impacts on recorded punctuality is studied to serve **the 6<sup>th</sup> research question.**

#### Case 2. Impacts of low-temperature on punctuality of trains

- Here the results from analyzing the punctuality and historical weather data (in Nordlandsbanen) are utilized, in order to analyse the impacts of low-temperature, on probability of occurrence and magnitude of delays, as a **response to the last research question.**

### Part 4. Conclusion and Further studies

This part is the closing part which:

- Briefly reviews the achievements of this research regarding the research questions,
- Gives suggestions to interested individuals for how the topic can be studied further,
- References are listed,
- Supplementary charts and figures are provided in the appendices.



## CHAPTER 2 – METHODOLOGY

Both qualitative and quantitative approaches have been followed to achieve the objectives of this study:

- The intention from performing a qualitative research has been to create a holistic picture over the study field, and to gain sufficient insight into its fundamentals. The qualitative part, has been based on reviewing qualitative-based literature, and conducting interviews with experienced railway practitioners. In this case, the aim has been to collect the available observations and experiences regarding the railways industry within the winter operations, in order to serve as a basis for investigating the problems and available solutions.
- On the other side, Quantitative approach is followed in order to quantify the observations by investigating available numerical data. In the quantitative research, the author used measurable data to formulate facts and to uncover trends and patterns in research. Particularly in this research, numerical data related to punctuality and travel-time variability as well as historical meteorological data has been the basis for quantifying the impacts of winter and effectiveness of countermeasures.



### Literature Review

The research commenced with conducting a literature study in order to gain the fundamental knowledge about railway industry and prevailing winter issues. This step contained gathering of the available information about the predominant winter-related problems and available technologies, as well as investigating the reasons for experiencing problems despite of all the available knowledge and solutions. In addition to the sources presenting the experiences within the Norwegian railway, a number of literature which examine the observations in other countries such as Canada, Russia, Germany, Netherlands, China, Japan, Sweden and Finland have been reviewed.

Furthermore, in order to have a clear understanding of theoretical concepts (which are necessary when discussing the quality of services in railway section), various

## CHAPTER 2 - METHODOLOGY

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resources have been looked which might not be directly concentrated on either of railways, or transportation industry. Though knowing them is a prerequisite for studying the railway systems as they are broadly used in transportation-related topics. Scholar.google.com and Oria.no have been the two main search engines that were used in order to find the relevant literatures. Searching for the initial key words such as: Winterization, winter preparation, winter management, winter operation, winter technologies, winter timetabling, winter maintenance, railways in winter, punctuality of trains, train delays, etc. has been the initial step. However, the key word list extended further in accordance to the requirements of each chapter. Moreover, in order to find the documents which are published only on the website of railway companies, associations, and governmental organizations, searching on Google led to many informative materials.

“Winter technologies for high speed rail”, an earlier master dissertation by Bettez (2011) was the starting point for this study. In this thesis, the proposed winter solutions for rolling stock, infrastructure and operation have been reviewed; and later are categorized into Passive and Active groups, and analyzed from an economical/beneficial point of view. A revised version of an informative report about the challenges for high speed trains in Nordic regions published by Transrail, titled “high-speed train operation in winter climate” by Kloow (2011) was another main resource. This report has investigated the winter challenges through interviewing individuals with different backgrounds in the railway sector and proposed applicable measures against each specific problem. A series of publications by UIC (International Union of Railways), was also among the highly related materials. In addition, “Punctuality of Railway Operations and Timetable Stability Analysis”, a PhD research by Goverde (2005) and the book “Reliability of Railway Systems” by Vromans (2005), beside tens of other academic publications have been explored and adapted to the current topic. A detailed list of all the references that have been used, can be found in the end of the document.

Deliverables and publications from a number of research projects with related topics have been adapted to the requirements of this study. The EWENT project (Extreme Weather impacts on European Networks of Transport) which assessed the probability, impacts and consequence of extreme weather events on all modes of transport systems in Europe, is the one of them (<http://ewent.vtt.fi/>). According to Pekka Leviäkangas et al. (2011), the critical thresholds for winter weather

phenomena and their expected consequences which are utilized in this thesis, are resulted after reviewing over 150 scientific references and 200 media reported cases.

The publications from WEATHER project (which studied the costs of extreme weather events on transport) and ARISCC (Adaptation of Railway Infrastructure to Climate Change) were also reviewed and referred to ([www.weather-project.eu](http://www.weather-project.eu) & [www.ariscc.org](http://www.ariscc.org)).

Many other online publications, such as “annual statistical reports” and “regulations booklets” published by Jernbaneverket - “National Transport Plans” by Norwegian Ministry of Transport and Communication - “Investigation reports” mainly by Transportation Safety Board of Canada - and “Leaflets” and “fact sheets” distributed by UIC and other railway associations, as well as few “standard booklets” have been also taken into consideration. Moreover, some articles from the online archive of news agencies of any kind have been reviewed in order to illustrate the public concerns and frequency of disruptions in transportation due to the winter issues.

EndNote software has been used as tool for managing bibliographies, citations and references which are listed in the final part of the report.



### **Interviews and Site Visits**

In order to update the knowledge regarding the predominant winter problems and applicable countermeasures, a number of qualitative interviews have been performed. On January 29<sup>th</sup> 2016, Professor Nils Olsson hosted two Korean railways representatives for a knowledge sharing session where three experienced Norwegian railway authorities from Jernbaneverket, Mantena and NSB were present. In this session the participants introduced both the Norwegian and Korean railway network and climate, and discussed frequent winter issues, available technologies and equipment-related solutions. Afterwards, the group had a visit from “Marienborg site” where winter issues were discussed with other experts with relevant experience and direct responsibilities for maintaining and developing the Norwegian railway systems. Administration offices of Jernbaneverket, and the central train control room, as well as the maintenance and de-icing workshops run by Mantena were visited and the procedures were presented by people in charge.

This meetings and visits gave the author a comprehensive picture of the cooperation and processes for opposing the winter-related problems, and many of the experts

expressed their willingness for sharing further information. Thus, they were connected several times later, through arranging short meetings and having E-mail communications. In addition, the managing director of a company which produces and installs anti-icing and de-icing solutions for railway systems has been contacted through the mail regarding the demand for, and effectiveness of such practices.



### **Data Analysis**

In order to evaluate the performance of railway services, and to quantify the impacts of winter and countermeasures on punctuality of services, different sets of data have been analysed, through utilization of different methods, and from various perspectives.

Approaches for analysis of data in different parts of the report are described thoroughly and separately in the corresponding chapters. Though, here is a brief explanation to provide the reader with a general perspective:

- In order to review the recent performance of Norwegian railways in term of punctuality, and for comparing the punctuality levels in winter seasons against the summers, the winter season has been defined as the timespan of 1<sup>st</sup> of November until the last day of March in each year. The average monthly punctuality for different types of train services have been used as the basis for the comparisons.

Required data were extracted and gathered from multiple resources, such as: an on-line punctuality database (Mitt tog), Punctuality reports (Punklighetsrapport), as well as Annual statistics (Jernbanestatistikk), all published by Jernbaneverket.

-With the intention of studying the development of Norwegian railways regarding the winterization measures, and based on registered information in “Bane Data”, previous changes in Norwegian railways infrastructure, and their distribution among the different lines are evaluated.

-In order to investigate the impacts of low-temperature on occurrence and magnitude of delays in Nordlandsbanen, punctuality data from “presis tool”, and historical weather data from “eKlima”, are analyzed. The scheduled and actual arrival time for selected train numbers, and the lowest noted daily temperature have been used as the basis for investigations.

**Part 2**  
**LITERATURE REVIEW**







## CHAPTER 3 – THEORETICAL CONCEPTS

There are a number of theoretical concepts that are broadly used when discussing the quality of railway services. This chapter takes a deeper look into these concepts and their definition from the railways' point of view:



### CHARACTERISTICS OF TRANSPORTATION SYSTEMS

#### Reliability

Reliability is a predominant quality performance measure in transportation, and a complex matter in railway transportation which concerns both customers and railway practitioners. (Anderson, Condry, Findlay, Brage-Ardao, & Li, 2013; Lai, Lu, & Hsu, 2015; M. J. Vromans, R. Dekker, & L. G. Kroon, 2006).

Depending on the systems and applications, a wide range of definitions for reliability can be found: In the business dictionary (2016), the reliability is defined as:

*“the ability of an apparatus, machine, or system to consistently perform its intended or required function or mission, on demand and without degradation or failure.”*

Bae et al. (2009) insists on necessity of clarifying the condition and the timespan for such expectations, and defines the reliability as “the probability that an item will perform its required function without failure, under stated conditions and for a stated period of time”.

Barron, Melo, Cohen, and Anderson (2013) and John Bates, John Polak, Peter Jones, and Andrew Cook (2001) associate the reliability with the concept of variability as it implies a notion of repetition, regulatory, predictability and minimization of any randomness effect.

In accordance to the current study, when investigating the reliability of transportation systems, “reliability of systems” and “reliability of services” are two different concepts which should be clearly differentiated (Bae et al., 2009; Barron et al., 2013; Lai et al., 2015; Moreb, 2007):

- **Reliability of systems vs. Reliability of services**

“**Reliability of systems**” in the railway industry, is mainly about the frequency of failures/malfunctions that prevent the systems or sub-systems from performing their expected functions. The most common measures for estimating the reliability of railway systems are the mean time between failures (MTBF) and the mean distance between failures (MDBF), which are normally provided by the suppliers of systems (or sub-systems).

Although the reliability of technical systems is a crucial matter, the incidents in railways operations are not limited to those caused by technical failures. Moreover, occurrence of incidents at different times or in different locations might have dissimilar impacts on the train operations. Thus, knowing the likelihood of failures does not give a clear image about how severe the consequences might be and how the users might be affected. Therefore, a more comprehensive indicator for reliability is the one which can also demonstrate the performance of railway companies in providing reliable services. Higher reliability of systems and reduction in frequency of failures does not necessarily lead to a better service reliability. Thus, “**reliability of services**” is defined as another term which identifies the impacts of incidents (technical failures, events) on operations, and the way the customers will be affected. The common belief is that the reliability within the transportation field is primarily related to the use of time, as unreliability of systems will mainly result in late arrivals and the corresponding time-related uncertainties. Therefore, it can be said that “service reliability” contains the service punctuality or delay, which also takes into account the customer satisfaction aspects (Barron et al., 2013; Lai et al., 2015). Accordingly, the punctuality level, and the public performance measure\* (PPM) are the most common indicators that present the reliability of railway services; and any discrepancy between realized and scheduled/advertised time can be interpreted as unreliability (John Bates et al., 2001; M. J. Vromans et al., 2006).

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\* The Public Performance Measure (PPM) is the industry standard measurement of performance in Britain (e.g. Networkrail) that combines the punctuality and reliability of passenger trains. It is the percentage of scheduled trains which successfully run their entire planned route, calling at all timetabled stations, and arrive at their terminating station 'on time'.

- **Operator-oriented vs. Passenger-oriented Reliability**

Barron et al. (2013) proposed two different perspectives towards reliability in the railways: One is from operators' perspective, and the other is from passengers' and freight customers' points of view. In the **“Operator-oriented”** perspective, the focus is on the vulnerability of the network to disruption and the operational performance of the network against agreed level of service (e.g., number of train cancellations, number of failures, average punctuality). While **“passenger-oriented”** perspective concentrates on the users' concerns, such as variability and uncertainty of the travel times.

After considering the aforementioned definitions and reviewing other opinions, in this thesis, the term “Reliability” is used to describe the predictability of a given travel time being realized, and the extent of variation around the average travel time (Barron et al., 2013; J Bates, Jones, & Polak, 1995; John Bates, Jones, Polak, & Han, 1997; Van der Mede, Palm, & Flikkema, 1996; Van Lint, Van Zuylen, & Tu, 2008). Therefore, a railway system can be said to be reliable if the trains' operations take place properly as they are scheduled, and without significant deviation from the optimal condition (The extent of allowed deviations are agreed upon), so the passengers or freight customers can expect to receive their services as it was promised, and under any circumstances.

### **Robustness**

There exist various definitions for robustness in systems, as well as robustness in scheduling and timetabling, which are described in many different ways (Salido, Barber, & Ingolotti, 2008): In this thesis, **“robustness of systems”** and systems' resistance are used interchangeably when referring to the ability of a system to withstand probable perturbations, which may disturb its normal functionality. Hence, a railway system is referred to as robust (or resistant) if it is solid enough to continue operation (with very low failure rate) when facing external disturbances, mainly from its environment. The overall robustness of systems is not, however, of particular importance to customers, while railway undertakings or infrastructure managers may need to keep an eye on it when investigating the performance of the railway systems (Nicholson, Kirkwood, Roberts, & Schmid, 2015).

When discussing the robustness of timetables in railways, it refers to the ability of a time table to absorb unexpected short disruptions and primary delays without

significant modification, so the total weighted real travel time in a robust railway timetable is minimized in case of frequent and small disturbances due to controlled secondary delays\* (De-Los-Santos, Laporte, Mesa, & Perea, 2012; Dewilde, Sels, Cattrysse, & Vansteenwegen, 2014; Goverde, 2005; I. A. Hansen & Pahl, 2008; Jensen, Landex, & Nielsen, 2014; Salido et al., 2008; Takeuchi & Tomii, 2005; M. J. C. M. Vromans, R. Dekker, & L. G. Kroon, 2006). Note that robustness of timetables aims at preventing and reducing both primary and secondary delays in order to sustain the stability of services, as a part of the overall robustness of the railway system (Goverde & Hansen, 2013).

As Salido et al. (2008) listed, the robustness (of timetables) can be improved by decreasing capacity, optimality (adding time contingencies) and heterogeneity (Using trains with the same characteristics). However, there is a limitation in resolving the disruptions as no reasonable timetable is robust enough to handle large disruptions and disturbance, without severe on-line and real-time railway traffic management tactics through retiming, reordering or re-routing (Goverde & Hansen, 2013; M. J. Vromans et al., 2006).

### **Resilience**

Hollnagel (2011) and Arenius and Sträter (2013) define the Resilience as the intrinsic ability of a system to adjust its functioning, before, during, or after any expected or unexpected changes and disturbances; so it will sustain its required operations anyway. In general, resilience is all about the ability of a system to deal with, and recover quickly enough after significant disturbances, and keep providing an acceptable level of service. Higher resilience can be achieved through redundant resources, distributed supplies and reliable delivery lines (Ip & Wang, 2011; D. Wang & Ip, 2009).

The concept of resilience in the railways can be expanded from the ability of a timetable in preventing or reducing significant delays through flexibility and real-time traffic management and dispatching (Goverde & Hansen, 2013), to general recovery of the whole railway systems after large scale disastrous events (Dorbritz, 2011).

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\* The concepts of primary and secondary delays are introduced later in the same chapter.

### **CHAPTER 3 – THEORETICAL CONCEPTS**

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Resilience can be viewed as the complement of robustness. In other words, a system is called resilient if it is able to recover and sustain the functionalities by real-time adjustments, when severity of disturbances exceed the robustness margins (Goverde & Hansen, 2013).



### PERFORMANCE INDICATORS

#### **Travel Time Variability**

Travel time variability, as one of the measures of reliability, is referred to the random variations in the mean travel time due to the congestions and incidents. The terms travel time variability, and timetable reliability are sometimes used interchangeably, while travel time variability is about variations from the mean travel time; and the timetable reliability is applicable when measuring variations from a specified timetable (Fosgerau, Hjorth, Brems, & Fukuda, 2008).

The consequences associated with travel time variability for customers are prolonged waiting time, missed connections, and difficulties associated with arrival at the destination either earlier or later than expected arrival time. These consequences can lead to anxiety and stress caused by uncertainty, and impose extra cost for the users which in the end will result in dissatisfaction and disutility of railway as a transportation mode (John Bates et al., 2001; Noland & Polak, 2002).

Considering slacks or safety margins in trains' schedules will reduce the variability of travel time. However, it will extend the travel time and reduces the capacity utilization of networks. In many cases travel time, variability, and cost attributes are highly tied where separated valuations cannot be identified (Fosgerau et al., 2008). However, when designing the schedules, it should be kept in mind that users of railway services attribute a higher value to reliability of travel time and reduction in variability, than to having a shorter mean travel time (Barron et al., 2013; John Bates et al., 2001; Noland & Polak, 2002; Small, 1982).

#### **Punctuality**

Punctuality is often used synonymously with being "on time". In general, punctuality has been referred to as the characteristic of being able to arrive to an appointed place, complete a task, or fulfill an obligation before, or exactly at a previously designated time.

In the railway context, punctuality is an indicator which is calculated and presented as the percentage of trains arriving at their destination on time, within a predefined margin from the scheduled arrival time (M. J. Vromans et al., 2006). In practice, this margin varies from a country to another, and also for different types of train services

(e.g. long distance services and commuter trains). In order to facilitate the international comparisons, a train is said to be punctual if it arrives to its destination within ten minutes of its scheduled time for long distance services and five minutes for short distance and commuter services (M. J. Vromans et al., 2006). However, in Norway and according to Jernbaneverket, this margin for regional, airport and suburban services is three minutes (3:59 minutes), and for the all other trains (including long distance services) the margin is five minutes and fifty-nine seconds.

Punctuality is usually calculated by dividing the number of punctual trains by the total number of trains in a line in a pre-set time period. Whereas cancelled trains may also be considered as unpunctual trains (Cancellation=Long time delay) or might be completely excluded (Li, Landex, Nielsen, & Madsen, 2013; Olsson & Haugland, 2004). In addition to the arrival punctuality, the departure punctuality can also be evaluated. Moreover, punctuality can be recorded at any point on the trains' route where the arrival or departure is agreed upon (Veiseth, Magnus Heggland, Wien, Olsson, & Stokland, 2011). However, the punctuality is most commonly (e.g. in Norway) measured at terminating stations, and based on arrival time, through comparing the actual arrival time, and the time announced in the schedules (Olsson & Haugland, 2004). When this is the case, punctuality, as an indicator of service quality, does not take into account the potential delay and disruption in each sections and to passengers using intermediate stops (Nicholson et al., 2015). Another point is that running ahead of schedule is also a sign for lacking punctuality (Olsson & Haugland, 2004). However, train punctuality is generally related to negative deviations from the appointed timetable. Therefore, in this report the train is consider as unpunctual or delayed only if it is lagging behind its schedule, exceeding the agreed margins.

Punctuality of services, as an ex-post measure, is a commonly-used key performance indicator for measuring the operational reliability in railway industry, which is highly valued by (a) customers, (b) railway companies and (c) governments (John Bates et al., 2001; J Bates, J Polak, P Jones, & A Cook, 2001; M. Dingler, Koenig, Sogin, & Barkan, 2010; Goverde & Hansen, 2013; Nicholson et al., 2015; Rietveld, Bruinsma, & Van Vuuren, 2001; Stenström et al., 2014; Veiseth et al., 2011): (a) A revision of previous studies by John Bates et al. (2001) have shown that the performance of transport systems in terms of punctuality is an influential factor for users when selecting a transportation mode. (b) In countries like United Kingdom where

operation of trains is contracted to privatized operators, if a rail operator fail to provide punctual services, they will be charged by financial penalties, as their low performance will reduce the punctuality of the entire network (Noland & Polak, 2002). (c) Improvement in punctuality is a determining factor when evaluating the alternative projects and allocating budgets.

### **Delay**

Delay, travel time variability and punctuality are three concepts which are closely connected to each other. In general, delay is defined as a situation in which something happens later than it should, and its magnitude is measured by calculating the time-difference between the scheduled time of an event and its actual realization.

In the railway traffic, delay is the negative variation in travel time, and its magnitude is described as the extra time it takes for a train to operate on a route when it is lagging behind the schedule. Delay can also be viewed as the difference between the minimum, or unopposed travel time and the achieved travel time; Or simply the difference between the scheduled and actual travel time (M. Dingler et al., 2010). In practice, delay is measured by calculating the negative deviation from the timetable in time units, which is usually minutes (Olsson & Haugland, 2004).

Being the opposite of punctuality, delay can also be measured along the route as well as in the final destination. It should be considered that a train might arrive punctually to the final destination in spite of suffering a number of delays along its route, through attaining a higher speed than planned on certain parts of its journey (Nicholson et al., 2015; Nyström & Kumar, 2003).

Delays have considerable impacts on reliability of services and customer satisfaction, so preventing delays has always been a main concerns for train operators (Barron et al., 2013; Noland & Polak, 2002). Delays can indicate the performance of railway services, and reduction in delay is often used by the railroads as the primary metric when evaluating the benefits of alternative projects and operational changes. Therefore, understanding the rout causes of delay is of importance for having effective and economic rail systems (M. Dingler et al., 2010).

Although a delay is any way a delay in customers' perspective, it can be categorized into different types based on the reason behind it:



- **Primary Delay vs. Secondary Delay**

“**Primary delays**”, also known as “initial delays”, “source delays” or “exogenous delays” are those delays which are caused directly due to the occurrence of disturbances (e.g. Accidents, failure of equipment or infrastructure, mistakes, bad weather conditions, excessive alighting and boarding time, etc.), and are not a consequence of other delayed trains and the interdependencies between them (Olsson & Haugland, 2004; Vromans, 2005; M. J. Vromans et al., 2006).

Goverde and Hansen (2013) also differentiate between initial delays and primary delays: They define the initial delays as departure delays at the origin station and delays of trains entering a network from the outside (such as country borders), while a primary delay is said to be caused by variations in a process by which the process takes longer than expected.

Reducing the disturbances and primary delays is said to be quite costly (Vromans, 2005); and the significance of impacts, caused by primary delays, can be measured by looking at means of the queue length, the total knock on delays, the number of links and stations involved, and the time taken for the service to recover to the normal operation (Nicholson et al., 2015).

On the other side, “**Secondary delays**”, also referred to as “knock-on delays” or “reactionary delays” are due to the interdependencies in railway timetables and other logistic plans, as they are caused by, and are the consequences of earlier delays of other trains in the network (Carey & Kwieciński, 1994; Olsson & Haugland, 2004; Vromans, 2005). The interdependencies between trains can be a result of sharing the same infrastructure, rolling stock connections, transfer in crew schedules, passenger transfers, and dispatching actions (M. J. Vromans et al., 2006). A secondary delay occurs only if a primary delay exceeds the buffer time between two or more train paths (Goverde & Hansen, 2013).\*

- **Scheduled vs. Unscheduled Delays**

In another categorization of delays, when looking at the reasons behind them, train delays can be the consequences of both scheduled and unscheduled events (Carey & Kwieciński, 1994; Fosgerau et al., 2008; M. J. Vromans et al., 2006), which in

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\* More elaboration on the concept of secondary delays can be found under the title “Delay Propagation” later in the same chapter.

addition to unopposed (or free flow) time will form the final realized travel time (Fosgerau et al., 2008):

Final realized travel time = free flow time + scheduled delay + unscheduled delay

“**Scheduled or systematic delays**” are those which are predictable and planned for. Delays that can be related to the systematic variations (E.g. time of the day (peak versus off-peak), or day of the week (weekday versus holidays)) are of systematic or re-current delays. It means that observing the characteristics of the trip, can make it possible for the operators to anticipate them, and will give them the chance to plan for it by integrating the necessary changes into the timetables. Therefore, scheduled delays are planned for, and integrated into the timetables as buffer time in order to handle the conflicts such as meets, passes, mainline restrictions and entry delay with other traffic.

“**Unscheduled delays**” on the other hand, are those which cannot be foreseen and taken into account. They are also referred to as unexplained or non-recurrent delays and are a primary factor in unreliability and instability of services. Unscheduled delays can be caused by various events including mechanical failures, malfunctioning infrastructure, weather conditions, excessive boarding times of passengers, accidents and so on.

### **Delay Propagation**

Delay propagation is the spread of delays throughout a railway network from both the aspects of time and location, and as a result of dependencies between services (Vromans, 2005). Unfortunately, occurrence of delays (primary delays) is sometimes unavoidable and out of the control. However, minimizing the propagation of delays (secondary delays) is a possible solution for increasing the reliability of railway services (M. J. Vromans et al., 2006).

Unlike the other modes of transportation, railway tracks limit the movement of a train to one dimension, so a train can move only forward or backward on one plane, parallel to track, which gives it a single degree of freedom (Yu-Lee, 2002). Thus, in cases where a train stops running or slows down on a single track, or when the track is congested for any reason, other trains will not be able to proceed anymore. As a consequence of interdependencies between different lines and services, a minor interruption in normal flow, can propagate a cascading effect of delays to other trains;

Which if not controlled, will result in disturbance of the whole network; Resembling a phenomenon which is referred to as the “domino effect” or “snow ball effect”.

There are a couple of factors which affect magnitude of delay propagation: It is widely agreed that when a route is being operated close to its maximum traffic capacity (during the peak hours or critical sections of the network), the probability that an initial delay leads to more consequential delays increases significantly, and recovering process to a normal operation would be more complicated. (Barron et al., 2013; M. Dingler et al., 2010; M. Dingler, Lai, & Barkan, 2009; Gibson, Cooper, & Ball, 2002; Jespersen-Groth et al., 2009; Kaplan, 2007; Krueger, 1999; L.-G. Mattsson, 2007; Noland & Polak, 2002; Schlake, Barkan, & Edwards, 2010; Trap et al., 2015; Vromans, 2005; M. J. Vromans et al., 2006; Weatherford et al., 2008). Moreover, a heterogeneous rail traffic, meaning sharing the same infrastructure by different services with different origin and destination, running speed and halting patterns, leads to many small headway times which is another main cause for propagation of delays (UIC, 2004; M. J. Vromans et al., 2006).

### **Capacity utilization**

Aligned with the discussions in previous section, it can be added that the unprecedented growth in demand for transportation in general, and increased utilization of limited capacity of railway infrastructure, has made the railway systems quite vulnerable to disruptions, which has resulted in lower punctuality and reduced level of customer satisfaction (M. J. Vromans et al., 2006).

Landex, Kaas, Schittenhelm, and Schneider-Tilli (2006) stated that there are several parameters involved in determination the capacity of railway networks which make it difficult to agree on an specific definition for it. Among all the proposed definitions, three following descriptions can give an appropriate impression over the concept:

- (a) The capacity of an infrastructure facility is its ability to operate the trains with an acceptable level of punctuality (Kaas, 1998),
- (b) Capacity is the capability of an infrastructure to handle one or several timetables (S. Hansen, 2004),
- (c) Capacity as such does not exist. Railway infrastructure capacity depends on the way it is utilized (UIC, 2004).

