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Reliability Modelling of ERTMS/ETCS

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Reliability, Availability, Maintainability and Safety (RAMS)
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BANE NOR

RAMS
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Master Thesis

Department of Mechanical and Industrial Engineering

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Preface

This master thesis report has been submitted as a partial fulfilment of the requirements to the master degree (MSc) in Reliability, Availability, Maintainability and Safety (RAMS), in the Department of Mechanical and Industrial Engineering (MTP) at Norwegian University of Science and Technology (NTNU). This thesis has been written during the spring semester of 2017, as a continuation of the master project submitted in the autumn semester of 2016.

This report is primarily prepared to study the reliability aspects of European Rail Traffic Management System/European Train Control System (ERTMS/ETCS). The emphasis is more on ERTMS/ETCS infrastructure and accordingly a case study is done to realize its reliability The report is written in cooperation with Bane NOR (Norwegian National Rail Authority) and DNV GL, where Bane NOR has provided the data for case study and was implemented using TRAIL software developed by DNG GL, London.

The intended readers of this report should have practical knowledge in reliability analysis or equivalent knowledge gained in Safety and Reliability Analysis (TPK4120) course at NTNU and some basic understanding of railway signaling methods.

Trondheim, 2017-06-11

Raja Gopal Kalvakunta

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A special thanks to Christos Pistolas of DNV GL, London for his interest to help and support the thesis with TRAIL software. In addition, his feedback through the thesis was helpful to accomplish the work.

I am pleased and obliged to the faculty of the RAMS study group at NTNU, who have contributed the knowledge and support in accomplishing the thesis.

I am thankful to my fellow RAMS students, for their encouragement in all phases of the study program and to my office mates who offered a friendly working environment.

Finally, I must express my very profound gratitude to my parents and my sister who have supported me with continuous encouragement throughout the past years and especially during my studies at NTNU.

R.G.K

Summary

System reliability analysis has a significant influence on making decision and defining requirements for future operations. Performing a reliability assessment for a complex system is challenging due to varied performance of different sub systems. European Railway Traffic Management System/ European Train Control System (ERTMS/ETCS) is a similar complex system addressed in the thesis for developing a reliability model and its assessment.

In order to implement the modelling of ERTMS/ETCS, an existing line operating on ERTMS level 2 is chosen as case study from Bane NOR. Since all the railway projects are implemented according to the railway standards, a general overview of these standards and the importance of RAMS is elaborated. A literature review is then performed to identify suitable methods for reliability modelling practiced in general railways and ERTMS. On performing a thorough assessment of the literature, a multi formalism modelling approach is proposed for modelling the Østfoldbanen Østre Linje (ØØL) ERTMS pilot line as a case study. As a part of multi formalism modelling, different conventional methods are applied initially and then simulations are performed using software programs to assess reliability.

Primarily reliability block diagram method is used to model the ØØL line in Relysim software with a combination of single station and bidirectional (BiDi) section, and then 1000 simulations are conducted to assess ØØL ERTMS infrastructure. It is estimated from Relysim results that this model has the potential to determine the performance of the infrastructure. From Relysim model it is deduced that predominant infrastructure failures that cause delays are due to partial interlocking fail, maintenance and track fracture, followed by failure of balise, axle counters and points.

Later a software developed by DNV GL called TRAIL is used for modelling, in which a usage based model is implemented at first based on the historical data of delays in 2016. The data is distributed to all stations and BiDi sections and simulated for 100 annual runs. Secondly, a time-based model is developed in TRAIL with inputs as infrastructure, reliability parameters, system dependency, timetable, routes etc. and again performed 100 annual simulations to estimate the reliability and punctuality. From TRAIL models' simulation, reliability and availability of ERTMS infrastructure present at stations and BiDi sections of ØØL pilot line is estimated along with the sections criticality. Additionally, the overall availability and punctuality of the train services operating on the ØØL pilot line is also measured.

The time based model in TRAIL is found to be more practical due to the fact that it considers all the constraints and the model is validated by comparing its results with usage based model results. Since all the models are developed with several assumptions and some uncertainty, suggestions are given for further research to Bane NOR and TRAIL in light of reliability modelling of ERTMS/ETCS.

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Chapter 1

Introduction

Railways play a significant role in developing the economy of a nation, which designates that it is important to execute the railway operations in an efficient, safe and reliable manner. It is a complex organization and functions by coordinating with different divisions like project planning, infrastructure, rolling stock, operations, signaling and communication. In railways, developing an existing system or planning to implement a new system, will raise many issues to railway authorities concerning the cost, operations, infrastructure, safety and customers. They consider all these factors from various entities and define the essential requirements that are to be met by train operators, infrastructure developers, and systems suppliers and later be approved by the rail authorities.

Even though all these procedures follow international railway standards in a systematic way, the rail infrastructure providers and operators are facing delays in their operations. As an attempt to provide a solution for identifying the contributing factors, the thesis focuses on assessing the reliability of infrastructure and operations by developing a reliability model of an ERTMS pilot line.

1.1 Background

In railway industry, the operations are changing every day and developing new technologies with the increase in capacity and demand has become a major concern. In the same context, Bane NOR, the Norwegian railway has planned to renovate the existing conventional signaling system to European Rail Traffic Management System/European Train Control System (ERTMS/ETCS), such that they attain the interoperability, and improve the availability and operational safety in their railways. They initiated the ERTMS National Implementation (ERTMS NI) project, which claims to modify all the existing conventional relay based signaling system to ERTMS/ETCS by 2030.

To implement the project successfully, Bane NOR has to follow the European railway standards and these standards state to perform RAM analysis before implementation. ERTMS is new in Norway and Bane NOR has an old RAM analysis technique which is used for conventional signaling system. It is impossible to conduct RAM analysis for ERTMS/ETCS using the old method. ERTMS/ETCS is a complex system distributed geographically and its fault detection in the early design phase will help in decision making to increase the reliability and availability, such that the analysis supports to assess ERTMS performance in other projects too. In addition, identification of failures at design stage is critical because it is easy to modify the system in the early stages and it also depends on the location, rolling stock, infrastructure and operations (Pistolas, 2016). In case it fails to assess in the early phase, then tracking the failures in the operational phase would be more challenging.

1.2 Problem Description

At present railways are being used more extensively for transportation by commuters and for freight. The main quality of such transportation system is to maintain the safety and reliability from the system design phase to operation phase, in other words the whole life cycle of the system. Railways is generally regarded as a complex network with dynamic operations because it depends on various aspects like infrastructure, design, geography, passengers, etc. In recent days, with the increase in population and extensive usage of railways, the punctuality of the railways is affected and results in competitiveness against other modes of transport (Pistolas, 2016). Therefore, there is a continuous urge to develop the operations such that the availability and punctuality of trains are increasing constantly. In order to achieve this, the performance evaluation of infrastructure systems and operations is important.

Bane NOR, the Norwegian rail authority has defined top-level criteria for the reliability of train traffic and are interested to assess the reliability of their infrastructure by developing new models. However, Bane NOR does not have systematic methods to approve that their design solutions are meeting the top-level criteria (BaneNOR, 2015). The existing methods are not including the reliability of components and their redundancy. In the literature as well, there aren't many methods to perform the real-time reliability modelling for ERTMS/ETCS relating to the infrastructure systems and their components, timetable and speed profile.

The challenging part is to develop a model that can consider the dynamic properties and evaluate,

- The overall reliability, availability and criticality of infrastructure systems
- Train operational availability and punctuality in various sections

1.3 Objectives

The aim of the thesis is to perform a reliability analysis of ERTMS/ETCS by developing a model. The realization of the aim is accomplished by realizing the sub-objectives listed below.

I. History of ERTMS/ETCS
    - To find the history and the way signaling system developed until ERTMS.
    - Distinguish various levels and compare them.

II. Study - state of the art of Bane NOR

- Discuss the implementation of ERTMS NI project
- Identify the potential case or existing line for analysis
- Analyze the defined requirements for the case study

III. Determine the possible reliability assessment methods
- Literature review of the existing reliability models
- Methods to model reliability of the determined systems (e.g. Reliability block diagrams (RBD), Fault trees (FTA), Failure Model Effect Analysis (FMEA), Markov etc)
- Discuss about the theory behind the software (Monte Carlo simulations)
- Develop a model and analyze using the data provided by Bane NOR

IV. Perform simulations to the model developed with given data
- Identify the possible software to perform simulations (TRAIL, Extendsim)
- Analyzing the results of the simulations

V. Discuss the results and scope of further research.

1.4 Scope and Limitations

An important aspect of the thesis is to perform a reliability modelling of ERTMS/ETCS and to make it simple the scope is narrowed down to the most commonly implemented ETCS level 2. Bane NOR for their ERTMS National Implementation project in Norway are adopting the same level 2 and it has been already operated in some regions. The reliability modelling performance and analysis is based on the reference architecture of ETCS Level 2 infrastructure systems. Furthermore, the modelling is mostly done at system or component level owing to its complexity and the reliability analysis is not performed very extensively due to lack of time. Some of the limitations of the thesis are mentioned below and other assumptions are discussed in the respective sections.

- Bane NOR is responsible for ERTMS/ETCS infrastructure only and thus lineside and trackside systems are considered for analysis, whereas the inadequate data on onboard system has limited its analysis.
- ERTMS is presumed to be a safe signaling system, so only RAM analysis is considered and safety is out of scope.
- Due to the system complexity, several assumptions are made in developing the model and these assumptions are verified by the Bane NOR and DNV GL.
- An existing ERTMS pilot line is considered as case study and only a length of 40 km track section is chosen for analysis.
- The quantitative results obtained during the analysis may vary in real-time; it is here just an estimation to realize the models.

1.5 Actors Involved

1.5.1 NTNU RAMS Group

The master thesis is done as a part of the course MSc. RAMS offered by the RAMS group at the department of Mechanical and Industrial engineering (MTP) in the Faculty of Engineering, Science and Technology (IVT). This course is one of the 49 international master's programs that are being conducted at NTNU. The RAMS group focuses to do research in the fields of safety, reliability and maintenance in various industries such as oil and gas, subsea, railways, infrastructure etc. In addition, other main research areas of the group are risk and reliability assessment of complex systems and safety-critical systems. They have collaborations with several industry partners and perform research activities to provide solutions on their present day complications.

1.5.2 Bane NOR

Bane NOR (previously Jernbaneverket.) is a Norwegian state owned railway infrastructure company. They expertise in planning, development, management, operation and maintenance of the national railway network. In addition, they also do traffic control, management, and development of railway property.

This project is written in coordination with their prestigious ERTMS National Implementation project, which is planned to be completed by 2030. Bane NOR in this project has planned to replace its total existing conventional railway signaling system to ERTMS/ETCS. Bane NOR is positive in providing the required documentation like RAM documents, design layouts and detailed plans of the Østfoldbanen Østre Linje (ØØL) pilot project. In addition, it was planned and accepted by Bane NOR to perform periodic quality checks on the work progress.

1.5.3 DNV GL

DNV GL is a consulting firm that enables the organizations to improve their safety and sustainability of their business. They provide technical assurance, certification and risk assessment in different fields like maritime, oil and gas, energy and transportation.

DNV GL's core assessment method is to develop software to respective industry and analyze. With this perception, the project is considering the TRAIL software developed by DNV GL for railway industry as tool to assess the reliability of Bane NOR's ERTMS operated line

1.6 Approach

The thesis begins with an overview of railway signaling systems, to realize the rationale for changing from ATP to ERTMS and to distinguish the ERTMS/ETCS levels. A pilot project is chosen as case study, where a detailed study is performed by referring the project layouts, documents and its reliability requirements. Then a literature review on the reliability modelling of ERTMS/ETCS is done, to understand the different approaches adopted by many authors. For the literature review, several scientific databases are referred. Some of them are Science direct, Scopus, Compendex etc. and relevant railway standards and regulations are studied. Relevant methods have been selected and explained, in order to give a brief perception of its application.

To realize the identified methods for modelling, the pilot project chosen is implemented with the methods to assess the reliability of the ERTMS/ETCS. The modelling methods are discussed in detail and validated based on the results obtained. Finally, few suggestions for further research are presented. The schematic diagram of the adapted approaches is given in Figure 1.1

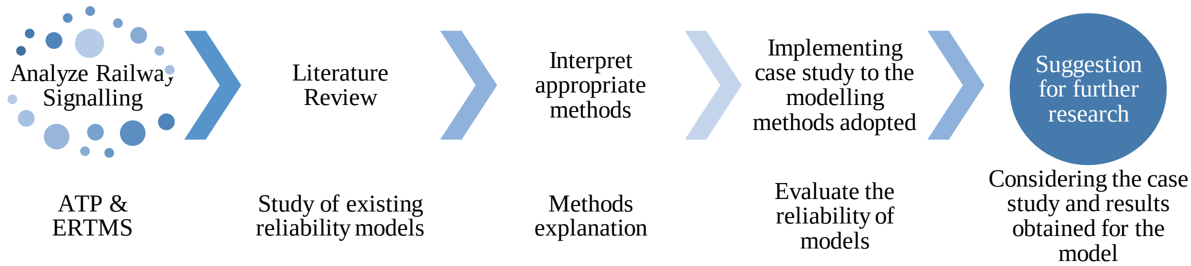

Figure 1.1 Adapted approach in the thesis

1.7 Structure

The remaining chapters of this report are as follows:

- Chapter 2: Describes different signaling systems and their operation. Introduces the ERTMS, explains the necessity to change from conventional signaling to ERTMS and the framework for ERTMS development over the years. Then the ERTMS/ETCS structural components, different levels of ETCS operations and their comparisons are illustrated.
- Chapter 3: As a case study, the pilot project chosen is described in detailed along with the reliability requirements. Besides railway standards review is done to express the requisite for following the standards and how the reliability modelling in the thesis is related to it.
- Chapter 4: This chapter deals with the overall literature review of modelling methods adopted in past. The identified methods are then explained in brief and their application is also stated.

- Chapter 5: The case study chosen is presented with the implementation of modelling methods adopted. In addition, assumptions were made for each modelling method and are stated in this chapter, followed by application and results obtained from the ERTMS/ETCS modelling.
- Chapter 6: An overall discussion is done based on the interpretations drawn from the modelling of ERTMS project, where chosen methods are validated and its shortcomings are discussed.
- Chapter 7: Finally, summary and conclusions are presented for the selected reliability methods, and recommendations are given for further research and development to models adopted.

Chapter 2

Railway Signaling System

The railway signaling system regulates the railway traffic and keep trains clear of each other every time. In a way, it protects, controls and supervises the railway traffic to ensure safe operation. The signaling system operate continuously at all times, supervising not only during a train pass but also in an idle condition too (Morant, 2016). They are complex in nature involving several different systems and the main function of the whole system is to operate in a synchronized manner with every other system. It is challenging to a train to halt instantaneously noticing a train running on the same track in opposite direction or in same direction, because the train is massive and has high inertia. In this case, signaling helps to maintain certain distance between them. The signaling system has been changing since many years with the improvement in technology, just like from manual signaling to automatic train protection system (ATP). An advanced development in such signaling system is ERTMS/ETCS and it enables the interoperability of passenger and freight transport between European nations.

2.1 Conventional Signaling System

For the safe movement of trains, signaling block system is being implemented since many days and still being continued. However, in the olden days the signaling system was not sophisticated as present. In 1850 which were the early days of railways, the signaling was manual where a person used a stopwatch and hand signals to convey the message to driver that the track is free to proceed or stop only few minutes before. In case if the track is occupied in the next section, the person signaling does not have any information on that. This led to many accidents in olden days. In the nineteenth century (1900), semaphores were introduced which directs the train to stop if it was in horizontal direction and vice versa. Later with the invention of telegraph and telephone, they used this technology to communicate if the track was clear or else occupied. Very soon in 1930 with the emergence of optical fiber cable, the information of the signaling block was transmitted via electric circuit and system of levers to indicate if the current block is accessible to the next train or not. The real signaling posts with colors red, yellow and green were used at this stage.

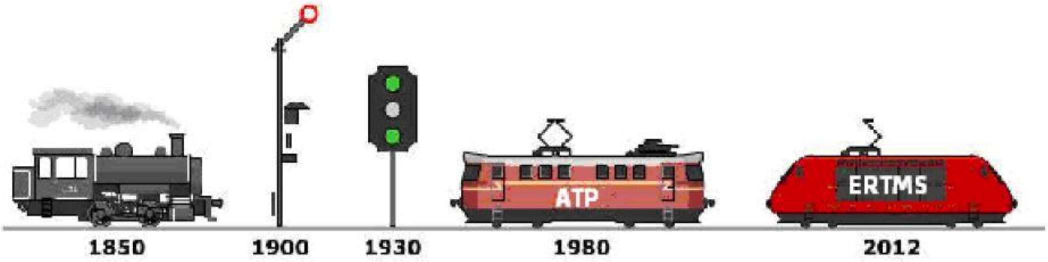

Figure 2.1 History of signaling systems (Maurizio Palumbo, 2014)

The technology has been developing every day and now it has become more automatic without any manual intervention. In 1980 the signaling system has introduced ATP (Automatic Train Protection) to monitor the speed and increase safety in railway operations. Here if the driver exceeds the prescribed speed limit, the train warns to slow down and if driver fails the train automatically applies brake. The latest advancement of 21st century is ATC (Automatic Train control) and can operate without driver intervention i.e. totally driverless operation. Figure 2.1 shows the development of signaling system over many years.

2.2 Automatic Train Protection (ATP)

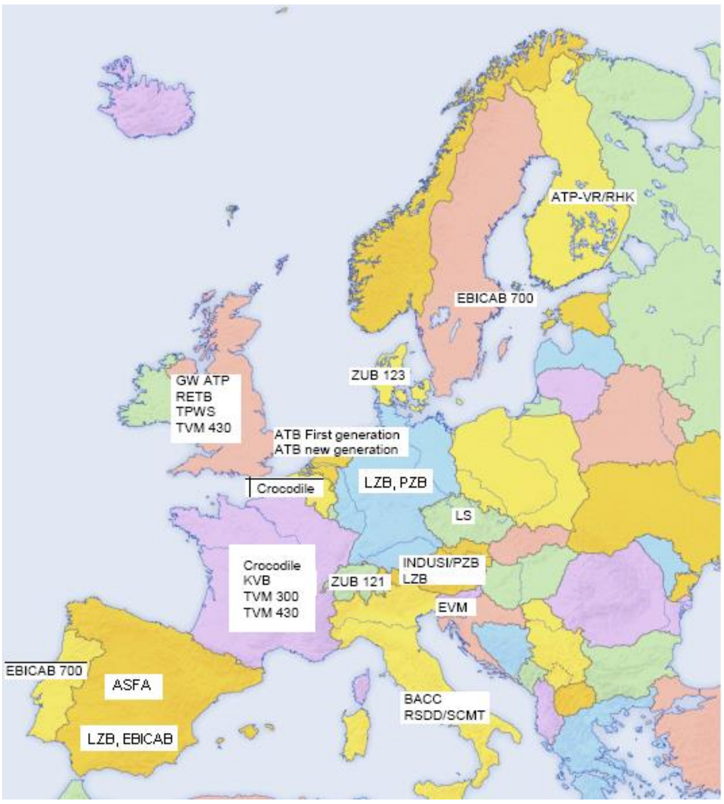

Figure 2.2 ATP systems in Europe (Source: European commission: History of ERTMS, 2016)

An ATP is a system that protects the train and the driver if the train is over speeding. It is a kind of safety protection system that has been developed in 1980. All the European nations have started to develop and implement their own ATP systems and were different from every other European nation, as shown in Figure 2.2.

This independent development of incompatible train protection and control system has created a challenge for cross-border operation of rail traffic in European network. It was also economically ineffective to install different train control systems on train and which was even more difficult to operate and maintain. Moreover, it accounts for more travel time and few trips. On integrating all European countries into European Union (EU) there was a necessary to establish common guidelines for the free movement of trains in all countries.

2.3 Initiatives of ERTMS/ETCS

In December 1989, EU initiated a project to find the complications with train signaling and control systems. By the end of 1990, European Institute of Railway Research (ERRI) began to develop ATP/ATC system, which would be compatible in the entire Europe. In June 1991, industry (EUROSIG) and railway (UIC, EERI A200) joined to develop the requirement specifications as the base for industrial development. They introduced a new on-board computer architecture (EUROCAB), a new data transmission system that is discontinuous (EUROBALISE) and a new continuous transmission system (EURORADIO). At the end of 1993, the EU council issued an interoperability directive and made a decision to create a structure to define the technical specification for interoperability. In 1998, UNISIG, a union of various European signaling companies was formed to finalize the specifications. By April 2000, first technical specifications for ERTMS were signed. These ERTMS specifications were adapted according to the railway's needs, reviewed regularly and managed under the supervision of European railway agency (ERA) in cooperation with the signaling industry and railway stakeholders.

Later in 2005, 2008 and 2012, Memorandum of Understanding (MoU) was signed by the European commission and railway stakeholders to deploy the ERTMS/ETCS. In July 2009, the ERTMS plan was deployed in Europe making it a major milestone in railway interoperability. At present, many national railway signaling systems are being upgraded to ERTMS and Bane NOR has planned to replace the existing signaling system in Norwegian rail network to ERTMS by 2030. In addition to European countries, many other countries worldwide have recognized this standard to be unique in railway signaling. Countries that are investing in ERTMS implementation program are India, China, Taiwan, South Korea, Algeria, Libya, Saudi Arabia, Mexico, New Zealand and Australia (Ghazel, 2014).

2.4 ERTMS/ETCS

European railway sector has different signaling and control systems in different countries, which is obviously a challenge for interoperability of trains across Europe. If many nations in Europe were relying only on their national signaling systems, it can influence the economy of their nation in future. In concern with the economic issues, emergence of high speed lines and rise in freight transportation, there was an urge to increase the cross-border traffic. This lead to the development of common signaling system in Europe called ERTMS.

The important objectives of ERTMS are

- To ensure the interoperability of both high speed and conventional lines all over Europe considering technical and operational interoperability.
- Standardize the railway control systems.
- Lower the equipment and operational costs.
- Increase the line capacities by saving time in systems switching (Barger, 2009).

The ERTMS is a European standard specification aimed at improving safety, reliability, performance and interoperability of European rail network (Flammini, 2006). It has three features which combine to enable the whole ERTMS as in Figure 2.3. ERTMS includes, European Train Control System (ETCS), which is responsible safe movement of trains; European Traffic Management Layer (ETML) manages the train traffic and optimizes the flow over the network; and a Global System for Mobile communications for Railway (GSM-R) that allows the radio communication system with all other systems (Flammini, 2014). After referring to many articles, it is found that many authors consider major components of ERTMS as ETCS and GSM-R and neglect EMTL.

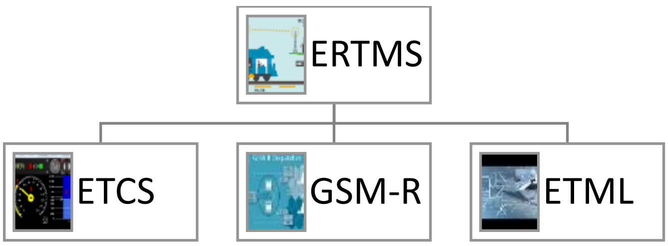

Figure 2.3 ERTMS Structure

ERTMS documentation provides a set of directives, technical specifications for interoperability (TSI), functional requirements specifications (FRS) and system requirements specifications (SRS) (Barger, 2009). The usage of the terms ERTMS and ETCS in many literatures is found to be ‘ERTMS/ETCS’ because of the different possibilities in executing ERTMS. ERTMS can be operated in different levels depending on the requirements of the traffic and other factors. If we consider to implement ETCS Level 1, it does not have a GSM-R module. Whereas ETCS Level 2 works along with GSM-R. ETML is generally the ERTMS traffic managing system and many of the authors consider it to be a normal traffic control system. Thus it has been most popular to consider ERTMS and ETCS as rather same. In the thesis, if ERTMS and ETCS are mentioned separately, then ERTMS is referred as a whole traffic management system and ETCS as a signaling control system. But in general usage ERTMS/ETCS is used as a common notation.