In another resource, Goverde and Hansen (2013) has given two separated definitions for capacity: “**Theoretical capacity**” is defined as the maximum number of trains

that can be operated in a specified time period, and is determined by the characteristics of both infrastructure and rolling stocks in a homogeneous traffic. While “**Effective capacity**” is the maximum possible number of trains per time-period, considering the real patterns such as train types, frequencies, orders and speeds.

Keeping these in mind, UIC has presented an analytical compression method for measuring the capacity consumption on railway lines. In this method the travel time in a line section is measured when the maximum capacity of line is being utilized (called compressed timetable). Then the ratio between the completion time of the uncompressed, and the compressed timetable will represent the capacity consumption level. Consequently, the ratio of capacity consumption will indicate the available buffer time between consecutive trains (Goverde, Corman, & D’Ariano, 2013; Jensen et al., 2014; U. UIC, 2004). According to the UIC, the capacity utilization is recommended to be at most 75% in peak hours and 60% for off-peak periods for mixed traffic lines and dedicated high-speed lines (Goverde & Hansen, 2013).

It should be considered that the capacity utilization on railway lines is very responsive to the characteristics of each networks. Therefore, it is not ideal to compare the capacity of lines without considering the specifications of examined lines or sections (Goverde & Hansen, 2013; Landex et al., 2006).

When deciding on which level of capacity to be utilized, a trade-off between different measures needs to be taken into account. According to UIC Code 406, in order to have a balanced capacity, many factors such as the number of trains, average train speed, heterogeneity and stability of the time tables should be considered together (Goverde & Hansen, 2013).



### TWO MAIN STRATEGIES: SLACK vs. PRECISION

In order to improve the quality of services through better reliability, two main approaches are to be followed:

“**Slack strategy**” is all about considering buffers and contingencies in time tables and redundancy (Reserve, Back-up) in resources, with the aim of reducing the risk of delay propagation (Jensen et al., 2014; Nicholson et al., 2015; Olsson & Haugland, 2004; Salido et al., 2008). Slacks and buffers in timetables minimize the total delay, when trains get closer to their final destination, which means that delays throughout the route will be compensated by available slacks in the time table (Rudolph, 2003). As a result, the total weighted real travel time will be minimized in case of frequent and small disturbances (Dewilde et al., 2014). Though, it should be kept in mind that if the disturbances are significant enough to exceed a specific threshold, time reserves cannot help. Generally, timetable reliability will increase with the size of time allowance (Rudolph, 2003). However, how big the time allowances should be (how many minutes per hour) varies based on the prevailing situations (Goverde & Hansen, 2013).

Implementation of slack strategy is quiet easy since there is no need for fundamental changes, and the objectives can be simply achieved by increasing time and resource supplements. However, the drawbacks with this strategy are that it might be costly due to not utilizing the maximum capacity of network, and waste of resources. There is always a challenge to balance the trade-off between (a) having enough slacks and (b) maximizing capacity utilization, (c) proper connections between services, (d) lengths and (e) frequency of journeys. Deciding about where to position the slacks and their extent to be sufficient is a complex task which requires analytical, stochastic and statistical methods (Goverde & Hansen, 2013; Jensen et al., 2014; Liebchen, Lübbecke, Möhring, & Stiller, 2009; Nicholson et al., 2015; Olsson & Haugland, 2004; Rudolph, 2003). Rudolph (2003) investigated an optimum between timetable reliability, capacity utilization and travel time (Figure 3). He proposed that considering dwell time allowances at stations, gives is a better result than running time allowance; and claimed that using his proposed approach results in 25% reduction in overall additional delay.

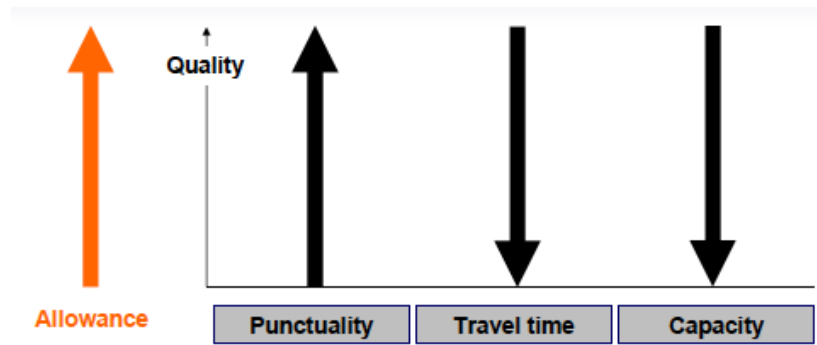


Figure 3- Variation of quality against allowance (Rudolph,2006)

**“Precision strategy”** on the other side, is about flawless operations by avoiding any failures and incidents (and the primary delays as the consequence) through focusing on keeping every component (Infrastructure, rolling stocks, operation) to carry out their tasks without any deviation through high resource utilization.

Concentration will be on minimizing the risk of failures and mistakes, as well as calibration of timetables based upon “on the second” departures by eliminating any kind of waste like waiting-times or speed reductions (as in “Just In Time” concept in modern manufacturing). However, the challenges with precision approach is its high resource demand and difficulties with maintaining a realistic time table while simultaneously striving in the direction of precision (Olsson & Haugland, 2004).

- ✓ This chapter clarified some the characteristics of transportation systems, and provided an in depth description of performance indicators in railways transportation. Moreover, two main strategies for assuring the reliability of train services were introduced. Knowing these concepts is believed to be the perquisite for understanding the following discussions.



## CHAPTER 4 – WINTER PHENOMENA & IMPACT THRESHOLDS



### WINTER PHENOMENA

Winter and its characteristics are generally known; though this section aims to give a better insight into different winter phenomena from the transportation perspective, through presenting their frequencies, and the way they affect the railway traffic.

#### Snowfall

Snow can cause great challenges for transportation by increasing the travel time, occurrence of delays and risk of incidents (Juga & Vajda, 2012). Precipitation of more than 15 cm snow in 1 day may create hazardous situations and can paralyze transportation (Schmidlin, 2013).

The entire Europe is subjected to snow events (at least 1 cm/24 h). However, amount of snow and the number of snowy days varies around the continent. The frequency and severity of snow events is higher in Northern and Eastern Europe, and the Alpine region, where the frequency of days with snow varies between 100-140 days/year. The Scandinavian mountains, Alps and Iceland are the most affected regions, experiencing between 45 and 55 days with 10 cm/24 h per year and 5–25 cases of more than 20 cm/24 h snowfall (Vajda et al., 2014).

#### Wind gusts

Strong winds can adversely impact all modes of transportation in any season. Though, occurrence of extreme wind gusts ( $\geq 17$  m/s) is more frequent during the winter seasons. Most of the European countries experiences 5-10 days per winter with strong wind gust, and this frequency is higher in Atlantic coastal area, British Isles and Iceland (Vajda, Tuomenvirta, & Jokinen, 2012). Typical consequences of strong wind gusts on railway are blocked lines and cuts in power lines due to fallen trees. Strong winds can also cause blockage and derailment by blowing debris, branches and trees from the trackside onto the track (Rauhala & Juga, 2010; Vajda et al., 2014). Moreover, strong winds can cause overhead power lines to sway and tangle around a train's pantograph (networkrail, 2016).

### **Low temperature / Cold spell**

The low temperature itself, is rather a modifier of hazardous conditions than a main cause. Coldness and its accompanied ice and frost may cause failures in railway traffic in several ways. The failures are mainly due to frozen liquids, stuck moving parts and changes in the characteristics of materials which result in non-functioning sub systems. For example, very low temperatures below  $-30\text{ }^{\circ}\text{C}$  can always have negative effects on materials, components or systems such as rubber, sealing, lubricants, current collection, etc. (Kloow, 2011).

According to Vajda et al. (2014), most of the European countries experience at least 1 to 60 days per year with daily mean temperature of below  $0\text{ }^{\circ}\text{C}$ . This number for Scandinavia has been 100 to 200 days per year, with higher values in the Scandinavian mountains and Iceland (around 220 days/ year). Adverse cold (Bellow  $-7^{\circ}\text{C}$ ), is recorded in 1–20 cases/year in the central and western part of the Europe, and in 100–110 cases/year in northern Scandinavia. Besides, temperatures below  $-20^{\circ}\text{C}$  with frequency of 5-30 days/year was experienced only in Scandinavia and north-eastern Europe.



## **COMBINATION OF SEVERAL WINTER PHENOMENA**

### **Blizzard / Snow storm**

A blizzard can be defined as a combination of low temperature, strong wind gust and considerable precipitating or blowing snow in form of a severe and long-lasting snowstorm. In general, blizzards are extreme forms of snowstorms, which are an important part of the winter season for much of the northern middle and high latitudes of earth. In order to separate the blizzard from snowstorm, certain thresholds for wind speed, visibility and duration are defined which vary from a country to another (Schmidlin, 2013). Blizzards can cause damage to structures and transport control systems, resulting in considerable disturbance to railway and consequent delays and cancellations (Vajda et al., 2014). The most affected regions during the past decades have been the western coast of Scandinavia and Iceland (Vajda et al., 2012).



**Ice formation (low temperature, wind, precipitation)**

Ice formation on different surfaces is a common issue during the winters. Findings from studies on ice formation on overhead wires by H. Liu, Tang, Ma, and Gu (2008), Heyun, Xiaosong, and Hanqing (2011), Wiebe (2010b) and Heyun, Xiaosong, and Wenbin (2012) have shown that the combination of different factors such as varying temperatures, wind speed and air humidity determines the types of ice and snow crystals. Each type is expected to form in a certain weather condition, and has its unique characteristics; thus will have unique impacts, and require specific responses.

In a study by French, Eggestad, Øvstedal, and Jahren (2010), and by referring to the AOPA Air Safety Foundation (2004), it was concluded that icing is most likely to occur when the ambient temperature is between 0 and -20 °C, but the worst icing will usually occur between 0 °C and -10 °C when freezing rain or freezing drizzle is present. Heyun et al. (2012) also claim that although the temperature of icing is always below 0 °C, in temperatures below -10 °C, icing is less likely to occur. While in case of super-cooled water drops, icing is probable to happen even in temperatures over 0 °C (about 1 °C), which will form dense glaze. Heyun et al. (2012) presented two categorizations for different types of icing. One is based on the formation mechanism (Table 2), and the other is based on appearance and texture (Table 3).

Table 2-Categorization of ice based on the formation mechanisms (Heyun et al.2012)

<b>Category</b>	<b>Features</b>
<b>Precipitation Icing</b>	Formed by freezing rain (super cooled water), or snowflakes on surfaces with temperature close to 0 °C or below. Because of slow speed of releasing latent heat during the process of freezing, a film of water would appear and glaze is formed. The density of glaze formed by precipitation icing is high and adhesive power is strong.
<b>In-cloud Icing</b>	Ice is formed by the super cooled cloud or fog in the air on contact with the surface. Icing mainly depends on humidity, air velocity etc. The fog droplets can release the latent heat quickly when freezing. Thus, it won't form a water layer on the surface. Therefore, in-cloud icing usually produces rime.
<b>Sublimation Icing</b>	a frost formed when water vapor in the air directly freezes on a surface. It is also called crystalline rime. Formed through sublimation. It has weak adhesion and can easily be shed. Therefore, it won't pose a big danger.

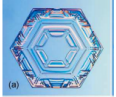
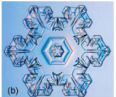
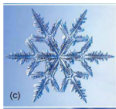
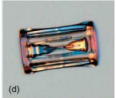
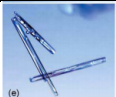

## CHAPTER 4 – WINTER PHENOMENA & IMPACT THRESHOLDS

Table 3- Categorization of ice based on appearance and texture (Heyun et al.2012)

Category	Features	Density (g/cm <sup>3</sup> )
<b>Glaze (ice slush/clear ice)</b>	Transparent, unbreakable and strong in texture. strong adhesive power and hard to shed	0.6 - 0.9
<b>Granular Rime</b>	Ivory opaque, loose and fragile in texture with air bubbles inside, sinuous surface and irregular shape	0.1 - 0.3
<b>Crystalline Rime</b>	White crystal with many air bubbles inside, loose and soft in texture, weak adhesive power and easy to shed	0.01-0.08
<b>Wet Snow</b>	Ivory or white, usually soft in texture Wet snow will turn into hard frozen body when the temperature continues to decrease	0.1 - 0.7
<b>Mixed Rime</b>	Ivory, large with many voids, is formed by the alternate freezing of glaze and rime on the surface	0.2 - 0.6

Wiebe (2010b) described the different forms of ice crystals in a different category as presented in the table 4, and stated that the needle-shaped crystals are the most problematic form of ice crystals for the railways (and other modern transportations), as they tends to build networks with other needles rapidly and extensively:

Table 4-Different forms of ice crystals (Wiebe,2016b)

Shape	Description	Dimension	Formation details
	Simple flat crystal plates with grooves	1.4 mm	0 °C to -3 °C -20 °C and below (smooth facets if low dampness)
	Flat crystals with structured facets and very symmetrical	2.1 mm	-15 °C to -20 °C
	Star-like dendritic (more branched) crystal	3.0 mm	In high relative dampness and temp. between 0 °C to -3 °C and -10 °C to -20 °C
	Simple, hexagonal, pin-like crystals with internal cavities and closed ends	0.45 mm	-5 °C to -10 °C -25 °C and lower
	Needle shaped crystals. In form of hollow cylinder with closed end(s)	1.1 mm	Around -5 °C
	Covered pin-like crystals. Hollow cylinder with star-like plates at ends	0.6 mm	-



### WORST WINTER SCENARIO

The worst winter conditions are described differently in different resources. In general, snow, low temperature, wind or combination of them would make different conditions for railways in various regions. Though, there are specific conditions which might be even more challenging. According to Kloow (2011) and interviewed individuals, railway operations are mostly harmed in cases of heavy snowfalls, especially when snow and wind are combined together: Heavy snowfalls call for intensive snow clearing measures, which is solely a challenging task. Wind can make the situations even worse by counteracting snow clearance and causing trees to fall on the tracks and electrification lines. In addition, three specific conditions are widely perceived to be problematic for winter operations:

#### **Dry snow**

Fresh and dry snow is one of the most problematic issues for the railways during the winter periods. Due to very fine particles and its light weight (Typically  $0,1 \text{ g/cm}^3$ ), dry snow can be blown by either wind or the air flow caused by passing trains, and might lead to various problems (Bettez, 2011; International Union of Railways, 2011; Jernbaneverket, 2016b; Kloow, 2011).

- **Snow smoke** (also referred to as cloud of snow)

Due to the air flow generated by passing trains, fresh and fine grained snow can be blown, and will whirl around the train while in motion (Bettez, 2011; International Union of Railways, 2011). The surrounding snow particles might lead to many technical problems in vehicles due to increased snow-packing and penetration of snow into critical areas.\*

- **Drifting snow** (or Blowing Snow)

Strong winds can make dry and loose snow to roll and bounce above the ground. The subjected snow can be either accumulated snow lifted from the ground surface, or it can be the falling snow. This phenomenon is a threat to both the rolling stock and the infrastructure. Drifting snow increases the snow-packing and risk of penetration to vulnerable areas in rolling stocks. Moreover, it counteracts the anti-icing and snow clearance measures on the tracks. Switches, even the heated ones, would get filled

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\* Such issues are explained thoroughly in Chapter 5- Winter issues

with snow again, shortly after cleaning, as it was the case in North America during the winter 2013-14 (Kelly, 2015).

### **Changing Temperature**

One of the facts that makes winter operations more challenging is that a train might encounter several climate conditions while running on a line (Bettez, 2011; Kloow, 2011). Weather conditions might be totally different during a journey, which is a common case in Norway. A train might pass through areas with extremely low temperatures and heavy snow, to some points with mild weather and higher temperatures. It is the same when trains pass through long tunnels with higher temperature and humidity in the middle. Temperature changes can be harmful to the rolling stocks in two main ways:

- **Intensifying snow accretion and ice build-ups**

Changing temperature can intensify ice accretion and snow accumulation on the vehicles. For instance, in situations in which a snow-covered train passes through a warmer region or a long tunnel with temperature above zero, the heat can cause the snow to melt. The water from melted snow might reach into sensitive systems and cause defects, or if not, when the train runs through the cold and snowy areas again, the wet surface can cause more snow to stick to the train components. Besides, the water from the melted snow can turn into hard ice. Similarly, when a train stops and the heat from the brakes or other hot parts melts the snow, the same scenario is likely to happen (Kloow, 2011). In a different scenario that has been frequent in Norway, even in the absence of snow, the combination of cold surfaces of the trains due to low ambient temperatures outside the tunnel, and high relative humidity level inside the long tunnels, has led to condensation and frost on trains' outer components (Jernbaneverket, 2016b).

- **Temperature shock**

The other issue with fast changes in temperature is the probable impacts on the trains' systems. Fast changes in temperature might be out of the tolerable design thresholds of the systems and can lead to failures. According to ref. EN 50125-1, in Norwegian tunnels, temperature gradients of more than 3 degree K/s and temperature variations of more than 40 degree K occur seldom (Jernbaneverket, 2016b). Though, European Railway Agency (ERA) in TSI (Technical Specification for Interoperability) has

stated that a maximum sudden variation of 60 °C in temperature shall be considered in train designs to avoid any unfavorable reaction (Kloow, 2011).

### **Avalanches**

Avalanches are common occurrences in mountain landscapes with significant annual snowfall and lack of vegetation. Precipitation patterns and intensity, as well as wind and heat condition are contributors to formation and occurrence of avalanches (McClung & Schaerer, 2006). The danger of avalanches is generally low in periods of stable weather, but will rise with increasing winds, snowfalls and variations in temperature (Jernbaneverket, 2016b).

Avalanches can cause serious damages to the railway infrastructure, or might close the lines by entirely covering the tracks. Running into masses of snow after an avalanche can increase the risk of train derailment as snow debris might have several meter height on the mountain side and just a meter on the valley side that can lift the train off the track. Another reason that makes avalanches more problematic is that they might happen shortly after snow clearance and inspections, so if not detected, there is a risk for trains to run into it.



### CLIMATE CHANGE AND FUTURE CLIMATE VULNERABILITIES

Depending on the region, climate change is likely to have both beneficial and adverse impacts on transportation systems. Therefore, since the influence of weather phenomena and their occurrence trends is not the same everywhere, different regions will need to respond to future changes in different ways (Pekka Leviäkangas & Michaelides, 2014).

Observing the present climate and projected future climate show that the occurrence of cold extremes, blizzards, snowfall and frozen precipitation are expected to decrease in many European countries, which means that transportation industry in Europe would benefit from milder winter conditions in the future (French et al., 2010; Pekka Leviäkangas & Michaelides, 2014; Vajda et al., 2012).

An issue with frequent mild winters is that it will probably reduce the level of preparedness of rail authorities, which then increases the consequences, if severe winters do occur (Doll et al., 2014; Vajda et al., 2012; Vajda et al., 2014).

Moreover, in Scandinavia and other countries in Northern Europe, decrease in number of days with extreme low temperature, means that the likelihood of days with temperature near 0 °C will raise. This means that the railways need to deal with higher probability of freeze-thaw cycle that can oppose negative inferences, at least for the infrastructure. Furthermore, heavy snowfalls are most likely to occur around this temperature, so it is projected that the probability of extreme snowfall would increase (Vajda et al., 2012).

Another concern with climate changes and increasing temperature is the thawing of permafrost. Permafrost is referred to a frozen ground that has remained at or below 0 °C for more than two years, and is a widespread phenomenon in the Arctic, and occupies almost 24% of the land area in the Northern Hemisphere. In the past decades the European permafrost has shown a warming trend, with greatest rates in Svalbard and Scandinavia; and this warming trend is projected to continue. Many railways infrastructures are located in permafrost areas. This fact makes thawing of permafrost a potential threat to railways as it might cause rail degradation, uneven ground settlement, increased risk of landslides, ground subsidence and flash floods from bursting glacial lakes. (Anisimov & Reneva, 2006; Füssel & Jol, 2012; Zhang, Heginbottom, Barry, & Brown, 2000).



### THE IMPACT THRESHOLDS FOR ADVERSE WEATHER PHENOMENA

Not all the winter conditions have the same effect on the railways. Therefore, predicting the probable consequences of different weather conditions, and indicating thresholds for each weather phenomena can provide valuable information for transportation authorities. Such information would allow them to make better decisions in case of harsh winters, as well as for improvement plans in order to establish a more reliable and resilient transport system. Within the “7 FP project EWENT” conducted by Pekka Leviäkangas et al. (2011), extreme weather events and their impacts and consequences have been thoroughly studied. According to the results of that project, the winter weather phenomena have been categorized into three thresholds based on their probable impacts (Juga & Vajda, 2012; P Leviäkangas et al., 2012; Pekka Leviäkangas, Sirra Toivonen, Pertti Nurmi, & Silas Michaelides, 2011; Vajda et al., 2012; Vajda et al., 2014):

- First threshold: Unfavourable impacts are possible, especially if the level of resilience and preparedness is not sufficient. (the probability of experiencing unfavourable impacts is set to 33%),
- Second threshold: Some adverse impacts are likely, and the severity of disturbance is depended on the resilience of the transport system. (the probability of adverse impacts is 66%),
- Third threshold: The weather phenomena are severe enough that certain adverse impacts are expected (the probability of being negatively affected is 99%).

All modes of transportation have been involved in defining these thresholds. Though, this report will focus on the impact thresholds from the railways’ point of view. The thresholds, and their expected impacts and consequences on railways are extracted from various publications related to EWENT project and are presented in the tables 5.

## CHAPTER 4 – WINTER PHENOMENA & IMPACT THRESHOLDS

Tables 5 - Critical impact thresholds for winter phenomena, Pekka Leviäkangas et al. (2011)

<b>Snowfall</b>		
<b>Threshold</b>	<b>Impacts</b>	<b>Consequences</b>
<b>SF ≥ 1 cm/24 h</b>	snowfall of 1–2 cm is less harmful for rail traffic.	If it is together with low temperatures and strong winds, it may impact rail transportation.
<b>SF ≥ 10 cm/24 h</b>	Reduced friction and slipperiness, rail switches may get stuck.	Delays and cancellations in rail traffic is probable.
<b>SF ≥ 20 cm/24 h</b>	accumulated snow banks. Poor visibility.	Plenty of delays and cancellations of trains might occur.

<b>Wind gusts</b>		
<b>Threshold</b>	<b>Impacts</b>	<b>Consequences</b>
<b>WG ≥ 17 m/s</b>	Trees can fall down over the railway and electricity lines.	Local problems in rail traffic.
<b>WG ≥ 25 m/s</b>	Plenty of fallen trees. widespread damage. Reduced visibility due to the blowing snow.	Electricity cuts, delays and cancellations in rail traffic.
<b>WG ≥ 32 m/s</b>	Huge amount of fallen trees, wide and long-lasting power failures. Damage to traffic control devices and structures, Reduced visibility	Delay and cancellation in rail traffic, Some railway lines might be closed for several days due to power failures

<b>Low Temperature</b>		
<b>Threshold (daily mean)</b>	<b>Impacts</b>	<b>Consequences</b>
<b>T ≤ 0 °C</b>	Ice formation commences, form of precipitation can be rain, sleet, snowfall, freezing drizzle.	The occurrence of freezing drizzle might be hazardous. Low temperature combined with precipitation and wind can have a disruptive affect on traffic.
<b>T ≤ -7 °C</b>	Rail points may get stuck by drifting snow	delays and cancellations in rail traffic are probable
<b>T ≤ -20 °C</b>	Freezing devices and fuel, Dangerous wind chill conditions occur when moderate winds prevail.	Delays and cancellation, Limitation for personnel working outdoors, fuel problems

<b>Blizzard</b>		
<b>Threshold</b>	<b>Impacts</b>	<b>Consequences</b>
<b>SF ≥ 10 cm/24 h WG ≥ 17 m/s T ≤ 0 °C</b>	Fallen trees, snow banks, slippery surfaces, poor visibility, rail points may get stuck.	delays, and cancellations in all transportation modes might happen.



## **CHAPTER 4 – WINTER PHENOMENA & IMPACT THRESHOLDS**

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- ✓ In this chapter, different winter phenomena and their frequencies and expected consequences are reviewed from the railways perspective. The worst winter scenarios, and future climatic changes and the associated concerns are discussed. And finally, critical impact thresholds for various winter phenomena and their probable impacts and consequences on railways are introduced. Some of the findings from this chapter will be used further in the part 4, where the impacts of low temperature on punctuality of trains are investigated.





## CHAPTER 5 – WINTER ISSUES

An important step in assuring the quality of railway services during the winter seasons, is identification of root causes that might disturb the optimal operations.

In general, especial winter conditions and safety measures, might slow down normal processes, which can lead to loss of optimality. Moreover, disturbed functionality of any of the railway systems, can directly or indirectly cause disrupted operations and subsequent delays.

Being aware of probable issues that might arise in winter seasons, is considered as a prerequisite for figuring out the effective solutions for eliminating them. Accordingly, in this chapter, the problems that have been experienced during the past winters are gathered. The former studies by Kloow (2011), Bettez (2011), as well as publications by railway companies such as UIC, beside interviewed individuals have been the main resources.

Technical issues and malfunctioning in both rolling stocks or infrastructure, are investigated, and the results are explained separately. In the end, the winter issues related to rolling stocks and infrastructure are summarised, and listed in form of separated tables.



### ROLLING STOCK PROBLEMS



Rough operational conditions in cold winters increases the risk of technical failures in the rolling stocks. Serious damages to the trains can stop them from proceeding on the tracks, and smaller problems will require a time to be fixed, which puts the vehicles out of service and causes lack of rolling stocks to serve the network. Another issue with winter operations is the inevitability of speed reductions in some areas in order to guarantee the safety and passenger comfort. Moreover, prolonged stops at the stations, as well as lengthened time for train formation and preparation processes have been some other common cases during the winters.

This section reviews the predominant winter issues affecting the rolling stocks:



### **Snow packing**

Snow cloud and drifting snow can lead to considerable amounts of snow stick to the trains exteriors. Packed snow and ice in the bogies and the under-frame, is a frequent problem which can negatively affect the railway traffic (Vajda et al., 2014). According to Kloow (2011), referring to the Railway Technical Research Institute, Snow packing is likely to happen, when the snowfall exceeds a certain limit (3 cm) and the ambient temperature drops below  $-4^{\circ}\text{C}$ .

Masses of snow can block the designed movements in springs, dampers and tilting mechanisms, resulting in damages to the components. In addition, increased weight due to accumulated ice and snow, beside blocked movements can interrupt the running dynamics of the vehicle and might force the drivers to reduce the speed. Moreover, access to the parts which require maintenance will be problematic which make the maintenance processes take longer time. Furthermore, snow packed in brake systems can lead to longer braking distance, which calls for lower operation speed. Additionally, masses of snow or ice might fall from the undercarriage and cause ballast pickup, or might hit switches or road crossings, causing damages to the infrastructure.



### **Suspension system and tilt mechanism**

The suspension system and tilting mechanisms (whether active or passive) are designed to absorb track forces, and to compensate centripetal forces when rounding the curves. This will provide a good running dynamic and prevent large lateral deflections. Though, limited movements in these systems due to stiffer springs in low temperatures and snow-packs, can make the operators to reduce the speed to maintain the safety and passenger comfort.



### **Under-frame equipment**

Under-frame components are constantly subjected to external threats such as humidity and extra low temperature. Moreover, they are frequently hit by ballast, hard snow, ice, carcasses, and other debris on the track. Higher intensity of such phenomena makes them more vulnerable under winter condition.



### **Wheel-Rail friction**

The adhesion characteristic of wheel/rail interface has a great influence on the wear rate, rolling contact fatigue, noise generation, running stability, security, and general

performance of operations, and inappropriate friction coefficient can highly affect the service performance (Olofsson, 2007; Olofsson & Lewis, 2006; H. Wang, Wang, & Liu, 2016). Acceleration and deceleration capabilities of rolling stocks are highly dependent on the adhesion level between wheels and rail (H. Wang et al., 2016; W. Wang et al., 2014). It is while varying weather conditions can affect the adhesion coefficient (Nilsson, 2003; Olofsson & Telliskivi, 2003):

- Frost, mud, and wet surfaces, would significantly decrease the adhesion coefficient (Collins & Pritchard, 1972; Olofsson, 2007; Olofsson & Lewis, 2006; H. Wang et al., 2016). Inadequate friction can lead to extended-stopping distances when braking, causing safety issue due to increased risk of passing signals and station overruns (Baek, Kyogoku, & Nakahara, 2007; Olofsson, 2007; Olofsson & Lewis, 2006; H. Wang et al., 2016). It will also affect the traction force when accelerating or climbing the slopes which will lead to lower performance, and even might increase the risk of a rear collision from a following train (Baek et al., 2007; Olofsson & Lewis, 2006). Moreover, the wheels sliding on the rail surface can cause damages to both wheel and rail surfaces (H. Wang et al., 2016; W. Wang et al., 2014).

- On the other side, a certain level of sliding is inevitable in the wheel-rail contacting zone. This is the reason for utilization of lubrications, to keep the adhesion level within the desired limits. An issue here is that available lubrications are being used under different weather conditions, and are expected to give the same result throughout the year. It is while varying temperature and relative humidity can have a pronounced effect on functionality of such friction modifiers by for example changing their viscosity, and affecting their durability and effectiveness (Lewis et al., 2013; H. Wang et al., 2016). Because of that, higher friction coefficient between rail and wheel in the case of poor lubrication effects in winters, can also result in increased wear and higher risk of defects in wheels and rails (Kloow, 2011; Olofsson & Lewis, 2006).



### **Wheels**

Decreased humidity and excessive friction between the wheels and rails increase the wear rate. Moreover, running with stuck wheels or sliding driven wheels specially when stiffness of wheel and rail alloys is higher, make the wheels more vulnerable during the winters (Bettez, 2011; Caldwell, 2005; Y. Liu, Ladubec, Preston-Thomas, & Magel, 2008). Apart from reduced comfort due to flatted and shelled wheels which

requires reduction in running speed, damaged wheels can result in damaged axles' bearings, rail breakage or even derailment. According to Transportation Safety Board of Canada (2004), for the period of 1999-2004, 86% of derailments due to broken wheels in Canadian Pacific Railway has occurred in the winter time.



### **Brake systems**

During specific winter conditions, the functionality of brakes cannot be guaranteed. According to Kloow (2011), apart from slipperiness and lower adhesion between rail and wheels, in case of pneumatic brake systems, formation of ice plugs in the pneumatic system might block airflow through air pipes and hoses, which can cause pressure loss and consequently reduced brake effort. Though, the problems are not limited to pneumatic systems. During the past winters, Norway and Sweden have experienced reduced braking effort on trains equipped with disk brakes as well. The reason was that in case of snow smoke, a thin layer of water, ice or snow can form on the disks surfaces which reduces the braking performance. Moreover, snow and ice might block the moving parts which in the case of magnetic brakes, will prevent braking pads from falling down towards the rail. In another way, frozen moving parts might lead to unreleased breaks and subsequent heat generation in the wheels and under-frames components and cause subsequent damages.

In order to battle the longer breaking distances as the result of lower performance of brake systems, either train lengths should be shortened or speed reduction policies should be applied, which means lowering the service capacity and sacrificing the quality (Kelly, 2015).



### **Car body**

Some of the frequent problems with car bodies during the winter is that snow can cover the lights and front window, which reduces the vision over the track for the driver, and also decrease the visibility for other trains, cars, etc. These problems can all lead to accidents and consequence disruptions. Moreover, as mentioned by Hudoklin and Rozman (1996), poor visibility can increase “task related stresses” for the driver, that might result in higher mistake probability, which can negatively impact the normal operations. Another common winter-issue is with ballast pick-up or hitting icicles which might break the glasses and damage the body.



### **Doors and Steps**

Frost and ice buildup can cause problems for doors, including jamming doors (networkrail, 2016). Trains equipped with foldable steps might also face problems with stuck steps. Jammed or malfunctioned doors and steps will disturb loading and unloading processes and increases the stopping times. In addition to non-functioning doors, slippery steps makes the stopping times longer as the passengers need to be more watchful on slippery surfaces when entering or leaving the trains(Kloow, 2011).



### **Axle and axle boxes**

Getting hit by ballast following the falling ice and snow bulks from the trains might cause cracks in axels. Moreover, ballast stones might get stuck between a rotating axel and other fixed parts and scratch around the axel. Scratches and cracks can lead to axle failures and derailment. In addition, inappropriate sealing or ventilation holes in axle boxes might result in water and moisture to negate the lubricants, which results in shorter life time for bearings and risk of axle lockage. Furthermore, increased track stiffness in winters causes more wheel-rail forces which consequently results in damages in bearings and axle failures. Additionally, Ice and snow might stop movable parts in adjustable axles to move freely based on different track gauges which may cause damages to the rails and axles(Kloow, 2011).



### **Couplers**

Couplers, are also exposed to external phenomena like cold and hits, so are more vulnerable in winter conditions. Train formation processes might take extra time in winters. During the winter of 2009/2010 NSB experienced problems with coupling trains due to hardened lubrication and necessity of being de-iced before coupling the units (Bettez, 2011; Kloow, 2011; Wiebe, 2010a).



### **Cables, Hoses and pipes**

Cables, hoses and pipes which are exposed to external environment are subjected to impacts by macadam, low temperatures and extra weight of accumulated ice on them (Kloow, 2011). They also can get pressed and squeezed by accumulated snow and ice in the bogie areas. Moreover, the liquids inside the pipes and hoses might freeze in low temperatures. Eventually, disconnected cables or damaged hoses and pipes can result in serious technical problems for the rolling stocks.



### **Power cars, motors and electrical components**

Winter condition can threaten the locomotives in various ways: Snow can block the air intakes and cause over heated engines. Insufficient protection and sealing can result in snow finding its way into critical parts and damage the moving parts, or might cause short circuit, flashovers and electrical failures (Guss, 2014; Kloow, 2011). In December of 2009, 5 Eurostar trains broke down and suspended the train services for 3 days. The main reason was that the air intakes sucked the melted water and snow into the power cars and onto electrical components, causing failures in the power cars (Johnston, 2014; Smith, 2011). Moreover, due to the amount of ice and snow that trains bring into the workshops, the humidity inside the buildings can be relatively high. So when a train leaves the workshop, the moisture inside the motors and other electrical equipment is subject to condense in the cold weather. Furthermore, as anti-freeze chemicals cannot be used in locomotives, motors with water cooling systems might freeze when parked in low ambient temperatures if not protected with locomotive Auxiliary Power Units (APU) (Genesee & Wyoming Inc, 2016).



### **Current collection and pantograph**

The winter can affect the current collection in electric driven trains. Rime on the overhead wires or third rails increases the wear of the carbon strip due to arcing and the corresponding heat. In addition, modern traction control systems, are sensitive to arcing and might break down (Jackson, 2011). Moreover, hitting the icicles in tunnels, or trees which are sagged due to weight of snow are another threat to the pantograph mechanisms. Any damage or malfunction of the pantograph can easily cause the overhead wire to be torn.



### **Collision with big animals**

Collision with big animals in rural regions is a frequent problem during the winter periods. According to Jernbanestatistikk (2015), between 1500 and 2200 incidents with animal fatalities become registered each year with higher frequency in winter seasons. Moose and reindeers are the most frequent species involved in train collisions, as they prefer to move along the tracks than in the deep snow beside them (Kloow, 2011). Crashing with large animals can damage the train body and couplers, and dead bodies can go under the train and cause serious damages or even derailment.





### **Issues with maintenance**

There are a couple of issues with rolling stocks' maintenance in the winter seasons: As previously mentioned, there will be a higher demand for corrective activities due to more frequent defects. Moreover, inspection and maintenance processes will become more troublesome and prolonged as there would be a need for de-icing before taking any action. In addition, due to the cold weather, lots of measures will not be possible to be taken outdoor which means over occupied workshops. Furthermore, transfer of the broken vehicles, replacing parts and, maintenance teams might not be as easy as in normal condition (for example due to impassable rails and roads). All these issues will cause many of the trains to be out of service for a longer time and put too much pressure on maintenance teams with a compressed schedules.



### INFRASTRUCTURE PROBLEMS



Railroad infrastructures refers to the whole line network and all the stationary structures and components which facilitate the railway services. Based on the definition by Jernbaneverket (2012), Principal components of the infrastructure can be grouped as below:

- Track bed and structures: embankments, cuttings, bridges and tunnels.
- Permanent way: Ballast, sleepers, rails, switches and crossings.
- Electrification: High voltage electricity grid, overhead wires and feeder stations.
- Signaling and Telecommunication systems.

Similar to the rolling stocks, railway infrastructures are also exposed to various threats during the winters which can interrupt their flawless functionality, and hamper the normal operations. In this section, the major winter-related problems that will affect the railway infrastructures are reviewed:



#### **Snow accumulation**

During the winter, accumulated snow on the tracks can slow down the services due to increased running resistance. Moreover, it has happened that trains got stuck or became derailed and block the line. Considerable amount of snow following avalanches can also close the lines. In the worst case, the railway structures might collapse under weight of snow.

As it was mentioned before, operating the trains on snow covered tracks might result in snow to penetrate into the critical areas, and ice lumps hitting the trains, may damage rolling stocks. One of the major tasks for the infrastructure administrators in winter seasons, is to regularly clean the tracks by using different machineries. Snow clearing processes demands considerable amount of time and effort, which depending on the access to the tracks and amount of snow, might disrupt the normal operations. Another challenge in case of significant snowfall is the lack of space for disposing the cleared snow. One of the experiences is that in narrower cuttings, despite of cleaned rail, hitting the disposed ice on the sides of track caused damages to the passing trains.



### **Tunnels**

Tunnels, as an important element in railways infrastructure, not only accelerate rail travel, but also help to make the infrastructure less vulnerable to natural hazards (Doll et al., 2014). Conversely, narrow space in the tunnels and risk of collusion with icicles, beside issues with temperature changes and high humidity levels can make the tunnels a problematic part of railway lines. Moreover, temperature variance in tunnels might cause snow and ice to fall off the trains and damage the infrastructure elements and the train.



### **Platforms, Stations and parking spaces**

Accumulation of snow at stations can disturb the accessibility for passengers and vehicles. Ice and snow will make the ground slippery and as a consequent, the simple acts of boarding and alighting would take extra time. Longer stopping times at the stations lengthens the total travelling, and can lead to disruption in networks.



### **Rails**

- **Rail degradation:** Even during the winter, there are some periods when the temperatures reaches above zero and thaws the snow. If the water is not properly drained from the track, it will remain and freeze again when the temperature drops. Freezing water in the ballast can result in “frost heave” which expands, and moves the track beds, and can cause track geometry irregularities. Track degradation increases the track force that beside disturbing the ride quality and lowering the speed, can result in derailment in the worst case (Doll et al., 2014; Faiz & Singh, 2009; Jernbaneverket, 2016b; networkrail, 2016).
- **Broken Rails:** Tracks are more vulnerable in winters and most broken rail incidents occur when the ambient temperature is extremely low (Brabie & Andersson, 2008; Juntti, 2011; Y. Liu et al., 2008; networkrail, 2016; Transportation Safety Board of Canada, 2004). The low-temperature increases the track stiffness and stimulates thermal tensile stresses in the CWR (continuous welded rail) tracks. Higher stiffness and reduced strength, in combination with increased wheel-rail force (especially when some of the wheels are flatted and hit the rail repeatedly) and higher tensile stress, can increase the risk of broken rails in winters. A secondary problem

with broken rails is that some signalers use a circuit through the track for recording the position of trains on the track. So with a track circuit failure as a result of broken rail, the trains must stop until the problem is fixed (networkrail, 2016). Broken rails will close the lines, and speed restrictions in low temperature is a common practice for minimizing the risk of rail breakage (Brabie & Andersson, 2008; Caldwell, 2005; Y. Liu et al., 2008).



### **Switches and crossings**

Malfunctioning switches is the most common reason for infrastructure-related troubles during the winter periods (Doll et al., 2011; Juntti, 2011; Kelly, 2015; Kloow, 2011). According to Juntti (2011) 25 % of all of failures in section Boden – Gällivare in Sweden during the period 2006 to 2010 were related to switches and crossings. Switches play a very critical role in railways, and any failure in their functionality can result in considerable disruptions in the network. Though, switches are very vulnerable components under the winter conditions. Snow build-ups falling from the running trains can easily damage the switches. Moreover, due to frozen parts and compacted snow or ice in their mechanisms, the moving parts might get stuck and fail to move when needed.



### **Ballast**

Ice build ups falling from the passing trains (Especially High speed trains) can make ballast to lift from the ground which can result in expensive damages to the trains and other equipment along the rail. Ballast pickup at the stations might also cause injuries to humans.



### **Overhead wire and third rail**

Damages to overhead wires or catenary is more common in winter times, in comparison with other seasons (Jackson, 2011; Kloow, 2011). Heavy snow or strong winds might result in broken trees which can seriously damage the overhead lines. In addition, ice formation on catenary might hinder current conduction to the pantograph which leads to consequent speed restriction and damages to the electric systems of trains. Some of the problems with imperfect current conduction are overloading, flash-over, electric arc and wire galloping (due to non-uniform icing),

which consequently might result in damages to power cables and the train traction systems (Heyun et al., 2012). Moreover, as discussed in rolling stock section, pantographs are subjected to more failures in the winter-time, and a damaged pantograph in turn will increase the risk of tearing the catenary down. Similarly, if third rails get covered by ice, the current conduction will be affected and reduced speed and damaged traction motors can be the consequences.

- ✓ This chapter, based on the findings through interviews and previous studies, gathered and reviewed the main issues for both the rolling stock and infrastructure during the winter seasons. Two separated tables, presenting a summary of above-mentioned problems are attached to the appendices. In the next chapter, the available solutions for addressing these issues will be presented.





## CHAPTER 6 – WINTER SOLUTIONS

The previous chapter, reviewed and listed the main issues with operation of trains during the winters. The intention here, is to present the main measures which are being taken in order to address those problems. However, it should be kept in mind that not all the measures can be related solely to either of rolling stock or infrastructure, as both systems might have reciprocated impacts on each other.

The solutions for each of the rolling stock and infrastructure are presented in three categories:

- Design aspects,
- Systems and Equipment (and structures),
- Instructions and Actions.



### SOLUTIONS FOR ROLLING STOCK



#### Design Aspects

Many of the winter-related problems related to rolling stocks can be minimized or prevented through applying some considerations during the design phase:

- Obviously, all the components and equipment which are exposed to external environment need to be robust, and made of proper materials in order to withstand hits, humidity, extremely low temperatures and temperature changes without significant variations in their features.
- When designing the rolling stocks, additional weight due to snow and ice build ups needs to be involved in the calculations. This should take into account the sufficiency of traction power, and capability of braking and suspension systems for an unaffected performance. Moreover, all the external components (E.g. pipes, hoses and wires), should be able to tolerate the extra weight of probable snow and ice build-ups.

## CHAPTER 6 – WINTER SOLUTIONS

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- Better design regarding the shapes (round surfaces are usually preferred), and avoiding the stagnation points, could help minimizing the snow and ice build ups.
- Designing sharp edges between flat surfaces which are supposed to move towards each other is recommended, as it will break the ice and minimizes the risk of blocked movements.
- If possible, open designs are preferable as the wind can blow the snow away and the accessibility for maintenance activities would be easier.
- However, some parts will need to be protected in boxes. If the protection boxes are necessary, using large boxes, covering the entire under-frame in one piece, is preferred over having several boxes. This reduces the stagnation points where snow will easily accumulate. Though when designing the boxes, sustaining necessary accessibility for maintenance processes is crucial as it would speed up the maintenance activities and reduces the amount of time that trains go out of service.
- Considering aerodynamics aspects, as well as integrating spoilers and splash covers into the rolling stock design, can deflects the snow, melted water, or other particles from critical points.
- Sensitive and critical components should be designed to be placed, with minimum exposure to hits, humidity, snow and cold. It is the same for air-intakes for cooling system and cabin ventilation, which must be designed and located properly, so that they do not get filled with snow, or that the snow does not get inside them.
- In addition to appropriate placement, sufficient insulation and ventilation needs to be considered for protecting the components which are vulnerable to low temperatures and moisture (i.e. electrical control systems, etc.).
- Regarding the hoses and pipes, choosing big diameters are recommended, as water freezes easier in thinner pipes.
- Since the occurrence of defects cannot be completely eliminated, it is clever to have redundancy for critical components. It means that if one of the components stopped functioning, the second one would be available to immediately take its tasks over.
- The parts and sub-systems which are vulnerable and at high risk of damage (such as couplers and frontier body parts) should be designed in a way to be easily replaced.





### Systems and Equipment

- **Automatic protection systems**

There are several protection systems which can protect the rolling stock against damages, or will minimize the effects of initial malfunctions by immediate intervention. For example, anti-slide electronic systems are designed to intervene in the moments where a driving wheel spins irrespective to the train's moving speed. So it can eliminate any unwanted rotation of drive wheels, and thus protects them against probable damages. Or the emergency drop system (Auto drop device - ADD), will automatically lower the pantograph in case of a damaged carbon strip (Bettez, 2011; International Union of Railways, 2011; Kloow, 2011) . There are other similar systems that can be programmed to be activated automatically at special conditions, without human interference. For instance, brake systems can be programmed to automatically check the functionality of brakes, or apply the brake in intervals in order to secure the performance of brake systems by avoiding blocked movements and keeping the brake parts snow and ice free.

- **Detection systems**

Utilizing stationary (wayside) and on-board detection systems can help preventing serious damages by eliminating mitigation of minor malfunctions. To name a few, pantograph detectors can be used to constantly monitor the forces between the overhead wire and the pantograph, to ensure that it will not exceed certain limits. Hotbox detectors, are another example which are aimed to guarantee a flawless functionality of rolling stock by scanning the passing trains and detecting unusual heat.

- **Air dryers, filters**

Such systems come to help for the rolling stock subsystems, wherever humidity and moisture is a threat. For example, ice particles in hydraulic and pneumatic systems might cause problems, or sensitive electronic devices cannot stand the moisture. Thus, these are possible solutions to prevent malfunctions.

- **Heaters and ventilators**

Using electrical heating systems is a simple solution for keeping the ice and snow away. However, the high energy demand, and secondary problems with melted water, restricts the utilisation of heating solutions to highly crucial areas.

- **Electrical de-icing and Anti icing systems**

Bettez (2011) proposed Electric pulse de-icing and DC Bias anti-icing in which the first solution will break the ice by pulses, and the former avoids ice adhesion by changing the polarity of the steel surfaces. These systems can be utilized to keep the surfaces free of ice.

- **Deflectors and Snow ploughs**

Snow ploughs mounted on rolling stocks and integrated in their design, will help for removing the snow and bigger obstacles from the track. So they reduce the risk of damages and probability of derailment. However, there are few points to consider when designing the snow ploughs and obstacle deflectors. The first one, is to design them in a way that the air flow will not cause ballast to pick up, and the other is focusing on minimizing the snow-packing and avoiding the snow from gathering behind the rear plough.

- **De-icing boots**

Bettez (2011) by looking at airplane industry has offered the possibility of utilising de-icing boots for train bodies. In this system, a thick layer of inflatable rubber can be installed on the body of trains. This membrane then will be inflated using a pneumatic system and will shed the ice away. However, application of this system will be limited to car bodies, so it is not a promising idea for other critical parts of a rolling stocks.

- **Wheel-Rail friction modification systems**

The adhesion characteristic of wheel/rail interface is an influential factor in railway transportation, as acceleration and deceleration of vehicles will not be optimal without adequate adhesion (Lewis et al., 2013; Olofsson, 2007; H. Wang et al., 2016). Excessive friction level on the other hand, increases the risk of damages to the wheels and rails. Therefore, effective control of friction through the application of friction modifiers is clearly advantageous and thus, widely growing within the rail

industry (Lewis et al., 2013; Olofsson & Lewis, 2006). Friction modifiers help with reducing the wear rate, as well as keeping the tangential forces low enough to allow heavy loads to move with minimum resistance, and high enough to support traction, braking, and steering of the trains (Olofsson & Lewis, 2006).

Olofsson and Lewis (2006) have presented three categorizations for friction modifiers as below:

- Low coefficient friction modifiers (in form of solid or liquid lubricants)
- High friction modifiers (providing high positive friction (HPF))
- Very high friction modifiers (friction enhancers, providing very high positive friction (VHPF) for both traction and braking).

The applications of friction modifiers can be achieved by utilising two systems: Sanding and lubricating systems:

**Sanding systems:** In case of low friction, application of sand as an adhesion enhancer is the most globally common solution to achieve sufficient traction and braking force in winters (Olofsson, 2007; Olofsson & Lewis, 2006; W. Wang et al., 2014). The sanding systems are generally mounted on rolling stocks (W. Wang et al., 2014), in which compressed air is used to blow the supplied sand on the train, through a nozzle attached to the bogie, and heading towards the wheel-rail contact. The sand-spraying can be initiated automatically, as an integrated process when applying the emergency brake, or can be controlled manually by driver when more traction force is needed (Olofsson & Lewis, 2006).

Applying sand is effective and easy. Though, it can cause further problems for rolling stock and track infrastructure, especially since it increases the wear rates of both wheel and rail materials. Moreover, maintenance of sanders, and dealing with sand build-up on the track are also issues that require particular attention (Olofsson, 2007; Olofsson & Lewis, 2006).

**Lubricating systems:** Lubricating processes, with the purpose of reducing the problems associated with high friction coefficient, are possible through three different methods for applying the lubricants (Liquid or solid) on the wheel-rail contact surface (Olofsson & Lewis, 2006):

- Mobile lubricators (by special vehicles which are designed for this purpose)
- Wayside lubricators (mounted next to the track and apply lubricant to the rail)
- On-board lubricators (an on-board system to rub/spray lubricants on to the wheel, which is then transferred to the rail.)

Among these, the on-board lubricating is the most common, and Norwegian National Railway Administrator (NNRA) expects that rolling stocks are equipped with lubricating systems and does not have lubrication equipment mounted on the track (Jernbaneverket, 2016b).



### Instructions and actions

- **Surface coating and covering**

Surfaces that need to be free of snow and ice can be protected, by utilising proper covers or special coatings:

Special coatings can avoid ice formation on surfaces through reducing the adhesion; And anti-icing chemicals can be used for the same purpose through creating a protective film which can either reduce the freezing temperature or avoid the ice and snow from sticking to the surfaces. However, short term durability of such materials on surfaces is a downside; moreover, surface coating or covering is not always applicable since some parts such as brake disks cannot be covered (Bettez, 2011).

Mounting covers (made of plastic, Plexiglas, etc.) which are deformable, elastic or vibrant can mechanically crack the ice and make them fall off. Another functionality of covers would be to provide mechanical protection and absorb the external impacts (E.g. on brake disc, suspension springs, etc.). Though the disadvantage of using covers is that they make the visual inspection difficult.

- **Ice and snow removal (De-icing)**

Despite all the above mentioned solutions for avoiding the ice and snow to build up on rolling stocks, there will be a need for de-icing and snow removal actions prior to maintenance measures, and to maintain the proper performance in operation.

De-icing is considered as a time-consuming and expensive process which requires lots of space and energy. Several mechanical, thermal and chemical methods are suggested to be performed at appropriate intervals in order to clean up, or to reduce further build-up of snow and ice. These methods vary from using direct flame, spraying liquids with high pressure, or living the trains in warm rooms, etc.

Among all the methods, de-icing by Propylene glycol is said to be simple, cheap, fast, environmentally friendly, and energy efficient method, which also provides anti-icing effects. The propylene glycol can be manually sprayed, or especial equipment can be

mounted at different points in the network. As an example, Kilfrost entered into collaboration with Nordigse (Nordic Ground Support Equipment) in 2011, and developed the “Nordic anti-icing system” which have become widespread in many countries (Wordsworth, 2013). According to managing director of Nordigse (2016), there are 5 Nordic anti-icing system in operation in Norway: 3 in Oslo, 1 in Drammen and 1 in Skien, and the information from the Norwegian railways is that they are very satisfied with these facilities.

- **Inspections and maintenance**

Not all the defects can be detected by detecting systems, so there would be a need for shortening inspection intervals, to be performed manually during the winters. Moreover, due to higher probability of damages, limited space in workshops and necessity of having more available trains, it is recommended to have all the interval maintenance before the cold season begins. So the fleet will be in their best condition, and maintenance activities would be limited to correcting the defects.



#### Design aspects

Several considerations within the design aspects of infrastructure will help having a more reliable & robust railway system against winter conditions:

- The first and the most initial aspect in reducing the winter related problems, is to minimize the exposure of railway networks to the winter threats. Thus, in depth investigations on geographical and climatic characteristics of each region during the early phases, will assure that the networks will be exposed to as minimum threats as possible through finding the best locations for building the lines.

- Designing the railway networks with sufficient capacity to meet the transportation demands without being saturated, is an obvious but not always realistic solutions. However, designating more indoor depots for parking the trains will reduce the problems caused by exposure of the trains to sub-zero temperature over a long period of time (Bettez, 2011).

- When designing the railroads, enough space for snow storage needs to be considered. In other words, having wider cuttings, will provide sufficient room along the tracks for disposing snow. The same applies for yards and stations, which calls for having designated area for the ploughed snow.