2.4.1 ETCS System

The European train control system is component of ERTMS program and is standardized, interoperable automatic train protection (ATP) or automatic train control (ATC) system used in Europe. ETCS is being implemented across Europe according to the EU directives and the signaling system used is regarded as the most complex layer (Smith, 2012). It inherits a safe operation of train movements throughout the network and simultaneously facilitates a higher carrying capacity. This can be performed by real-time monitoring, analyzing the data obtained regarding movement authorities, precision in train location, train speed, braking curves and system integrity. Depending on the analysis of this data, the required signals are sent to rail operators such that they decide which route they would prefer either shortest or most efficient way (Ngai, 2010).

Some of the common railway lineside and trackside infrastructure elements are points, axle counters and signals, these can be regarded as non-ERTMS elements. However, they are working in combination with ERTMS systems and hence in the thesis they are analyzed under the ERTMS category.

- Points are used to switch the trains from one track to other.
- Axle counters basically count the number of axles entering at a section and number of axles leaving that section. On matching the count of axles it sends a green signal representing the track to be free and is open for the next train to pass, else it shows a red signal at the signal post indicating the section is occupied by a train.

ETCS system is heterogeneous with distributed components installed on the train, partly along the trackside, partly along the lineside and in many control centers. This helps to categorize the ETCS into three main subsystems (Flammini, 2014). They are as follows:

- Trackside subsystem
- Line side subsystem and
- On-board subsystem

A reference ERTMS/ETCS architecture is shown in Figure 2.4 and their subsystems are explained in following sections along with the components and their functions.

2.4.1.1 The Trackside Subsystem

Trackside system monitors the train movements and transmits the train data to central train control center. The trackside system components are concentrated in some locations to extract the train running statistics. It has four major components and they are GSM-R, Radio Block Centre (RBC), Wide Area

Network (WAN) and the interlocking system (IXL). Of all these the vital component is RBC, which controls the movement of trains and maintains a safe distance between trains.

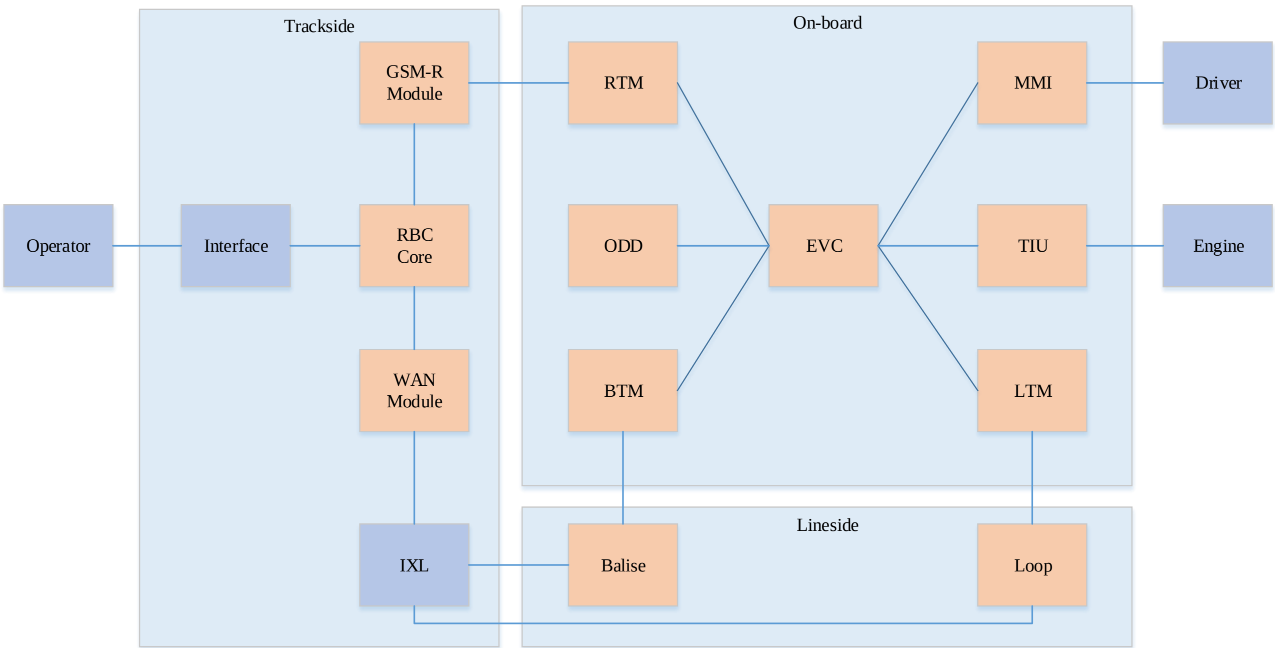

Figure 2.4 ERTMS/ETCS Architecture

Radio Block Centre (RBC): It is a computer based communication system, in which it receives the information from interlocking (IXL) like track occupancy, route state, etc. and then sends the message to train on-board systems. These messages provide the movement authority to allow the safe movement of trains in a particular block or section under the influence of that particular RBC. Here the data is exchanged through the GSM-R communication with the trains and WAN is used for the communication of messages between every other RBC. RBC's exchange the information in order to have a continuous train operation and the exchange of one RBC to other is called handover. When a train leaves the area of one RBC and handovers to other RBC, is called HandOver RBC (RBC_{HO}) and the train entering the new RBC is called Accepting RBC (RBC_{ACC}) (Palumbo, 2014). As RBC has an important function in ETCS, its reliability and availability is critical.

GSM-R: It is a radio communication system that enables the transfer of voice and data between track and the train. This is a standard GSM network and has frequencies dedicated for railway applications with more advanced functions (Ngai, 2010). Some of the operational frequency bands are 876-880 MHz and 921-925 MHz, functions in on-board signaling (Smith, 2012).

2.4.1.2 The Lineside Subsystem

In ETCS, the tracks are continuously distributed with the lineside systems. They communicate with the on-board system and RBC by providing the status of trains in every block section. The lineside system components are EuroBalise (Balise), Euroloop (Loop), EuroRadio and Lineside Electronic Unit (LEU), these are placed along the line together in every section which are displaced at regular distances.

EuroBalise (Balise): It is a transmission device that has the feature of discontinuous unidirectional communication system from lineside to the on-board system. Balises are electronic devices and placed in between the tracks. They send the telegrams/messages to on-board system and are organized in groups of two or more (EEIG, 2012). The combination of telegrams sent from the balise group define a message of train status and can also be used as milestones in the detection of train location. A typical balise on a track is shown in Figure 2.5.

Figure 2.5 Eurbalise (Balise) in between railway track

EuroRadio: It a continuous communication system, that interacts with both onboard system and track side equipment via GSM-R.

EuroLoop: It provides a signal in advance indicating the actual main signal in the direction of train running. It is employed in the ETCS Level 1 only and has functional components on both onboard system and trackside systems.

Lineside Electronic Unit (LEU): It consists of some electronic devices and these devices generate the telegrams that has to be sent by balises. The LEU receives the information from external trackside equipment and is used only in ETCS Level 1 like EuroLoop.

2.4.1.3 The Onboard Subsystem

The function of the onboard system which is present on the dashboard of train is to communicate with trackside subsystem and achieve a safe movement in the rolling stock. The interoperability requirements for ERTMS/ETCS onboard system depends on the functionality and data exchange between trackside and onboard subsystem. In addition, it also depends on the data exchange between onboard subsystem and the driver, the train and the onboard part of the existing national train control systems (EEIG, 2012).

Onboard system is a computer based system. It has features of calculating the speed profile by taking into account the information received from movement authorities and the train characteristics. The movement authorities are received from the RBC. Onboard system has many functions like indicating the current speed and speed to be maintained in the approaching sections. They are designed with high safety standards and protection systems. In case if the train driver exceeds the specified speed limit, the automatic train protection (ATP) system will be activated by starting the braking procedure and controls the speed of the train. The on-board system is mainly composed of seven components as shown in the Figure 2.4. They are EVC, MMI, TIU, ODD and transmission modules RTM, LTM and BTM.

European Vital Computer (EVC): EVC is the on-board computer and is the core of the entire on-board system. It processes all the train borne functions safely based on the information received from trackside system, data produced by the driver and the data received from onboard system. It is fail safe computing system (Flammini, 2014). A wide area network (WAN) is used to connect with other RBCs whereas GSM-R interface is used to communicate with the trains.

Man Machine Interface (MMI): It is sometimes also referred as driver machine interface (DMI) as it is the main means of interactions between the driver and the on-board ETCS system.

Train Interface Unit (TIU): It enable the feature of interaction between ETCS on-board systems and some of the devices in the train.

Odometer (ODD): It evaluates the kinematic train variables (speed and position), based on the information obtained from the sensors for measuring the covered distance.

Radio Transmission Module (RTM): This module communicates the data that has to be sent and received on GSM-R network via EuroRadio protocol.

Loop Transmission Module (LTM): It reads the data from the track loop via EuroLoop protocol.

Balise Transmission Module (BTM): It receives the information from balise and reads the data from them via EuroBalise protocol.

2.4.2 ETCS Levels

ETCS levels are defined based on how the route is equipped with and the way of interaction between the track and the trains (Ghazel, 2014). To be precise, the level definitions are associated with the type of trackside equipment used, the information exchange between trackside and the onboard units and the process of their respective functions. Different levels are well-defined such that each individual railway management can select an appropriate ETCS trackside equipment, according to their infrastructure and performance criteria. Moreover, the application levels permit the interfacing of individual signaling system and train control system to ETCS (EEIG, 2012). The ETCS can be operated in three distinct levels for train control systems namely ETCS level 1, level 2 and level 3. Also an additional ETCS level 0 and National Train Control (NTC) system are defined to operate, when the lines are not equipped with ERTMS/ETCS trackside and lineside systems but equipped with train onboard system.

2.4.2.1 ETCS Level 0

Level 0 corresponds to the operation of train equipped with ETCS, where trackside infrastructure may be ETCS and / or national system but lineside is without ETCS. The trains being operated in level 0 are controlled by lineside optical signals and these signals regulate the train movements. The onboard system has no control over the train operations other than displaying the maximum design speed of the train and maximum permitted speed in that block section. The train detection and supervision in this level is achieved by trackside equipment of the signaling system like interlocking and track circuits using the axle counters.

2.4.2.2 National Train Control

The level National Train Control (NTC) system permits to run the ERTMS/ETCS equipped trains with NTC and speed supervision systems. The train integrity supervision is not fulfilled by ETCS but is performed by the external equipment of the underlying NTC system. Train control information that is generated on the trackside by NTC is transferred to train by the communication channels supervised by NTC. Operation of an ERTMS/ETCS equipped train on NTC completely depends on the configuration of the specific NTC and the ETCS installed onboard of the train, and the interface between them.

2.4.2.3 ETCS Level 1

Level 1 is a signaling system intended to be compatible with the existing national signaling systems and can provide the automatic train protection (ATP) functions (Barger, 2009). In this level, the trackside, the lineside and the train onboard are equipped with ETCS systems. Level 1 follows the general lineside signaling system, where the block control is achieved by the conventional interlocking, based on the information transferred from track circuits and axle counters. Eurobalises (balises) are used for the track-train communication where these are placed along the track next to lineside signals at required distance and are connected to train control center (Ghazel, 2014). These balises are linked to signals or interlocking through the lineside electronic unit (LEU) and they transmit the route data as a movement authority to the trains.

A structural model of ETCS level 1 with different components is shown in Figure 2.6. The onboard computer (EVC train borne) evaluates the data continuously that is received from the balises and determines the maximum speed of the train. It uses this technique to calculate the next braking point, considering the braking characteristics of train and track description data received from the balises.

In order to increase the existing capacity of lines, an additional infill balises between the distant and main signal are installed. By this method the status is updated regularly via radio GSM-R corresponding to a balise in advance of the train. This facilitates the train to accelerate such that it does not require to brake till next balise and waste time by waiting for the signal to clear (Ngai, 2010).

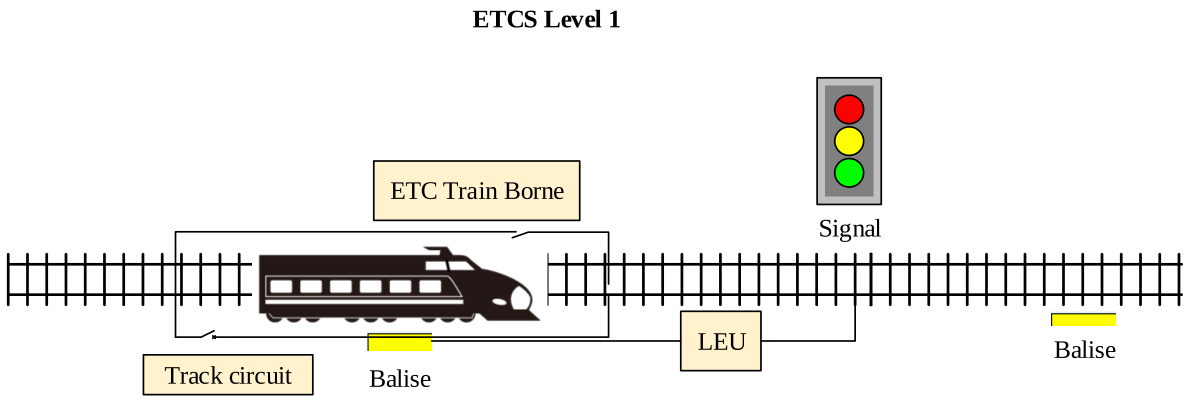

Figure 2.6 Model of ETCS level 1 structure

The first ETCS commercial application in the world was done in October 2001 in Bulgaria. It was designed for a length of 430 km from Sofia-Burgas. Some of the European countries where ETCS level 1 is being operated are Bulgaria, Croatia, Finland and Greece. ERGOSE is operating ETCS level 1 from Athens to Bulgarian border in Greece for 1083 km distance (UNIFE). Level 1 is also installed on the Beijing-Tianjin Intercity rail in northeast China (Ngai, 2010).

2.4.2.4 ETCS Level 2

The main difference between ETCS level 1 and level 2 is that level 2 does not require lineside signals. However, it is optional to have lineside signaling as a backup (depending on the operating rules). In the ETCS level 2, the movement authority is communicated directly to the train onboard system from radio block center (RBC) via GSM-R network. The train position is detected by balises, which are acting as passive positioning beacons or electronic milestones (EEIG, 2012). Balises are only used to report their exact location, line profile and speed limit. The positioning balise are also used normally as reference point to calibrate the distance measurement errors.

A structural model of ETCS level 2 with different components is shown in Figure 2.7. The onboard computer system or EVC continuously monitors the transmitted data from balise including movement authorities, track characteristics and status ahead and the distance to next balise. With all these data the onboard computer evaluates continuously and determines the optimal speed of the train. In case if a train exceeds its permissible speeds, then the onboard computer automatically applies the brake and protects against the overrun of the authority or reduce below the permissible speed (Palumbo, 2014). The control system of this type can increase the capacity of the line and enable higher operational speeds.

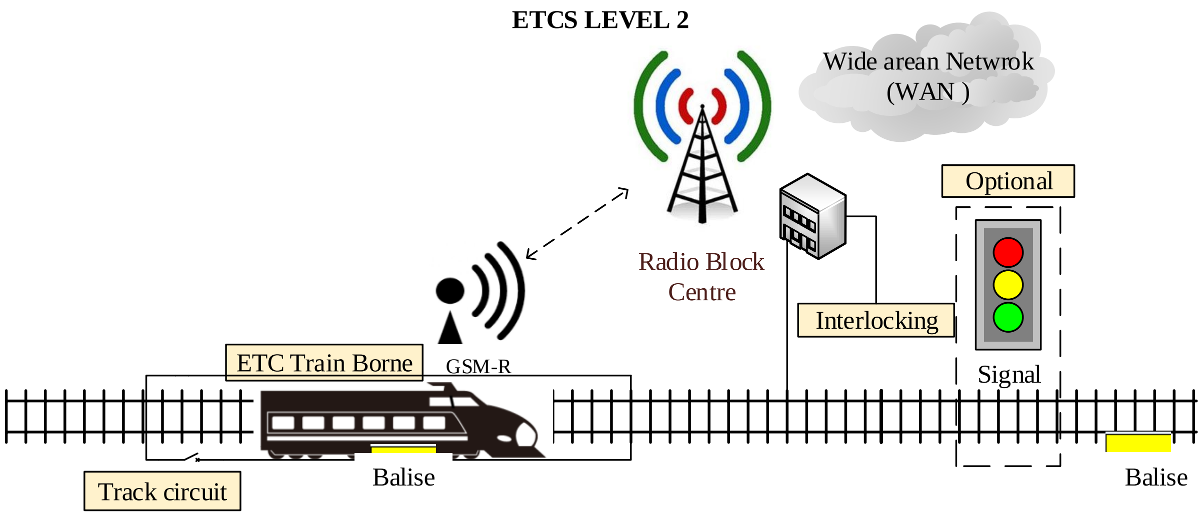

Figure 2.7 Model of ETCS level 2 structure

ETCS level 2 is more advanced than level 1 and in terms of safety, it is highly sophisticated system. It is the most popular and highly recommended train control system for existing lines and also for new lines that are being planned to install. Some of the existing high speed and high capacity lines equipped with ETCS level 2 lines in Italy are Turin-Novara, Bologna-Florence and Rome-Naples. In Europe, presently there are many installations of ETCS level 2 in Italy, Germany, Switzerland, Luxembourg and Netherlands. By the end of 2030, the Norwegian National Rail Administration (Bane NOR) has planned to completely renew the existing old signaling system to ETCS Level 2 Baseline 3 under its ERTMS National Implementation Plan (BaneNOR, ERTMS National Supplier conference, 2016).

2.4.2.5 ETCS Level 3

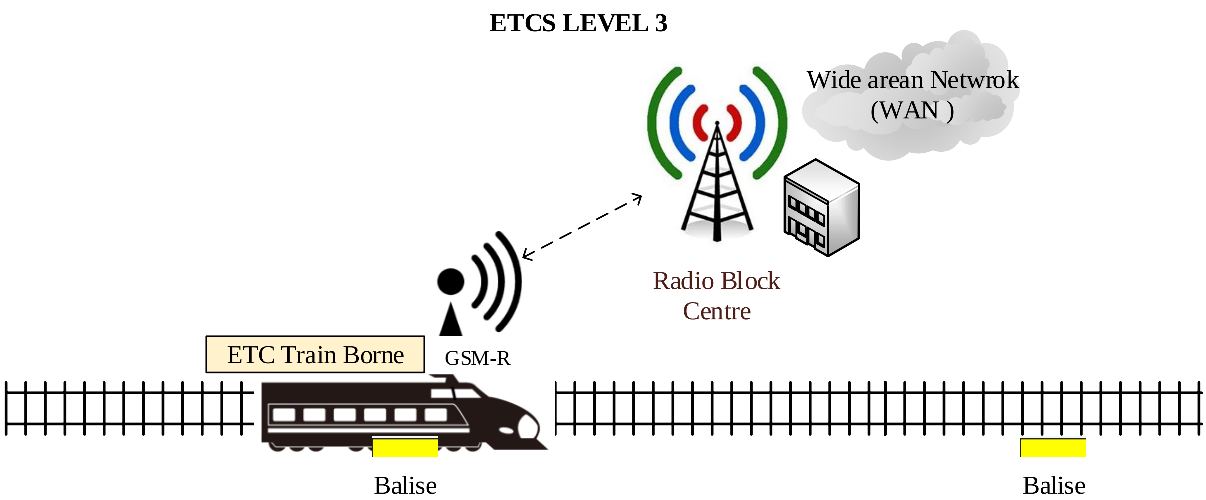

Figure 2.8 Model of ETCS level 3 structure

This movement authority is also shared with the preceding train in order to maintain the absolute braking distance spacing or moving block. Hence this level is also known as moving block train control system (Durmuş, 2012). All the information regarding the movement authority, speed and braking distance are displayed in the train odometer and is received from the RBC via GSM-R radio communication. A typical ETCS level 3 structure is shown in Figure 2.8. As the interlocking no longer controls the train, it is feasible to operate the railway system with high capacity and minimum trackside equipment. The balises are sometimes used and are optional, their usage only helps for location readjustment (Ghazel, 2014). At present the ETCS level 3 is only in a conceptual phase under i.e. planning and development, it is yet to be deployed.

2.5 Comparison of ETCS Level 1, Level 2 and Level 3

The application of different ETCS levels depends on the requirements of the track infrastructure, operation frequency, line capacity and other factors. As of now ETCS level 2 has the highest priority as it is safer and technically advanced control system than level 1. It is not always that only certain level has to operate only in that level, it possible to operate different levels in other levels according to defined standard functions and procedures. An ETCS level 2 can be operated in all national train control (NTC), ETCS level 1 and also in its corresponding level 2.

The general characteristics of different ETCS levels are given in the below Table 1. As the ETCS level 0 and NTC are lacking some prerequisites of ERTMS, they are not included. The only difference that lacks in level 2 compared to level 3 is the train integrity. But in overall all ETCS level provide a high end safety for the operation of railways when compared to the conventional lineside optical signaling system.

Table 1. Characteristics of different ETCS levels

Functions/ ETCS Levels	**Train Integrity**	**Data Transmission Method**	**Lineside Electronic Unit**	**Lineside Signals**	**Track Detection Devices**	**Radio Block Center**
	Onboard Equipment ⟵⟶		Trackside Equipment ⟵⟶			
Level 1	x	Balises / Balises + Infill				x
Level 2		Balises + Radio	x	x	x	
Level 3		Balises + Radio	x	x	x	

2.6 Significance of ERTMS/ETCS Reliability

Reliability in railways is generally referred in terms of availability and punctuality. The development of new signaling systems with modern technologies are increasing the complexities in system. In order to have a reliable operation of these complex systems, the systems are required to be defined with high reliability, maintainability and availability requirements. Furthermore, the infrastructure availability in ERTMS/ETCS directly influences the punctuality and capacity of the railway network (Ambika P. Patra, 2010). To derive such reliability parameters for ERTMS/ETCS infrastructure system and their operations, an intense analysis is required. In this thesis, the ERTMS/ETCS reliability is assessed by adopting a modelling approach for a case study using software and mostly availability and punctuality are concerned for analysis.

Due to the ERTMS/ETCS safe and reliable train control system, there is huge demand in its application from all over the world. Implementing ERTMS/ETCS signaling system enhances the availability of trains to commuters on time thereby improves punctuality in operations. Also it enables interoperability between European nations is creating an open market to various opportunities and thus increasing the overall economy.

Advantages of ERTMS/ETCS system:

- Interoperability of both passenger and freight trains across the Europe.
- Improves the safety standards in both national and international train traffic.
- The train operations are become more punctual, flexible and also increase the capacity.
- Less trackside equipment and thus reduces the number of breakdowns.
- Creates an open market for signal system suppliers and increase the competition.
- Increase operational throughput and reduce the maintenance cost
- Chances to develop new technologies in the areas of rail traffic management

Chapter 3

Bane NOR ERTMS National Implementation

The implementation of the European Rail Traffic Management System (ERTMS) on the Norwegian railway network is planned by Norwegian National Rail Administration (Bane NOR) and they aim to accomplish the project by 2030. This project is a part of the National Transport Plan 2014-2023 (BaneNOR, 2015). Geographically Norway shares border with Sweden and they almost have the same national signaling system. The impelling cause for implementing ERTMS is the need for renewal of signaling systems more than the need for interoperability. Since 2007, the entire railway network is in service with the GSM-R and only the other signaling systems has to be changed. The ERTMS NI plan is to completed the entire project by 2030 and the planned map is represented in the below Figure 3.1.

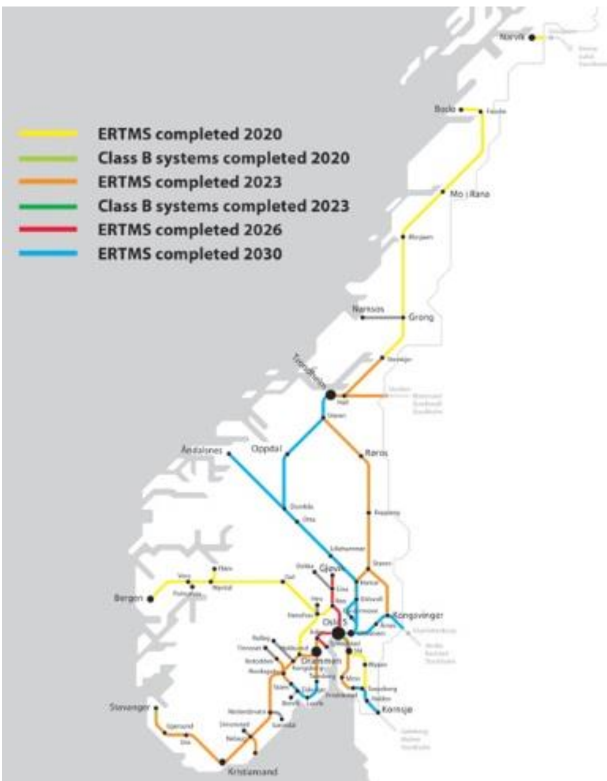

Figure 3.1 ERTMS NI deployment map of Norway (Bane NOR ERTMS NI plan, 2015)

An agreement was signed by Norway with the European Union named European Economic Community (EEC) that regulates the cooperation between Norway and EU. According to this agreement, the EU directives are adopted into Norwegian law and similarly as a part of EU directives; the ERTMS is implemented based on the TSIs (Technical Specification for Interoperability). The ERTMS plan is to implement ERTMS level 2 and is done in synchronization with the Swedish ERTMS plan in order to facilitate interoperability (BaneNOR, 2015). The existing GSM-R network will be retained for communication between train and infrastructure. Whereas the rolling stock will be modified by either installing ERTMS onboard systems to old vehicles or ordering new vehicles equipped with ERTMS on board system.

3.1 Pilot Project - Case Study

The ERTMS pilot project in Norway is implemented in the Østfold region of Norway and is called Østfoldbanens østre linje (ØØL). The pilot line is presented in the Figure 3.2, and runs form Ski to Sarpsborg over a length of 80 km (Norwegian ERTMS Pilot Line project plan, 2015). This conventional existing line has been chosen to get an upgrade to ERTMS, as the first of its kind in Norway for some reasons:

- The traffic was manually regulated by dispatchers at each station and there was an urge to upgrade the traffic management system.
- As the pilot line is located near to Oslo, it is convenient to travel for surveying and testing during the project implementation phase.
- This line has very few trains running and it facilitates to install only limited amount of onboard equipment.

Figure 3.2 ØØL pilot project overview (Bane NOR ERTMS Pilot Line project plan, 2015)

The pilot line has eight stations starting at Ski and continues through Kråkstad, Tomter, Spydeberg, Askim, Mysen, Rakkestad and ends at Ise (Bane NOR ERTMS ØØL detailed plan, 2011). There are three other stations in the ØØL pilot line and they are mainly planned for crossing of trains because the pilot line is being operated on single track. The planning and execution of this project is done according to the rules and regulations of Bane NOR and Norwegian laws.

Bombardier Transportation won the contract to accomplish a fully operational ETCS/IL (Interlocking system) and they have the responsibility to perform and manage all the processes and activities required to integrate ETCS/IL system. All the activities carried by Bane NOR and Bombardier Transportation are done in compliance with the 'Teknisk Regelverk' and if any deviations are acknowledged, then they have to perform according to the international CENELEC standards like EN 50126 , EN 50128, EN 50129, EN 50506, LC/TR 50126, CLC/TR 50451 (Norwegian ERTMS Pilot Line project plan, 2015). Throughout the implementation of this pilot project, all the data concerning the requirements specification, traffic rules, RAMS process etc. would be recorded and updated such that these can be referred while implementing ERTMS/ETCS on the rest of the railway network.

3.2 Project Reliability Requirements

Bane NOR has defined some top-level criteria for the ERTMS operated lines. The lines running on ERTMS must meet these requirements to reflect that the system is highly reliable. Some of the important requirements are:

- Punctuality: 90 % - trains should arrive at their respective final destination within four minutes after scheduled arrival time.
- Regularity: 99 % - the number of trains cancelled as planned in timetable.
- Availability: 99.3 % - the trains must arrive at the stations within four minutes after scheduled arrival time.

Of all the above three reliability requirements, the thesis will be mostly dedicated in identifying the availability. The reason is that the availability of trains directly affects the economy of the railway organizations. When the trains are arriving as per schedule the passengers intend to use more, else the passengers try to shift to modes of transportation. The main cause for affecting the availability is the delays caused due to system failures that affect the traffic management.

3.3 Implemented Railway Standards

As mentioned earlier, the ERTMS National Implementation is executed as per the European CENELEC standards. These European Standards are developed and published by the European Committee for Electro technical Standardization (CENELEC) to ensure safe and secure operation in railway applications. The safety related electronic systems, signaling system and other equipment involved in railways are developed according to the system lifecycle described in CENELEC standards like EN 50126, EN 50128 and EN 50129. These standards are prepared from the standard IEC 61508 which dedicated for functional safety of electrical/electronic/programmable electronic (E/E/PE) safety related systems (Krenželok, 2010). Each of these standards focus on certain system and together following all the three standards is essential to implement a railway project. Some standards emphasize on the process of executing and others on critical systems like the signaling system (ETCS) (Cimatti, 2012). A general overview of these standards is mentioned in Table 2.

Table 2. CENELEC standards and their description

Standards	**Description**
EN 50126	The Specification and Demonstration of Reliability, Availability, Maintainability and Safety (RAMS)
EN 50128	Communications, Signaling and Processing Systems – Software for railway Control and Protection systems
EN 50129	Communications, Signaling and Processing Systems – Safety related electronic system for Signaling

The EN 50126 describes the terms of Reliability, Availability, Maintainability and Safety (RAMS), their interaction and a process based on the system lifecycle for managing RAMS (EN50126, 1999). In addition, a systematic process for specifying RAMS requirements is defined and it validates that these requirements are important to achieve.

The EN 50128 specifies processes and technical requirements for the development of programmable electronic systems for railway control applications and protection systems, mainly focusing in the safety implications (EN50128, 2011). In contrast to the EN 50126, it is developed exclusively for the software and its interaction between different systems.

The EN 50129 refers to application of safety related railway signaling system, subsystems or equipment. Moreover, this standard can be used in accordance with EN 50126, in order to identify the safety requirements related to the system. EN 50129 applies to overall lifecycle of signaling systems starting with the specification, design, construction, installation, acceptance, operation, maintenance and modification phases (EN50129, 2003).

As the scope of this project is limited to reliability aspects, EN 50126 standard is referred as the basis to do reliability modelling. Reliability is distinctive in RAMS assessment and railway RAMS is a characteristic of the railway systems' long term operation (EN50126, 1999). In particular, EN 50126 address the techniques that are used to assess the system dependability for critical control systems and about the interrelation between railways RAMS elements. The RAMS elements of railway are show in

Figure 3.3, where the railway RAMS is dependent on safety and availability and further these are interdependent on reliability and maintainability as one factor and operation and maintenance as other factor. Some of the definitions of the RAMS terms according to EN 50126 are given below to understand the standard in detail.

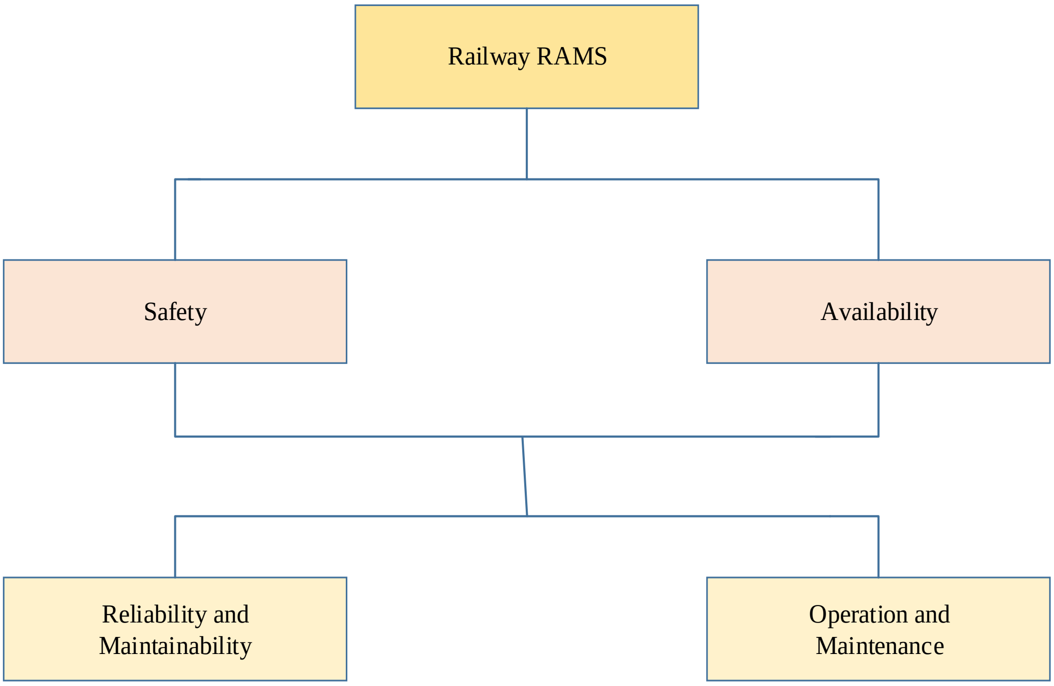

Figure 3.3 Inter-relation of Railway RAMS elements according to EN 50126

Availability: The ability of a product to be in a state to perform a required function under given condition at given instant of time assuming that the required external sources are provided (EN 50126).

Safety: Freedom from unacceptable risk of harm.

Reliability: The probability than an item can perform a required function under given conditions for a given time interval (IEC 60050 (191)).

Reliability performance is measured in terms of

- All possible system failure modes in specific applications
- Rate of occurrence of failures
- The effect of failure on functionality of the system

Maintainability: The probability that a given active maintenance action, for an item under given conditions of use can be carried out within a stated time interval when the maintenance is performed under stated conditions and using stated procedures and resources (IEC 60050 (191)).

Maintainability performance in terms of:

- Time to perform a planned maintenance
- Time to detect, identify and locate the faults
- Time to restore the failed system (unplanned maintenance)

To interpret the inter-relation of RAMS standard in Figure 3.3, an example is used to illustrate this. Consider that a new track is laid with latest ERTMS/ETCS infrastructure on an existing NTC system. As per scheduled timing the train has to start but due to some error the signal is still red and train is waiting for green signal to proceed, this indicates that some error is present. The error can be due to a fault in the trackside or lineside transmission modules. The reasons for the problem can be use of unreliable components or lack of maintenance. This directly reflects on the availability of the train at next station, which is a major concern rather than safety. This indicates that reliability of the components put into service and maintainability of them are crucial for the overall availability.

Table 3 RAM Failure categories as explained in EN 50126

Failure Type	**Failure Category**	**Definition**	**Example**	**Failure Classification**
Immobilizing Failure	Significant	Failures preventing train movement or causing delay above a specified time and/or generating more cost that certain limit.	A wrong signal indicated by false detection of the balise or wrong counting by axle counters and blocking one section for long time.	Dangerous Detected (DD Failure)
Service Failure	Major	Failures that can be rectified in order to achieve required performance, does not cause delay or cost greater than the minimum threshold specified for significant failure.	The train receiving correct signals from RBC but fails to update on DMI due to some electronic system failure, this can delay the operation until it is repaired.	Safe Detected (SD Failure)
Minor	Minor	A failure that does not allow the system to achieve any specified performance, but also it should neither meet. criteria for significant nor major failure	The failures can cause unscheduled maintenance and they cannot be categorized as any of above failures	Not Applicable

EN 50126 defines some of the RAM failure categories referring to railway applications. These failure categories are categorized according to their severity of the consequences, i.e. significant, major and minor. The failure types and their definitions are presented in Table 3. In addition, the failures are further classified upon their effects as, the immobilizing failure to be a dangerous detected (DD) failure and severe failure to be safe detected failure (SD). This standard also proposes to conduct risk analysis by identifying hazards, defining risk acceptance criteria and risk evaluation. Furthermore, it also explains about the safety integrity requirements at system level and component level.

The railways are designed to operate such that they attain a safe mode under any failure and this has been following since many years. This concept is based on the analysis of components for various failure modes and a safe condition is achieved in case of any failure (EN50126, 1999). The EN 50126 standard also complies with the same principle of fail-safe mode and therefore this thesis does not consider safety in the analysis presuming safety is always attained.

3.4 RAMS Lifecycle phases

In the clause 5 of EN 50126, the management of RAMS in railways is discussed. A process is defined based on system lifecycle and qualifying to control RAMS factors. Indeed, the process supports in:

- Defining the RAMS requirements
- Assessing and controlling threats to RAMS
- Planning and implementing RAMS tasks
- Achievement of compliance with RAMS requirements
- Continuous monitoring during the lifecycle and compliance

These standards suggest that RAMS requirement have to be met at every stage of system lifecycle starting from the design and system definition phase to the disposal phase. To implement a railway project successfully, it has to pass through various phases and the standard EN 50126 describes RAMS lifecycle phases. The system lifecycle provides a structure for planning, managing, controlling, monitoring and delivering all aspects of a system considering RAMS in all phases. As per the standard, there are fourteen lifecycle phases and each phase has defined general, RAM and safety tasks. The system lifecycle phases and their respective tasks are discussed below in Table 4.

It can be witnessed from Table 4, performing reliability and availability assessment is a part of RAMS process in the design and implementation phase. This analysis can be used to predict the performance and it widens the opportunity to make systems more sophisticated, safe and reliable. The lifecycle phases in many industries are represented in a typical 'V' model and in the same way, this standard also presents all the phases in 'V' model as in Figure 3.4. The left side (top-down) of the 'V' model indicates the development of the project and implementation, by a systematic approach from concept definition to system manufacturing. Whereas the right side (bottom-up) branch focuses on installation, system verification and validation.

Table 4 Lifecycle project phases and their related tasks (Adopted from EN 50126)

Lifecycle Phase	**General Tasks**	**RAMS Tasks**
1. Concept	Define the scope, establish railway project management and goals	Review earlier RAM performance, review safety policy and targets
2. System definition and application conditions	Prepare system description Identify strategies for operation and maintenance, analyze the influence of existing infrastructure	Perform a preliminary RAM analysis, set RAM policy Perform PHA, develop a safety plan, define tolerable risk criteria
3. Risk analysis	Perform risk analysis related to project	Preform system hazard analysis and set up hazard log
4. System requirements	Do requirement analysis, specify overall system requirements	Specify RAMS requirement, establish RAMS program, state safety functional requirements
5. Apportionment of system requirements	Specify sub-system & component requirements	Specify sub-system & component RAMS requirements
6. Design and Implementation	Perform planning, design and development, analysis and testing, verification, implementation and validation	RAMS implementation, perform reliability, availability assessment Implement safety plan, hazard log, perform hazard analysis, prepare safety case
7. Manufacturing	Production planning, manufacture and testing components, establish training	Perform RAM improving testing, Failure Reporting and Corrective Action System (FRACAS)
8. Installation	Installation of systems, assembling	Maintainer training and spare parts provision
9. System validation (Safety acceptance and commissioning)	Commissioning, operate and test for probationary period, undertake training	Perform RAM demonstration and prepare application specific safety case
10. System acceptance	Carryout system acceptance based on the acceptance criteria	Assess RAM demonstration and special safety case
11. Operation and maintenance	Operating the system for long term and doing regular maintenance	Perform reliability centered maintenance (RCM), monitoring hazard log and safety
12. Performance monitoring	Analyzing and evaluating the operation performance data	Collect and analyze the RAM and safety statistics
13. Modification and retrofit	Implementing modification and retrofitting as per request	Consider RAMS implications for modification and retrofit
14. Decommissioning and disposal	Plan and undertake the decommission and disposal	Develop safety plan and execute, perform hazard & risk assessment

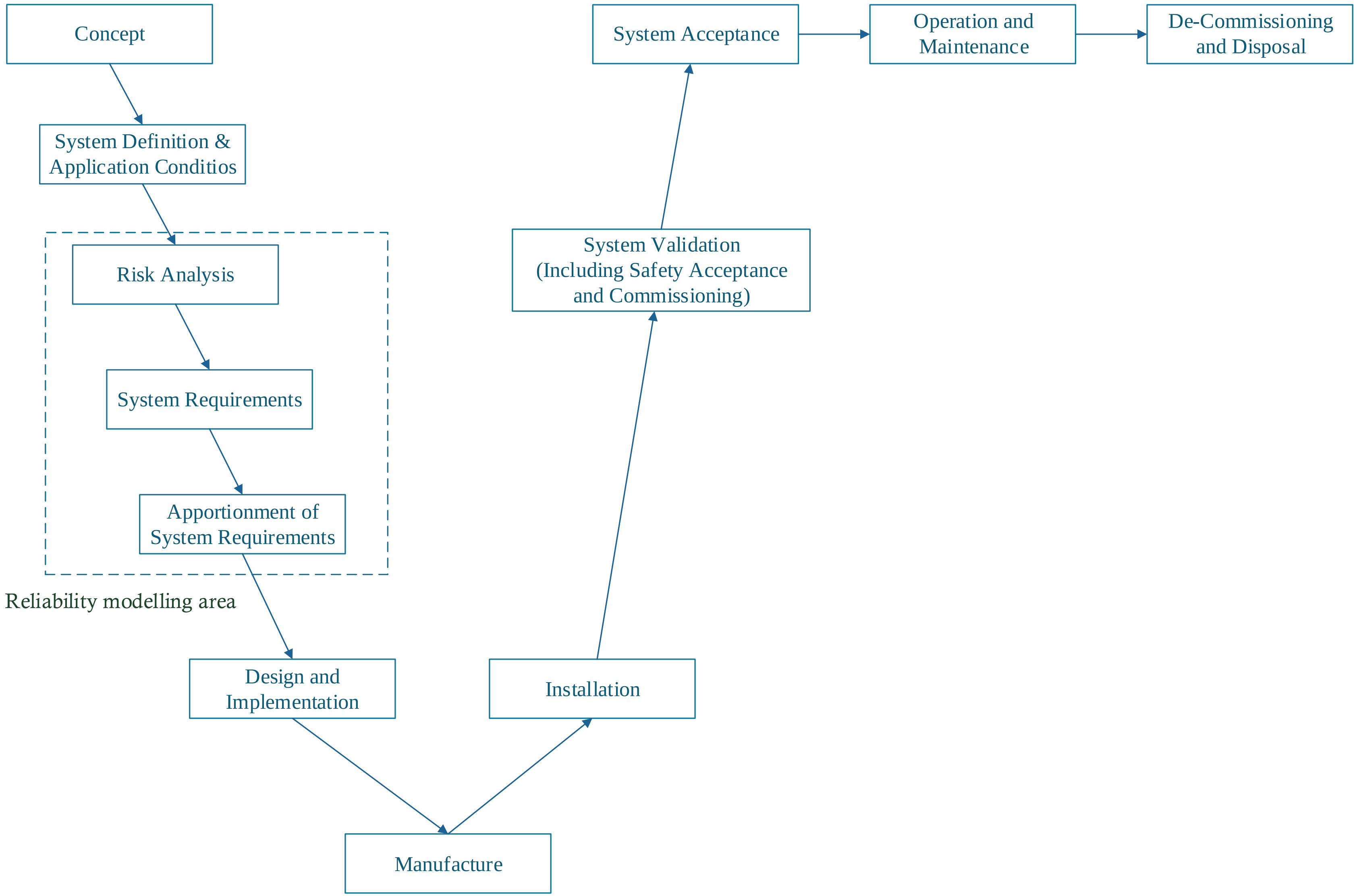

Figure 3.4 'V' cycle – Different RAMS lifecycle phases from initial concept to disposal phase

As the thesis aims to develop a model for reliability assessment, it can be said that this assessment is a part of the RAMS ‘V’ cycle covering the risk analysis, system requirements and apportion of system requirement phases as indicated in the Figure 3.4. The 'V' cycle illustrates to do an apportionment of system requirements in the fifth phase followed by design and implementation in sixth phase, where reliability assessment is to be performed based on the system and sub system requirements.

To perform the reliability assessment for the case study discussed in above sections 3.1, it is essential to choose suitable methods to model. Therefore, in the following chapters a literature review is done to identify proper methods. The methods chosen and applied to the case study are both qualitative and quantitative types, later they are implemented in a software program for analysis.

Chapter 4

Reliability Modelling

ERTMS/ETCS is considered to be a complex control system and the availability of the control system is important to operate the railways in a reliable and punctual manner (EEIG, 2012). Reliability aims to achieve the system function in all instances. It focuses on determining reasons for potential failures and their probabilities in order to make sure that they operate as intended (Rausand, 2004). ETCS being a real-time distributed and a complex heterogeneous system dependent on subsystems like lineside, trackside and on-board subsystems, it must comply strict safety constrains (Hoinaru, 2013). To have an effective train control mechanism and to maintain the punctuality of trains, it is convinced that all the dependent subsystems has to coordinate in a right mode simultaneously and continuously. M.Vromans (Vromans, 2005) describes that in general consideration reliability measures are Mean Time between Failures (MTBF), but in case of railways the system is said to be reliable if the train are available at stations, meaning that punctuality has to be maintained. Though reliability is obviously an important characteristic of any transportation system, it is tough to do the quantification for railways explicitly.

The thesis methodology is to determine an appropriate model that involves all the component failure modes and realizing the real-time operation of railways. To identify relevant models and methods, a literature review is performed to get an overview approaches adopted by various authors.

4.1 Literature Review

The literature review is performed using several different scientific databases like Science direct, Scopus, Compendex, NTNU Oria, etc. In these databases, search words like ERTMS/ETCS, reliability modelling, failure modelling, reliability aspects in railways signaling and reliability assessments of railways were used. Along with the key words operators like AND, OR helped to get more relevant articles and research papers. The advanced search method that avails to select the appropriate criteria and limit the results to fewer articles was more beneficial in finding the most relevant papers. In addition, classification by selecting the number of citations, categories, department of study and many more assisted to find the best of all the literatures.

Although ERTMS/ETCS has been deployed over a decade and developing constantly, only very few scientific papers discuss about the reliability modelling and availability of ERTMS/ETCS. The number of articles that direct towards failure modelling are even less compared to general modelling structures or behavior of ERTMS/ETCS.

Different approaches were used to analyze the dependability of ERTMS/ETCS and one of the methods is system of systems (SoS). The ERTMS level 2 is considered to be SoS, as its trackside, lineside and on-board subsystems are geographically distributed. SoS method is used to evaluate the dependability parameters like availability and verify if they are meeting the RAMS goals set to each system. Qiu et al (2014) used statecharts to model the behaviour of SoS and demonstated that statecharts are more advantageous compared to markov chains, as markov chains number of states grow exponentially and is tough to understand. Many researchers found that it is difficult to model all subsytems into single model. Hermanns et al (2005) uses Unified Modelling Langusage (UML) statechart extension to perform dependability evaluation of train radio system. Vernez and Vuille (2009) see ERTMS level 2 as complex macro system and use functional failure mode, effects and criticality analysis (FMECA) method to optimize the dependability. Faber et al (2005) analyzes the reaction time of the driver to respond to the signal that is received from the RBC in real-time using FTA. There are numerous approaches for system modelling and very limited methods model the reliability. The conventional models suggested by the scientific community are Fault Tree Analysis (FTA) and Reliability Block Diagrams (RBD), both these methods are limited in expressive power but are easy and efficient to use (Flammini, 2005). ETCS being a complex technical system, Continuous Time Markov Chains (CTMC) and other Stochastic Petri Nets (SPN) can model such complex networks but it is not feasible to model very large systems. As the ETCS is also dynamic in nature its maintenance or repair after failure is difficult to model using Repairable Fault Trees (RFT) (Flammini, 2006).