- Improved design for infrastructure sub-systems in order to increase their robustness against winter phenomena will reduce the need for protection, maintenance and decrease the risk of malfunctions. For example, the rail switches need to be designed in such a way that they can perform perfectly under any possible circumstances.

- In some cases such as in open lands, raising the track above the ground is recommended, as wind can blow the snow away from the tracks, so less snow clearance activities will be required.

- As discussed earlier, the space in workshops is limited, and at the same time the need for maintenance activities on rolling stocks is higher in the winter time. It means that more trains will be waiting to get maintenance services. Thus, considering some extra free tracks for parking the trains which are waiting for repairs will prevent disturbed services as a result of trains being parked all over the network.

-When designing and building the infrastructures, accessibility to the track and yards for both personnel and machineries, is another important point to be taken into account.

-In order to tackle the problems related to ballast pick-up there are some solutions recommended: Designing the concrete beds (also referred to as slab-track) instead of traditional ballast is considered to eliminate the risk of ballast pick up. However, higher monetary demand, difficult maintenance and higher noise pollution are some of the drawbacks which makes railways to only concentrate on shortening (and not avoiding) the ballast tracks. Other solutions are lowering the macadam ballast level (approximately 3-5 cm below top of the sleeper) and decreasing the distance between sleepers which are widely being practiced.

- Selection of more modern material for rail alloys is said to reduce the risk of damages to both rail and rolling stocks due to increased stiffness in low temperatures, as well as reduced wear rate and enhancing the running comfort.

-Regarding the tunnels and in order to avoid the issues related to temperature changes, extremely long tunnels either should be avoided or ventilation aspects should be considered in their design.



### **Systems, equipment and structures**

- **Barriers, fences and protections**

In those parts of the lines where avalanches, a lot of snow and wind and snow drift are probable, erecting permanent or temporary physical barriers, such as walls, snow sheds, fences and tunnels, as well as afforestation are said to give protection to the tracks against impacts of avalanches and drifting snow (Doll et al., 2014; Kelly, 2015; Wanek-Libman, 2012). The (figure 4) illustrates different forms of barriers (Noguchi & Fujii, 2000). Erecting fences and walls along the tracks is also another task to do by infrastructure administrators for preventing big animals from trespassing on the track and crash with passing trains.

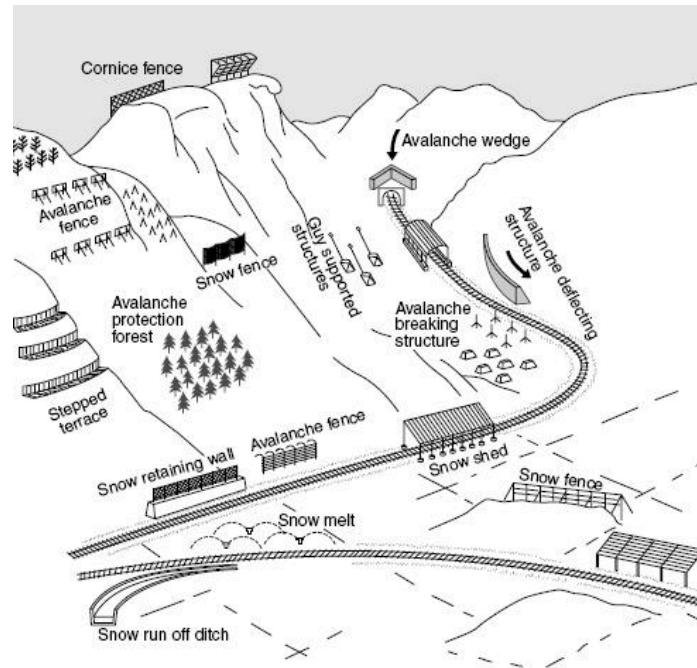


Figure 4 - Physical barriers (Noguchi & Fujii, 2000)

Fences and barriers are highly used in Norway, and specially in Bergensbanen. The justification can be that, in addition to all the considerable benefits that this solutions offer, they usually require small investments and can be erected without interrupting the networks operations (Bettez, 2011).

- **Automatic weather stations**

Being aware of real-time weather elements can facilitate in time and precise interventions. Having automatic weather stations, capable of measuring the temperature, snow depth, wind speed, etc. will be a privilege for infrastructure practitioners.

- **Ballast nets**

Covering the ballast with nets at critical points is suggested and practiced as a simple and cheap solution in cases where concrete beds are not used.

- **Switch heaters and protections**

Every railway network has a huge number of switches (on average about 200–400 switches per 100 km network) (Doll et al., 2014). Switches are a critical part of the railways' infrastructure, and their flawless functionality needs to be guaranteed through special considerations: Erecting snow fences and sheds can give a relatively good protection against snow drift at critical sections. However, they will not help



with issues related to falling snow and blocked movements due to freeze. Thus, pneumatic and thermal solutions are introduced for protecting the switches. A very common practice is to use electrical heaters for melting the ice and snow that gathers around the switches. Choosing the appropriate heating power, besides the possibility to turn the switches on and off according to the conditions are two key factors to be considered. In order to eliminate the further issues with melted water, the drainage systems around the switches should be effective, and motors and mechanisms need to be sufficiently sealed against water penetration so the freezing water will not cause blocked movements.

Furthermore, a product by Midwest Industrial Supply group (2015a) offers chemical solutions based on glycol-based fluids, which is said to be more efficient than heating methods. The system can be activated remotely when needed, and the supplier claims that it prevents switches from freezing in the temperatures down to  $-56^{\circ}\text{C}$ .

In addition, mounting different kinds of switch covers and spoilers (made of rubber, or in form of brush, usually in combination with other methods) are said to help keeping the switches functioning by deflecting the snowdrift, and insulating the heat generated by switch heaters.

The problem with covers is that they cannot entirely cover the movable parts; and they might get broken or become loose after getting hit by falling ice from the trains, or the strong turbulence streams under the passing trains.

However, in cases of heavy snow or when big pieces of snow build-ups fall off the trains on the switches, there would be no other choice than performing the manual cleaning by maintenance teams or driver as a dangerous and time consuming process.

- **Heating systems for current collection components**

Besides the manual cleaning, or chemicals de-icing methods, and when the heat generated by friction is not sufficient to clean the contact wires and third rails, utilization of resistive heating systems and heating strips are suggested. Resistive heating systems are being used in railway and tram systems in Japan, France, South Korea, China and the UK (Heyun et al., 2011; Heyun et al., 2012; networkrail, 2016). Additionally, Heyun et al. (2011) proposed a system called “expert system” that can control the heat in accordance with meteorological parameters such as air temperature, relative humidity and wind speed.

- **Sprinklers and slush-mixture pumping systems**

With the purpose of keeping the tracks free of snow, and eliminating the issues with disposed snow, sprinkling system have been practiced in some parts of Japan. It works as a cycle of spreading hot water on the track, recollecting it and heating it again to be sprinkled again. As an alternative for getting rid of snow, slush-mixture pumping system has been installed in Japan. In this system, a conventional rotary snow removal train, dumps the snow in designated gutters along the track. Then, the snow will be mixed with water and disposed to a nearby river (Bettez, 2011).

- **Track drain systems**

Variations in ambient temperature and rising to over zero, as well as the heat generated by heaters (E.g. switch heaters) and rolling stocks can also melt the snow. The water can freeze again and result in blocked movements or rail degradation. Thus, in order to minimize the risk of rail degradation, and to maintain the necessary movements, it is crucial to have effective drain systems that can keep the area free of water.

- **Avalanche warning systems**

Avalanche warning system is a solution for predicting the avalanches, where a permanent solution is not in place, or is not feasible at all. The occurrence of avalanches can be forecasted by processing data related to snow-cover, meteorological conditions, and the terrain, which are usually gathered in a platform called Geographic Information System (GIS) (Jaedicke, Syre, & Sverdrup-Thygeson, 2014). When a high risk of avalanche is forecasted, helicopters and explosives can be used to trigger controlled avalanches when the trains are not running; and the debris can be removed under safe condition (Kelly, 2015; Wanek-Libman, 2012).

Utilization of avalanche warning systems in Norway began after Norwegian Geotechnical Institute (NGI) established the Fonnbu station in 1973, and a new national warning service, is being used since 2013, that covers 22 selected mountainous regions (Engeset, 2013; Jaedicke, Kristensen, Lied, & Bakkehøi, 2008).

- **Avalanche detecting systems**

Avalanche warning systems are aimed to forecast avalanches before they occur. However, being aware of where an avalanche has occurred (and its severity) can also eliminate the risk of trains getting stuck or becoming derailed after running into snow

masses. Besides, infrastructure administrators will be able to take the clearing measures in a good time.

- **Monitoring and measurement systems**

Specific and advanced monitoring processes are only possible manually. Though, automatic or semi-automatic monitoring systems can facilitate continuous identification of defects in real time (Baker, Chapman, Quinn, & Dobney, 2010; Doll et al., 2014; Lindgren, Jonsson, & Carlsson-Kanyama, 2009). Regular and in-time detection of defects in any of the systems can help railway companies with providing better services through facilitating preventive maintenance actions and minimized maintenance time.

Regarding the infrastructure, utilising remote monitoring systems in many cases will minimize the need for site visits, as they provide maintenance personnel with information about the problem and its exact location. As an example, Sno-Net® connectivity is widely being used to monitor the switches in remote areas in North America (Kelly, 2015; Sneider, 2011).

Monitoring and measuring systems as a part of railways infrastructure can also be used for checking the passing trains. Utilizing train way-side monitoring systems have shown promising results, such as fewer occurrence of derailments due to defected wheels (Stewart, 2012). Various levels of train monitoring systems, based on infrared thermography, laser scanning, and ultrasonic audio analysis and video camera controls have been developed which are capable of identifying the defects in dynamic condition and while the trains are in motion: Hot box detectors, and wheel impact load detector are some of the most common systems that are installed at different points (approximately 40 km apart) along the rail (Brabie & Andersson, 2008) to check the status of wheels, bearings and brakes.



### Instructions and Actions

- **Snow clearance**

The need for snow clearance is a common issue in winter time, as it is necessary to remove the accumulated snow from the tracks, tunnels, yards and platforms before it causes serious problems.

The location, accessibility and amount of snow, determines the type of machinery and method to be used:

For example, snow removal at **yards** can be performed by using graders, loaders, tractors and excavators (Wanek-Libman, 2012). Though, due to higher demand for space for parking the trains waiting for repairs, removed snow cannot be pushed to the sides and needs to be transported away. In order to ease the disposal, a new method has been developed in Sweden, which a machine sucks the snow in, and melts it with warm water. The melted water then is stored in tank wagons and can be emptied as surface water (Kloow, 2011).

Regarding the **tracks**, passing trains, and especially those with heavy locomotives can to some extent deal with snow as they can clean the snow off the track while running normally (Jernbaneverket, 2016b). Thus running empty trains during the night, and using locomotives before, or ahead of multiple units are commonly practices in order to help keep the tracks clear (Kloow, 2011).

However, according to Scotland's online railway community (2013), when the snow depth exceed 20-30 cm, trains are required to be equipped with proper snow ploughs. Different types of snow ploughs exist which need to fit the specific regional and operational conditions: Miniature snow ploughs will allow trains to keep operating whit the snow depth up to 45 cm. However, when amount of snow is beyond the capability of miniature ploughs, trains shall not be solely used as snow plough machines as it will result the train sets to get stuck in the snow and block the track. Therefore, other snow clearance machineries will be needed. For instance, former locomotives can be equipped with large Beilhack-type ploughs which are capable to plough drifts up to 1.8 meters with running speed of up to approximately 70 km/h. Moreover, modified ballast regulators such as Jordan spreader can be used for the purpose of cleaning large amount of snow. Additionally, big rotary snow blowers are being used, which can throw the snow up to 50 meters away. In addition, there exist some special ice-treatment trains fitted with snow ploughs, hot-air blowers, steam

jets, brushes and heated deicer, and compressed air to quickly thaw frozen points. In certain cases where the snow and ice should be removed manually, dry ice blasting is recommended by Bettez (2011) as a promising method. Especially since it is a completely dry process, and perfectly clean the surfaces, without being abrasive, conductive or corrosive.

- **Tunnels insulation**

In order to eliminate the problems with icicles and ice sheets in the tunnels, any water leakage in tunnels must be prevented. This is possible through covering the inner layer of tunnels by utilizing different types of materials in forms of mounting mats or sprayed dough.

- **Vegetation management**

Vegetation along the track needs to be controlled and cut in order to minimize the risk of falling trees. This will protect the electrification equipment and eliminates the consequences of running into broken or bent trees.

Artificial afforestation is also recommended for controlling the risk of avalanches and drifting snow, in which the kind of vegetation need to be decided based on the region and the hazards the infrastructure is exposed to (Doll et al., 2014).

- **Hillside securing**

Various methods are available for protecting the rail tracks against falling rocks and ice bulks from the mountains. To name a few, removing the dangerous rocks or securing them by using long bolts will reduce the risk of falling objects. Moreover, mounting safety nets and digging ditches will eliminate the risk of damages in case of falling objects.

- **Inspection and maintenance**

During the winter time, more manual inspections of the track and other infrastructural components (besides remote and automated inspection solutions) will be required. For instance, in addition to remote monitoring system, Networkrail uses helicopters, equipped with thermal imaging cameras to identify malfunctioned switch heaters. Regarding the rails, they need to be constantly monitored in order to detect any deviations in geometry parameters or other defects, so preventive or correcting measures can be taken before they result in incidents (RB Faiz 2009, network rail).



### CATEGORIZATION OF SOLUTIONS

The 2 previous sections in this chapter, reviewed the available solutions for encountering the winter-issues related to rolling stocks and infrastructure. The existing solutions and systems can be sorted and categorized in many ways. This section, aims to introduce three of them:

#### **Proactive versus Re-active**

The approaches which can be followed when dealing with winter operation can be categorized into two main groups: Proactive and Re-active.

Proactive measures, also referred to as preventive, are those actions which can be taken prior to the winter-events, with the aim of mitigating the risk of undesirable incidents and consequences. On the opposite side, are the reactive or corrective measures, which are responses to the incidents and problems, after they occur. Correspondingly, from the maintenance point of view, all the measures which are about predicting and preventing the probable failures are grouped as proactive; while any action which deals with fixing and correcting an already occurred failure is reactive (Stenström et al., 2014). A clear example of proactive solution for rolling stocks are the anti-icing methods which aim to prevent ice formation and the following consequences. Accordingly, all the de-icing tactics for removing the ice and snow from the surfaces fit into re-active category.

Proactive measures are advantageous, as they help preventing large economic consequences of disruptions in transport systems (Bardal & Mathisen, 2015; R Faiz & S Singh, 2009). However, not everything can be predicted or eliminated in advance, and a successful winter program requires to have both proactive and reactive measures in place.

#### **Passive versus Active**

Bettez (2011) compared the winter technologies/measures with those in fire protection, and proposed a new categorization. In this classification, the measures and technologies have been divided into two groups: Passive and Active.

Passive technologies do not require any energy inputs in form of motion or heat in order to provide the expected results, thus they demand a very low or no further maintenance. Those solutions such as selecting the proper material and surface design

or coatings are examples of passive solutions related to rolling stock; And better design for cuttings and switches, installation of physical barriers and switch protectors (brushes, etc.) are some of the passive solutions in infrastructure.

Active methods, on the other hand, consist of items and systems which require motion, heat and human interference in order to work. So it is said that the risk of malfunctions, as well as the operational cost is higher in cases of active solutions. Accordingly, all the solutions which are based on electrical systems (such as heaters, electric pulse and DC bias, slush-mixture pumping systems, etc.) and those with motion (E.g. De-icing boots), as well as those with human interactions will be grouped as active solutions.

### **Anti-icing versus De-icing**

When introducing the solutions for rolling stocks and infrastructure, anti-icing and De-icing were briefly mentioned. Anti-icing and De-icing are possible through different technologies and methods (mechanical, chemical, thermal).

Midwest Industrial Supply Group (2015b) by concentrating on chemical method, establishes the differences between them as below:

Anti-icing is a more proactive and preventive approach, which is about pre-treating the surfaces to create a protective barrier between the surface and the precipitation, prior to a winter event.

De-icing, on the other hand, is a reactive approach to deal with icing problems after they occur. It is about defrosting the surfaces by breaking the ice loose from the surfaces.

De-icing is said to be less effective, less efficient and more expensive. Thus, anti-icing is highly preferred as it is more efficient and effective than de-icing. Although, de-icing will be needed anyway, but will be much easier when anti-icing actions have already been in place.

- ✓ This chapter, presented the available solutions in different countries, regarding the design aspects, systems and instructions, to be used for encountering the winter-issues affecting the railways. Though, the applicability and functionality of each solution is dependent on the characteristics of the target region.







### CHAPTER 7 – ORGANIZATIONAL & OPERATIONAL CONSIDERATIONS

Having the best infrastructure and rolling stocks solely, does not result in optimal operational results. Coping with the special winter conditions calls for a couple of organizational and managerial considerations to be in place before, and during the winter months.

There are some preventive measures that can prepare the railways for facing the expected winter conditions, and other considerations will help reducing the impacts of unpredictable and inevitable events; So the railways can confront undesirable situations better, and will recover faster in case of probable disturbances.



#### ORGANIZATIONAL REQUIREMENTS

##### **Authority approval and winter testing**

A fundamental step, is to define accurate procedures for authority approval in procurement projects. A solid and thoughtful authority approval process can assure that all the trains and infrastructural systems have passed a sufficient level of winter testing, and are qualified to be used under the worst winter conditions of target regions. However, it should be kept in mind that being tested and receiving authority approvals does not guarantee a flawless functionality under any circumstances. Another point to be covered with authority approvals is to assure that all the rolling stocks entering the network comply with the specifications such as standard coupling to haul or be hauled in the line clearance activities (Jernbaneverket, 2016b).

##### **Coordination and communication**

Comprehensive coordination and smooth flow of information among involved people and sub-contractors within the different sections (infrastructure and operations), and in all the organizational levels is a key in achieving higher winter performance (Kloow, 2011). Moreover, mutual trust in each other's capabilities is an important issue: According to an interviewed authority in Jernbaneverket, when authorities in charge of infrastructure confirm that the track condition is safe for passing with a

certain speed, train operators are not supposed to reduce the speed as it might result in trains getting stuck.

In addition to the internal communication (E.g. between operation and infrastructure and maintenance parties), communicating with external units such as weather forecasters or other transportation providers, will help the railway systems with combatting winter issues (Bettez, 2011; Kloow, 2011). As an example, being aware of upcoming weather incidents (E.g. prior to avalanches, snowstorms, etc.), helps infrastructure companies to arrange better and earlier actions, and operations can be adjusted in accordance with forecasts. Services Such as European Severe Weather Database ([www.eswd.eu](http://www.eswd.eu)) and ([www.meteoalarm.eu](http://www.meteoalarm.eu)) are examples of European databases for gathering and sharing the forecasted weather events, with the aim of providing relevant information needed to prepare for extreme weather, expected to occur somewhere over the Europe.

Interdependencies between the railway networks, calls for a new mind-set that goes beyond just keeping the home territory operating (Kelly, 2015). A train might pass through many countries, which emphasize the necessity of having standardized communication agreements (Doll et al., 2014). Disruptions in a line can simply cause secondary delays in other networks or even in another country. Hence, comprehensive coordination and communication among different networks and lines will give a better result if expanded beyond the internal boundaries.

Finally, a good coordination with other modes of transportation (Road, sea, ...) facilitates new alternatives and combinations in case of impassable rails.

### **Trainings and standardised instructions**

Having the personnel trained and prepared is an important requirement in dealing with special winter situations. It is crucial to have good strategies for keeping the knowledge updated, and share the experiences among involved personnel.

Having predefined and standardized procedures regarding how everything should be done, will organize the involved people in a way that they will know how they are going to contribute in accordance with varying conditions from mitigation, to crisis control and stabilization (Brabie & Andersson, 2008; Kloow, 2011).

### **Active Learning and continuous improvement**

In order to keep learning from previous winters, the railways companies will need to continuously document their experiences. Every year, the newly gained insights should be implemented, and the plans for the coming winter should be modified, to assure that resources and procedures are in place in accordance with each region's unique requirements (Kelly, 2015).

### **Maintenance strategies**

Proactive strategies for constant and proper maintenance of systems in both trains and infrastructure are necessary for achieving customer satisfaction, through sustaining the capacity and providing safe and punctual services (Abdi, Lind, & Birgisson, 2014; Pekka Leviäkangas & Michaelides, 2014; Li et al., 2015; Uday, Parida, Karim, Söderholm, & Candell, 2009) Having proactive maintenance strategies based on standardized requirements is crucial for keeping the existing infrastructure and vehicles resilient and reliable (Doll et al., 2014; Pekka Leviäkangas & Michaelides, 2014). As standardization of maintenance processes can enhance the preparedness of the networks against winter issues (Doll et al., 2011).

Transferring of maintenance services from public sector to private sector, has been said to have beneficial effects, however designing appropriate and separate contracts for winter maintenance is suggested to obtain greater efficiency and improvement in the quality of the winter maintenance measures (Abdi et al., 2014; Pekka Leviäkangas & Michaelides, 2014; H.-Å. Mattsson & Lind, 2009).

Correspondingly, in Norway and according to “kjøretøyforskriften”, all the vehicles must be assigned an approved entity in charge of maintenance, and the railway undertakings have the responsibility to ensure that the systems, parts and components are constantly in accordance with national and international standards in Technical Specification for Interoperability (TSI).



### WINTER MODE

#### **Winter preparation program**

In addition to having the personnel ready, preparedness and availability of relevant equipment, plays an important role in on-time arrival of trains to their destination through harsh winter condition (Johnston, 2014). Therefore, it is important to have the maintenance, clearance and surviving teams, armed with sufficient amount of high performance equipment, strategically positioned around the network.

For the most of railways companies to become fully prepared, a general winter preparation program is followed annually and during the fall (September-October depending on weather forecast). As a part of winter preparation, technical rooms are re-supplied with spare parts and fuel; and outdoor equipment are lubricated and sealing are changed with winter types (Bettez, 2011). During the preparation program, the existing machineries and equipment will be checked, serviced and located in the right place in order to be ready to be used (Kloow, 2011). Any shortage in machineries and equipment should be resolved by in-time procurement of proper items. All the necessary maintenance actions and upcoming intervals for components of the rolling stocks and railway infrastructure need to be re-scheduled to be performed before the winter arrives, so everything will be in its best shape (Kloow, 2011), so the focus will be only on probable corrective actions.

#### **Expanded fleet and Extra personnel**

In order to compensate the trains which are out of service due to maintenance issues, and to have enough capacity for rescue-missions and snow-clearance measures, Bettez (2011), Smith (2011) and Wanek-Libman (2012) recommend to assign extra rolling stocks to be stand-by to serve the lines when needed. As procuring new locomotives and snow clearance machineries only for a certain period of year does not have economic justification, they claim that older locomotives (even those in museums) can become handy in crisis, as they did in Denmark in 2009/10 and Canada and Northern America in 2013. The alternative option is also to look at the leasing market to see if leasing companies and other railroads have spare locomotives to be rented (Guss, 2014).

In order to have sufficient human resource to handle the crisis and perform the necessary manual tasks, there should be more people available and located at critical

points (Bettez, 2011; Wanek-Libman, 2012). In addition to higher need for personnel, Bettez (2011) also points at higher rate of absenteeism in winter time which emphasizes the necessity of having backup personnel during the winter time.

### **Winter scheduling and planning**

Robustness of time table and transport capacity are two key factors that should be considered simultaneously when planning for train operations (M. Dingler et al., 2010; Salido et al., 2008; Trap et al., 2015). When scheduling the winter services, the time required for conducting the snow clearance activities, planned speed reductions, as well as contingency plans should be fully integrated into the timetables (Kloow, 2011; Louwse & Huisman, 2014). However, in many of the cases, the railway infrastructures are already being utilised close to their maximum capacity. It means that considering extra time for any of these winter-considerations, without reducing the transportation capacity might be very idealistic.

Moreover, sometimes during the winters, and in order to eliminate the risk of disturbances due to malfunctions (E.g. malfunctioning switches) there is no better choice than limiting the operations by focusing only on main parts of the line. For example, it is better to operate the lines with just a limited number of switches involved. Thus, a fewer number of them can be used more frequently while the rest are left untouched (Bettez, 2011; Kloow, 2011; Trap et al., 2015). However, applying this solution will either increase the concentration of trains on a section to a risky level, or if the number of trains are reduced, it will significantly cut the transportation capacity. Thus, except in cases of crisis, this solution is not expected to give promising results.

It is obvious that reduction in utilizing networks' capacity and planning for operating less frequent services will minimize the risk of delays and severe disturbances (not the occurrence of incidents, but the propagation of impacts). Though, it will result in loss of transport capacity (M. Dingler et al., 2010; Trap et al., 2015). Thus, one solution will be lengthening the trains to compensate the capacity loss. But its possibility is debatable due to platform constraints and the fact that trains' length is sometimes already at its maximum.

Therefore, as a practical solution for enhancing the robustness of timetables without sacrificing the capacity, it is recommended to distribute the trains around the network in a way that avoids concentration of trains in certain sections (E.g. around the major

stations) through re-routing some of them to longer or slower routes, or by re-scheduling them to off peak hours (Kloow, 2011).

In another perspective, and with the goal of minimizing the risk of trains getting stuck, restricting the length of trains and instead, running more trains is said to reduce the risk of disturbances (Guss, 2014). In order to avoid the troubles related to coupling issues, Bettez (2011) by referring to International Union of Railways (2011) proposes to minimize the need for coupling through using shorter train formations, and suspending the splitting and jointing events during extreme weather. However, this is only possible if there are enough number of locomotives in a fleet and the operation cost is of a very low importance.



### **Emergency Response Preparation**

#### **Emergency plans**

The solutions that have been discussed earlier, concentrate mainly on preparedness and minimizing the risk of disturbances. However, even with the maximum preparedness, the unpredictability of winter events might surprise the rail operators with a new problem. Hence, having a good applications of common emergency strategies, like well-prepared emergency plans and predefined communication protocols, are needed to be created and practiced in such a way that facilitate immediate intervention and earlier responses. Such emergency plans are aimed to minimize the impacts and propagation of undesirable situations, as well as increasing the chance of regaining reasonable level of services in a short time. The earlier the responses to events are, the higher is the probability of rapid recovery and ensuring of reasonable level of service (Pekka Leviäkangas & Michaelides, 2014). As a part of an emergency plan, prioritized tracks and stations on each route, as well as alternatives such as rerouting possibilities should be agreed on (Kloow, 2011; Wanek-Libman, 2014).