FTA model is adopted by many authors and it is possible to map directly a FT into a Bayesian Network (BN) (Bobbio, 2001). Similar to FTA, Bayesian Networks (BN) do have the expressive power and solving efficiency to model reliability aspects. Flammini et al (2014), recommends modelling different subsystems using various models and integrating to analyze them. In one of his paper he used only FTA for subsystems and Bayesian Networks (BN) for overall system (Flammini, 2006). In another paper he supports his proposals using RFT for trackside subsystem, FTA model for onboard and Generalized Stochastic Petri Nets (GSPN) are combined using BN for movement authority delay (Flammini, 2005). For the reliability modelling of ERTMS/ETCS, the multi-formalism approach seems to be more promising than many other approaches. Subsequently, assessing the failure modes of various systems at component level by FMEA and analyzing them in FTA can help to obtain a realistic reliability. As railways is dynamic in its operations, developing a reliability model using RBD simulation and other simulation tools can be considered to be more realistic.

4.2 Modelling Procedure Selection

The reliability modelling can be applied to any engineered system to measure its performance. These measures enables to meet performance criteria, to quantify comparisons between various options, and helps to make economic decisions. The final goal of reliability analysis is to answer the questions like "is the system reliable enough?" "which arrangement will fail less?" and "where do we need to invest to improve the system reliability?'' (Brown, 1996).

On assessing the literature of the existing reliability approaches in the above section, one of the methods of failure modelling by multi-formalism was found to be more optimistic and realizable. As mentioned earlier, ERTMS/ETCS being a complex system and the punctuality of this system is dependent on the availability and reliability of the subsystems. In many cases, opting a single modelling approach for analysis will not cope with all aspects of complex system. A solution to this can be multi-formalism modular approach, since it allows to apply the appropriate formalism and solution technique to model and analyze several components of the system (Flammini, 2014).

In general, the methods to perform the reliability assessment are simulation and analytical. Simulation is a very flexible method but requires more computation time and uncertainty of precision (Rausand, 2004). Whereas, analytical methods depend on the type of reliability approach chosen, either qualitative or quantitative. This thesis aims to evaluate the performance of railway infrastructure implementing the latest ERTMS/ETCS signaling system in Norway. In response to this, the ISO/TR 12489 standard is referred and it explains the selection process for reliability analysis using a flowchart. A flowchart is illustrated in Figure 4.1, using predefined criteria and a model is chosen corresponding to those criteria. The end methods that can be used for the reliability assessment are Reliability block diagrams, Fault Tree analysis, Markov models and simulation techniques. Before proceeding to these methods, the system to be analyzed has to be defined and their failure modes are to be detected. Performing Failure Mode Effect Analysis (FMEA) to the identified system will reveal different failure modes and their effects. Based on the obtained failure modes, critical systems or components can be a chosen to Fault tree and Reliability block diagram.

Usually, the reliability modelling methods analyses the structures on either the system level or component level. Bane NOR being responsible for the infrastructure development, their prime motive is to maintain their infrastructure more reliable and operate their railways punctually. As discussed earlier, ERTMS/ETCS has three different sub-systems Trackside, Lineside and Onboard system. Bane NOR is responsible for the trackside and lineside systems but not onboard system. Therefore, the reliability modelling analysis here is limited to trackside and lineside systems at component level. Some of the systems like Radio block center (RBC) and GSM-R have complex structure and network, they are assumed as single entities.

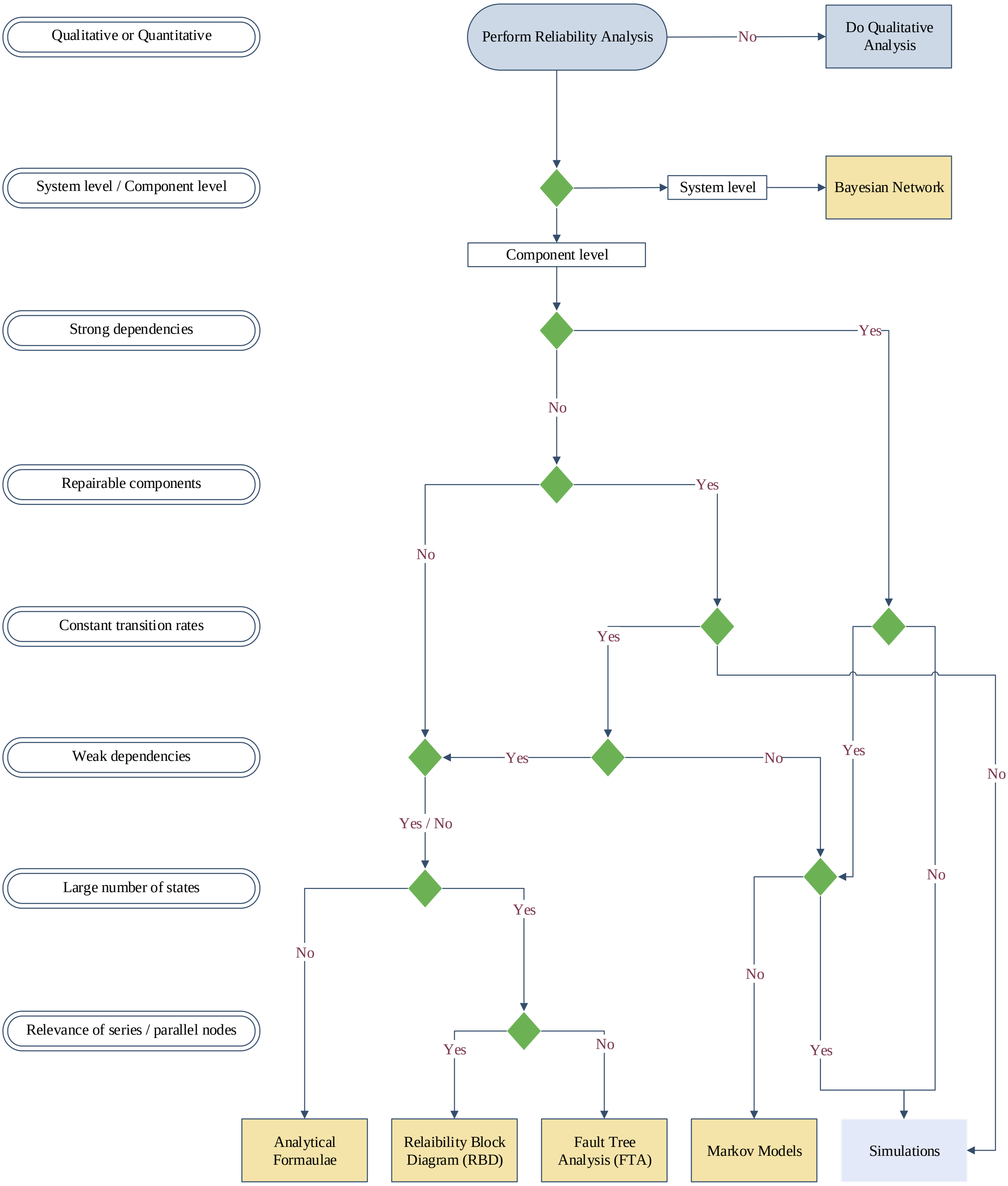

Figure 4.1 Flowchart to determine the reliability modelling method

As the ERTMS/ETCS is having a complicated structure with many systems and components, the most commonly used analyses are at component level. To assess the reliability of ERTMS/ETCS at component level, FMEA technique is used to analyze all the failure modes of each component. Similarly, other methods like Fault Tree Analysis method, Reliability block diagram and Simulation techniques are adopted to estimate system availability and reliability. The methods are explained briefly in next sections and are implemented in the case study to analyze the ERTMS/ETCS in real-time.

The availability and reliability of a system can be assessed by adopting several approaches. Some of them are Reliability block diagrams (RBD), Fault tree analysis (FTA), Markov methods, Flow networks, Petri nets and Monte Carlo simulations (Rausand, 2004). RBD is a simple method where each block can either have a functioning state or failed state. It is a static system modelling and is consequently not a best approach to model complex systems with repair strategy. Similarly, FTA has the same limitations as RBD cornering the systems with complex repair and maintenance strategy. Markov methods are best suited to model systems with complex maintenance strategies, but when these systems have numerous components then the system states increase drastically. Flow networks are basically graphical representations of the links between systems and can be assumed to be an extension of RBD. To represent flow networks are simple, but when it comes to complex system a computer program is required to implement it. Finally, Monte Carlo next event simulation (Monte Carlo simulation) is a very flexible approach to perform an availability assessment of repairable systems, and it facilitates to include many constraints depending upon the system requirements. The simulations has to be done using a computer program and the program may set certain limitations according to system requirements. The following sections describe the assessment methods and these methods are implemented to the case study in the next chapter.

4.2.1 Failure Mode Effect Analysis (FMEA)

FMEA is a method used to identify the potential failure modes of all the functional elements or components in a system and also to study the effects of the identified failures on a particular system. FMEA is basically recommended to be implement in the early design phases of any system. However, as it includes a thorough study, it has become a common technique to perform a detailed reliability analyses and maintenance planning (Rausand, 2004). FMEA is more qualitative in nature and further if the criticality of failures is concerned, then it becomes more quantitative assessment called FMECA (Failure Mode Effect Criticality Analysis). In FMECA, the failure modes are ranked by severity and frequency and these failure modes are assigned with a risk priority number (RPN). Thus FMECA facilitates to perform a criticality analysis to determine the severity of failure mode by evaluating and ranking (RPN) (Rajiv, 2005).

The thesis considers that all the systems in ERTMS/ETCS signaling are critical and hence only FMEA shall be performed here. The two different methods to develop an FMEA are,

- *Top-down approach*: This method is implemented in an early design phase before the complete system structure is decided. FMEA is carried out on the system or sub-system level rather than component level failures.

- *Bottom-up approach*: This method is implemented when the system concept is already defined. FMEA is carried out on the component level and the effect of each failure mode is studied on subsystem level.

The case study chosen in this thesis is mostly focusing at component level. The ERTMS/ETCS trackside and lineside components are identified as critical infrastructure systems that can cause delays in train operations. To determine the failure modes associated with these systems, an FMEA is performed such that this analysis would further help to develop an FTA to analyze the component dependency. So the Failure mode and effect analysis (FMEA) here is a well-structured bottom-up approach that begins with a known failure mode of a component at one level by finding the cause of failure and how the failure is detected. In the next stage, it studies the effect on the subsystem level and system level functions. Finally, some measures are suggested to mitigate the risks and failures.

A systematic approach (Rajiv, 2005) to develop an FMEA are given below:

1. Identify the system on which FMEA is to be carried out and divide the system into subsystems or components.
2. Construct a functional block diagram indicating their relationships.
3. Determine the potential failure modes of each component, along with their causes and effects on subsystem and system level.
4. Determine how the failure can be detected and suggest the risk reducing measures.

The advantages of developing a bottom-up approach FMEA is that it takes into account all components of a system for analysis. It is an efficient and reliable method to evaluate the components dependency in a complex system. FMEA on one hand is very easy to apply and on the other hand, the process can take long time for a complex system.

The objective of performing an FMEA in this thesis is to study the criticality of infrastructure systems in ERTMS/ETCS and based on these components an FTA is developed to demonstrate how these systems failures will contribute to the blocking of train in either bidirectional section or at station. The functional block diagram of systems, detailed FMEA process and systems considered are discussed in later chapter 5.2.1.

4.2.2 Fault Tree Analysis (FTA)

The FTA method is implemented to determine the potential components that are causing the failures. FTA is more effective in revealing the possible potential failures of an event. It is a deductive approach, where first the system failure is specified and then failures that lead to that particular system failure are analyzed. These failures and the events causing it are connected using the Boolean algebraic functions (OR and AND gates). The main intention of applying the FTA is to assess the safety and reliability, weakness and quantify the failure contributors of the systems. Fault trees are the most commonly used technique in complex systems dependability assessment. It is most widely applied failure modelling technique in various industries like aerospace, medical, railways, military and nuclear (Bouissou, 2003).

A step by step process to develop a fault tree is given below,

1. Define the failure or an unwanted event as the top event.
2. Then resolve the failure event is into immediate causes (events).
3. Immediate events are further resolved into basic events that are primarily the basic causes.
4. Faull tree is then constructed based on the logical relationships between these events.
5. For quantitative analysis, basic events probability is calculated to analyze top event probability.

A typical fault tree is show in Figure 4.2, representing the type of events and the logic gates that can be used. In this fault tree, only basic gates are used and there are many other symbols that are used in fault tree but they are not relevant to know in this study. Some of the inferences from the typical fault tree are given below.

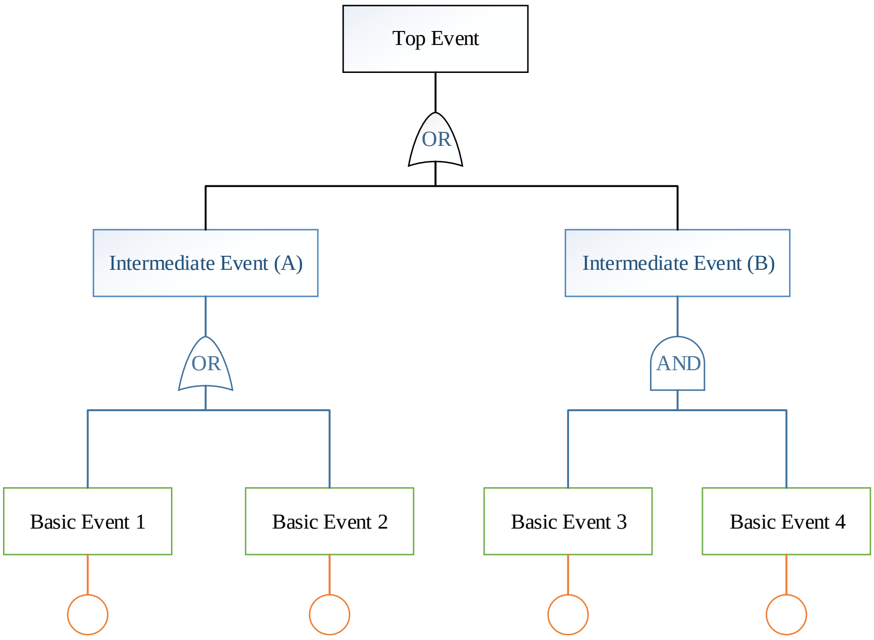

Figure 4.2 A typical fault tree representing different events and logic gates

- Top event: It is the main system failure event and is caused due to intermediate events A, B connected through logic gate OR. If either of any intermediate events A or B occur (fail) then the top event will occur.
- Intermediate events: These events are occurring due to failure of basic events. Here the basic events 3, 4 are connected to intermediate event B via an AND gate, implying that the intermediate event B will happen only if the basic events 3 and 4 occur together (fail here).
- Basic events: These are the primary events. If these events fail to operate, they will result in the intermediate events.

- The cut sets for a fault tree are defined as the set of basic events and which upon failure will give rise to the occurrence of the top event.

When the system become very complex, the fault tree becomes even more complex to evaluate. In these cases, implementing the FTA by a software is an ideal choice to make the assessment simple and easy to realize. The advantages and disadvantages of applying the FTA are

Advantages:

- The developed fault tree helps in exposing the critical path and finds the root cause.
- It is easy to follow and understand simultaneously.
- FTA enables to program using the software that can improve analysis.
- The system behavior can be studied thoroughly, as it can handle multiple number of failures.

Disadvantages:

- For a reasonably large system containing numerous components, the FTA becomes enormous.
- If a system works even on having partial failure, FTA assumes it to be a full failure
- A single system failure can be modelled in different fault tree methods; it is non - generic.
- The top event probability depends on the basic events probability. If the basic events' probability is not accurate then it affects the credibility of FTA.

The main intention of discussing FTA here is to illustrate how the failure events are depending on the components. Two fault trees are developed one each for blocking a train in bidirectional section and at station in section 5.5.3., which indicates the dependency of ERTMS components failure resulting in the delays or affecting the punctuality.

4.2.3 Reliability Block Diagram (RBD)

RBD is a method of describing the function of a system, where the system components are represented in blocks and interlinked logically. This method is generally applicable for systems that are irreparable and not concerned with the occurrence of failures (Rausand, 2004). Reliability block diagrams are usually in series or parallel or as a combination of both. In a series RBD, the system works if and only if all the components connected in series work. Whereas as for a parallel structure, the whole system works if any of the component is working. Usually RBD's of technical systems would be a combination of both series and parallel structures.

In this thesis, Relysim software is implemented in the section 5.4 for reliability assessment of ERTMS/ETCS infrastructure systems. To fulfil this, a RBD is built for station and bidirectional section with ERTMS system components in the form of blocks. The blocks are assigned with failure events (down events) and their corresponding MTTR and MTTF, which are then simulated for assessment. In a normal RBD, it is not feasible to assign failure events and reliability parameters. Therefore, a software called Relysim is used to make RBD and perform simulations to meet the dynamic quality of railway ERTMS/ETCS operations.

4.2.4 Monte Carlo Simulations

Monte Carlo simulation is a random simulation technique, based on theory of probability and statistics. It assures its reliability and accuracy by the central limit theorem in the probability theory and is used to calculate the probability of failure (Steinhauser, 2013). Monte Carlo method is usually carried out for assessing the typical lifetime of a system using a software program. When simulations are run in the computer by a program, a series of random events are generated according to the system definition. The different events can be random events based on various component failures, scheduled maintenance events and conditional events (i.e., events initiated based on the occurrence of other events). When all these events are included during the simulation of system for a lifetime, then the simulation scenario can be regarded as real lifetime scenario (Rausand, 2004).

Consider a Monte Carlo simulation technique is performed on a project that has various tasks and having uncertainty in time to complete. In this case, a random value is selected for each of the tasks, depending upon the range of estimates. On simulation it generates a random value for the task and result of model is recorded. This process in a typical Monte Carlo simulation will be repeating as defined in the computer program (can be 100 runs or 1000 runs or more). When the simulation is completed, a large set of results are obtained and these are used to describe the likelihood or probability of accomplishing the tasks in the project.

The application of this method is quite different to numerical problems and physical systems. In the application of Monte Carlo simulations, some of the physical processes do not even require a differential equation to describe their system behavior rather they can be simulated directly. However, there is one requirement that for the physical systems have to be described by a probability distribution function (PDF) to perform the simulation (Steinhauser, 2013). Once the system is defined by a PDF, the Monte Carlo simulations can be performed by random sampling of PDFs. After performing the simulations, the average number of observations are taken as results.

The advantages of Monte Carlo method is that it has the tendency to reduce the error by increasing the number of simulations. In addition, the method has good convergence in simulation, such that there is no need to linearize the limit state function and to normalize the random variables (Yaohui Lu, 2010). Hence the reliability analysis by this method becomes simpler by avoiding mathematical difficulties.

Monte Carlo simulation is considered to be a key method in this thesis because, the simulation is done using TRAIL (Transport Reliability Availability and Infrastructure Logistics simulator) software to assess the reliability and availability of the ERTMS/ETCS. Marvin Rausand in his book of ‘System

Reliability Theory' (Rausand, 2004) suggest that the following data is required as input to Monte Carlo method

- System description, their components inter dependency and control
- Information about the component failure modes, effects and causes of failure (basically FMEA)
- Component failure and repair data, can be MTTF, MTTR and MTBF
- Repair strategies and duration for different failure modes
- Inspection frequency and planned maintenance data
- Resources data like availability of maintenance spare parts and maintenance crew

4.3 RAM Indicators

RAM indicators are defined in this section, which are later applied in the thesis for a quantitative assessment of ERTMS/ETCS case study performance. A dedicated group for defining the ERTMS standard was formed in the name of ERTMS Users Group, a part of European Economic Interest Group (EEIG). It was formed in the year 1995 by the French, German and Italian railways, later many other railways that joined group were Bane NOR - Norway, ADIF - Spain, ProRail - The Netherlands, Network Rail - Great Britain and Trafikverket - Sweden. The group has used some existing European railways RAM related information for signaling system and realized the RAM requirements for ERTMS/ETCS, in order to improve the accuracy of the RAM parameters estimation. The preliminary RAM related activities are system identification and failures identification, and are then used to define requirements.

The group has also mentioned maintainability requirements along with the reliability requirements, but as the project scope is confined to reliability, we are not considering the maintainability. Some of the reliability indicating terms used in the thesis are MTBF, MTTR, MTTF and MLD. The reason for choosing only these indicators is that these indicators are calculated mean values from all the failures, repairs and delays record for certain system.

***Mean Time between Failures (MTBF)*:** MTBF is the average time between one failure to the next. It can also be defined for repairable devices as the sum of Mean Time to Failure (MTTF) and Mean Time to Repair (MTTR). It is a basic measure of a system's reliability and availability and is usually represented as units of hours.

If the total operating time is $T(t)$ and number of failures are r, then MTBF is

$$MTBF = \frac{T(t)}{r} \tag{1}$$

As MTBF is defined for repairable items only, it is representing the same parameter as mean life (θ). If there are n items that are operated until they fail, then mean life (θ) is merely the arithmetic mean time to failure of the total items and is given by

$$\theta = \frac{\sum_{i=1}^{n} t_i}{n} \tag{2}$$

Where t_i = time to failure of the i_{th} item and n = total number of items

If we assume to have a constant failure rate, then the reliability function will be

$$R(t) = e^{-\lambda t} = e^{-\frac{t}{\theta}} = e^{-\frac{t}{MTBF}} \tag{3}$$

and the failure rate λ if can be written as

$$\lambda = \frac{1}{MTBF} \tag{4}$$

The above λ and $R(t)$ are used to calculate the reliability of the ETCS components, based on the results obtained from Relsyim model in section 5.4.3 and presented in Appendix C.

***Mean Time to Failure (MTTF)*:** MTTF is a reliability measure to calculate the mean time expected until the first failure of a system. Mostly MTBF is used to a repairable item, while MTTF is used for non-repairable items. However, MTBF is commonly used for both repairable and non-repairable items.

If the failures are random the failure times follow a distribution with a probability density function $f(t)$, and its corresponding reliability function $R(t)$ then the MTTF in given by the mathematical expression

$$MTTF = \int_0^\infty t f(t) dt = \int_0^\infty R(t) dt \tag{5}$$

***Mean Time to Repair (MTTR)*:** MTTR is the average (expected) time taken to repair a failure. It includes the time taken to detect the defect and time taken to physically repair the failure. Just like MTBF and MTTF, MTTR is also represented in hours.