#### **Rapid response centres**

Notice that due to the uncertainties, relying on a single predefined disruption scenario would not suffice. Thus, rapid response centres should be formed, which as a responsible authority (Can be a team of infrastructure and operation experts) can

make the in-time decisions in cases of chaotic situations (Bettez, 2011; Kloow, 2011; Trap et al., 2015; Wanek-Libman, 2014). Currently, accurate simulators are available which can help the decision makers to predict and evaluate the impacts of different alternatives through mathematical algorithms (Espinosa-Aranda & García-Ródenas, 2013; Nicholson et al., 2015). Such systems aid control centre staff in making the best decisions in case of disruptions, following unforeseen technical or winter-related incidents.

In order to quickly resolve probable technical problems, (especially in the regions with lowest temperatures and a higher likelihood of ice and snow accumulation) special teams of Mechanical Rapid Responders should be ready to intervene 24-7 (Kelly, 2015).

- ✓ As it was mentioned earlier, in addition to proper infrastructure and vehicles, some organizational and managerial consideration are required for responding to the especial winter conditions. These chapter, reviewed these organizational requirements and winter preparation procedures, and presented the common practices from several railway companies.







## CHAPTER 8 – WHY WINTER STILL CAUSES PROBLEMS?

Although the winter and its special requirements are known, and operation of trains has been practiced over the years, occurrence of disturbances and delays due to winter-related issues is still a frequent case which is expected, and accepted in many countries.

Reviewing different perspectives through the literatures, revealed some of the main causes for having lower service reliability when it comes to winters:

### **Low priority of improvement plans**

Improving the reliability of railway systems has not been a matter of high priority for many railways companies, and there are only a few, which are moving towards it (Lindgren et al., 2009). One reason can be that not all the individuals in charge of decision-making have the enthusiasm for enhancing the operational performance (Nicholson et al., 2015). It is while implementation rate of improvement measures is highly dependent on the commitment of top management (Veiseth et al., 2011). Too often, preferences of decision makers and public managers towards other priorities such as reformation, revenue generation, or drive for efficiency stops the railway organizations from considering the improvement plans (economist, 2011; Jackson, 2011; Pekka Leviäkangas & Michaelides, 2014; Nicholson et al., 2015).

Moreover, In some countries, winter is just a temporary period of the year which might not last for too long, or even might not happen for many years; so extreme weather conditions with the potential of causing serious operational problems are unlikely to be expected often. Hence, thinking about taking ground steps towards improving the winter preparedness is not of a high priority all year around and railways companies tend to maneuver around acute and short-term solutions, only if the problems arise.

### **Wrong attitude**

In some cases, too much focus on preparation of railway systems for ultimate extremes, which occur seldom and are usually uncontrollable, distract the transportation managers from paying attention to less severe events with high

frequency (E.g. snowfalls), which in the end will result in the most significant performance loss (Pekka Leviäkangas & Michaelides, 2014)

### **Lack of long-term perspective**

Success in dealing with adverse weather conditions, requires long term strategic plans, which involves all the aspects from designing phase to operations (Doll et al., 2014). Many winter problems can be prevented by considerations during the design phase. So if the winter requirements are not integrated into the design, future modifications might not be easily possible (Lai et al., 2015). Another sign of not having long-term perspectives is that there is not a fully established procedure for including the risks and costs of weather events in project appraisals; and the long-term implications of weather phenomena which the transport systems are anyway going to face during their life cycle are being disregarded (Pekka Leviäkangas & Michaelides, 2014).

### **Short memory**

Due to what Kloow (2011) called as “short memory” after a number of mild winters with controllable situations, the responsible people in the industry tend to forget essential preparations for facing a harsh winter. The same story applies in countries with seldom harsh winter conditions, where winter mainly affects punctuality, especially at the beginning of winter, and the longer winter periods last, the negative impacts decrease as the system and operational procedures get adjusted to the prevailing conditions (Doll et al., 2014).

### **Short sighted money saving approaches**

Railways systems are a composition of expensive vehicles and infrastructures. Correspondingly, maintaining the railways, or making any changes in such a way that sustains high service quality, might have a very high monetary demand (M. H. Dingler, Lai, & Barkan, 2012; Li et al., 2015).

The high monetary demand, which may not have short term results, might dissuade the decision makers from investing on improvement plans (for example building a resilient and durable infrastructure which could have long term benefits) (Pekka Leviäkangas & Michaelides, 2014).

Moreover, determining how much to invest on winter preparation is a challenging task: Spending too much resources on unnecessary measures and equipment, makes it hard to justify the costs (especially in countries with rare problematic winters).

On the other side, insufficient investment can cause severe disruptions in operations which is followed by losses of revenue, penalty and compensation claims by the customers, and damages to reputation (Abdi et al., 2014; Merkert & Mangia, 2012).

Additionally, drive for money saving in order to remain competitive, can also negatively affects the quality of proactive measures.

It is true that the railways should focus on profitability and efficiency, though saving the money that should have been spent on taking proactive measures or performing research projects in this field can seriously weaken the industry's ability to cope with winter and probable disruptions (Faiz & Singh, 2009; Jackson, 2011; Kloow, 2011).

### **Trade of between durability and easy maintenance**

In some situations, good maintenance possibilities and good winter durability cannot be achieved together. For example, installation of covers and protectors (E.g. on axels, suspensions, brakes, etc.) beside the advantages they offer, will complicate the maintenance and visual inspections (Kloow, 2011). So a tough decision should be made between easy maintenance for the whole year, or just better resistance against winter condition.

### **Complexity of organizations and long decision making processes**

Railways system as a whole, is an interconnected composition of several levels of decision making, various operators and contractors and a mix of public, commercial and individual users (Doll et al., 2014). When planning for a single project, many different sub-processes including multiple sectors, administration levels and authorities are involved. All these complexities can make the adaptation of the entire sector to the possible weather events very long and challenging (Doll et al., 2014). For example, according to Norwegian Ministry of Transportat and Communication (2012/2013), for major rail projects it takes on average about 10 years from the start of planning to commencement of construction.

### **Communication problems**

Fragmentation and lack of communication between the infrastructure managers and multiple operators is sometimes argued to be the origin of the setbacks in responding to the disruptions (E.g. when it comes to prioritizing the tracks) (Jackson, 2011; Kloow, 2011).

Klok and Klein Tank (2009) also point at delays in insertion of daily climate observation in the European database which usually takes time, so updates from the data providers are usually received with some delay.

### **Insufficiency of infrastructure/ High capacity utilization**

Overcrowded networks and high capacity utilization has been known as a fundamental cause for propagation of disturbances after an initial incident regardless of seasons. Though, long lead times and heavy economic investments demand for expanding the infrastructures, forces railway companies to operate more trains on existing lines (M. H. Dingler et al., 2012; Espinosa-Aranda & García-Ródenas, 2013).

### **Lack of machinery and personnel**

Difficulty of determining the right level of spare resource and dedicated machinery to provide adequate redundancy, and the fear of being overstaffed or wasting resources, might result in insufficiency of spare locos and crews at times of trouble (Jackson, 2011). The main reason again might be that investing on expensive equipment and seeing them being left unused will be considered as waste of resources.

### **Inapplicable standard designs**

Locomotives and railway systems are built in many countries, and based on certain standards. However, extraordinary weather condition in some regions might demand particular requirements. For example, when it comes to special winter conditions in Scandinavian countries, European standard designs might not be always practically applicable (Kloow, 2011).

### **Lack of detailed documentation and statistic data**

Obviously, improvement plans require budget and railways companies may not be able to generate support for public investments, without being able to fully estimate and evidence the benefits of potential investments (Barron et al., 2013). It is while the

data on past climate-related impacts on transport are restricted to individual extreme events and there is a lack of reliable statistical data for a sound cost assessment of weather impacts on transportation (Barron et al., 2013; Pekka Leviäkangas & Michaelides, 2014).

- ✓ This chapter, reviewed and listed the main obstacles for having well prepared networks, personnel and procedures for facing the inherent and expected winter problems. The solution to overcome these obstacles might be increased awareness about the necessity of winter-improvement considerations. This, can be achieved through knowing how the loss of optimal performance can impact the users and railway undertakings in long term. As a suggestion, conducting accurate and in depth cost/benefit analysis and involving all the costs associated with loss of reliability (in presence of precise documentation), can provide the decision makers with motivation for prioritizing effective winterization considerations; And this, will be projected in better organizational procedures and communication strategies which will also speed up the implementation of improvement plans.



**Part 3**  
**CASE STUDIES**







### CASE 1 – WINTERIZATION OF NORWEGIAN RAILWAY

#### ABSTRACT

Infrastructure and its preparedness level, play a vital role in facilitating high-quality train services all year round. This study reviews the development trends, and distribution of winter-related solutions within the Norwegian railway infrastructure. Further in this work, the performance of Norwegian railways in terms of punctuality in the recent years (2000-15) are studied. Finally, the impacts of winter-related measures on punctuality of three types of passenger trains, during the winter months are investigated. The results reveal that higher number of winter-related actions, besides maintaining the existing items, has a correlation with improvement of winter-punctuality.

Key words: Railways, infrastructure, winterization, punctuality.

#### RESOURCES

The geographical and meteorological characteristics of Norway and Norwegian railway have been extracted from on-line publications by Jernbaneverket, NSB and Norwegian Meteorological Institute (MET).

“Bane data” has been the main source of the information regarding the winterization measures in Norwegian infrastructure. The datasets - in form of separated excel sheets - present the winterization-measures, which have been taken in Norwegian rail network during the past decades, starting from since 1905 until March of 2016. The datasets contain the dates for installation and the latest changes for a total of 9 categories of winter equipment/measures. In the same files, some additional information such as location, specifications and the line/company they belong to can be found.

Values for monthly punctuality of different trains are extracted from multiple resources, which all are published by “Jernbaneverket”: Punctuality reports (Punklighetsrapport), for the years 2000-2007, together with annual statistics (Jernbanestatistikk) for 2000-2015, as well as an on-line punctuality database (Mitt tog) have been the main ones.

### **METHODOLOGY**

The intention from reviewing the taken winterization-measures, has been to find the trends for their developments, and the way they are distributed along the network. Depending on the availability of details for the registered items, several charts, displaying development trends for each items were created. To do so, the accumulated values have been used, and the number of items with unknown installation dates were put as the starting points in the line charts. Then, the years between 1905 and 2016 were divided into 5-years portions, and the absolute number of items added, related to each category, was determined. Finally, in order to present the distribution of items, the number of items in each line were counted, and transferred into percentage. Lastly, pie/bar charts have been used for presenting the results.

Regarding the punctuality data, there was not a comprehensive resource found, that provides punctuality data for all the demanded months, and for all types of trains. Though, compiling available annual reports, and conducting minor modifications, provided us with a completed table, filled with average monthly punctuality of long distance, medium distance, and Airport trains. Then, the months of the year were separated into 2 sets: summer, and winter months. The winter season has been considered to start from November 1<sup>st</sup> and last until end of March in the next year.\* Afterwards, the average punctuality for winters and summers, separately, have been used as basis for comparisons.

### **LIMITATIONS AND ASSUMPTIONS**

This study, only covers a certain time period (2000-2015), and studies the punctuality in a national level for a certain types of train services. It is while the winter condition and its impact varies throughout the country and for different train types.

Moreover, the impacts of prevailing weather conditions at times has not been involved; and it was simply assumed that all the winters have been the same.

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\* For example:

Summer 2009 = From 1/4/2009 - Until 31/10/2009

Winter 2009 = From 1/11/2009 – Until 31/03/2010.

Some minor mismatching issues were noticed when compiling the punctuality data from different resources. These were assumed to be caused by minor variations in scales and involved trains, which have been overlooked in this study.

In addition, there exist some limitations in utilizing the datasets related to winterization-measures. Such issues are due to a number of uncertainties as a result of relatively low quality of registered data. Thus, available information is perceived only as a representative for development trends and not as a basis for definite conclusions. To name a few, (a) the excel sheets for various items, cover different time periods: Few of them from 1905, some from 1920, and there is one presenting only 2010 and onwards. (b) The closer it gets to the present time; the more items are registered. Therefore, it can be argued that having a high number of installations/actions in the recent years might be due to better documentations. (c) Whether all the lines and every single item is registered in the datasets is uncertain. Looking at the number of more recent developments (or maybe selected ones), without knowing the total accumulated number of available equipment might make the results inaccurate. (d) It is assumed that all the installed items are still in use as they all have a registered date regarding the last changes during the past few years. Though, there is no information available for the removed items.

## **INTRODUCTION**

### **About Norway**

Norway is a very long country (a span of 13 degrees of latitude from south to north) with various weather zones which are different in period, length and severity of winters. The coastal regions in southern and western parts of Norway, have a climate with relatively mild winters throughout the year. Whereas, inland areas have a continental climate with comparatively colder winters (Meteorologisk Institutt, 2016). In the Northern-Norway and in mountainous regions, winter periods are longer and winter weather conditions are less favorable. For example, the Finnmark plateau, with mean monthly temperature of around -15 °C and the lowest measured temperature of -51.4 °C, recorded on January 1st 1886 is the coldest area in Norway.

### **Environmental conditions in Norway**

**Altitude:** Norway is a mountainous country in which altitude varies significantly along its railway lines. Majority of railway lines are located 1000 m above sea level (Jernbaneverket, 2016b), and trains should go through a lot of ups and downs; so will be exposed to diverse weather conditions during their journeys. At 1222 meters, Fines is the highest railway station in Norway in Bergensbanen; and the altitude along this line reaches its highest point at 1237 meters.

**Temperature:** Temperature is highly variable throughout the year and also from region to region. In some areas, the temperatures below  $-40\text{ }^{\circ}\text{C}$  can be expected in winters, while it might reach up to  $+35\text{ }^{\circ}\text{C}$  during the summers. Many of the Norwegian rail lines pass through areas with typical maritime climate with moderate temperatures, as well as mountainous areas with extreme conditions (Jernbaneverket, 2016b).

**Wind:** Open coastal areas and high mountain are more frequently exposed to strong winds (Jernbaneverket, 2016b). In one of the recent cases, strong wind gust at 49 m/s was recorded in Nordøyen Lighthouse in Nord-Trøndelag in November 2013 (Amund Aune Nilsen, 2013).

**Snow:** The whole country is subjected to precipitation in form of snow during the winter season. However, based on geographical characteristics, there exist a large variation in amount and consistency of snow, as well as the length of snow covered periods (Jernbaneverket, 2016b): In the coastal regions of Southern and Western-Norway, frequency of snowfall is normally low and the snow-covered periods are usually short. In inland areas, where temperatures are lower, there is long periods of moderate snow. While in high mountain the amount of snow is considerable and the snow arrives early and lasts until late spring.

### **Winter season in Norway**

Considering the descriptions above, it is a big challenge to define a winter period that is applicable to the whole country (Merkert & Mangia, 2012). The Norwegian Meteorological Institute refers to the period from December to February as winter season in Norway. However, due to presence of the winter weather condition out of that period, in this study, the winter is regarded to start from first of November and last until the end of March.

### **Norwegian railway network**

The Norwegian railway network is consist of 30 service lines, making a total of 4.209 km railway line; which serves 5.2 million inhabitants. In 2015, 74 million passenger journeys and 31 million tonnes of freight were transported using the railways (Jernbaneverket, 2016a)\*.

The whole national railway is being run by three main players: (1) The passenger train services are mainly operated by NSB. (2) CargoNet is in charge of operating the freight trains; and (3) Jernbaneverket both owns and operates the infrastructure, and is responsible for traffic management.

### **Current situation of Norwegian railway**

Looking at the increasing number of passenger journeys and tonnes of freight transportation in the past 20 years, as well as growing number of visitors to the Norwegian railway museum, clearly demonstrate a growing trend in popularity and development of the railways transportation in Norway (Jernbaneverket, 2016a).

This, emphasizes the need for taking a forward-thinking approach towards constant developments, which is already projected in the increased expenditure on operations, maintenance and investment in the recent years (From 4000 million NOK in 2000 to more than 17000 million in 2015 which is more than 4 times higher). Increasing number of employees and training courses, are also other evidences that prove the existence of high ambitions for developing the railway transportation in Norway.

The Norwegian government emphasizes on expanding the role of railway transportation, and is working on shifting the transportation from road to rail through increasing its competitiveness. This is believed to be achievable through better operational stability, and improved punctuality and regularity. The commitment of government in realizing the objectives in previous National Transport Plans has already shown improvements in terms of punctuality and regularity of trains. According to Norwegian Ministry of Transportation and Communication, the Norwegian Government presented the next National Transport Plan for the period 2014–2023 in spring 2013, and the content of the plan has been accepted by the Norwegian parliament. The main contents of such plan for railways are based on

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\* Key figures for the Norwegian rail network in 2015 is attached in the appendices.

increasing the capacity of network and establishment of new services with higher quality in services, through faster and more effective planning processes.

**Development of Winter Solutions in Norwegian Infrastructure**

Based on the available information in “Bane data” for the period 1905 - 2016, This section reviews the development, and distribution of a number of winter solutions within the infrastructure of Norwegian railway:

**Automatic weather stations**

According to the registered information, Jernbaneverket has installed 25 automatic weather stations between the years 2007 and 2013. Most of these stations are equipped with temperature, wind and moisture sensors as well as gauges for measuring snow-depth and the rainfall. The weather data recorded by these stations together with information from other meteorological centers provides the railway practitioners with real-time weather information.

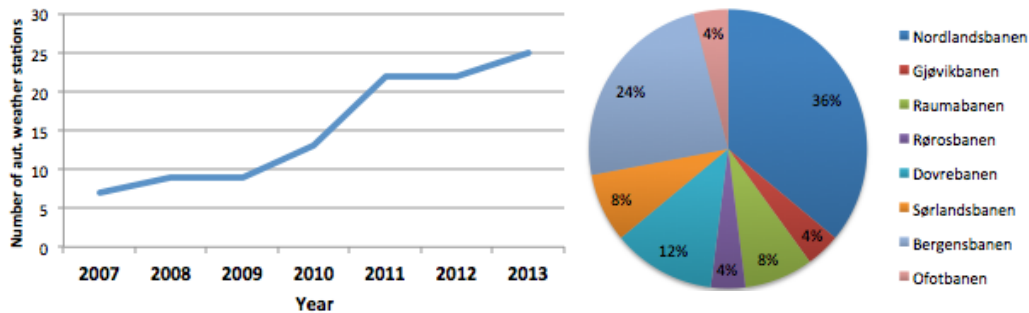


Figure 5-development trend and distribution of Automatic weather stations

**Hillside securing**

Various methods have been practiced in Norway with the aim of protecting the railways against falling rocks and snow bulks from the mountains. Different types of hillside securing considerations in Norway have been:

- Removing dangerous rocks / vegetation
- Mounting safety nets / bands
- Erecting retaining / support walls
- Creating ditches
- Spraying concrete
- Using long bolts for securing the rocks.

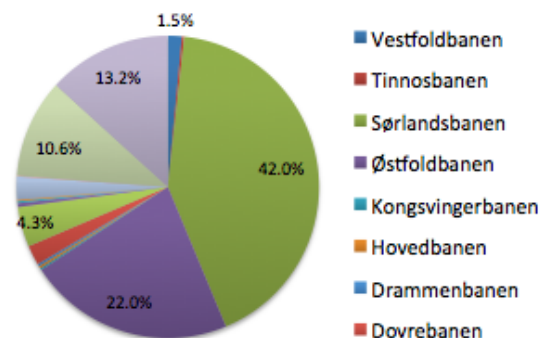


Figure 6 - Distribution of hillside securing

## CASE 1 – WINTERIZATION OF NORWEGIAN RAILWAY

Hillside securing has been one of the oldest winterization-measures that has been registered in Norwegian infrastructure since 1922. However, the number of such measures shows a considerable growth after 2011 by adding 792 within 5 years (figure 7).

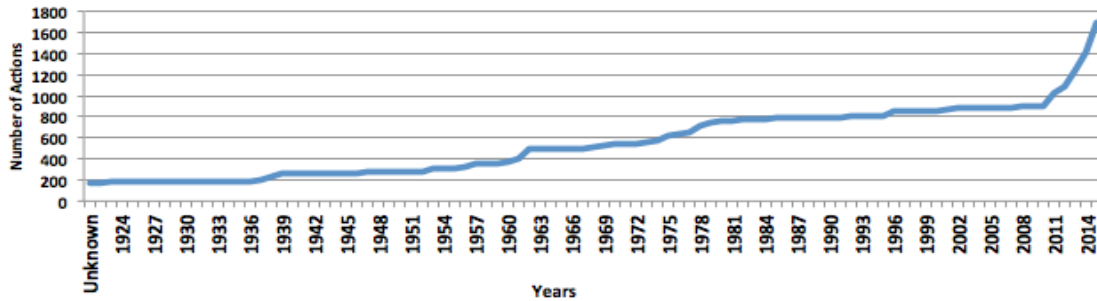


Figure 7- Development trend for Hillside securing measures

### Landslide warning systems

The first registered landslide warning system (rasvarslingsanlegg) in the dataset has been in use since 1905 in Sørlandsbanen. More and more warning systems were added during the 70's, 80's and 90's with installation of 8, 6 and 4 items respectively; and the most recent item has been added in 2014, resulting in a total of 27 registered landslide warning systems, with majority of them in Bergensbanen.

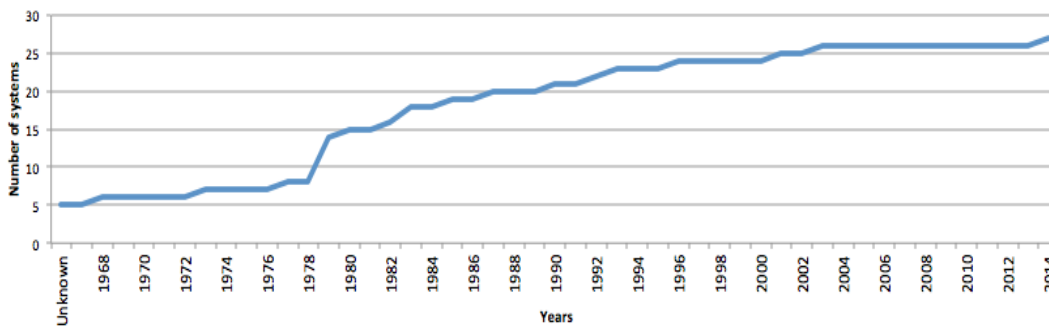


Figure 8 -development trend of Landslide warning systems

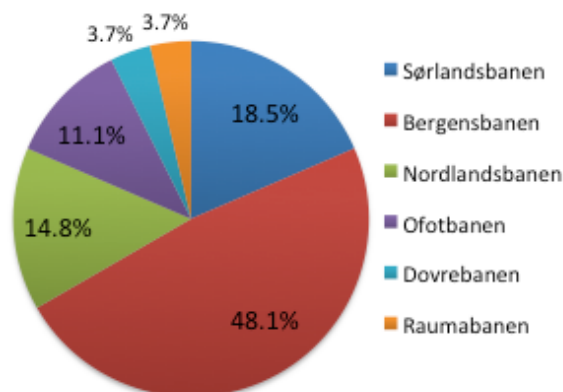


Figure 9- distribution of Landslide warning system

**Tunnels insulation**

The practiced methods for insulating tunnels in Norway against water leakage and minimizing the risk of frost and icicle formation have been covering the inner layer of tunnels by:

- polyethylene foam
- rubber mats
- concrete bricks
- spraying / molding concrete
- Oldroyd drainage mats.

Tunnel insulation, as a common practice within the whole network, had been constantly improved between 1940's and 1970's before a long recession. However, adding 210 extra insulation solutions in 2005 was a big step towards securing the tunnels against water leakage (Figures 10 and 11).

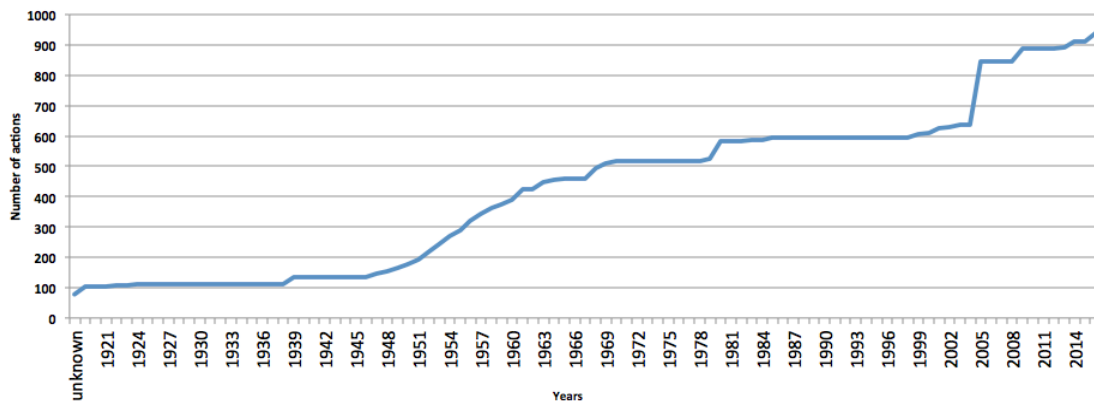


Figure 10- development trend of tunnel insulation

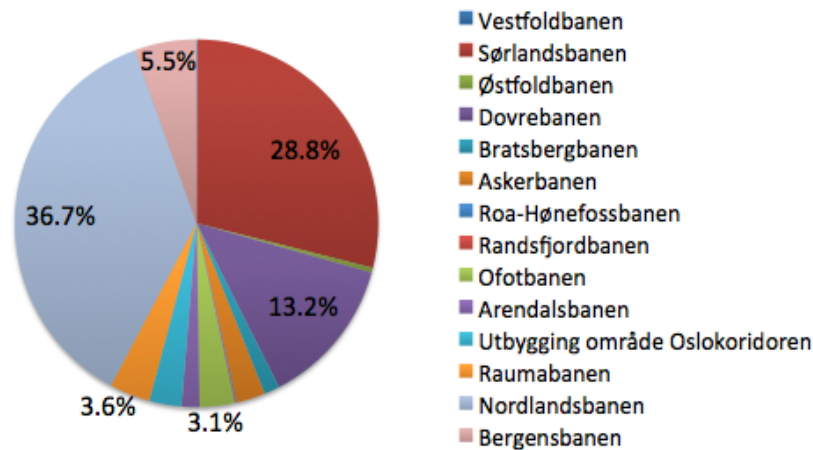


Figure 11- Distribution of tunnel insulation



**Switch Heaters**

A total number of 2286 switch heaters with various heating capacity are registered; of which the oldest one was installed in 1960. Figure 12 displays a constant and gradual increase in number of switch heaters between 1960 and 2010, with a considerable growth between 2010 and 2015. Hovedbanen is equipped with the highest number of switch heaters (447) followed by Dovrebanen and Sørlandsbanen with 319 and 273 switch heaters respectively.

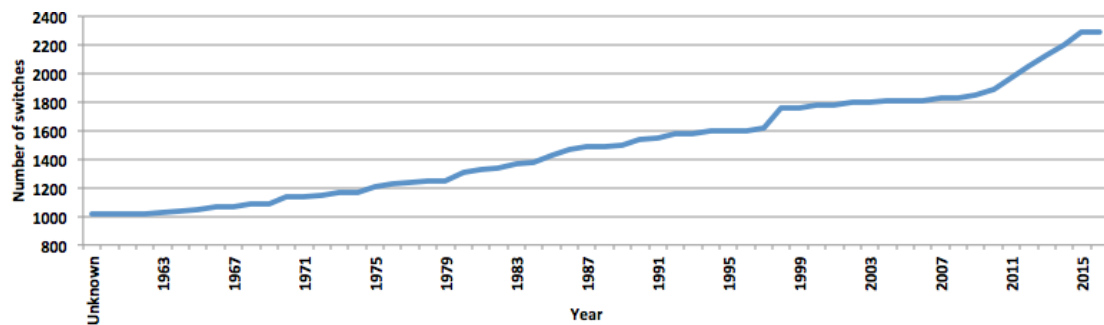


Figure 12-development trend of switch heaters

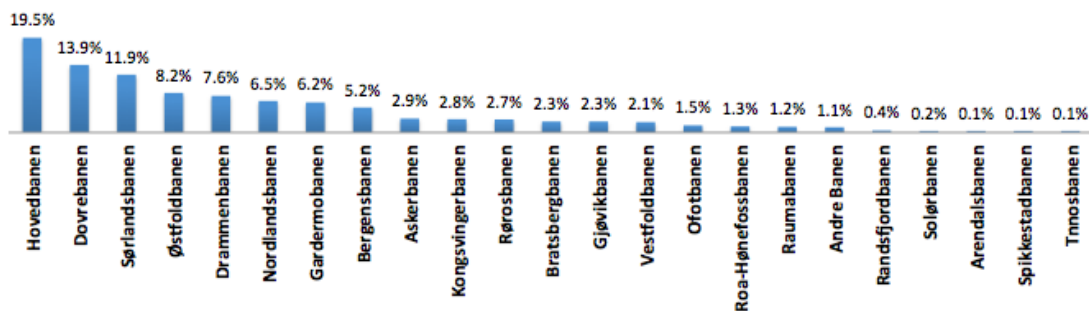


Figure 13- Distribution of switch heaters

**Barriers, fences and protection screens**

Two types of protection barriers are registered in the available dataset: Avalanche fences (rasvarslingsgjerde), and snow screens (Snøvern).

- Barriers grouped in the first category are “avalanche fences” which are mounted to protect the lines, in case of avalanches and landslides. The 36 registered barriers are made of various materials such as plastic, wood or metal; and their length varies between 21 to 650 meter, and their height reaches go up to 3 meter. The installation date for this type of barriers is not available. Though, according to the

last-change registration dates, 50% of them have been at least checked between 2010 and 2015.

- The other type of physical barriers in use, are in form of “snow protection screens”. The snow screens are made of wood, steel, aluminum or stone, and are mounted to protect the lines against drifting snow through collecting or deflecting the snow. The registered items are in different lengths from 18 to 1150 m and can be up to 6 m high. In total, 93 items are registered which have been built since 1909. After 9 screens were added in 1960, no considerable changes in number of snow screens is recorded except that many of them have been upgraded in 2014-15.

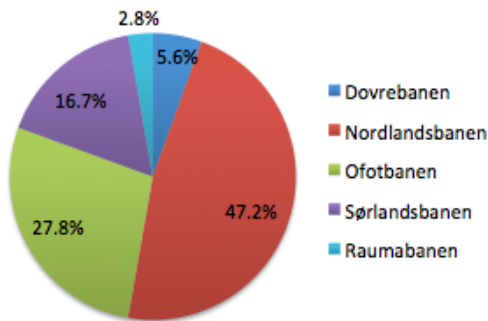


Figure 14-Distribution of avalanche fences

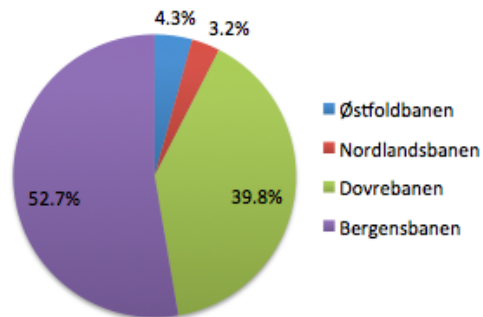


Figure 15- Distribution of snow screens

**Wheel damage detectors**

In the available records, only four wayside “wheel damage detecting systems” are registered: One is in use since 2013 in Drammenbanen, and Three new systems have been installed during the year 2015 in lines Dovrebanen, Drammenbanen and Ofotbanen. The type of installed detecting systems is “Track IQ” Wheel Condition Monitor (WCM®) which is known as a cost-effective trackside system for automatically monitoring the wheels’ condition. According to the producer (Wabtec), the WCM is a hybrid system consisting of both accelerometers and strain gauges which gives a complete wheel surface coverage which facilitate detection of multiple defects on a wheel, such as wheel spalls, out of round (OOR), shelling, wheel surface defects, etc.

### RESULTS 1 - DEVELOPMENT TRENDS AND DISTRIBUTION

By studying the trends, it can be seen that the number of new winter-related actions have fluctuated a lot during the past decades\*.

In general, a growing trend can be witnessed in the recent years: Particularly, the number of hillside securing actions, as well as installation of automatic weather stations, switch heaters and wheel damage detectors shows a significant growth in the recent years (2010-15).

Comparing the number of actions in different time periods for each of the categories, reveals that the period 2011-2015 was a productive age with a considerable growth in number of new winterization-measures. On the other side, the period 2006-2010 is seen to be the least active time-period in the past decades; with only few measures taken (mainly tunnel insulation).

Looking at the number of newly registered items, beside the information about regular maintenance of the existing ones, can be perceived as an evidence that the network is becoming more and more equipped each year, as the number of measures in place, is constantly accumulating.

Regarding the distribution of registered items in each line, it can be seen that hillside-securing has been an important measure in Sørlandsbanen and Østfoldbanen. Besides, the highest number of registered switch heaters are in use in Hovedbanen, Dovrebanen and Sørlandsbanen, respectively. In addition, insulating the tunnels, and number of automatic weather stations have the highest rate in Nordlandsbanen.

This can be looked at, from two sides: The lines with higher number of new measures, either were lacking them, or they had a sufficient level of winter preparedness and have become better equipped. Anyhow, more winterization measures, means they have been developing in terms of winterization.

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\* A figure showing the measures for 5 years' periods can be found in the appendices.

### RESULTS 2 - WINTER PERFORMANCE OF NORWEGIAN RAILWAYS

This section reviews the performance of Norwegian railways in terms of punctuality. The figure below, illustrate the average annual punctuality of different train services in the past 15 years. A general trend towards higher punctuality can be witnessed between 2001 and 2005, followed with a gradual decline.

The gradual decrease in punctuality continued, until it became significantly low between 2009 and 2011; and reached its lowest level since 2000 for freight and airport train services in 2010 (Figure 16).



Figure 16- Average annual punctuality of different train services (Jernbaneverket 2016)

An unusual weather pattern during the winters of 2009 and 2010 was said to be the cause of widespread delays and cancellation around the Europe, including Norway\* ; and the reason for such low performance in those years.

Thus, a more detailed look into winter performance of Norwegian railways in those years could have been clarifying, regarding the influence of winter-performance on the average annual records.

Defining the winter season from November to March, and comparing the average punctuality level in winter months with their preceding summer for 3 different train types, is illustrated in the figure-17. The graphs show big differences between punctuality levels in winters and summer months.

Although the punctuality performance in those summers was not the highest, this still proves that the low average punctuality in 2009-10 was to a high extent influenced by very low punctuality records during the corresponding winter months.

\* References can be found in Chapter 1 – Introduction – Current situation.

## CASE 1 – WINTERIZATION OF NORWEGIAN RAILWAY

Looking separately into punctuality levels in winter months also gives another remarkable result: The graphs, also show a significant trend in improvement of winter punctuality for studied train types after the winter 2009\* (figure 17).

This trend for airport and medium distance services have resulted in achieving the highest records in the past 15 years. This is while, no specific trend for changes in summer punctuality can be found.

Surprisingly, for both short distance and long distance trains, and after 2010, the level of winter punctuality has been constantly higher than punctuality in summer season which calls for further cause analysis.

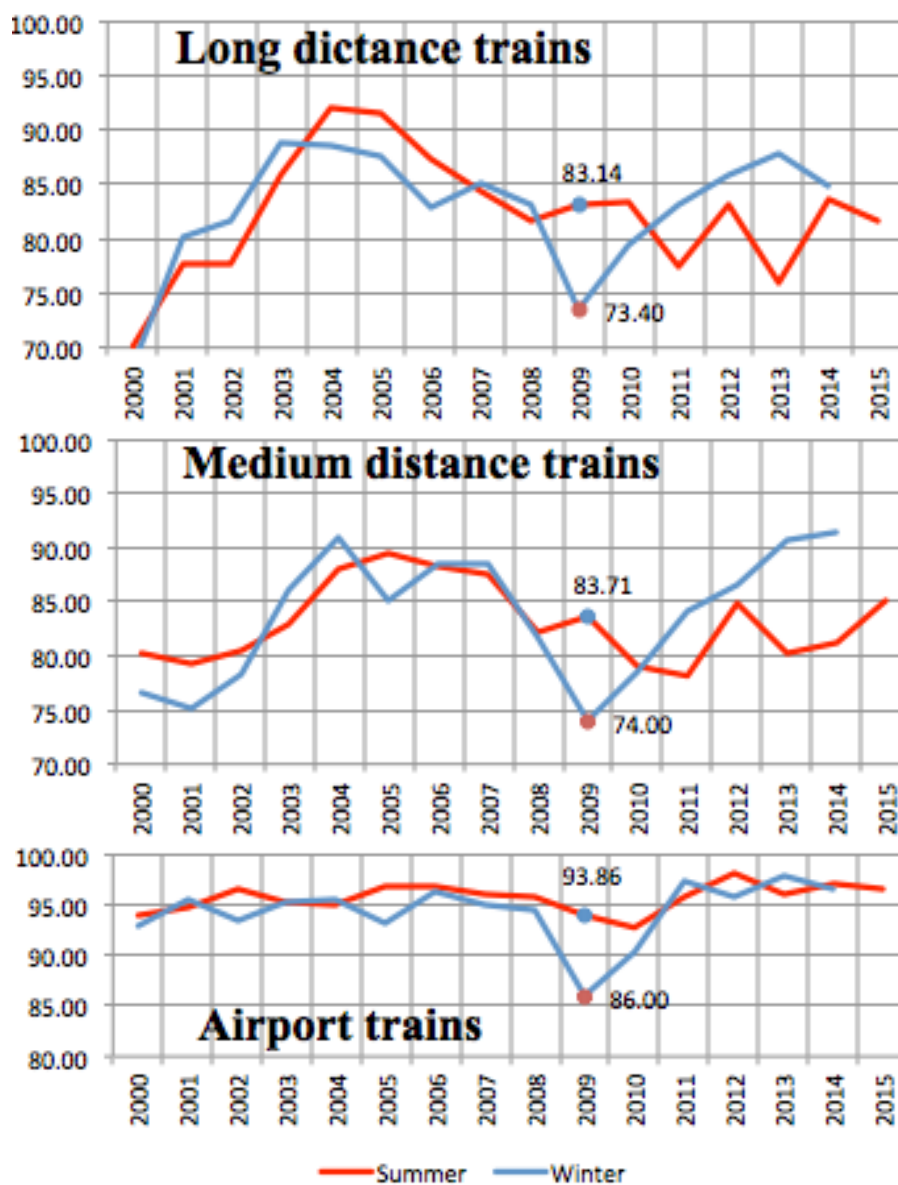


Figure 17- Winter punctuality vs. summer punctuality

\* A figure, presenting the average annual winter punctuality for all train types is attached in the appendices.

### **DISCUSSION & CONCLUSION -WINTERIZATION VS. PUNCTUALITY**

Comparing the number of newly added items during the different time spans, revealed that the period 2011-2015 has been a big step towards a better winterization in Norwegian railway's infrastructure; which can be claimed to be in line with the ambitions of Norwegian government in the recent years regarding the improvement plans.

Higher number of new winterization-measures in infrastructure, can be considered as a sign for more effort and investments on other aspects of winterization as well. Relating the growth in number of new measures after 2010, to the achieved improvements in winter-punctuality in this period, can show that more effort and investment in winterization-measures (specifically in infrastructure), will result in better punctuality performance. Though, experiencing milder winter-conditions in those years, to some extent, weakens the validity of this claim, which calls for further investigations with involvement of prevailing weather patterns.

Looking at it from the other side, it was noticed that 2006 to 2010 timespan has been one of the least active periods regarding the winterization in the past decades, with only few measures taken in infrastructure. Counting this as an evidence for less attention to winter preparation in a wider scale during those years, justifies the failure of Norwegian railways in maintaining the services punctual, when harsh winter of 2009-10 hit the country. Thus, it can be concluded that: Lack of constant and continuous improvement measures, regarding the winter preparation considerations (in infrastructure), can result in significant loss of punctuality performance in case of severe winters. Hence, the railways should constantly work on their preparedness level, to be able to battle probable extreme winter conditions in the future.

Another fact to be mentioned, is that maintaining the existing winter-related components, besides adding new items over the years, will result in an accumulated number of them to be in place. Thus, residual of current commitment and continuous developments in infrastructure, are expected to make the future winters less troublesome; so higher punctuality performance is expected to be recorded.



## CASE 2 – IMPACTS OF LOW-TEMPERATURE ON PUNCTUALITY OF TRAINS

### **Abstract**

Reliability of services is one of the main quality factors in the railways industry. Punctuality, as an indicator of reliability, is highly valued by customers, railway companies and the governments. However, special weather conditions during the winter seasons, have the potential to cause delays by disturbing the normal operation of trains. Among all the winter weather phenomena, low-temperature, as a modifier of hazardous conditions, may cause failures in railway traffic in several ways. This section, studies the impacts of low-temperature and its different thresholds on occurrence of delays in Nordlandsbanen. The arrival delays at terminating stations for four selected trains running on Nordlandsbanen between 2006 and 2016 are used as a reference for the investigation. The results show that the lower the temperature goes, the more probable will be the occurrence of delays. There is also a correlation between “probability of delayed services and magnitude of delays”, and “number of regions along the route with low temperature”.

Key words: Norwegian railways, winterization, low-temperature, punctuality.

### **Introduction**

Nordlandsbanen (Nordland line) is the longest main line in Norway (729 km), which connects Trondheim in Sør-Trøndelag to Bodø, up in the Nordland, by passing through Nord-Trøndelag. The line goes through a wide variety of climate zones, from coastal areas to inland regions and high mountains. Nordlandsbanen consists 300 bridges, 155 tunnels and 690 level crossing and 42 stations with passenger traffic. The whole line is single track (0 km double track), and non-electrified (Jernbaneverket, 2016a).

The main rolling stocks operating in Nordlandsbanen are “Di 4” and “Vossloh Euro” diesel locomotives and DMUs class 92 and 93, with maximum speed of up to 140 km/h. Though, the infrastructure in Nordlandsbanen except in some regions, limits the running speed to 75-100 km/h (Jernbaneverket, 2016a).

## CASE 2 – IMPACTS OF LOW-TEMPERATURE ON PUNCTUALITY OF TRAINS

Number of trains per day is normally less than 70 in both directions. Although this number is much less than in Oslo area, in some sections (e.g. between Trondheim-Steinkjer, around Mo I Rana, and between Fauske-Bodø) the average capacity utilisation reaches to 85 % and even exceeds 100% in peak hours\*.

Figure 18, presents the average annual punctuality of passenger trains in Nordlandsbanen for the recent years. The goal in Norwegian railways is to keep the punctuality of such services above 90%; which has not been realized so often. Therefore, there is an on-going intention for taking improvement measures for achieving the set goals.

According to National Transport Plan 2014-2023, and in order to enhance the operational performance of Norwegian railways as a whole, there are some plans for increasing the capacity of Nordlandsbanen through construction of passing loops. There are also some plans for developing full remote control of the entire route (Norwegian Ministry of Transportat and Communication, 2012/2013).

Correspondingly, this work concentrates on punctuality of services in winter seasons, and aims to study the impacts of low-temperature on occurrence of delays in Nordlandsbanen.

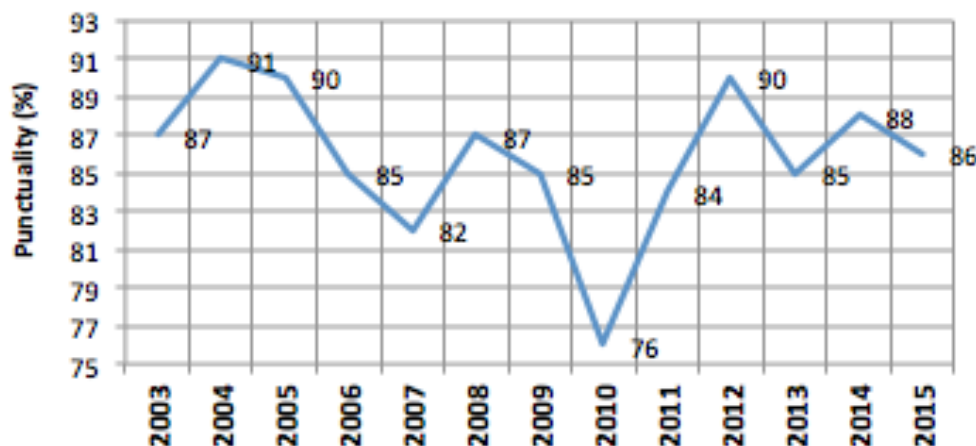


Figure 18-average annual punctuality of passenger trains in Nordlandsbanen (based on data by Jernbaneverket)

\* 100% capacity utilization indicates the maximum number of trains which can be run at maximum operational speed. By accepting a reduced operational speed or increased journey time, it is generally possible to run an increased number of trains. This will give capacity utilization in excess of 100%.



### **Resources**

2 types of data have been utilized for following the goals of this study: Punctuality data, and historical weather data.

- The “punctuality data” have been collected from the “Presis tool” which is the outcome of a research project with the same name. The “Presis project” has been a collaboration between research institution SINTEF, Institute of Transport Economics at NTNU, the Norwegian railway infrastructure manager Jernbaneverket, and train operators Cargonet, NSB and Flytoget. The project concentrates, mainly on travel time variability. However, the characteristics of available raw data suit the requirements of similar studies on punctuality. The retrieved data, in form of excel sheets, consist of scheduled and actual time for daily arrivals and departures, at 66 stations along the line “Nordlandsbanen”, which are equipped with time registry systems.

Moreover, in order to review the average punctuality performance of passenger trains in this line, annual reports, published by Jernbaneverket have been used. In cases where required information were not published in annual reports (e.g. year 2011), an on-line portal “Mitt tog - Punklighet” on Jernbaneverket’s website came in handy.

- The “historical weather data” are collected from eKlima; which is a web-based portal that gives access to the climate database of the Norwegian Meteorological Institute (MET). The climate database contains data from all present and past weather stations of the Norwegian Meteorological institute, as well as data from other institutions that are allowed to be distributed. eKlima gives the user the possibility to pick out simple lists and sophisticated analysis, in demanded formats.

### **Limitations**

- Studying the impacts of winter conditions on performance of train services in a national level could have been an intense task, which goes beyond the constraints of a master’s thesis. Therefore, a particular line had to be chosen in order to help with narrowing the perspective. While looking at different lines, “Nordlandsbanen”, being the longest railway line in Norway (729 km) and passing through various geographical and climatic regions between Trondheim and Bodø, became selected.

## CASE 2 – IMPACTS OF LOW-TEMPERATURE ON PUNCTUALITY OF TRAINS

- The initial intention had been to study the time period between 2000 and 2016. However, due to the limitations in the availability of punctuality data in Presis, the time frame for the study had to be shortened to the span of between January 2006 and November 2016.
- Although the available dataset from Presis contains both arrival and departure time at different stations, the author chose to base the study only on the arrival time. The explanation is that the departure delay is of a lower importance for train users, as long as the trains arrive to their destination on the scheduled time.
- The delays that occur along the line can be compensated through taking corrective measures which self, presents the capabilities of railways companies in regaining the optimality of the operations. Therefore, instead of looking at probable delays at every single station, the concentration has been only on the terminating station. It means that for trains running from Trondheim to Bodø, and for trains heading to Trondheim from Bodø, the arrival delay at “Bodø” station and “Trondheim S” are considered respectively, as the reference for calculating the delays.
- Various train numbers have been running on Nordlandsbanen. Though, 6 train numbers with different characteristics which had regular services between 2006 and 2016 were selected. The selected train numbers, includes 3 trains, running in each direction; in which 2 of them are passenger trains and 1 is freight train. The train numbers are deliberately chosen in a way that both day and night trains are involved. The selected train numbers are:

Table 6-Selected train numbers

Direction	Bodø - Trondheim			Trondheim - Bodø		
Train Number	472	476	5790	471	475	5791
Category	Passenger	Passenger	Freight	Passenger	Passenger	Freight
Departure time (approximately)	12:20	21:00	9:20 - 10:57	7:40	22:20 - 23:40	19:40
Day / Night train	D	N	D/N	D	N	N

## **CASE 2 – IMPACTS OF LOW-TEMPERATURE ON PUNCTUALITY OF TRAINS**

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- Various winter-weather phenomena might affect the train operations. Though, among all the phenomena, the focus in this study, is only on low temperature as a modifier for many hazardous winter-events. Therefore, the impacts of wind, precipitation, snowfall or other winter-related phenomena are not involved.
- Although in many studies, the mean daily temperature is used, this study is based on minimum daily temperature. As the failures are most likely to happen in case of extreme weather condition.
- When identifying the delayed services, early arrivals, and those with less than 5:59 minutes delay are overlooked. Thus, a train is considered as delayed only if it lacks behind its schedule for more than 6 minutes.

- ✓ To sum up, the arrival delays at terminating stations for selected train numbers, running on Nordlandsbanen between 2006 and 2016 are to be used as a reference for investigating the impacts of low temperature on occurrence and magnitude of delays.

### **Methodology**

- **Calculating daily delays for the selected trains**

The analysis commenced with calculating the delays at terminating stations for each of the train numbers. An excel document was created with listing the dates for the time span in the first column, starting from 1/1/2006 until 4/11/2016.

In the top row, the train numbers in both directions were listed. Then the absolute delays (in minutes) for each train and in each day was calculated by subtracting the scheduled arrival time from the actual arrival time:

Absolute Arrival Delay (in minute) = Actual Arrival Time – Scheduled Arrival Time

Then, by using the conditional formatting function in excel, the cells showing a delay of 6 minutes or more became highlighted. The delays equal or greater than 6 minutes are highlighted, because in the Norwegian railways, a long distance train is considered as delayed, if it arrives to its destination later than 5:59 minutes.

- ✓ The result became an excel sheet with 3964 rows and 7 columns, containing dates, train numbers and absolute arrival delays. Figure 19, illustrates a small section of that sheet.

## CASE 2 – IMPACTS OF LOW-TEMPERATURE ON PUNCTUALITY OF TRAINS

Absolute arrival delay at the terminating station (in Minutes).						
Train Category	Passenger	Passenger	Passenger	Passenger	Freight	Freight
Train Number	471 TND-BO	472 BO-TND	476 (NIGHT TRAIN) BO-TND	475(NIGHT TRAIN) TND-BO	5791(NIGHT) TND-BO	5790 (NIGHT/DAY) BO-TND
13/12/10	-2	10	0	-2	2	10
14/12/10	-2	12	4	-4	0	1
15/12/10	6	7	0	11	-2	7
16/12/10	0	13	2	3	11	14
17/12/10	8	16	0	0		25
18/12/10	1	0	4	59		

Figure 19- Methodology sample 1

### • Applied Modifications

- In the cases, where either the scheduled or actual arrival time (or neither) for terminating stations (BO or TND) was not registered, the delay at the first preceding stations with registered time have been used. The table below shows the alternative stations for Bodø and Trondheim respectively:

Table 7- Alternative train stations

Trondheim	Lademon, Leangen, Ranheim, Vilhammar, Midtsandan, Hommelvik, Hell, Stjordal.
Bodø	Mørkved, Oteraga, Valnesfjord, Fauske, Rognan.

- A few dates were noticed in which neither of terminating station nor the preceding stations had a complete registered time. In those cases, it is assumed that trains were not in service, so corresponding cells were left blank. This blank cells are distributed evenly throughout the timespan, so it was assumed that they would not have considerable effect on the final results.

- Checking the departure and arrival time for each of the train numbers, revealed that in case of night trains, the major part of the 729 km route is proceeded in the day after departure date. Thus, the probability of having extremely low temperature in the major portion of trip, which is over the night, would be higher. It is while the delays are assigned to the departing date (e.g. Saying that the train departed on 15<sup>th</sup> at 21:00 was delayed for X minutes, while there is a higher probability that those X minutes delays be resulted, and occurred between 12:00 and arrival time in the next morning). Therefore, when a train departs after 21:00 (e.g. on a Monday), it makes more sense to count its delay for the next day (e.g. Tuesday). Therefore, in order to simplify the modification processes, the first row in the matrix for the night trains were deleted so all the rows where shifted one step up.

## **CASE 2 – IMPACTS OF LOW-TEMPERATURE ON PUNCTUALITY OF TRAINS**

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- After filling the matrix with terminating delays, it was noticed that the two freight trains did not have daily and regular services to be compared with daily weather values (many blank cells). Moreover, the calculated delays for the days with available data, showed relatively longer delays with non-sense trends and regardless of seasons in many cases. Therefore, in order to minimize the effects of missing or extreme values in the final comparisons, those two freight services were left outside, and the study proceeded by looking at the 4 remaining passenger trains; resulting in 15287 single journeys between Trondheim and Bodø in 3961 days.

- ✓ Up to this step, a complete and modified calendar for delayed journeys for 4 passenger trains and for the whole time span was created.