Availability as mentioned earlier, it is the ability to perform an action at certain time. Whereas average availability (A_{avg}) denotes the mean proportion of time the item is functioning (Defense, 1998). For example, if we have balise and if it is repaired to “as good as new” condition every time it fails, then average availability is given by

$$A_{avg} = \frac{MTTF}{MTTF + MTTR} \tag{6}$$

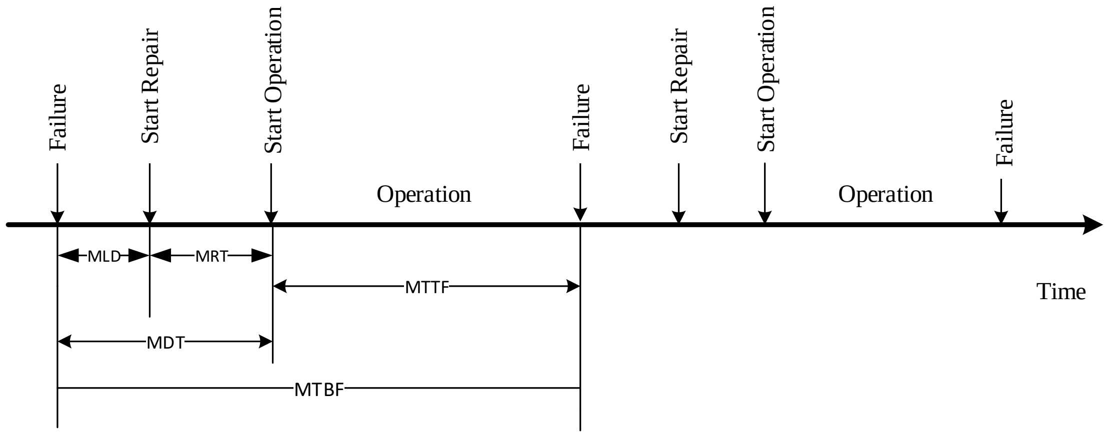

Figure 4.3 Representation of reliability indicators over a timeline

Mean Logistic Delay (MLD)**:** MLD is the time measured from the instant of failure detection to the start of repair. It includes the time required to diagnose and locate the failure, arrange spare parts, tools and personnel and the travel time to the location of the failed subsystem.

$$MTBF = MTTF + MTTR + MLD \tag{7}$$

Important interpretations from the reliability indicators:

- The higher the MTBF value is, the higher will be the reliability and availability of the system.
- Availability is dependent on the MTTR, so if MTTR is higher it takes a long time to recover a system from a failure. Thus, the system is going to have a low availability.
- If MTBF value is very high than MTTR, then will result in a high availability.

In Figure 4.3 a general representation of all the reliability parameters discussed above are shown over a timeline for understanding.

ERTMS Reliability Targets**:** The reliability targets are classified in both qualitative and quantitative requirements. The quantitative requirements are specified here in terms of Mean Time between Failures (MTBF) and is categorized by criticality (Immobilizing, Service and Minor) of failures (EEIG, 2012). Some of the ERTMS reliability requirements are mentioned in Table 5.

Table 5 ERTMS quantitative reliability requirements (Source: ERTMS RAM specifications, 1998)

Failure Type	**ETCS System (MTBF not less than)**		
	Trackside	Onboard	Lineside
Immobilizing Failure	$3.5 \cdot 10^8\ h$	$2.7 \cdot 10^6\ h$	$1.2 \cdot 10^5\ h$
Service Failure	$4.0 \cdot 10^7\ h$	$3.0 \cdot 10^5\ h$	$1.4 \cdot 10^4\ h$
Minor Failure	$1.0 \cdot 10^5\ h$	$8.0 \cdot 10^3\ h$	$3.6 \cdot 10^2\ h$

From the above quantitative requirements, it can be inferred that immobilizing failure on trackside occurs very rarely, because ETCS system use highly advanced technology and systems that are more reliable. If this fail occurs, the main drawback is that it affects the availability or punctuality and ultimately reduces the capacity of line. Lineside failures may occur a bit more frequent due to the continuous exposure to different weather conditions. The above specified requirements are very critical and they must be fulfilled by any ERTMS implementing company.

Moreover, ERTMS/ETCS RAM requirements specifies to perform various activities and one of them is reliability modelling, prediction and apportionment. Performing such reliability modelling assists to identify the systems that are weak and vulnerable for failures.

In the next chapter, the identified methods from literature review in the above sections are implemented to the case study of ØØL pilot line. The methods FMEA, FTA and RBD are qualitative, whereas Monte Carlo simulation using the RAM (reliability) indicators is a quantitative. These two types of methods are later realized in software programs. At first an RBD model of ØØL is made and simulations are done in Relysim, later another software called TRAIL is used for simulation by giving FTA and other inputs.

Chapter 5

Reliability Modelling of the Pilot Project

Bane NOR began to plan and implement ERTMS NI project in 2012 and Østfoldbanen Østre Linje (ØØL) was chosen as a pilot project to implement ERTMS level 2. ØØL pilot project is the line operating from Ski - Sarpsborg. The upgradation of this line from the existing conventional signaling system to ERTMS/ETCS level 2 took place during 2012-2014 and began to operate in 2015 (BaneNOR, 2011). The modification was performed in different phases for upgrading stations and different sections, this planned process included design, installation, testing and commissioning of the total system at ØØL. Furthermore, the migration had RAM analysis in various phases to identify the measures that has to be implemented to support RAM targets and ensure the safety during the modification.

The reliability modelling of this pilot project in this thesis is more concerned with the infrastructure elements of ERTMS/ETCS for which Bane NOR is responsible. The modelling and analysis methods, steps and their benefits were discussed in last chapter and the methods are implemented in this chapter. A systematic approach is adopted here to understand how the modelling was performed. It starts with the system description, RAM analysis, modelling inputs and finally implementing the models using the software programs Relysim and TRAIL. The main reason of using the software tools to model and analysis is that the prediction of system failures and reliability could be improved with small changes in the design of the system (Krenželok, 2010).

5.1 System Description

The pilot project implemented in Norway is to the south of Oslo running from Ski to Sarpsborg with a stretch of 80 km and stations present in between Ski and Sarpsborg are Kråkstad, Tomter, Spydeberg, Askim, Mysen, Rakkestad and Ise. Initially the modelling was planned to perform for the entire length of 80 km bur concerning the time constraint of thesis and complexity of the system, the modelling of the pilot project was limited to half of the length. So the system under consideration for modelling here is from Ski to Mysen with a distance of 40 km. One more reason for choosing only half of the section is that the signaling system from Rakkestad is operating both on ERTMS/ETCS level 2 and conventional signaling. If this was also considered in analysis then the model would become vague due to the interference of both signaling systems.

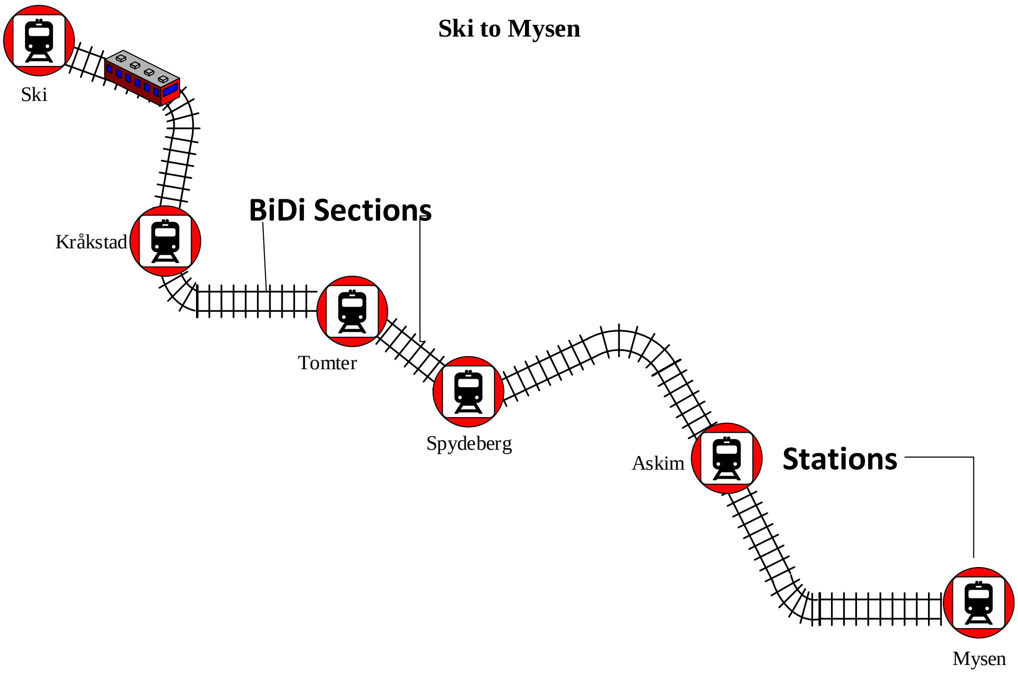

Figure 5.1 ØØL route map with section classification

A geographical or physical layout is represented in the Figure 5.1 with six stations and the 'BiDi Sections' are the bidirectional sections with single track. The whole network is operated on a single line outside the stations, whereas the stations are having certain number of platforms and tracks. In addition to these six stations there are three other stations used for crossing. One is Skotbu between Kråkstad and Tomter, other is Knapstad between Tomter and Spydeberg and the last is Slitu in between Askim and Mysen. The crossing stations are considered in the analysis and are not represented in Figure 5.1.

In the entire section from Ski to Mysen, the ERTMS/ETCS elements considered for reliability analysis are only trackside and lineside systems excluding the onboard systems. Referring to the ERTMS/ETCS architecture in Figure 2.4, along with the trackside and lineside equipment other general systems like signals, points, axle counters, track and maintenance are taken into account for reliability modelling. The intention to have them in the model is to make the model more practical. For a successful operation of the ERTMS/ETCS level 2, the ETCS components like balises and information transfer via GSM-R has to coordinate with signals, interlocking and points for train movement on the tracks.

In a normal ETCS level 2 axle counters are removed and the balises only detect the train position. However, the Norwegian railways and Bane NOR are installing axle counters along the tracks for monitoring the train movement in a block section in addition to balises to ensure more safe operations. Hence the ERTMS/ETCS components that are focused for modelling in this thesis are track, points, axle counters, interlocking, GSM-R, balises, RBC and planned or periodic maintenances.

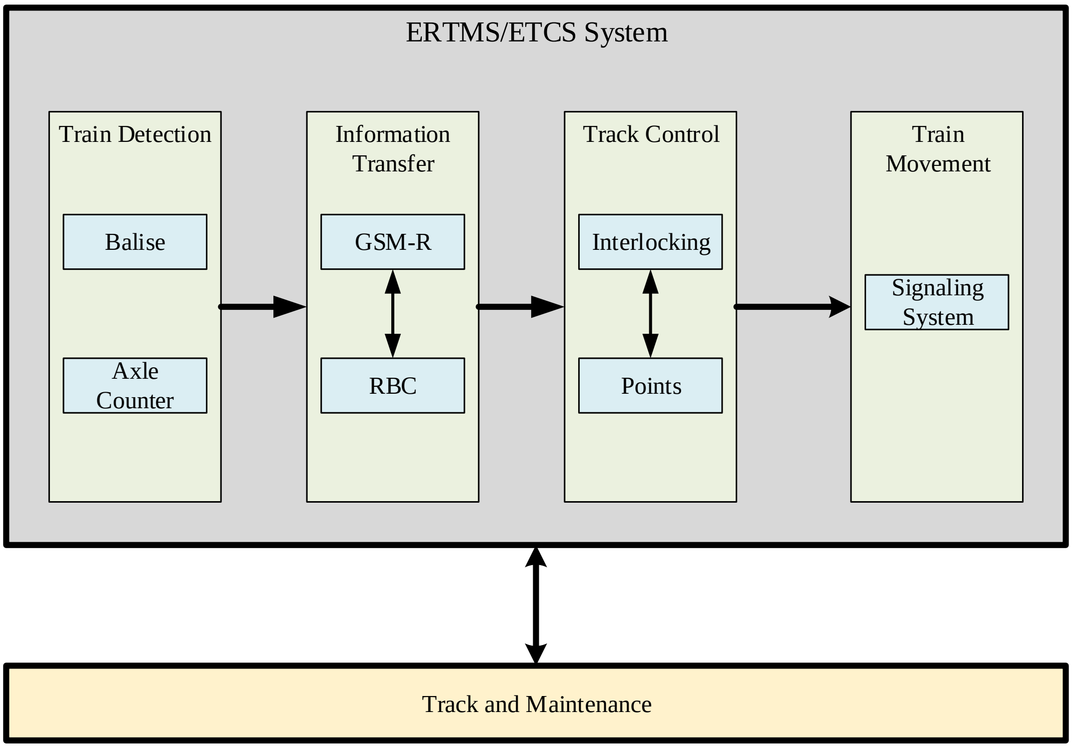

Figure 5.2 Functional block diagram of ERTMS/ETCS system used for analysis

A functional block diagram of ERTMS/ETCS level 2 is illustrated in Figure 5.2, to understand the function of the components and relation between them. The detection of train in a section is done by balise or axle counter and when the train passes over balise, the information about speed and position is sent to RBC via GSM-R network. Then RBC sends the movement authority to train onboard system, whether the train must proceed further or wait for more information. If the train driver neglects the message from RBC then automatically the onboard system regulates the speed and stops the train. Also RBC control the interlocking such that the points are operated to change the track and control the crossings. Axle counter present in various section count the number of axles entering one section and leaving the same section. If the number mismatches, then the section is considered to be occupied and sends the signal to signal post to indicate as Red, which stops the train for proceeding further and results in a delay. Also if any track damage or maintenance work is carried out, it results in the delay of trains at next station.

For the ERMTS operations in Norway (in the pilot project), Bane NOR suggests that when the train is running in ETCS level 2 system and if the train driver does not get the signal from RBC (due to failure in balise or GSM-R network or RBC down) on the onboard system, the driver can proceed until the next block section and stop until a signal is received. This makes the ERTMS system failsafe. If the driver receives the signal to proceed at the next block, the train can be operated normally. So here the working of two consecutive balises or axle counters is crucial for successful train operation and if they fail the train gets blocked in that section.

5.2 RAM Analysis

This pilot project by Bane NOR is executed in compliance with the CENELEC standard EN 50126 and the standard recommends to perform RAM analysis in all the phases of system lifecycle. The use of RAM analysis is to evaluate the performance of the systems and their components. A typical lifecycle phases in a 'V' shape is shown in Figure 3.4, where after defining the concept of the project in phase 1 and system definition in phase 2, a RAM analysis is required to be done in phase 3 for the identified system. Figure 5.3 illustrates the flow RAMS implementation plan adopted by Bane NOR for the pilot project (BaneNOR, 2011).

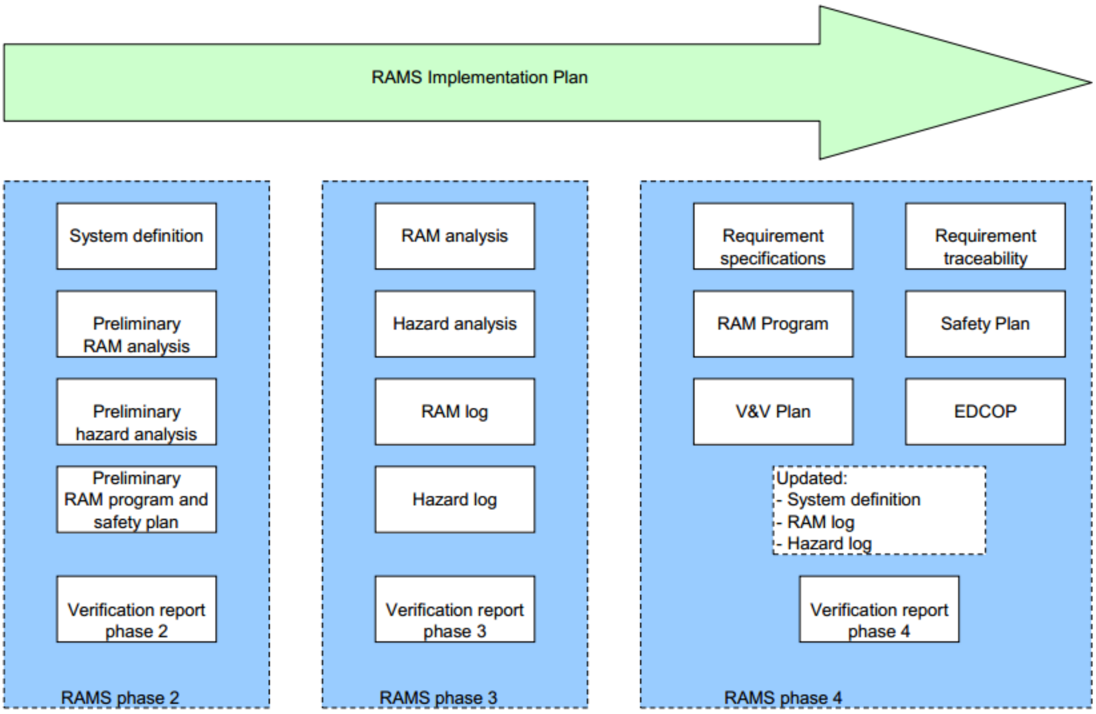

Figure 5.3 RAMS implantation plan adopted by Bane NOR

The methods for conducting RAM analysis in phase 3 may involve,

- Investigation or performance analysis of similar existing systems
- Failure identification and detection (FMEA)
- Fault tree analysis (FTA) of system failures
- Hazard analysis and log (HAZID) at system and component level

The RAM analysis carried out by Bane NOR included basic ERTMS system components (objects) as well as the existing conventional objects (e.g. tracks, signals, axle counters, ballast, etc.). The main objective of this RAM analysis is to evaluate the expected level of delays caused by failure in infrastructure related systems and conditions. Bane NOR had considered all the systems like catenary, transmission, ballast etc. for their analysis. However this thesis focusing on only ERTMS/ETCS components the catenary, level crossing and other conventional systems are neglected as they do not affect the reliability analysis of ERTMS/ETCS system.

Therefore, the system components that count in for further analysis and modelling of ERTMS pilot project are points, axle counters, interlocking, GSM-R, balises, RBC and track. These systems are modelled in the Relysim and TRAIL software to perform the reliability and availability analysis in the following sections. For the RAM analysis, Bane NOR considers that if a train arrives at its terminal station not later than 3:59 minutes (<4 minutes) after scheduled arrival time, then those trains do not contribute to the delays. If an ERTMS/ETCS system or component failure caused a delay of arrival time 4 minutes (or >4 minutes), then it is recording that particular had caused that delay. A system FMEA is prepared in next section for the above mentioned ERTMS components.

5.2.1 System FMEA

A system FMEA is developed for the identified ERTMS/ETCS components used in the pilot project. The method adopted here is bottom-up approach because the components are already known and the criteria here is, how these systems will contribute to the train being blocked in a section or at station. The steps to develop an FMEA are discussed are in section 5.2.1 and followed here. In connection to these steps a functional block diagram of the ERTMS/ETCS system components is in Figure 5.2. On occurrence of all ERTMS system failures, it is resulting in the signal failure which indicates that the signal shows wrong indicator (possibly red instead of green). This affects the train operations causing delay due to the incorrect signaling system.

The failure modes in the failure mode and effect analysis (FMEA) are determined based on the description of the intended function of each subsystem over the entire system. The FMEA developed is presented in Appendix A, and it traditionally includes

- All the failure modes
- The possible cause for each failure mode
- The effect of the failure on the subsystem and system level
- The detection of each failure mode

On carrying a thorough analysis and examining the FMEA, the interrelationship between various failure modes and systems affected are identified and used to build system FTA.

5.2.2 System Reliability Parameters

In order to assess the system reliability and availability of complex systems, certain parameters are required to indicate the performance of operation. The reliability parameters are defined to calculate the frequency of component failure, time taken to identify the failure and to repair the system, such that it gets back into operation. The parameters MTTF, MLD, MTTR and MTBF are discussed earlier in the section 4.4.

For further modelling in this thesis the reliability parameters are essential. During the implementation of RAMS plan in phase 3, Bane NOR had performed RAM analysis for the ERTMS/ETCS components and determined the corresponding MTTF, MLD and MTTR to each and every failure mode described in the FMEA. These components are classified as trackside and lineside systems for convenience such that they can be compared with the ERTMS/ETCS users group's RAM requirements.

Table 6. Reliability estimates of ERTMS/ETCS components for the ØØL pilot project

RAM analysis of ERTMS Trackside and Lineside (Bane NOR)						
System	**Failure Components**	**Failure Modes**	**MTTF (hours)**	**MTTR (hours)**	**MLD (hours)**	**MTBF (hours)**
Trackside	**Point Failures**	Control over straight track but not on switching	120000	2	0.75	120002.75
		Control over switching but not on straight track	120000	2	0.75	120002.75
		No Control	120000	2	0.75	120002.00
	Interlocking	Interlocking processors down	440000	1	0.75	440001.75
	GSM R	One decentral failure affecting two or more base stations	175200	5	0.75	175205.75
		One central failure impacting all base stations	175200	2.5	0.75	175203.25
	RBC	RBC down	440000	8	0.5	440008.50
	Track	Fracture	365000	2.5	0.75	365003.25
	Maintenance	Delayed for whole track segment	8760	1	0	8761.00
Lineside	**Axle Counters**	Failure of axle counter per location	220000	4	0.75	220004.75
		Request for reset	87000	0.25	0	87000.00
	Balise	One balise dead (per balise)	440000	1	0.75	440001.75

The Table 6 above shows the derived reliability estimates for the ERTMS/ETCS level 2 operated pilot project by Bane NOR (ØØL ERTMS Project RAM analysis, 2015). Bane NOR’s methodology to obtain these estimates is mostly based on the experience and expert evaluation. Some of these are

- The MTTF is determined by using the statistical data of the comparable systems that are in use today which is combined with the inputs from expert evaluation along with internal operational and technical experts
- MLD and MTTR are defined by the maintenance personnel who have sound knowledge on the specific line under evaluation or a similar new line which is under development, based on specific applied maintenance strategies.
- MTBF = MTTF + MTTR + MLD

On comparing the derived reliability parameters for ØØL pilot project with the standardized parameters defined by the ERTMS user’s group RAMS requirements specifications, some requirements concerning the failure types were not met by the derived parameters. The failure types stated in EN 50126 standard are immobilizing, service and minor failure and these are discussed in section 4.3 and Table 5. In view of a trackside immobilizing failure, this failure can occur if any one of the components fail or in combination with failure of other components too. So assuming an immobilizing failure had occurred due to trackside system fail, then all the MTBF’s of all trackside component failure modes is summed together and compared with the specified MTBF in RAMS requirements. In a similar way the lineside system is also compared and shown in below Table 7.

Table 7 Comparison of defined and derived MTBF for ERTMS system

Failure Type	**ERTMS/ETCS system MTBF (hours)**			
	Trackside (Defined)	Trackside (Bane NOR)	Lineside (Defined)	Lineside (Bane NOR)
Immobilizing failure	> 3.5 E+08	> 1.96E+06	> 1.2E+05	> 5.27E+05
Service failure	> 4.0E+07		> 1.4E+04	
Minor failure	> 1.0E+05		> 3.6E+02	

Referring to the above Table 7, the comparison shows that the derived parameters for trackside system components is less than the required MTBF. This indicates that there is high probability for the occurrence of immobilizing and service failures due to the failures in trackside system. The lineside system components axle counters and balises MTBF is greater than the defined MTBF and thus Bane NOR is meeting the requirements here. As the failure chance of lineside systems is low when compared to the trackside systems, the delays may happen majorly due to trackside system failures. In the following sections more detailed analysis is performed by modelling and simulation methods to identify which section of the ØØL pilot line is more affected and which system failure is accountable for it.

5.3 ØØL Modelling Description

The modelling of ØØL ERTMS line is primarily done on infrastructure elements and then reliability parameters are added to the systems to evaluate the performance. The ØØL line is basically divided into two segments, stations and BiDi (bidirectional) sections. In the stations side, it is assumed to have different platforms, points, signals, axle counters, balises, interlocking and other tracks. BiDi sections are those sections in which trains are running in two directions and these sections are assumed to be equipped with balises, interlocking, axle counters and signals but not points. The other infrastructure elements like RBC, GSM-R and track are presumed to spread all over the pilot line.

A system is said to be reliable if it perform its set function on demand, similarly the ERTMS/ETCS is said to be reliable when all these ERTMS infrastructure systems function properly. Furthermore, a perfect ERTMS system operation is achieved only when all the infrastructure systems specified above function simultaneously. To realize the modelling, it is considered that delays are occurring due to failure in ERTMS system either at station or BiDi block section. In order to support this, fault trees are developed to show the ERTMS component dependency and the events in it are assigned with MTTF and MTTR for reliability analysis. Later, the entire structure data along with timetable was implemented using software to evaluate the performance of the ØØL ERTMS line.

Based on the route map of ØØL, the stations and the bidirectional sections were divided according to the project layouts of various section. These layouts were used to identify the type of trackside and lineside systems installed. As mentioned earlier that this thesis concerns more about the infrastructure elements, some of the layouts referred to count the number of systems were cable layouts, track layouts, schematic plans and balise positioning layouts. The main components that are considered for analysis were discussed in section 5.2 and the counting of systems was only done for balise groups, axle counters, interlocking and points. The count of the systems may be arbitrary because of the fact that it was quite difficult to understand the layouts. The number of systems present in each section from Ski to Mysen are presented in Appendix B and are given as asset inputs to TRAIL model. Although ERTMS/ETCS components are separated as trackside and lineside, for Relysim and TRAIL modelling they are combined together for system reliability analysis.

From the start of ØØL pilot project in 2015, Bane NOR kept a track of the delays that occurred during the operation. The data on delays happened in year 2016 was received from Bane NOR and was used as the base for usage based analysis in TRAIL, where the Non-ERTMS failures were also included. In time based analysis of TRAIL, the ERTMS/ETCS components were defined as assets along with their MTTF's and FTA is developed to interpret the components dependability. In short the modelling inputs for both software programs are

- Number of components present in each section

- MTTF and MTTR of the determined components
- Delays encountered in the year 2016 (historical data)
- FTA developed for train blocking in bidirectional (BiDi) section and station

5.4 Relysim Modelling

Relysim is a reliability simulation software used in the thesis to model and analyze the ERTMS/ETCS infrastructure components. This software is developed by Imagine That Inc., as an extension to their widespread Extendsim software used to study the process flows. Relysim models the systems using reliability block diagrams and perform a discrete event simulations. As the railway operations are dynamic, the modelling of ØØL pilot project should also consider the dynamic properties like trains passing over the balises, axle counters, interlocking, points, signals etc. Primarily Relysim is chosen to model ERTMS/ETCS system because it avails to model all the system components and perform simulation, such that a realistic system performance can be obtained and assessed later. Since RBD modelling and simulation methods are used here, it can be considered as a multi formalism modelling.

The RBD modelling by Relysim facilitates to do an availability and reliability analysis, which can further be used to plan the maintenance activities for system components as per the availability. In Relysim, a certain function may be defined using the system components and these components are represented as blocks of a RBD. Each block (component) in Relysim has an option to define its failure by a down event representing that the system is under trouble and requires maintenance. To these down events for various blocks, the time to failure (MTTF) and time to repair (MTTR) can be added with different distribution functions. This indicates how the system components failure influence the overall system operation. For more advanced analysis of the system dependability, the Relysim can be connected to Extendsim process flow models in which by developing a control logic the component wearing and repair process is determined. Relysim is the only RBD tool that allows to program custom control logic and this makes it to be more unique.

5.4.1 Relysim Introduction

The Relysim is implemented in the Extendsim software platform using the Relysim library shown in Figure 5.4, and their functional importance is as follows:

- Component - it represents a block in RBD, in which the down events are defined along with reliability parameters (MTTF and MTTR).
- Distribution Builder - in this the distributions for down event MTTF and MTTR are defined (for example: Exponential, Weibull, Normal etc.).
- End Node - it is the terminating node of the defined system, when this node is reached the system starts to simulate again depending on the number of simulations.

- Event Builder - all the defined down events are present here, the associated relationship between the down events and other system components can be altered.
- Execute - it executes the developed model simulation
- Start Node - the system starts at this node and the down events presented here indicates that if particular down event (failure) occurred then the entire system is shut down until maintenance takes place.

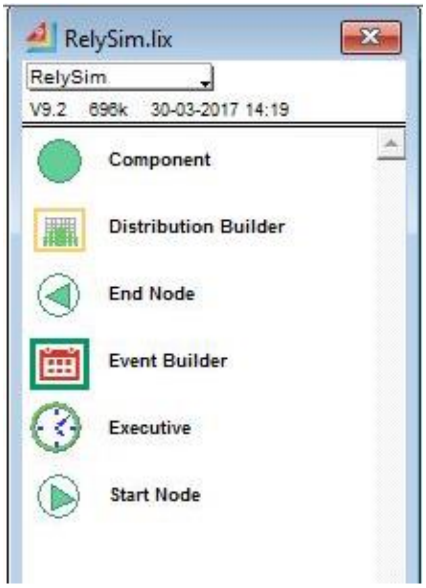

Figure 5.4 Relysim library elements

The simulation technique applied in Relysim is discrete event simulation and is a specific application of Monte Carlo simulation. In this simulation technique, the systems majorly go through a series of events which occur stochastically over a period of time. Majorly the complex systems behavior is studied using the discrete event simulation and is an imitation of the events happening in a system In the thesis, ERTMS/ETCS is assumed to be a complex system and each component is defined with discrete event for the simulation process. Some of the requirements for conducting an effective discrete event simulations are,

- A predefined starting and ending points in a system that are discrete events in time.
- All the events corresponding to various components must be discrete in nature.

5.4.2 Modelling Assumptions

The Relysim software is a newly developed software and the guidelines to use this method are not available like Extendsim. Therefore, the modelling by Relysim is implemented only for a section in ØØL with certain limitations. In the ØØL pilot line, the section from Mysen station to Askim station, where only bidirectional section (BiDi) is considered by neglecting the Askim station. This section is chosen randomly to do the analysis. The assumptions that are considered for the modelling are,

- The components considered for modelling in both station and BiDi sections are only balises, axle counters, interlocking and points.
- The station has two platforms and if one platform is occupied by a train, then the point before changes the route to other platform.
- Signals are ignored because failure of other components contribute to a signal failure.
- As all the components are laid on the track in series, number of components in each section are summed up and the component MTTF and MTTR are set accordingly, shown in Appendix B Table B.2.
- For simple analysis the MTTF and MTTR are assumed to be exponentially distributed.
- The system component wearing is ignored, due to the fact that it was quite new method and ending into errors when implemented.
- The simulation is done only in one direction, assuming the train moving in that direction.
- In case of a failure, the maintenance or repair is done immediately without any delay.
- RBC, GSM-R, Track fracture and maintenance are spread all over the RBD, which indicates that if failure in RBC and GSM-R or track fracture and maintenance takes place the entire section is shut down by causing a delay in the operations.

5.4.3 Relysim Application

Initially a reliability block diagram (RBD) is constructed in the Relysim as per the assumptions made. The blocks in RBD represent the ERTMS/ETCS components which are connected according to the ØØL layouts. At first it is assumed that train starts from Mysen and goes to ether platform 1 or platform 2 as per the availability. However, it can be considered that if the station was not Mysen, then the represented station would be arbitrarily any station because of the point place just before the station entrance.

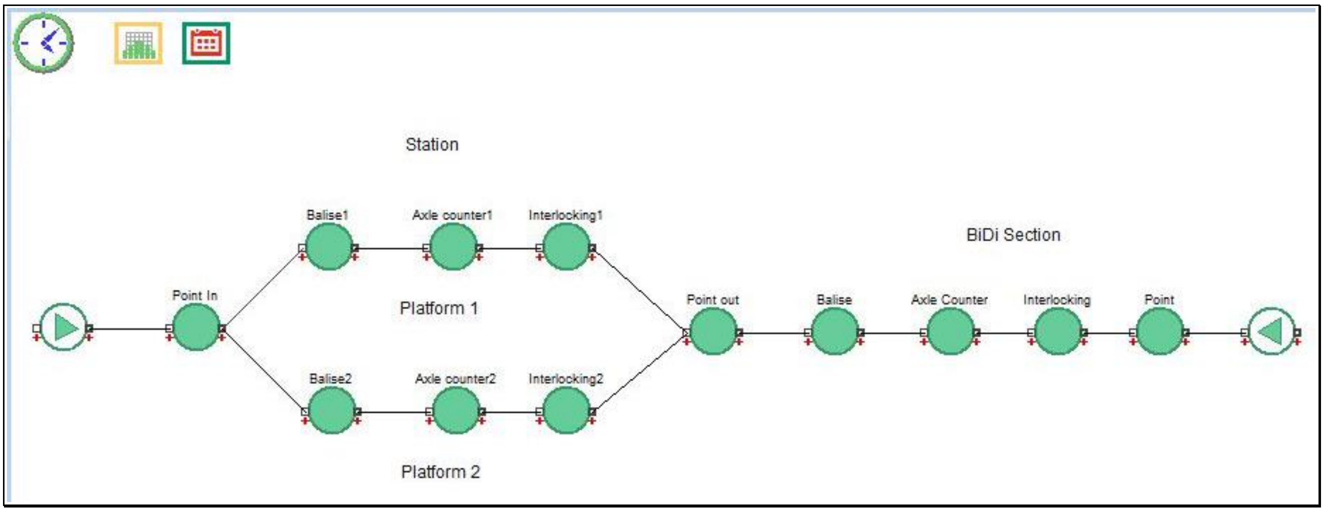

Figure 5.5 Relysim model of a station and BiDi section

Similarly the BiDi section may be another section in the whole ØØL pilot line and the only change would be the number of such ERTMS/ETCS components placed in a block section. Both the station and BiDi sections have normally points at first, followed by balise, axle counter and interlocking. Initially these blocks are connected from start node to the end node, and then are defined with the down events to each node. Starting with start node shown in Figure 5.6, the down events here are RBC down, track fracture, GSM-R fail and maintenance. This shows that if any of these down events occur then the whole section is shut down and the train is blocked in that particular section until it gets repaired.

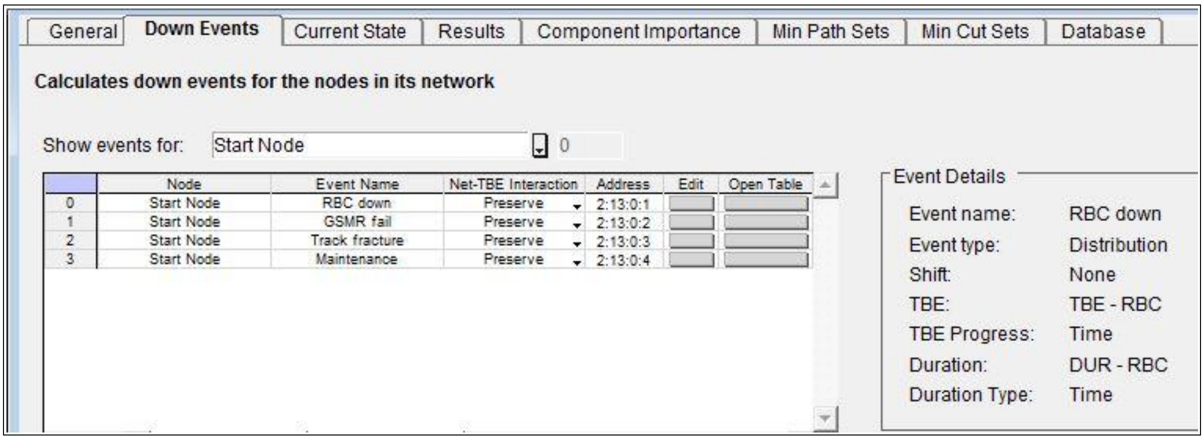

Figure 5.6 Down events defined for start node in Relysim

The frequency of these down events and repair time are taken from the Table 6, derived by Bane NOR. In the Figure 5.6, TBE (time between events) is MTTF and DUR (duration) is MTTR and are represented for the RBC system. Similar to start node all other blocks are also assigned with down events and their respective reliability parameters as presented in the Table 6. Since there are many balises at the station and BiDi sections the MTTF's are adjusted using the below equation 8, to develop a precise model and get accurate results. As the Relysim represents RBD, the system which are in series are represented as only single entity, for example a balise group. The same has been followed in case of axle counters, points and interlocking.

$$MTTF = \int_0^{\infty} e^{(\sum_{i=1}^{n} \lambda_i)}\, dt = \frac{1}{\sum_{i=1}^{n} \lambda_i} \qquad (8)$$

where i is the number of similar components placed in series, and λ_i is the corresponding rate of failure.

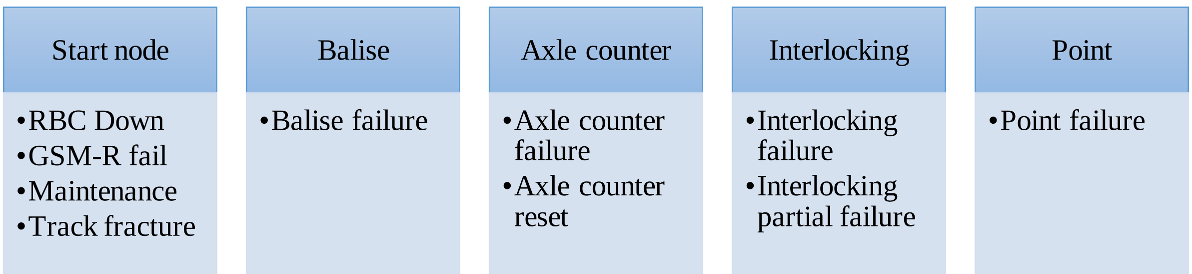

Figure 5.7 Down events of all the blocks in Relysim model

The number of ERTMS/ETCS components in the ØØL pilot line are mentioned in Appendix B together with the average number of components that are considered for the analysis in both station and BiDi sections. All the down events defined in Relysim for various blocks is shown in Figure 5.7 and their MTTF and MTTR are presented in Appendix B.

After assigning the down events along with reliability parameters, the model is arranged for simulation. The main concept of developing a model and performing simulation is to match with the real-time application of train running in a section, in which all the system components are in working condition. In order to predict the future operational performance and maintenance of ERTMS/ETCS, performing simulation is an ideal solution. The simulation for the model developed in the Figure 5.5 is setup for 1 year (8760 hours) with 1000 runs and analysis is performed based on the results obtained. The actual simulation setup in Relysim is presented in Appendix B.

In the simulation process, in the beginning all the ERTMS/ETCS system components are assumed to function properly. When a component with least time to failure (MTTF) fail, it results in a delay of the train. This delay may result in delay of the following train and it might be continued until the fault is rectified. As soon as the fault is cleared or maintained, the system is back to its operation. Since all the events are discrete in nature the process continues till the end of simulation time.

On running the simulation for the developed model over the defined time period, a series of events occur which are the failure times of various system components. These failures are the down events of each particular component that occurred in the simulation process. The time between each down event which is basically a MTTF is recorded and summed up to analyze the criticality of each down event over the system. The down events and their corresponding sum of MTTF's are plotted in the Figure 5.8 and the corresponding data is presented in Appendix B.

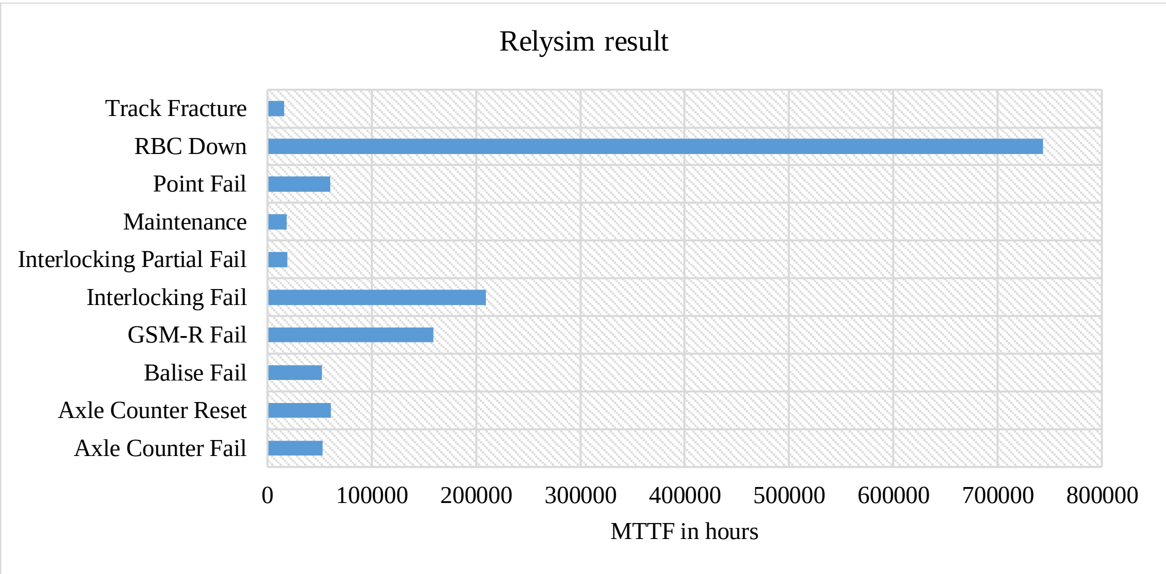

Figure 5.8 Simulation result representing the sum of MTTF's for 8760 hours and 1000 runs

It is evident from the plot that interlocking partial failures, maintenance and track fracture are most common failures that are causing the delays in a BiDi section or at a station. Apart from them the axle counter fail, axle counter reset, balise fail and point failures are also contributing to the delays, rather in less proportion. The RBC down, GSM-R fail and interlocking fail do not occur very often compared to other down events and thus these systems are more reliable. Though every ERTMS/ETCS component have different reliability the overall system reliability for a year is found to be 99 %. The individual components reliability and availability are presented in the Appendix B.

The obtained reliability of the entire ERTMS/ETCS system is meeting the requirements set by Bane NOR. However, this may change in reality because the developed model is only for a section consisting of a station and BiDi, the model can be expanded by merging the model into single block and connecting with other similar blocks such that the whole ØØL pilot project is modelled. In addition, the developed model is lacking to consider the following factors,

- Speed profile of rolling stock
- Time table of trains operating
- Precise number of system components in each section
- Availability of maintenance resources and crew
- Train onboard system working properties
- Trains incoming to the starting station

In order to develop a more precise model that counts for the above factors, modelling by TRAIL software could be an ideal choice. In the following section, the TRAIL implementation for the ØØL pilot line is discussed.

5.5 TRAIL Modelling

TRAIL is a performance simulation software developed by DNV GL on FORTRAN language platform. It provides a quantitative approach to measure the systems' ability to perform a desired function. TRAIL stands for Transport Reliability Availability and Infrastructure Logistic simulator, designed explicitly for the lifecycle simulation in transport industry. The principle used by TRAIL is discrete event simulation technology i.e. Monte Carlo simulations, where it can simulate the entire transportation infrastructure systems. As the thesis topic is of same interest, this software has been adopted for modelling ERTMS/ETCS ØØL line and was accomplished with a constant support from DNV GL side.

5.5.1 TRAIL Introduction

TRAIL allows to perform a detailed simulation of transport network by identifying the areas of poor performance and suggests measures for improvement. The Monte Carlo principle used involves repeated sampling of failure and repair times from selected probability distribution. When Monte Carlo discrete events are performed to a model using TRAIL software, the implementation results in creating a virtual system in the software where same statistical failure patterns are followed similar to component operating in real-time (Pistolas, 2016). In addition, it considers the maintenance strategies and crew availability to repair the upcoming component failures, and thus makes the model more precise. RAM analysis using TRIAL provides some predictive insights and issues that may arise in operational phase of a project.

As the main objective of TRAIL is to evaluate the operational performance of a railway line, some of the key elements that affects the operations are given as inputs to TRAIL. Figure 5.9 shows the main scope of the TRAIL inputs, where the infrastructure assets acts a foundation to the model. The asset register defined in TRAIL includes the physical systems like signals, axle counters, balises, points, interlocking, RBC and GSM-R. These are mostly set in series for different sections and stations. Whenever any of these components in asset register fail, there is an impact on the service performance and this is based on the specified failures modes, reliability data of the components and their dependency as defined in the fault trees. As TRAIL avails to assign each asset with respective failure mode, it shows that the complexity of the system is broken down to perform an in depth analysis. Then the time table, rolling stock and maintenance resources are defined in the TRAIL, such that the model can simulate the train operations in more practical manner.

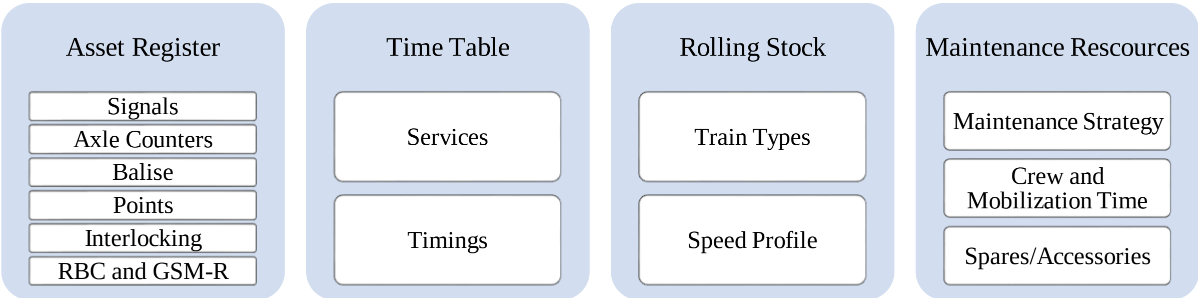

Figure 5.9 Main scope of input to TRAIL

Once the model is established, it is stimulated and results obtained are in the form of lateness analysis, delay analysis, infrastructure and operational performance. The overall process of TRAIL simulation is represented in the Figure 5.12. The sensitivity can be managed by changing the imported parameters and system structure, such that the expectations are met on simulating the system. From this the performance evaluation becomes more precise and easy to compare different designs or operating scenarios, in which uncertainty is also taken into account. This indicates that TRAIL is flexible to use for any kind of system and various type of trains operations like regional rail, metro rail, mono rail, tram service etc. Some of the lines where TRAIL has been utilized are West Coast Main Line, East Coast Main Line and Crossrail in the UK, London Underground Metropolitan and also by Perth-Midland metro line in Australia for the analysis of points' reliability and maintainability.

5.5.2 Modelling Assumptions

The ØØL pilot line is chosen as a case study for reliability modelling of ERTMS/ETCS and its system performance is analyzed using TRAIL. Similar to Relysim, TRAIL is also not publicly available and there is no trial version. However, a reliability model using TRAIL was developed in cooperation with a DNV GL member in London. The plan was to develop a more practical model but handling its complexity was quite difficult. Therefore, to develop a model that is more realistic, the following assumptions were made:

- The modelling is done in the Up direction as Mysen - Ski and Down direction as Ski - Mysen, and the rest of the ØØL pilot project line is ignored.
- Systems present in ØØL pilot line are distributed as per Bane NOR layouts.
- In the layouts, some stations had many tracks, but is assumed to have only two tracks at station in order to simplify the model.
- Points are assumed to be the part station and not a BiDi section.
- FTA is done for both BiDi and stations and is valid for all BiDi's and stations.
- Non-ERTMS failures obtained from usage based model are applicable for time based model.
- The total number of balises or axle counters in the BiDi or station are taken as the average number of systems present in all the BiDi sections and stations, as presented in Appendix B.
- RBC, GSM-R, Track fracture and maintenance activities are spread all over the ØØL system.
- In the usage based analysis, all the delays registered by Bane NOR for the year 2016, are caused due to ERTMS infrastructure or onboard system failures.
- The onboard system is assumed to be same for all the trains operating in the ØØL pilot line and their failures are valid for both usage based and time base analysis.

5.5.3 System FTA

An important feature present in TRAIL is that it can relate the failure of one or more components leading to the system failure by using conditional elements and logic gates. The fault tree analysis is the most suitable method that enables to define the failure modes of various components and link using the logic gates. How to develop an FTA is explained briefly in section 5.2.2 and implemented here for BiDi and Station section to give as a qualitative input to TRAIL.

As the thesis deals with availability of trains, the top event for both station and BiDi section is defined as train being blocked in either station area or BiDi section. To realize the occurrence of this top event, the ERTMS/ETCS infrastructure component failures are defined as conditional and basic events. All the infrastructure elements are mostly aligned in a series of systems and realizing their relation is quite challenging. Since there are many balises and axle counters along the tracks, Bane NOR's operational regulations are taken as reference here. Bane NOR has a guideline that if a train loses its contact with the RBC, it can move until the end of the Movement Authority or for a given amount of time 90 seconds, whichever happens first. It is estimated from the layouts that the balises are placed at a distance of 1 km on average between each balise and for a train running at average of 50 km/h takes 80 seconds to reach next balise. Therefore, it is assumed that if two consecutive balises fail then the train has to stop until a signal is received to proceed further. A similar approach has been adopted in case of axle counters, where two consecutive axle counters need to function for continuous operation.