- **Gathering daily weather values**

As mentioned earlier, eKlima can generate the reports for observed weather elements in the requested format. In accordance with the objectives of the study, the requests for reports were set as below:

- Type of report: Diurnal > Daily values – full year.
- Time period: From year 2006, To year 2016
- Selected weather elements: TAN (Lowest noted temperature this hour/day).

The “TAN” has been chosen, as a representative for the most extreme temperature condition that has been experienced in each day. “Lowest noted temperature” has more to do with the characteristics of the current study, as defects and failures are supposed to be more probable under extreme conditions; and they would have been overlooked if “mean” or “average” daily values were used.

In the next step of ordering weather-reports, the demanded weather stations in each county should have been picked from a list of all present and past weather stations. The approach here was to select all the weather stations, which are/were close to the paths that Nordlandsbanen goes through. Comparing the line map with location of weather stations, resulted in 50 weather stations along the line within the three counties: Sør-Trøndelag, Nord-Trøndelag and Nordland. Among this 50 stations, 29 stations were equipped with measuring and recording facilities for the “daily minimum temperature” in varying time spans: Some of them give the TAN data for 2006-2016, while others may cover only a part of this period.

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- ✓ Up to here, the daily values for minimum temperature at different regions along the line had been collected.

- **Dividing the Nordlandsbanen into its sub-regions**

In order to investigate the relationship between dispersal of low temperature and occurrence of delays, the 729 km length of Nordlandsbanen has been split into 11 sections, each covering around 60-70 km of the route. The table below presents the defined regions and the length of “Nordlandsbanen” located in each region. The last column in the table, contains the identification codes for weather stations providing TAN data in the corresponding regions:

Tabell 8 - Sub-regions in Nordlandsbanen

	<b>Regions</b>	<b>Starting km</b>	<b>Ending km</b>	<b>Length (km)</b>	<b>Code of Weather Stations with TAN</b>
1	Trondheim-Ronglan	0	69,65	69,65	68125-65050-68860-69100-69150-69020
2	Ronglan-Byafossen	69,65	130,34	60,69	70150-70680-71000
3	Byafossen-Agle(Myrset)	130,34	194,66	64,32	70850
4	Agle-Flåtådal	194,66	266,05	71,39	73550-72800-74350-72710
5	Flåtådal-Sefrivatnet	266,05	331,69	65,64	77425
6	Sefrivatnet-Halsøy	331,69	408	76,31	77550-77280-77230
7	Halsøy-Finnefjord	408	473	65	78360
8	Finnefjor-Dunderland	473	543,3	70,3	79600-79700
9	Dunderland-Kjemåga	543,3	610	66,7	81775-79764
10	Kjemågå-Finneid	610	670,23	60,23	81680-82000
11	Finneid - Bodø	670,23	729	58,77	82110-82260-82990

At this stage, separated excel files were created for each of the regions; each containing 11 pages named with the years' number from 2006 and 2016. For each year, the daily TAN values from matching weather stations were inserted. The result then became 11 pages for each region, with several matrixes, varying from 0 to 6 matrixes in each page. 0 matrix means that the weather stations located in that specific region did not have the TAN values available for that particular year (This

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has been the case for the year 2006 in region 4, and 2006-08 for region 9). 6 meaning that 6 weather stations provided TAN values for that particular region and in that specific year.

- **Setting temperature thresholds**

The same thresholds as those in EWENT project has been used\*:

- First impact threshold:  $T \leq -20 \text{ }^{\circ}\text{C}$
- Second impact threshold:  $-20 \text{ }^{\circ}\text{C} < T \leq -7 \text{ }^{\circ}\text{C}$
- Third impact threshold:  $0 \text{ }^{\circ}\text{C} \leq T < -7 \text{ }^{\circ}\text{C}$

Accordingly, in this study, the same thresholds are respected. Though, since temperature below  $0 \text{ }^{\circ}\text{C}$  and above  $-7 \text{ }^{\circ}\text{C}$  is very frequent in Norwegian climate, the two first thresholds have been used as a basis for studying and comparing the impacts of low temperature on punctuality of services.

At this stage, by using the conditional formatting function of excel, the cells in the previously created excel sheets, containing values related to each threshold were identified. As a result, in each page, the days with TAN values related to those two thresholds were highlighted.

Afterwards, 2 new matrixes with the dates in the first column and the 11 regions in the heading row was created; One set for each threshold.

In the matrix for the first threshold (Temperature below  $-20 \text{ }^{\circ}\text{C}$ ), under each title (regions) the lowest recorded temperature from all the available weather stations was inserted. Meaning that for a particular day in a region, if the recorded values from different stations (e.g. four available) were -19, -15.5, -22 and -25, the number -25 which is the lowest value have been picked as a representative for having temperature below  $-20 \text{ }^{\circ}\text{C}$  in that region and on that specific day.

Then, the number of regions with temperatures below  $-20 \text{ }^{\circ}\text{C}$  in a certain day were counted and inserted in an added column. The result from this step was a matrix as is shown in figure X:

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\* More information about these thresholds can be found in chapter 4. The difference is that instead of mean daily values, the minimum noted temperature in each day have been used.

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fx -21.9												
F	G	H	I	J	K	L	M	N	O	P	Q	R
Regions with temperature below -20											NUMBER OF REGIONS	
	TND RONGLAN	RONGLAN BYAFOSSEN	BYAFOSSEN AGLE	AGLE FLÁTÁDAL	FLÁTÁDAL SERFIVATNET	SERFIVATNET HALSØY	FINNEIDFJORD D	FINNEIDFJORD DUNDERLAND	DUNDERLAND KHEMÅGÅ	KHEMÅGÅ FINNEID	FINNEID BODØ	
25/11/10			-27.5	-22.4	-25.1	-22		-24	-22.5	-23.7		7
26/11/10			-26	-23.7	-22.3			-23.2	-20	-23		6
27/11/10			-27.9	-23.8				-21.5		-23.1		4
28/11/10			-28.7	-26.7	-25.1	-22.3		-22.9	-21.3	-23.8		7
29/11/10			-28.3	-25.7	-26.4	-23.8		-24.8	-20.4	-24		7

Figure 20- Methodology sample 2

The similar approach has been followed for the other threshold ( $-20\text{ °C} < T \leq -7\text{ °C}$ ) with a minor difference: For the threshold  $-7\text{ °C} \leq T < -20\text{ °C}$ , if a temperature below  $-20\text{ °C}$  had been already recorded for a region in a certain day, the related cell has been left blank; even if temperatures between  $-7\text{ °C}$  and  $-20\text{ °C}$  was recorded in other weather stations. The explanation for this is that the impacts of that extreme temperature had already been considered when studying the impacts of temperatures below  $-20\text{ °C}$ .

- ✓ At this level, for each day, the number of regions with temperatures related to each critical impact thresholds were identified.

- **Investigating the annual and winter weather condition**

Counting the number of regions with recorded temperatures, related to each threshold and for each day, gave the information about the number of days in each year (and in each winter) that the temperatures between  $-7\text{ °C}$  and  $-20\text{ °C}$ , or below  $-20\text{ °C}$  were experienced.\* Counting the number of days with such records, provided the information about weather patterns (in terms of temperature) for selected timespans.

- **Reviewing the winter-punctuality of selected trains**

Number of on-time services (with delay values less than 6 minutes) were counted, and divided by the total number of services in the same time span. For example, the punctuality level in winter of 2009 was calculated by dividing the number of on-time journeys, by total number of realized services between 1<sup>st</sup> of November 2009, and 31<sup>st</sup> of March 2010.

\* Detailed information for number of regions for each threshold is attached to the appendices



- **Investigating the impacts of low temperature on punctuality**

Having the daily records for delayed trains and the minimum temperature in various regions, provide us with a basis for investigating the impacts of low temperature on expected level of punctuality.

- In order to study the correlation between prevailing weather patterns, and recorded punctuality levels, the number of cold days in each year, and in each winter, was used for comparisons against achieved punctuality of selected trains.

- ✓ The correlation between the prevailing weather patterns and realized punctuality was studied.

- In order to investigate the impacts of different temperature thresholds on probability of delays, the dates in which at least (a) one of the four trains were delayed, and at the same time (b) the temperature below  $-20\text{ }^{\circ}\text{C}$  was recorded in “one” or “more” of the 11 regions were identified and counted.

It should be noted that the number of delayed trains (out of four) in each day are not involved, as having at least one delayed train has been considered as a representative for existence of some problems in operation of the line.

- Dividing the resulted number by the total number of days with temperature below  $-20\text{ }^{\circ}\text{C}$  gave us the probability of delays to occur when one or more of the regions experience  $-20\text{ }^{\circ}\text{C}$  or lower (Which percentage of journeys were delayed when the temperature in at least one region was below  $-20$ ). In the same way, the probability of delays with having more than 2 regions with temperature within that threshold can be calculated, and so on. The same process is done for the other threshold to compare and see if the probability of delays varies when the temperature ranges are different.

- ✓ This process, helped with quantifying the relationship between number of regions with low temperature and probability of delays to occur.
- ✓ The changes in probability of delays, when temperature goes below a certain level (in different thresholds) can be determined. Therefore, based on the results, it can be decided if the statement “the colder the weather gets, the more will be the probability of delayed services” is true or not.

## **CASE 2 – IMPACTS OF LOW-TEMPERATURE ON PUNCTUALITY OF TRAINS**

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-The prepared data sets has also the potential for studying the impacts of low temperature on severity of delays (To study travel time variability, and not the occurrence of delays and level of punctuality). The chosen approach to conduct this research is to calculate the sum of absolute delays (in minutes / even below 6 minutes / excluding negative values) in each day for all the four trains and use the “median” to compare it with number of regions experiencing low temperature.

- ✓ This approach clarifies the relationship between number of cold regions and magnitude of delays.
- ✓ Moreover, the effects of different temperature ranges on severity of delays can be investigated.

**Results & Discussions**

**Annual weather records vs. annual average punctuality**

Investigation on historical weather data for the past 11 years, shows that temperatures less than -7 °C are recorded along the route in almost more than 100 days annually. This means that operation of trains in extremely low temperatures is a common case in Nordlandsbanen.

As it can be seen in figure below, 2010 has been the coldest and 2015 was the least cold periods in the investigated time span (Figure 21).

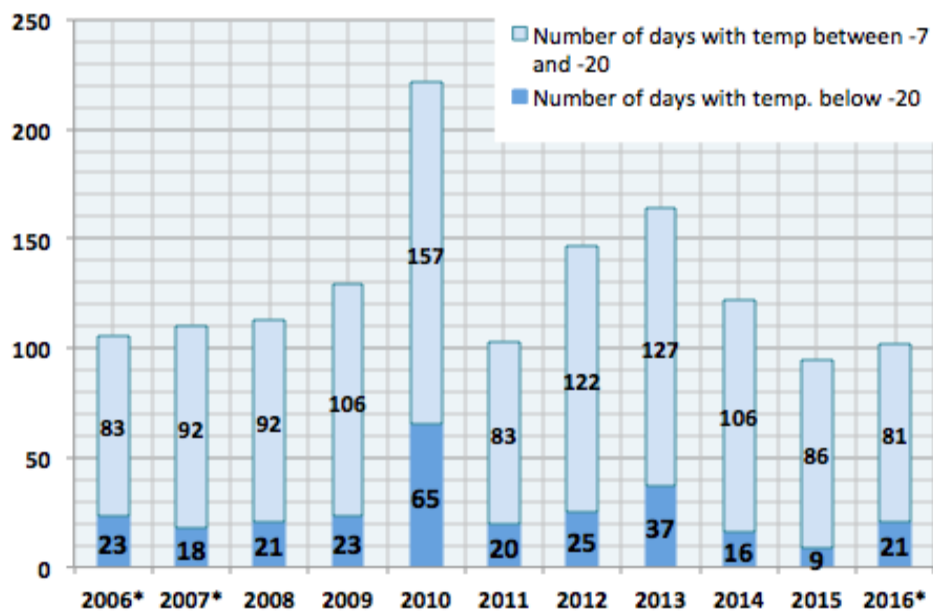


Figure 21- Annual number of days with extreme low-temperature\*

Comparing this with the recorded annual punctuality in Nordlandsbanen for all the passenger trains (Figure 18) shows a relationship between high number of cold days and considerable loss of punctuality in 2010 and 2013. Thus, it can be said that:

- ✓ The concurrence of high number of extreme cold days, and low punctuality performance in 2010 and 2013, might be an evidence for existence of a correlation between low-temperature and punctuality loss.

\* In 2006 and 2007, TAN values for 2 regions were not available.  
The records for 2016 are valid for 1st of January until 4th of November.

## CASE 2 – IMPACTS OF LOW-TEMPERATURE ON PUNCTUALITY OF TRAINS

### Winter weather patterns vs. winter punctuality records

In order to check the validity of correlation between number of days with extremely low temperatures (below  $-7^{\circ}\text{C}$ ) and punctuality loss, this section concentrates only on winter months, and focuses on the calculated punctuality performance of 4 selected passenger trains. By doing this, the impacts of performance in summer time would be excluded, and the results will specifically represent the performance of our selected trains, which travel the entire route.

Figure 22 presents the number of cold days in each winter\*, and figure 23 shows the calculated punctuality of 4 selected trains, separately for the winter and summer months:

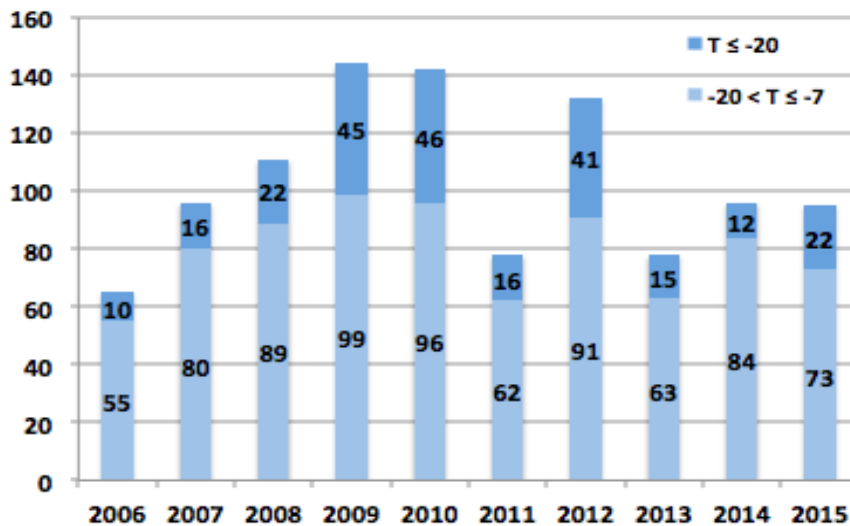


Figure 22- Number of extremely cold days in each winter

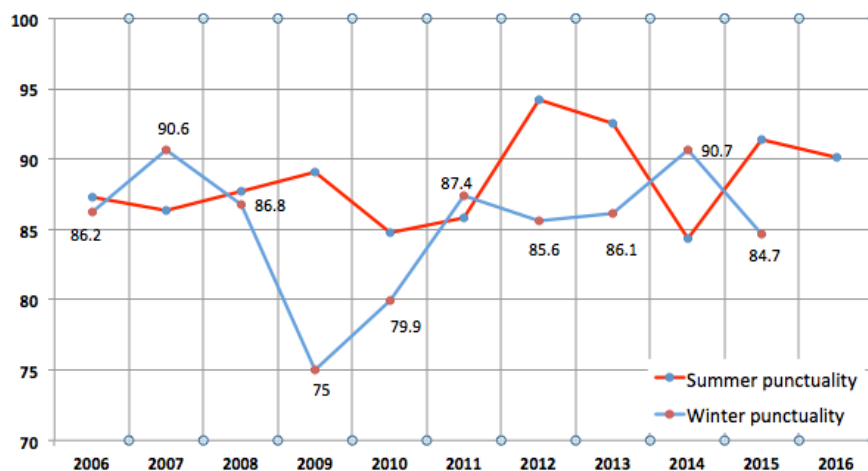


Figure 23- calculated punctuality of 4 selected trains

\* In figure 22, 2006 means the winter of 2006 (Nov 2006 – Mar 2007) and so on.

## **CASE 2 – IMPACTS OF LOW-TEMPERATURE ON PUNCTUALITY OF TRAINS**

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Looking at Figure 22, shows that the winters of 2009, 2010 and 2012 have been the coldest winters in the past 10 years in Nordlandsbanen, with more than 130 days with temperatures below  $-7^{\circ}\text{C}$  along the route. Matching this with the winter punctuality of corresponding years, reveals that in 2009 and 2010, the punctuality has been in its lowest level; and in 2012, although the punctuality was not significantly low, but the difference between summer and winter performance was considerable.

Figure B, also illustrates that except in 3 years (2007, 2011 and 2014), the winter-punctuality has always been less than punctuality levels in the warmer seasons. Remarkably, among those three exceptions, winter of 2011 had one of the mildest weather conditions.

- ✓ Up to here, the validity of correlation between cold winters (with high number of cold days) and decrease in the punctuality level has been approved.

With the aim of finding more evidences for this correlation, and to see how the winter skills evolved during the years, the changes in number of cold days, and changes in winter-punctuality for every 2 years are reviewed. Results from looking into year by year changes in weather patterns and winter-punctuality are shown in the table 9.

Table 9- Year by year changes in weather patterns and punctuality in winters

<b>Year</b>	<b>Weather changes</b>	<b>Achieved winter punctuality</b>	<b>As expected?</b>
2006-2007	Colder	Better	No
2007-2008	Colder	Worse	Yes
2008-2009	Much colder	Much worse	Yes
2009-2010	As cold (Almost)	Better (but still low)	Yes
2010-2011	Much warmer	Much better	Yes
2011-2012	Much colder	A little worst	Yes
2012-2013	Much warmer	A little better	Yes
2013-2014	Colder	Much better	No
2014-2015	As cold	(much)Worse.	No

## **CASE 2 – IMPACTS OF LOW-TEMPERATURE ON PUNCTUALITY OF TRAINS**

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In most of the cases (6 out of 9), the changes in weather patterns and corresponding winter-punctuality are aligned with our expectations. However, in 2 cases (From 2006 to 2007 and from 2013 to 2014) despite the increase in number of cold days, the punctuality performance was enhanced. Moreover, although the winters of 2014 and 2015 were very similar, the winter-punctuality dropped dramatically. In addition, when the number of cold days in 2012 was much higher than 2011, the punctuality record shows only a very slight decline (1.8%).

- ✓ These exceptional cases stop us from claiming confidently, that there is a direct correlation between low-temperature and lower punctuality. But observations show that extremely harsh winters (specifically those with more than 130 cold days) have always resulted in low punctuality performance.

Low performance can have its roots in many other factors, other than especial winter conditions. This fact, stops us from certainly approving or rejecting the definite impacts of winter phenomena on punctuality.

For example, when none of the expected winter-issues\* are likely to happen in warm seasons, still, there are some years with very low punctuality records in summers. This shows that many other factors are involved in determining the realized punctuality level. Therefore, although the negative impacts of winter condition on optimum operations cannot be rejected:

- ✓ We cannot confidently claim that colder winters, will definitely result in lower punctuality; at least not in Nordlandsbanen.

In order to follow the research question further, in the next section, the relationship between “number of regions which are affected by low-temperature”, and “the probability of delays to occur” will be investigated.

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\* Refers to chapter 5- Winter Issues

## CASE 2 – IMPACTS OF LOW-TEMPERATURE ON PUNCTUALITY OF TRAINS

### Temperature thresholds and probability of delays

After concluding that colder winters will not necessarily lead to lower punctuality records, this section presents the results from a more detailed investigation. This investigation is consisting of a day-by-day study on real samples, with the aim of exploring the impacts of different temperature ranges and their dispersion (how widespread the low-temperature is along the line) on probability of delays to occur. Later on in this section, their impact on the magnitude of delays will be studied.

- **Probability of delays in Threshold 1 ( $T \leq -20$  °C)**

In total, 278 days, with at least “one region”, with recorded temperature of below  $-20$  °C (in at least one of the weather stations), have been experienced in 2006-16 timespan.

Looking into the delayed services, revealed that in 131 cases (out of 278), at least one of the four trains were delayed.

In other words, the probability of delayed services, when one or more regions had a temperature of under  $-20$  °C, was 47.84 %.

Similarly, when 2 or more regions had the same temperature condition ( $T \leq -20$  °C), in 90 cases, at least one train was delayed; which means the probability of delayed trains increased to 49,72%.

Correspondingly, comparing the delayed services, with number of regions with temperature within that threshold gives the results in (Table 10).

Table 10- Probability of delays vs. number of cold regions - Threshold 1

	N = Number of regions with temperature less than or equal to $-20$								
	1 ≤ N	2 ≤ N	3 ≤ N	4 ≤ N	5 ≤ N	6 ≤ N	7 ≤ N	8 ≤ N	9 ≤ N
Number of days with N...	278	181	126	85	59	35	20	8	9
Number of days in which at least one train was delayed	133	90	74	55	38	25	14	8	9
<b>Probability of delays</b>	47.84%	49.72%	58.73%	64.71%	64.41%	71.43%	70.00%	100.00%	100.00%

- ✓ Based on the results, it can be said that, the more widespread the low-temperature (below  $-20$  °C) was, the higher became the likelihood of delays to occur.

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This probability increased significantly when more than 7 regions out of 11 (63% of the route) were influenced by the coldness: In cases, where more than 8 regions (more than 72% of the route) were having temperature below  $-20\text{ }^{\circ}\text{C}$ , the occurrence of delays was imminent (Figure Y).

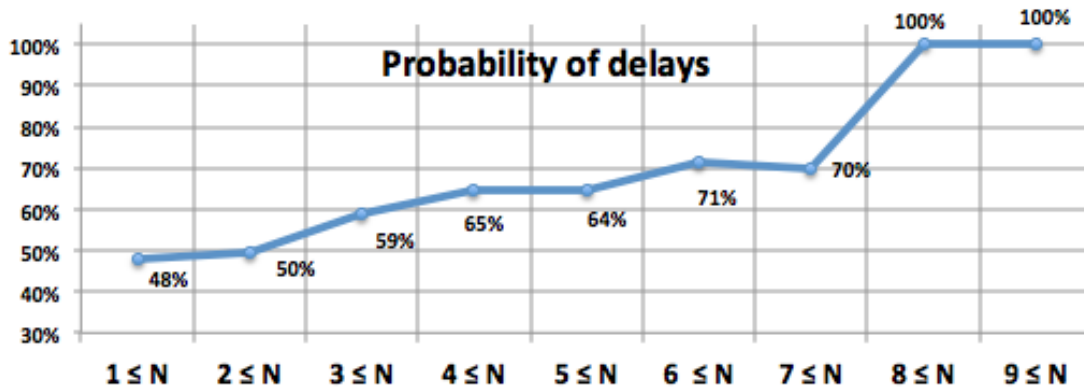


Figure 24- Probability of delay vs. Number of regions - Threshold 1

- ✓ In cases of widespread cold where more than 72% of the route was affected by low-temperature of below  $-20\text{ }^{\circ}\text{C}$ , the delays were inevitable.

- **Probability of delays in Threshold 2 ( $-20\text{ }^{\circ}\text{C} < T \leq -7\text{ }^{\circ}\text{C}$ )**

Following the same approach for the second temperature threshold, shows that between the years 2006 and 2016, 984 days had the “lowest noted temperature” of between ( $-20\text{ }^{\circ}\text{C} < T \leq -7\text{ }^{\circ}\text{C}$ ) in at least one of the regions along the route; Where in 405 cases, at least one of the 4 trains were delayed, giving the probability of 41.16% for occurrence of delays. The table 11\* presents the values for different N values (Number of regions with temperature  $-20\text{ }^{\circ}\text{C} < T \leq -7\text{ }^{\circ}\text{C}$ ).

Table 11- Probability of delays vs number of cold regions - Threshold 2

	N = Number of regions with temperature less than or equal to $-7$ and bigger than $-20$										
	1 ≤ N	2 ≤ N	3 ≤ N	4 ≤ N	5 ≤ N	6 ≤ N	7 ≤ N	8 ≤ N	9 ≤ N	10 ≤ N	11 ≤ N
Number of days with N...	984	815	692	580	490	397	298	214	127	65	23
Number of days in which at least one train was delayed	405	337	292	250	214	173	130	95	55	26	8
<b>Probability of delays</b>	<b>41.16%</b>	<b>41.35%</b>	<b>42.20%</b>	<b>43.10%</b>	<b>43.67%</b>	<b>43.58%</b>	<b>43.62%</b>	<b>44.39%</b>	<b>43.31%</b>	<b>40.00%</b>	<b>34.78%</b>

\* The highest number of regions with temperature below  $-20$  in a day was 9, while there were some days with 11 regions with temperature between  $-7$  and  $-20$ .



## CASE 2 – IMPACTS OF LOW-TEMPERATURE ON PUNCTUALITY OF TRAINS

Using the findings to examine the correlations, shows a very slow but consistent growth in probability of delays, as the number of affected regions increases. Though when the number of regions goes beyond 9, the line drops sharply.

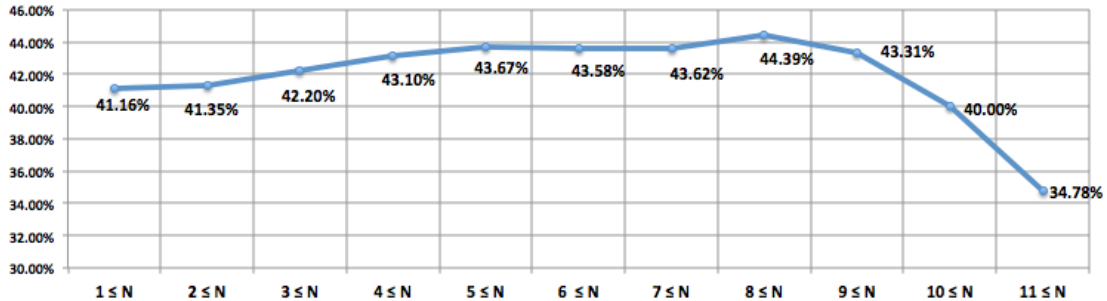


Figure 25- Probability of delay vs number of regions - Threshold 2

Comparing the results for these two thresholds (the values for probability related to a certain number of regions), shows that the probability of delays to occur was higher when the temperature reached below  $-20^{\circ}\text{C}$ , (in comparison with when it was between  $-7^{\circ}\text{C}$  and  $-20^{\circ}\text{C}$ ). Thus, it can be said that the temperature is an influential factor that can affect the probability of delayed services; and this can be used as a proof for the statement that:

- ✓ The lower the temperature goes after a certain limit, the higher will be the probability of delays to occur.