Station FTA:

If any of the events like repair or damage in the track, maintenance, signaling system fail and point fail occur, the train is restricted to leave the station or platform until the fault is cleared. This results in the occurrence of top event which is train blocked at a station and the fault tree is shown in Figure 5.10.

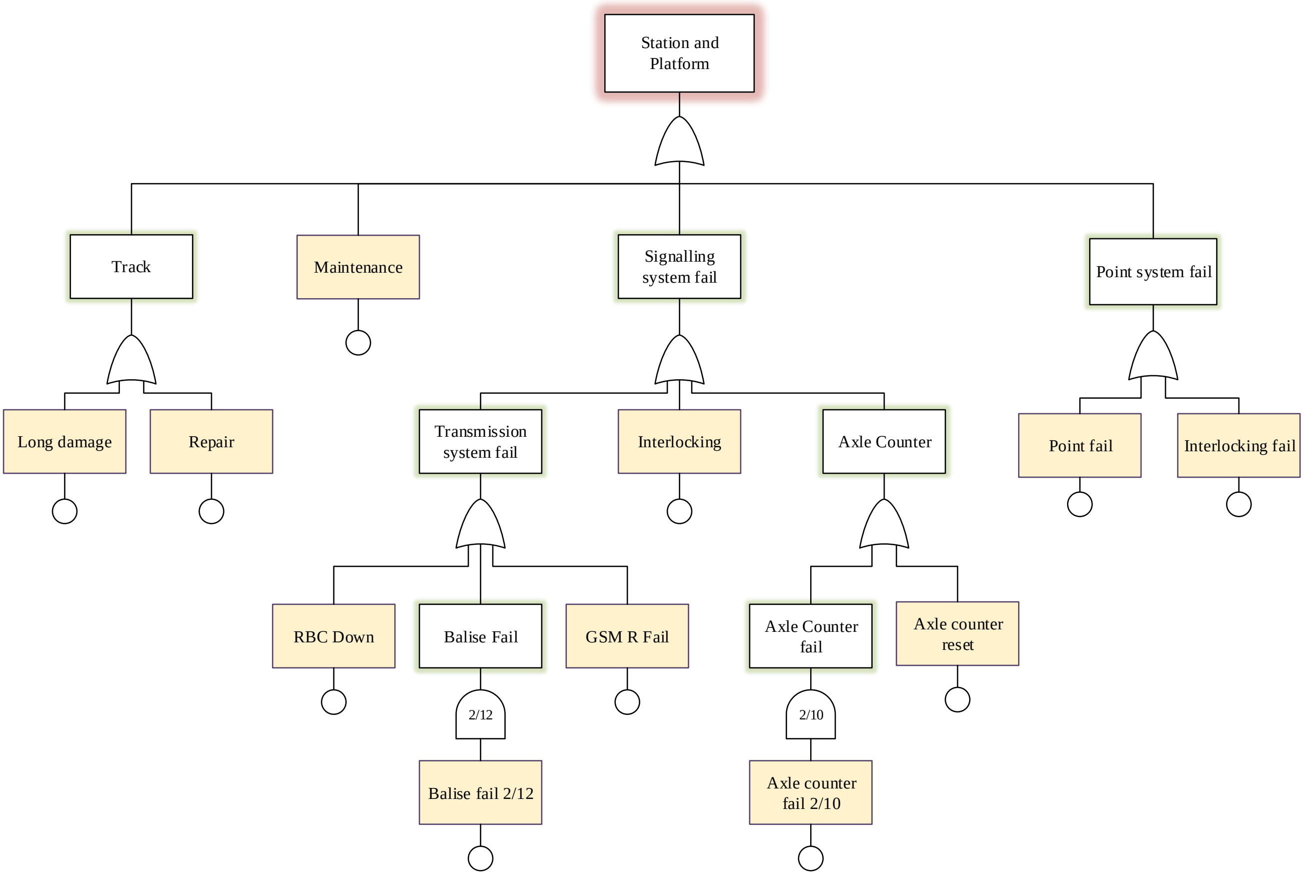

Figure 5.10 Fault Tree for train being blocked at a station

The conditional event of signaling system or point system failure can happen if any of the following basic events occur,

- Transmission system fails to transmit the data due to RBC down or GSM-R network fail or if any two consecutive balises fail in recognizing the train position and speed.
- Interlocking processors are down.

- Any of the two consecutive axle counters fail or requires a reset.
- Point system fail due to faulty switching or interlocking failure.

BiDi Section FTA:

A BiDi section FTA is shown in below Figure 5.11, the top event 'BiDi Block due to ERTMS failures' is mainly caused because of track failures, maintenance or signal system failures. The occurrence of the conditional event signaling system failure is similar to station FTA, and BiDi has no point failure. In the BiDi FTA, the number of balises and axle counters are varied as per the section layouts.

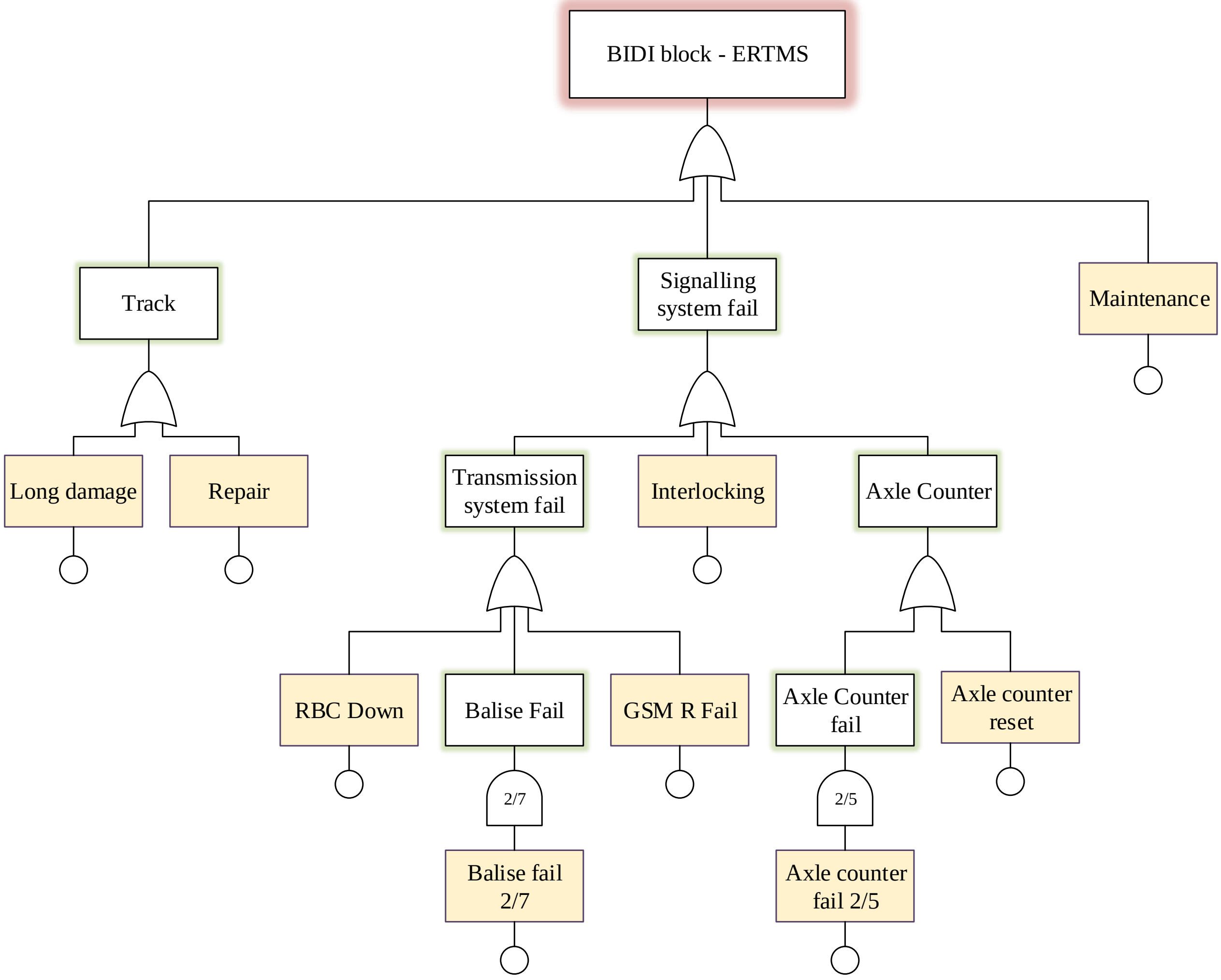

Figure 5.11 Fault Tree for train being blocked in a BiDi section

The FTA for station and BiDi section developed here are associated to infrastructure assets segment in the TRAIL. Later in the section 5.5.4.2, how the BiDi FTA is realized is discussed and is shown in Figure 5.19.

5.5.4 TRAIL Application

The ERTMS/ETCS operated ØØL pilot line is modelled in this section using TRAIL software, in which the failure modes discussed in FMEA and system fault trees are combined for model development. This model is then finally set to perform the Monte Carlo simulations for the reliability, availability and punctuality assessment. As TRAIL has included different methods like FMEA, FTA and simulation process, the method adopted can be regarded as a multi formalism modelling approach.

A general overview of TRAIL implementation process is shown in Figure 5.12. As denoted in the process, all the essentials in input segment were given to TRAIL. The rolling stock was compensated with the speed profile and onboard failures for various sections, and the timetable provided by the Bane NOR is presented in graphical form (Grafisk rute ØØL vår 2017) in Appendix C. In addition, the infrastructure system referred for TRAIL as input is discussed in section 5.1. To analyze the ERTM/ETCS system and developed model, two types of analyses are done using TRAIL and they are

- Usage based analysis
- Time based analysis

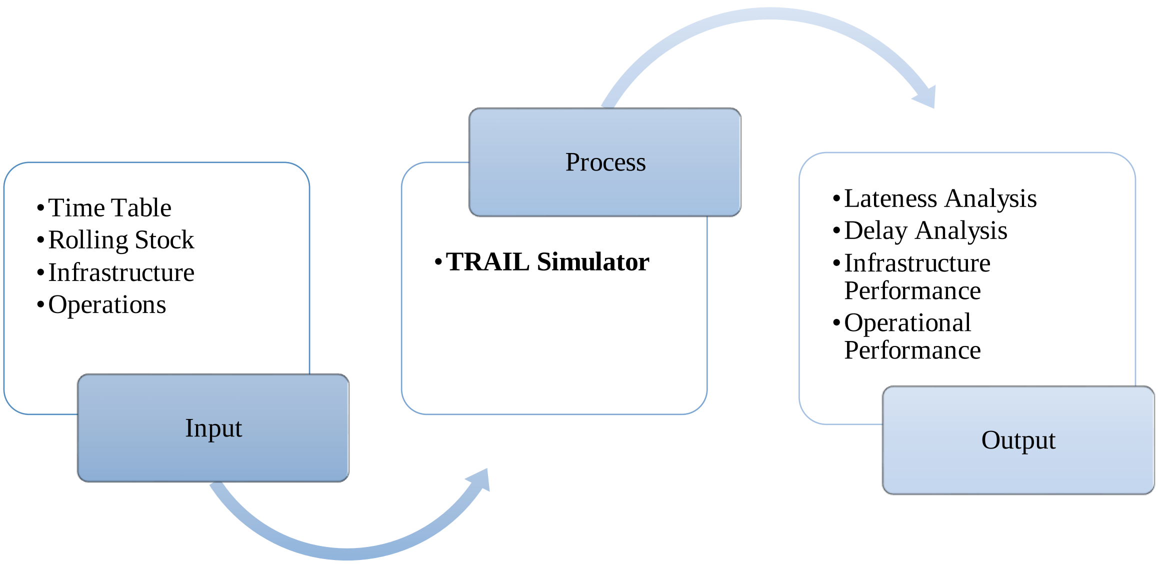

Figure 5.12 Overview of TRAIL implementation process

5.5.4.1 Usage Based Analysis:

To assess the performance of the ØØL based on historical data, a usage based analysis approach is chosen. The main motive for performing a usage based analysis is that it supports to validate the developed model and its corresponding time based analysis. As the TRAIL has the flexibility to change its system parameters to meet the requirements, the usage based analysis can help to setup some benchmarks and justify the obtained results for modelling.

A hierarchy of the ØØL pilot line systems defined in TRAIL is shown in Figure 5.13, representing the stations, assets, routes and journeys at higher level. The assets are classified into sections Mysen - Slitu, Slitu - Askim, Askim - Spydeberg and so on, and further each section is categorized into various systems. As an example, the Slitu - Mysen section is categorized as follows,

- A particular BiDi section, which is further divided as ERTMS and non - ERTMS failures.
- Signal Slitu - Mysen and Mysen - Slitu.
- Platform at Mysen station towards Slitu (downwards).
- Platform at Mysen station for trains incoming from Slitu (upwards).

In the similar way, all the sections in ØØL are categorized in the assets segment. To the hierarchy the routes and journey times of all the trains are assigned according to the time table in Appendix C. The hierarchy of usage based model in TRAIL software is presented in Appendix D.

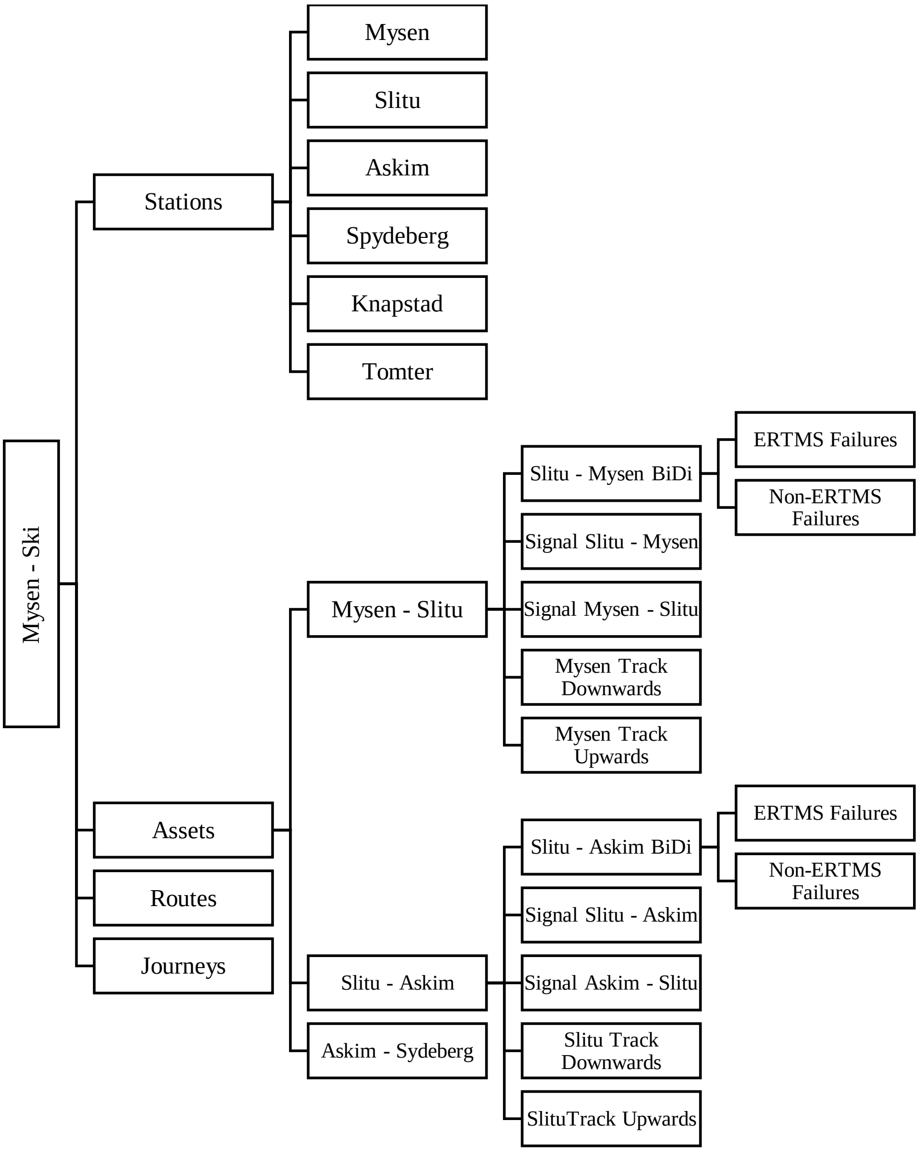

Figure 5.13 Hierarchy of the ØØL pilot line systems defined in TRAIL for usage based analysis

Bane NOR has recorded the delays encountered during the year 2016 and this historical data was used as input to TRAIL For the usage based analysis, by. The received data had many delays that were deemed as knock on effects due to primary delays and other unwanted information. These were later filtered and only the initial system failures that constituted for primary delays were considered. The reason for taking primary failures only is that the TRAIL is capable to assess the consequences (i.e. knock on effects) of initial failures by simulation process. Therefore, any knock-on delays that were recorded in the historical data were omitted. The delay log obtained from Bane NOR was studied and classified into ERTMS and non-ERTMS categories. These delays were further divided into various types of ERTMS infrastructure failures that caused the delays. Similarly, from the 2016 delay log of ØØL pilot line, the delays due to the onboard system failures are also considered for analysis.

The data obtained on delays from Bane NOR was distributed randomly and uniformly for all the stations and BiDi sections in TRAIL. Onboard failures are imported to the TRAIL model in a time based mode. Failures are associated to the rolling stock so that the failure events appear to occur evenly throughout the network as services (and associated rolling stock) progress. The effect of these failures and impact on services is basically governed by the service propagation and network structure. Each failure has a reliability on demand figure and repair distribution associated to it. The majority of the analysis in this section is done for BiDi sections because the failure or delay data at the stations and platforms is lacking.

Delay Analysis:

After allocating the data to the TRAIL model, Monte Carlo simulations are performed for 100 annual simulations to identify which systems and sections of ØØL pilot line are affecting the performance of ERTMS/ETCS operated line. The reason for performing 100 annual simulations is that the mean delays obtained due to failures is constant after 55 runs to 100 runs and is shown in Appendix E.

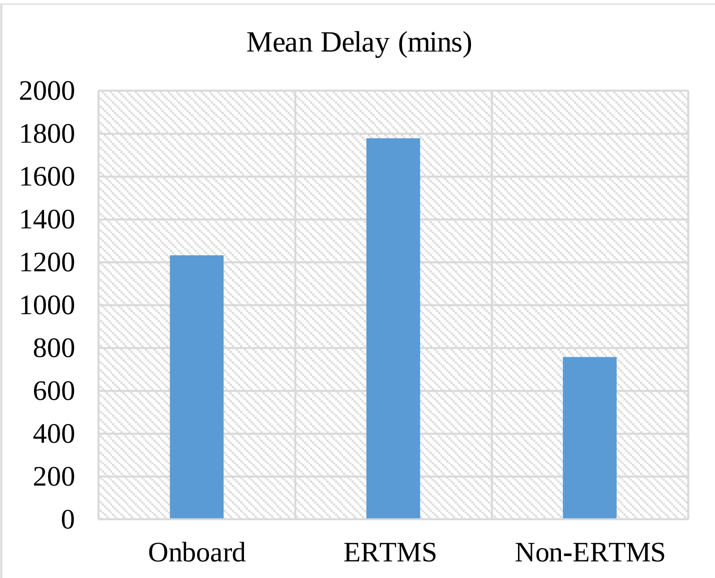

Figure 5.14 Mean delays caused due to various system failures

Due to the limitations in using TRAIL and time constraints, the usage based analysis is done with the onboard, ERTMS and non-ERTMS systems only. On executing the TRAIL simulation for the model developed, it was found that the ERTMS and onboard system failures have contributed to the highest amount of delays compared to non-ERTMS failures. The graphical representation of this analysis is shown in Figure 5.14 and the simulated data is presented in Appendix D.

The probability distribution of the usage based repair of ERTMS failures obtained from the simulation process is shown in below Figure 5.15. It is evident from the analysis that almost 80% of the repairs can be done within half an hour (< 30 minutes) and 100% of all ERTMS repairs in 2 hours.

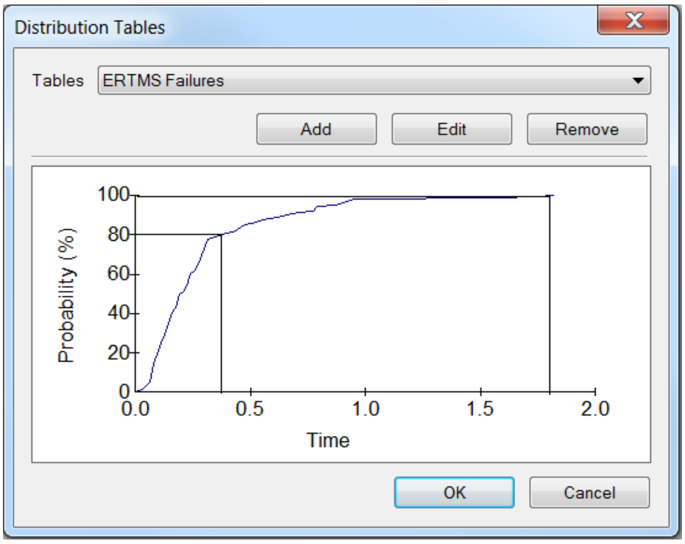

Figure 5.15 Usage based repair distribution for ERTMS failures

Section Reliability Performance:

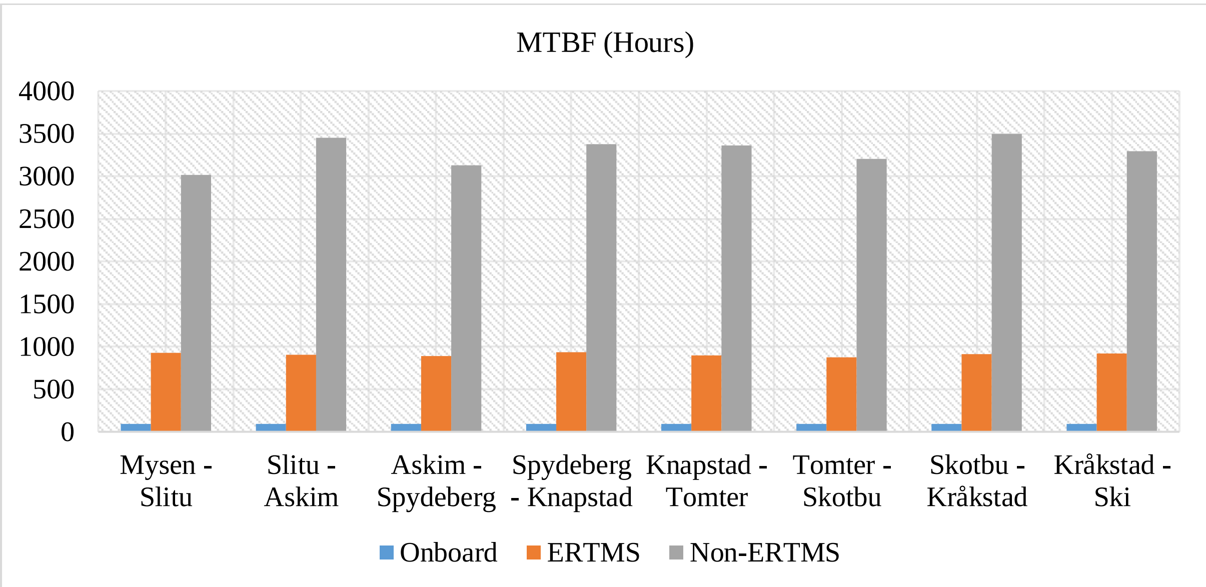

Figure 5.16 Section criticality in various sections of ØØL

In order to identify the effect of these elements in various sections of the ØØL pilot line, an estimation of the element criticality is attained from TRAIL simulation using the reliability parameter MTBF as reference for assessment. As the onboard system is assumed to be same for all the trains operating in ØØL, it has a constant MTBF of 93.67 hours for all the sections. Also the MTBF for ERTMS elements looks almost linear with an average of 900 hours and is higher than the onboard system, this is because the failures are distributed uniformly for all sections. Whereas the non-ERTMS failures are found to have the highest MTBF values compared to onboard and ERTMS systems of the entire ØØL line. The above plot in Figure 5.16, represents the MTBF of various elements and sections of ØØL.