The results from studying “the probability of delays in comparison with the number of regions with temperatures within the second threshold, is aligned with the findings from the first case, when up to “8 or more” regions are involved ( $8 \leq N$ ). Though, when more than 9 regions are affected by temperatures within the 2 threshold, the gradual upward trend changed to a sharp drop.

This can be resulted from three causes: (a) Before the February 2009, there are some periods in which one or two regions are missing temperature records (TAN values). It means that all we have is weather records from 9-10 regions (depending on the time). Thus, when considering 9 or more regions with temperatures within the range, the impact of missing data will become more significant. Moreover, (b) dates in which one of the weather stations had recorded temperature of below  $-7^{\circ}\text{C}$  were excluded. It means that the regions with temperatures in range of  $-20^{\circ}\text{C}$  to  $-7^{\circ}\text{C}$  in some of the

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weather stations were left outside, even if in only one weather station, the temperature was out of that range. So a considerable amount of data is excluded as they had already been considered when studying the other threshold. (c) The other reason can be that maybe the resulted trend for second temperature range (-7 to -20), is just a matter of randomness, and the temperatures above -20 have only occasional impact on operation of trains. If taking this as a fact, the results can be viewed from the preparation and adaptation perspective; and it can be argued that since the temperatures within the second threshold are more expected in geographical/climatic situation of the line (984 vs. 278 cases in this timespan), the line is more equipped and the railways are better prepared to deal with its threats. So the negative impacts of such temperatures will be more occasional.

By assuming that these hypothesizes are true, and by relying on the results for up to 9 regions with low temperature, it can be claimed that there is a correlation between the number of cold regions along the route, even for the temperatures in range of -7 to -20, and the probability of delays. Based on this, the limitations to first threshold can be removed and it can be claimed that:

- ✓ Number of regions with extremely cold weather (or how widespread the coldness is), can influence the punctuality of trains by affecting the probability of delays to occur; in a way that in cases of widespread extreme cold, delays cannot be compensated until the terminating station. And by extremely cold weather, it means temperatures below -7 °C which covers both thresholds.

Up to here, in this study, having one delayed train (out of four), was taken into account as a representative for occurrence of affected services due to low temperature. In the next section, the aim would be to find: how the “magnitude of delays” can be affected by “different temperature thresholds” and “how widespread the cold is”.

### Impacts of low temperature on magnitude of delays

The results from totaling the absolute delays in minutes for each day (early arrivals excluded), and finding the medians for the days, when more than a certain number of regions were affected with temperatures below  $-20^{\circ}\text{C}$ , are shown in the figure 26. It shows that the median of total daily delays, for all the days when more than one region experienced the temperatures less than  $-20$  was 8 minutes. And this total delay increased as the number of affected regions was higher.

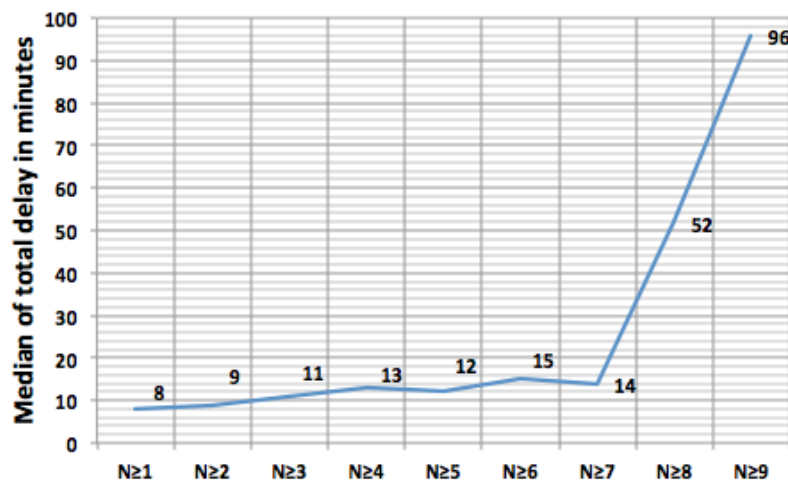


Figure 26-Median of delay vs. Number of regions - Threshold 1

Based on this result, it can be said that when higher number of regions were affected by temperatures less than  $-20^{\circ}\text{C}$ , the total delays became longer:

- ✓ Having more regions along the way with minimum temperatures below  $-20^{\circ}\text{C}$  will increase the magnitude of delays in the final stations.

For the other temperature threshold, no specific correlation has been noticed between number of regions and median of total delay values. It can be perceived as less significant impact of low-temperature in range of  $-7^{\circ}\text{C}$  and  $-20^{\circ}\text{C}$ . Though, the resulted medians were, one by one, less than those for the colder threshold (The maximum median was 6). Therefore, it can be taken as proof for claiming that:

- ✓ The colder it gets, the longer the delays are expected to be.

### CONCLUSION

The goal in this work has been to study the impacts of low-temperature on punctuality of trains.

Investigating the number of extremely cold days (below -7) in the recent years, and comparing the results with average annual punctuality in Nordlandsbanen, revealed a correspondence between numerous days with extreme-cold, and significant loss of punctuality in 2010 and 2013. Moreover, separating the winter months and looking thoroughly into changes in weather patterns against realized punctuality, showed that winter-punctuality records were considerably low in case of high number of extremely cold days. Though, some exceptional cases were found that do not support the causal relationship between higher annual number of cold days and decrease in punctuality.

Further investigation on the impacts of different ranges of low-temperature on probability of delayed trains, discovered that the more extreme the low-temperature becomes, the higher will be the probability of delays to occur.

It was also concluded that the number of regions with extreme cold weather, can influence the punctuality of trains. As in cases of widespread extreme-cold, delays were more likely to occur in both temperature ranges. Though, this increase in probability was more significant for the temperatures below -20°C. For example, when more than 72% of the route was affected by low-temperature of below -20 °C, the occurrence of delay(s) were inevitable. While for the temperatures above -20°C and below -7°C, this probability never reached to more than 50%, even when the temperature between -7°C and -20°C was recorded in the entire route. In addition, studying the impacts of low-temperature on magnitude of delays, resulted that having more regions along the route with temperatures below -20°C, can lead to longer delays in the final stations. While such relation was not observed for the temperatures between -7°C and -20°C, which reveals that the probable delays due to this level of coldness are shorter than those delays caused by temperatures below -20°C.

From the last 2 findings, it can be concluded that the low-temperature is highly influential, only when it goes below a certain level (-20°C). This means that either low-temperature in range of above -20 does not have significant effects, or the Nordlandsbanen has, to some extent, succeeded to encounter the problematic issues with less extreme low temperatures.

Part 4  
CONCLUSION AND  
FURTHER STUDIES



### CONCLUSION

This thesis, provides the readers with a comprehensive reference regarding the issues with operation of trains under the winter conditions, as well as the effects of winter-conditions and related countermeasures on performance of services:

The report begins with an in-depth review of the main characteristics of transportation systems. Then, the main indicators for evaluating the railways systems are thoroughly investigated, and an outline of the two main strategies for improving the reliability of services is provided.

In order to gather the probable impacts and consequences of winter on the railway operations, this report investigates the various winter phenomena and their combinations, as well as the worst probable cases and the future climatic vulnerabilities. Three critical impact thresholds for adverse weather phenomena are introduced, which help with predicting the possible impacts and consequences of different winter phenomena on the railway traffic.

Conducting an in-depth research on the winter-related problems that might arise, resulted in a comprehensive list of technical and operational issues that might negatively affect either of the rolling stock or infrastructure. It was found that most of the problems are due to defects and malfunctions in sub-systems, or prolonged processes. The predominant problems with rolling stocks are caused by blocked movements, increased stiffness, snow covered surfaces, inappropriate friction coefficient, extra weight and increased frequency of physical hits, as well as penetration of humidity into critical components. On the other side, masses of snow, fallen trees, and frozen components are some of the root causes for blocked tracks, malfunctions or defects in the railways' infrastructure.

Afterwards, the available countermeasures for experiencing less problematic operations under winter-conditions are reviewed. It showed that considering preventive aspects when designing the railways systems, is the most effective step for better winter operations. Moreover, utilization of various systems and equipment, as well as erecting protection structures can help with preventing, or minimizing the

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negative effects of adverse winter conditions. Furthermore, performing some activities, and following some special instructions will be required to maintain the optimality of railway operations. It was also realized that preventive measures through utilization of passive solutions will be the ideal case; though the need for reactive actions and active solutions is inevitable.

It was also argued that having the best railway systems, without integrated organizational and managerial practices, will not assure the optimality of winter operations. Thus, presence of proper strategies and procedures in the railways organizations, as well as some forward-thinking adaptations would be necessary to be taken into consideration.

Further in the report, the fundamental reasons for experiencing frequent disruptions of services during the winters, despite of all the available experiences and solutions, are addressed. Based on the reviewed literature, it was found that low motivation and lack of awareness, together with improper organizational procedures have been the main obstacles for not having appropriate level of preparedness.

Later on, the development of winterization measures in Norwegian railway infrastructure is presented, and the effects of such developments on punctuality-performance is argued. To do so, the trends in development of Norwegian infrastructure has been compared with the variations in achieved punctuality records in a national level: Observing the number of newly added items during the 5 years' time spans, revealed that the period 2011-2015 has been a big step towards a better winterization in Norwegian railway's infrastructure. On the other side, reviewing the winter performance of Norwegian railways in terms of punctuality, discovered an improvement trend after 2010. Matching these two findings, and taking the developments in infrastructure as an evidence for increased effort in a bigger scale, showed that more attention to winterization-measures, have resulted in better punctuality performance. Though, the impacts of different winter-conditions must not be neglected.

It was also noticed that the timespan of 2006-10, with only few measures taken in infrastructure, has been one of the least active periods regarding the winterization in the past decades. This can be taken as an explanation for the failure of Norwegian railways in maintaining the punctuality, when the harsh winter of 2009-10 hit the



## CONCLUSION & FURTHER STUDIES

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country. These findings, prove that lack of constant and continuous improvement measures, regarding the winter preparation considerations, can result in significant loss of punctuality performance in case of harsh winters. Hence, the railways should constantly work on their preparedness level, to be able to battle the probable extreme winter-conditions in the future. Another fact to be mentioned, is that maintaining the existing winter-related components, besides adding new items over the years, will result in an accumulated number of them to be in place. Thus, residual of current commitment and continuous developments in infrastructure, are expected to make the future winters less troublesome.

Studying the impacts of low-temperature on punctuality of trains in Nordlandsbanen, revealed a correspondence between numerous days with extremely low temperature, and significant loss of punctuality in 2010 and 2013. Separating the winter months and looking thoroughly into changes in weather patterns against realized punctuality, showed that winter-punctuality records were considerably low in case of high number of extremely cold days (above 130 days). Though, some exceptional cases were found that do not support the causal relationship between higher annual number of cold days and decrease in punctuality. Further investigation, discovered that the more extreme the low-temperature becomes, the higher will be the probability of delays to occur. It was also concluded that in cases of widespread extreme-cold, delays are more likely to occur; especially for temperature ranges below  $-20^{\circ}\text{C}$ . For example, in the studied case, when more than 72% of the route was affected by low-temperature of below  $-20^{\circ}\text{C}$ , the occurrence of delay(s) were inevitable. While for the temperatures above  $-20^{\circ}\text{C}$  and below  $-7^{\circ}\text{C}$ , this probability never reached to more than 50%, even when the entire route was affected by low-temperature in that range. In addition, studying the impacts of low-temperature on magnitude of delays, resulted that having more regions along the route with temperatures below  $-20^{\circ}\text{C}$ , can lead to longer delays; While such relation was not observed for the temperatures between  $-7^{\circ}\text{C}$  and  $-20^{\circ}\text{C}$ . From the last 2 findings, it was concluded that the low-temperature is highly influential, only when it goes below a certain level ( $-20^{\circ}\text{C}$ ). This means that either low-temperature in range of above  $-20$  does not have significant effects, or the Norwegian railways has, to some extent, has succeeded to encounter the problematic issues with less extreme low temperatures, at least in Nordlandsbanen.

### FURTHER STUDIES

The characteristics of this topic, makes it an almost endless study. All the covered areas in this report have the room for being studied much further. This section, gives some suggestions regarding the relevant further studies:

#### Part 2:

- Each region has its unique geographical and climatic conditions, and the level of preparedness is not the same in all the countries (not even in different the lines in a country). The results in EWENT project are addressing the impacts of extreme weather in the whole Europe. Though, when studying the impacts of winter phenomena on railway operations and identifying the critical thresholds, each country or region can be studied separately.
- New studies, based on reported defects and malfunctions, their location/time of occurrence will help with identifying and analyzing the problem areas; which will provide the authorities with root causes, to be resolved.
- The future climatic changes, and setting long-term adaptation plans can still be studied further.
- There is a possibility for more detailed technical studies on the effects of cold and ice, on the railway components, to be followed from an engineering perspective.

#### Part 3 - Case 1

- It is possible to get better results from studying the case 1: Studying longer time periods, using datasets with higher quality, etc. will result in more reliable results.
- The concentration in this study, was mainly on passenger trains (Long/Medium distance, and airport trains). Tough other types of train services can be involved when reviewing the punctuality in a similar study.
- This work studied the development of winter solutions in infrastructure in a national level. Though a more in-depth comparison between different lines regarding the effects of utilized winter solutions is possible.

## CONCLUSION & FURTHER STUDIES

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- When comparing the developments with changes in punctuality, the impacts of different weather conditions were not involved. Involvement of changes in weather patterns in this study, will lead to more reliable results.
- The development of winter solutions for the rolling stocks and in operational level can be studied to be combined with this study; so the judgment about impacts of development measures on punctuality will be more reliable. However, conducting researches based on the annual investments on winter preparation, maintenance, etc. will give a more comprehensive result than studying the railways systems separately.

### Part 3-Case 2

- The same study as the one in case 2 can be followed by using “mean daily values” (instead of minimum noted temperature). So the results from the new study can be compared with the findings of the EWENT project.
- The case 2, concentrated on effects of low-temperature among all the other winter phenomena. Similar investigations are easily possible to be based on studying the impacts of other winter phenomena such as daily snow fall, wind speed, etc. The best result will be achieved by considering as many influential factors as possible and through studying their combinations.
- In the case 2, the delays along the route are not considered at all. Therefore, instead of looking only at delays at termination stations, the recorded punctuality at the other main stations along the way can be used as the reference for reviewing the delays in each section. As a result, the more vulnerable areas can be identified to be prioritized for taking improvement actions.
- While studying the winter-punctuality, it was noticed that in many cases, the performance was better in winters (compared to summer times). Therefore, finding the reasons for fluctuations in summer-punctuality will shed light on the other influential factors which might also be present in winter times. Being aware of such issues, and considering them when studying the winter performance, will make it possible to make certain and definite judgements about impacts of winter on punctuality variations.

## **CONCLUSION & FURTHER STUDIES**

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The cover photo and all the black and white icons are downloaded from [www.thenounproject.com](http://www.thenounproject.com).

## APPENDICES

Table 12- Winter issues – Rolling Stock

Winter issues – Rolling Stock	
Category	Problems
Snow packing	Blocked movements Limited accessibility for maintenance Increased weight Loss of running dynamics Damages to infrastructure Damages to rolling stock
Suspension and tilt mechanisms	Limited movements
Under-frame equipment	Damages due to being struck
Wheel-rail friction	Low friction coefficient /slipping High friction/ improper lubrication
Wheels	Broken wheels Flattered or shelled wheels
Brake systems	Reduced braking capabilities Frozen liquids Blocked movements
Car body	Broken windows Snow-covered lights and windshield Damaged body
Doors and Steps	Jammed doors Slippery surfaces Stuck foldable steps
Axle and axle boxes	Failed axles Negated lubrication Lockage in adjustable axles
Couplers	Hardened lubrication Damaged couplers
Cables, Hoses and pipes	Squeezed and pressed Torn Frozen liquids inside pipes and hoses
Motor and cooling systems	Blocked cooling systems channels Mechanical failure Electrical failure Frozen cooling liquid
Pantograph	Blocked movements Damaged carbon strip
Collision with big animals	Damage to car body Damage to couplers Damage to under-frame
Maintenance issues	Higher demand Troublesome inspection Limited accessibility Prolonged maintenance time

Table 13- Winter issues - Infrastructure

<b>Winter issues - Infrastructure</b>	
<b>Category</b>	<b>Problems</b>
Snow accumulation	Slower train services Trains getting stuck Derailment Collapse of structures Lack of space for disposing snow
Tunnels	Collusion with icicles Temperature changes Falling ice
Platforms, stations and parking spaces	Slippery surfaces
Rails	Broken rails Rail degradation
Switches and crossings	Blocked movements Damaged switches
Ballast	Ballast pick up
Overhead wires and Third rail	Improper current conduction Damaged systems

Table 14- Key figures for the Norwegian rail network in 2015 ( Jernbaneverket 2016)

Bane/Line	Km bane hovedspor / Route-km <sup>4)</sup>	Km dob- beltspor / Km double track	Broer / Bridges	Tunneler / Tunnels <sup>6)</sup>	Planover- ganger / Level crossings	Stasjoner / Stations <sup>5)</sup>
* Nordlandsbanen (Trondheim - Bodø)	729	0	300	155	690	42
x Sørlandsbanen (Drammen - Stavanger)	546	14	498	190	126	45
x Dovrebanen (Eidsvoll - Trondheim)	475	14	327	42	259	28
* Rørosbanen (Hamar - Støren)	384	0	227	6	468	27
x Bergensbanen (Hønefoss - Bergen)	371	0	204	145	172	33
x Østfoldbanen, vestre/Østfold line, western (Oslo S - Kornsjø gr.)	169	64	131	17	71	23
x Vestfoldbanen (Drammen - Eidanger)	140	23	98	17	102	12
x Gjøvikbanen (Oslo S - Gjøvik)	124	2	73	7	90	22
x Kongsvingerbanen (Lillestrøm - Charlottenberg gr.)	115	0	62	0	69	13
* Raumabanen (Dombås - Åndalsnes)	114	0	106	5	179	4
* Solørbanen (Kongsvinger - Elverum)	94	0	31	1	194	0
x Hovedbanen (Oslo S - Eidsvoll)	68	20	66	5	19	21
x Østfoldbanen, østre/Østfold line, eastern (Ski - Rakkestad) <sup>1)</sup>	55	0	31	0	57	11
* Meråkerbanen (Hell - Storlien)	70	0	47	1	47	4
x Gardermobanen (Etterstad - Eidsvoll)	64	60	24	4	0	3
x Randsfjordbanen (Hokksund - Hønefoss) <sup>2)</sup>	54	0	22	1	70	2
x Bratsbergbanen (Eidanger - Nordagutu)	47	0	45	20	48	2
x Ofotbanen (Narvik - Vassijaure gr.)	39	0	7	23	43	5
x Drammenbanen (Oslo S - Drammen)	41	41	27	11	2	16
x Arendalsbanen (Nelaug - Arendal)	36	0	17	3	44	8
x Roa - Hønefossbanen	32	0	27	3	47	0
x Flåmsbana (Myrdal - Flåm)	20	0	2	21	39	8
x Askerbanen (Lysaker - Asker)	17	17	9	8	1	0
x Spikkestadbanen (Asker - Spikkestad)	14	0	10	0	8	5
x Tinnosbanen (Hjuksebø - Notodden) <sup>3)</sup>	9	0	17	5	17	2
x Brevikbanen (Eidanger - Brevik)	10	0	18	0	5	0
* Stavne - Leangenbanen	6	0	10	2	0	1
x Alnabru - Loenga	7	0	0	0	0	0
x Alnabanen (Alnabru - Grefsen)	5	0	6	0	1	0
x Skøyen - Filipstad	2	1	0	0	1	0
<b>Sum, baner med regulær trafikk / Total, lines with regular traffic</b>	<b>3857</b>	<b>256</b>	<b>2442</b>	<b>692</b>	<b>2 869</b>	<b>337</b>
<b>Sidebaner uten regulær trafikk / Branch lines without regular traffic<sup>3)</sup></b>	<b>352</b>	<b>0</b>	<b>135</b>	<b>44</b>	<b>741</b>	<b>0</b>
<b>Totalt / Total</b>	<b>4209</b>	<b>256</b>	<b>2577</b>	<b>736</b>	<b>3610</b>	<b>337</b>

x - Elektrifisert jernbanestrekning / Electrified lines

\* - Ikke elektrifisert jernbanestrekning / Non-electrified lines

1) Østfoldbanen, østre linje (Ski-Sarpsborg) har regulær trafikk til Rakkestad / Østfold line, eastern (Ski-Sarpsborg) has regular traffic to Rakkestad

2) Randsfjordbanen, (Hønefoss) - Bergmoen snupl. har ikke regulær trafikk / No regular traffic between Hønefoss and Bergmoen

3) Tinnosbanen har regulær trafikk til Notodden / Tinnosbanen has regular traffic to Notodden

4) Avstand mellom stasjonsmidt / distance between midpoints of stations

5) En liste med alle persontrafikkstasjoner etter bane finnes i vedlegget / A list of all the passenger traffic stations by line is attached in the appendix

6) En sammenhengende tunnel kan unntaksvis være registrert som flere tunneler grunnet ulike egenskaper i tunnelen / One coherent tunnel may exceptionally be registered as more due to different features in a tunnel

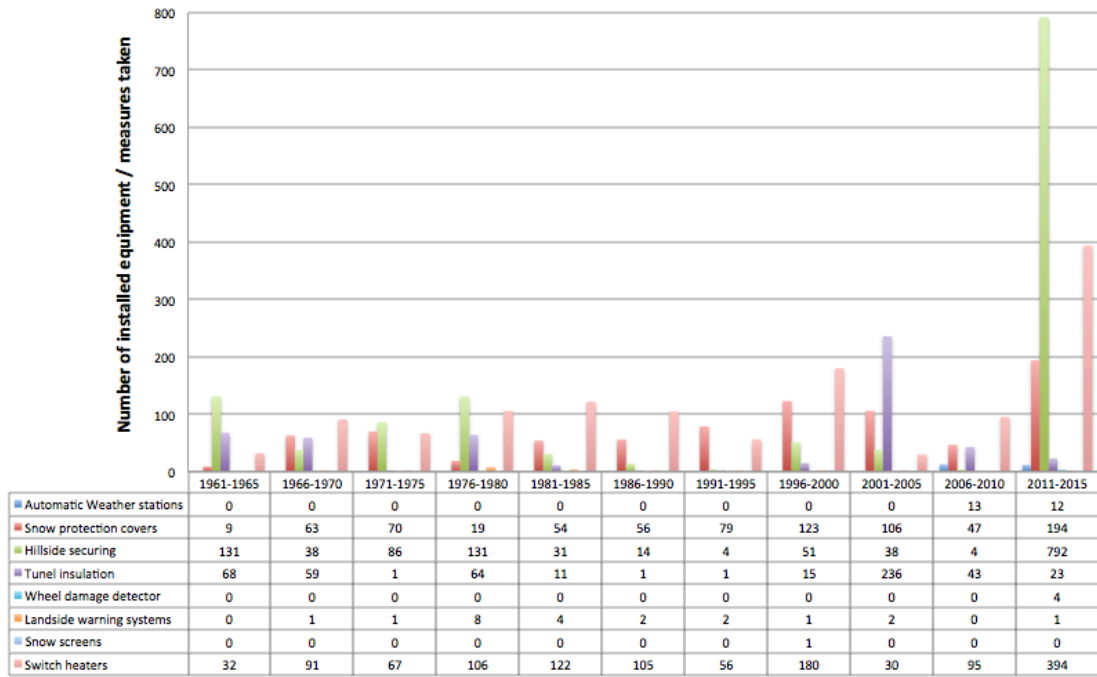


Figure 27- Number of added items in 5 years periods

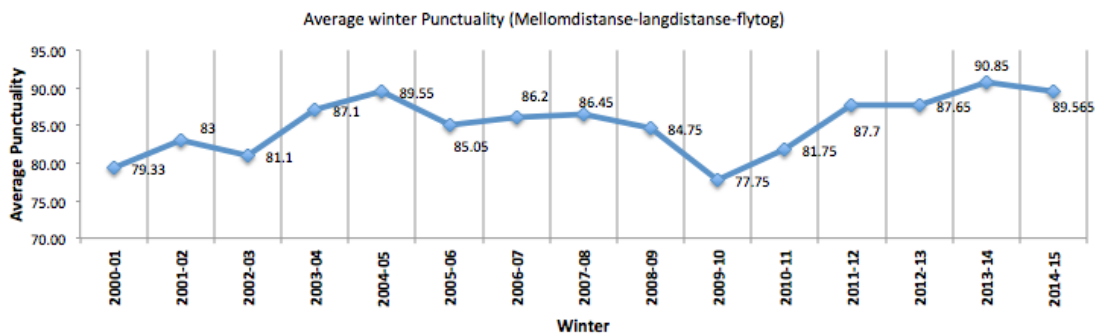


Figure 28- Average winter punctuality

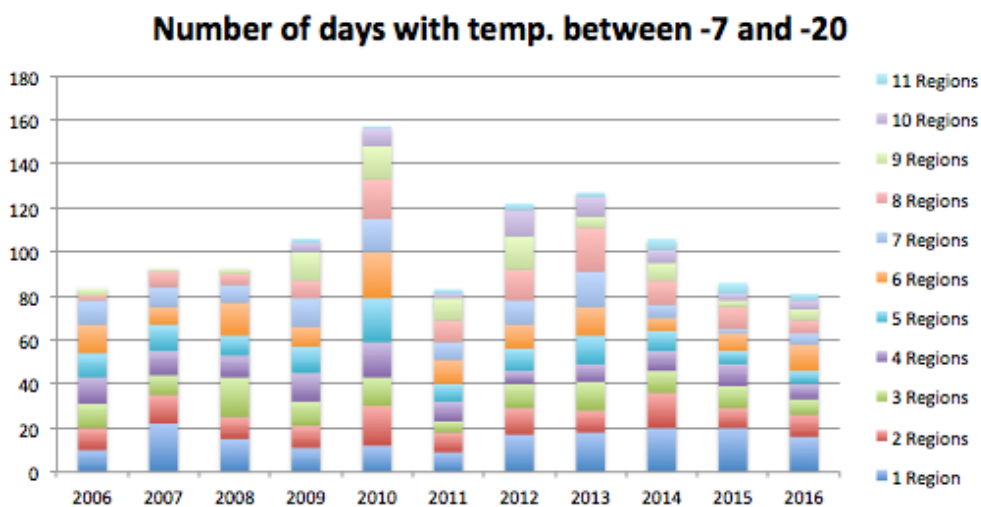


Figure 29- Number of days with temperature  $-7 < T < -20$  in different regions