Section Operational Performance:

Operational performance in the BiDi section is shown in the below Figure 5.17, with total accumulated delays for each section. The section Askim to Spydeberg has the highest delay with 360 minutes compared to all individual sections. When the crossing stations Skotbu, Knapstad and Slitu were ignored then the critical sections would change relatively. The most critical section would be Spydeberg to Tomter with a total accumulated delays of 652 minutes, followed by Mysen to Askim and Tomoter to Kråkstad with the delay time as 597 minutes and 592 minutes respectively.

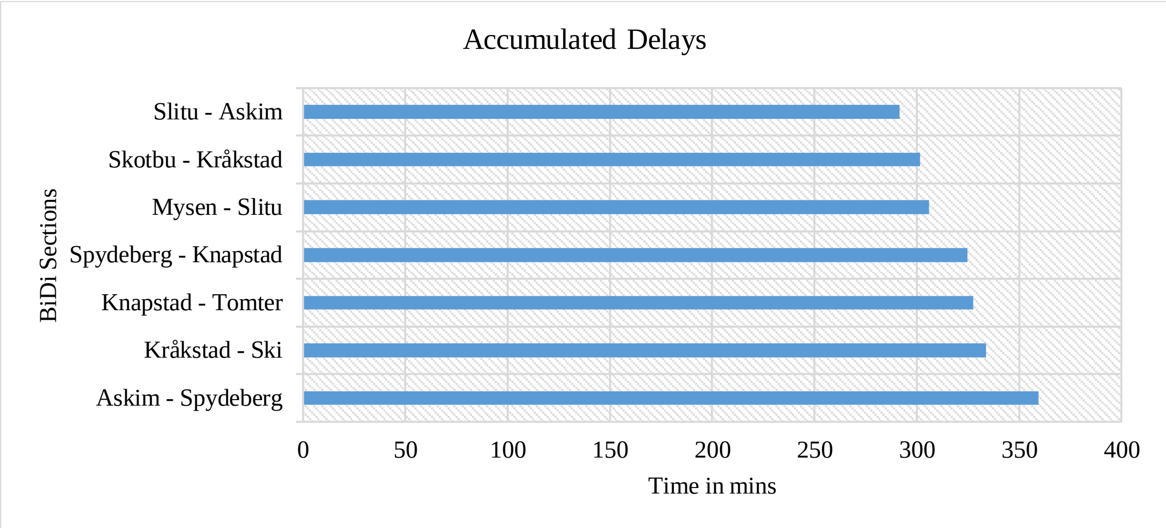

Figure 5.17 Usage based model accumulated delays of all BiDi sections

5.5.4.2 Time Based Analysis:

This section is the central part of the thesis, in which a time based analysis is performed for the ERTMS pilot line model in TRAIL. The previous models developed in Relysim and usage based analysis are lacking to include many constraints that affects the real time operation of ERTMS/ETCS lines. In order to evaluate the ERTMS systems thoroughly, time based analysis has been adopted because it has the potential to evaluate the ERTMS system in a deeper sense. The analysis is supported by taking into account of ERTMS, non-ERTMS and onboard system failures for all the BiDi sections and stations along the ØØL pilot line.

A hierarchy of systems like stations, assets, routes and journeys are given as inputs to TRAIL as in the below Figure 5.18. The representation of the hierarchy in TRAIL software is shown in the Appendix E for the time based model. System non-ERTMS failures in time based analysis is taken from the usage based analysis, because Bane NOR has no reliability parameter set for non-ERTMS failures.

In the hierarchy, the stations are divided into up and down platforms and these are then assigned with the numbers of components present at each station recovered from the layouts as in Appendix B. Similarly BiDi's also follow the same procedure and they are defined in the assets segment. Further to each and every station and BiDi section's system components failure modes are allocated, according to the failures identified for the components in FMEA along with reliability parameters from RAM analysis discussed in section 5.2.

The ERTMS system failures covered in the analysis here regards to points, axle counters, interlocking, balise, GSM-R, RBC and track fractures. The interdependency of these failures for both station and BiDi section in TRAIL are realized from the fault trees developed in section 5.5.3. BiDi section from Slitu - Mysen is taken as an example and the way BiDi fault tree is realized in TRAIL is shown inFigure 5.19. Some interpretations of the realized FTA in TRAIL are

- All the elements in the fault tree are connected in the form of RBD and further each block has internal basic events defined.
- The effect of non-ERTMS failures from usage based analysis is applied here.
- Controller conditional elements control the entire network and if any of these fail the system, the trains experience delays. These elements are GSM-R, RBC and Maintenance
- The conditional element Slitu - Mysen BiDi block fails, then the train has to stop until the repair is carried. This is shown in Figure 5.19 as Delay@F (failure) and Stop@R (repair).
- Similarly, other conditional elements specified in fault tree based RBD are axle counter fail, balise down, transmission fail, signaling system fail and track off.
- Primary failures of the ERTMS components which are the basic events of fault trees are allotted here as equipment failure in the final level.
- All the basic events are assigned with the MTTF and MTTR in hours.

Above mentioned factors such as conditional elements and controllers are linked in TRAIL by using the function trigger set properties which is presented in Appendix E Figure E.1. These represent the logic gates in a conventional fault tree. On assigning all the system components, failures and their reliability parameters, timetable and dependency using fault trees, the model is ready to undertake the Monte Carlo simulations. Since the aim of the thesis is to determine the reliability of ERTMS/ETCS system for one year, the simulation was carried out for 52 weeks and 100 runs (100 annual simulations).

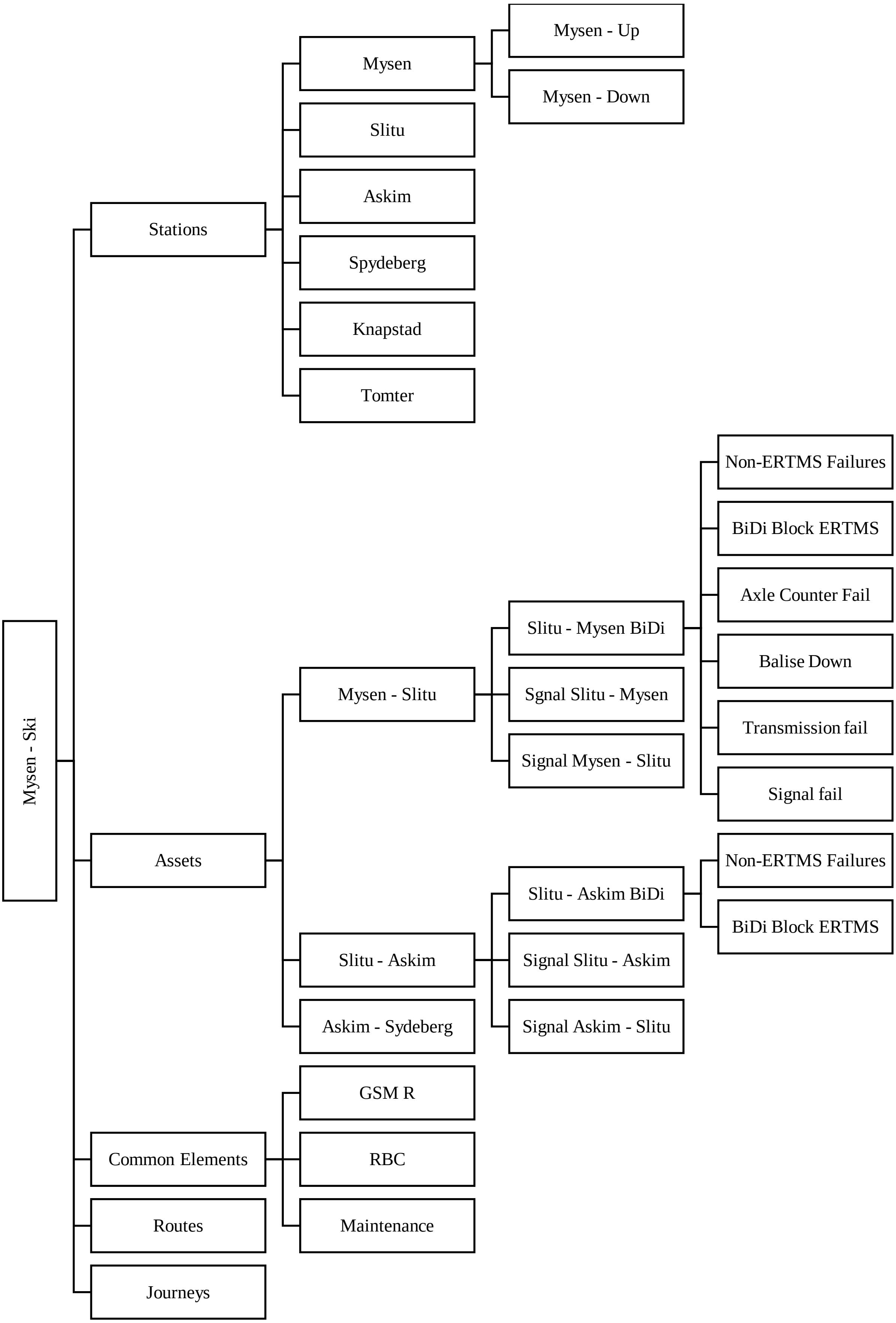

Figure 5.18 Hierarchy of the systems defined in TRAIL for time based analysis

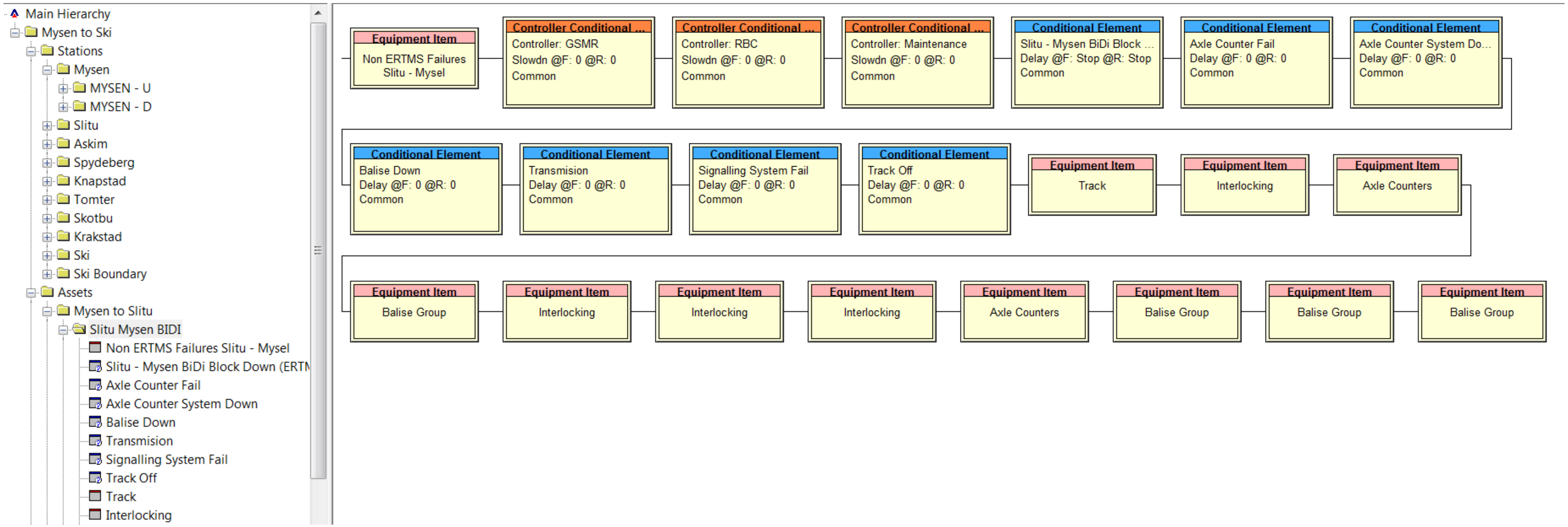

Figure 5.19 Realization of developed BiDi Fault Tree in TRAIL

Delay Analysis:

A delay analysis is plotted in following Figure 5.20, which describes the failures that led to the delays in BiDi sections. The simulation process has revealed that non-ERTMS failures contribute very less when compared to ERTMS and onboard system failures. From the plot, it is evident that Askim to Spydeberg has the highest amount of delays of all BiDi sections, even though there are few ERTMS components. A possible reason for this could be that at Askim there are many ERTMS components and their failures could in turn effect the operations at succeeding section.

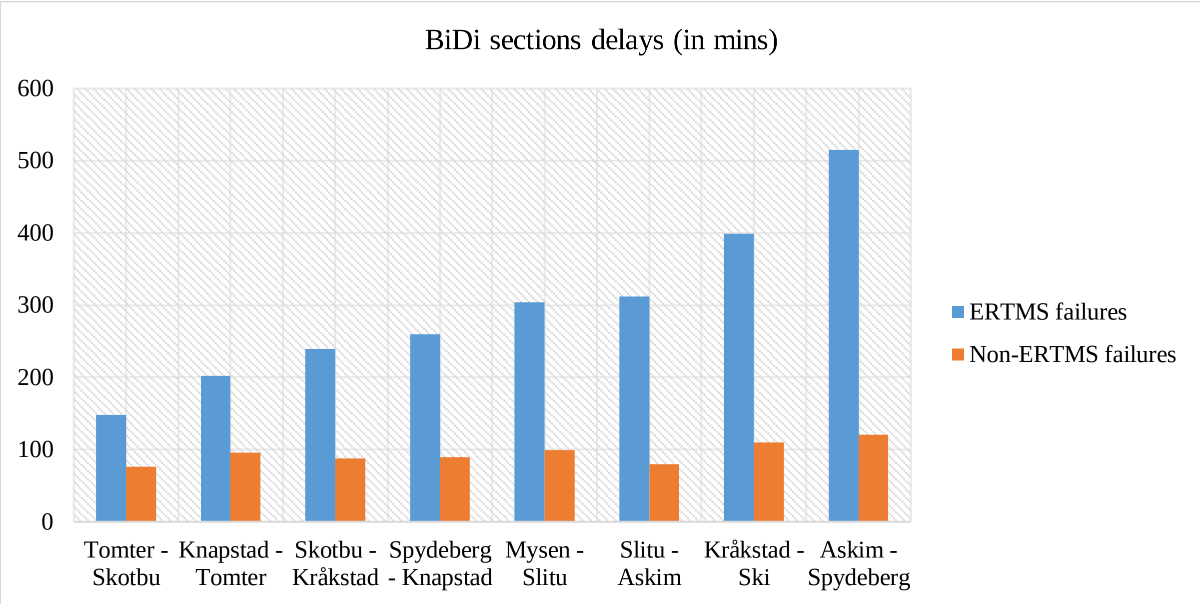

Figure 5.20. Delays in BiDi section due to ERTMS and non-ERTMS failures

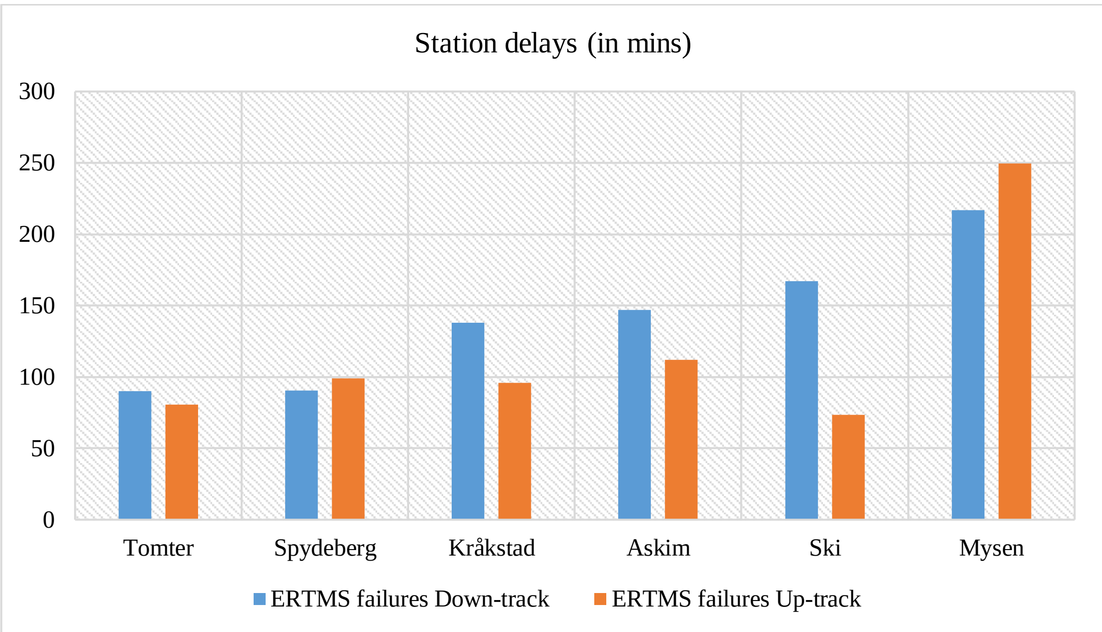

Figure 5.21 Delays at stations for Up and Down tracks due to ERTMS failures

The stations usually consist of many platforms and for the analysis they are just classified into Down and Up tracks. These tracks at all the stations in ØØL are allocated with ERTMS system as per the layouts and deduced number of systems presented in the Appendix B. On simulating the developed model in TRAIL, a delay analysis is performed for station in ØØL for both Down and Up platforms as illustrated in Figure 5.21. Of all the stations, Mysen, Ski and Askim stations' Up and Down tracks are experiencing highest amount of delays due to ERTMS failures compared to other stations. The delays at Kråkstad and Ski stations are also relatively high than Spydeberg and Tomter.

Section Reliability Performance:

In order to analyze the reliability based on the type of failures and their frequency that caused delays in BiDi section, a graph is plotted in the following Figure 5.22, based on the simulation results. The onboard and non-ERTMS failures were imported from usage based analysis, while the ERTMS failures were obtained from developed model simulation. Hence the onboard and non-ERTMS failures followed a similar trend as usage based. The ERTMS MTBF is changing due to the assets that were distributed in various BiDi locations. MTBF obtained here counts in the exponentially distributed MTTF and MTTR of all ERTMS infrastructure elements, timetable and journey routes.

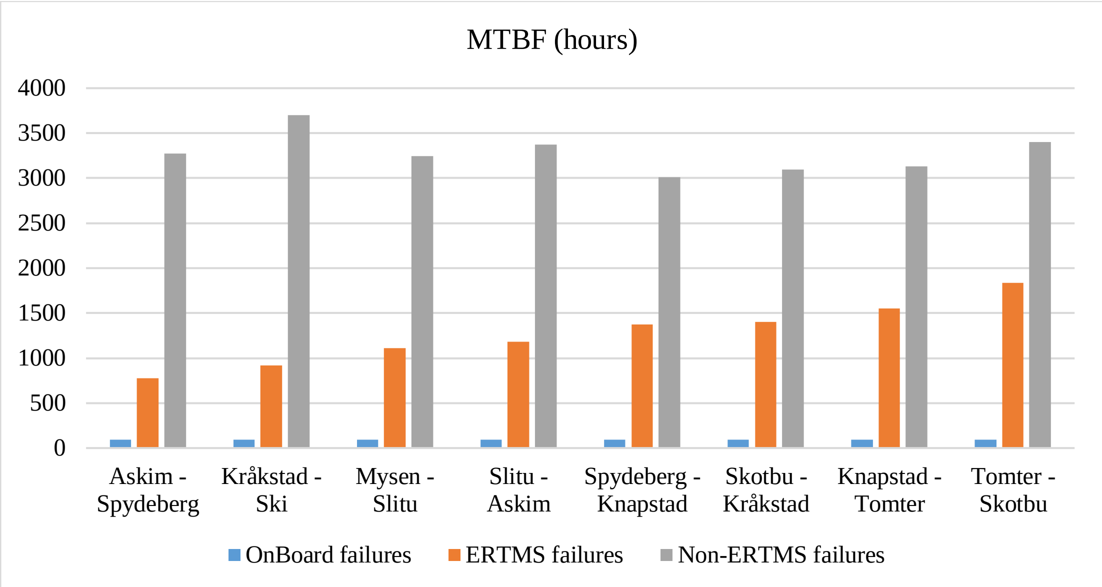

Figure 5.22 Failures criticality in BiDi sections

Infrastructure Performance:

Infrastructure performance in TRAIL is a key feature to analyze the systems operation in the long run. The entire ØØL pilot line ERTMS infrastructure performance obtained from 100 annual simulations in TRAIL is illustrated in the below Figure 5.23, the failure modes of ERTMS infrastructure system that occur with high frequency are found to be balise groups, followed by axle counters and interlocking. Failures due to points and track are occurring rarely and it can be observed that GSM-R, RBC and

Maintenance failures are almost negligible. As the balises and axle counters are widespread over the entire ØØL project, there is a high possibility of having more failures in the long run. These systems are placed openly and can be influenced by harsh weather conditions.

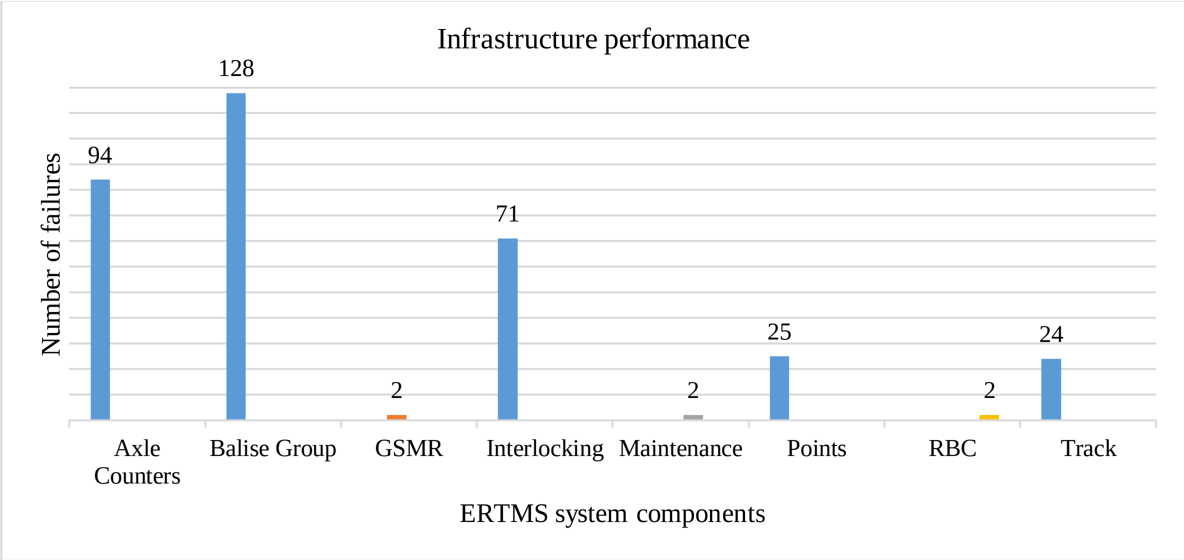

Figure 5.23 ERTMS Infrastructure system performance in ØØL pilot line for 100 annual simulations

Operational Performance:

The onboard system operational performance is also assessed on the basis of the usage based analysis. Though Bane NOR is not responsible for onboard systems, they are interested to assess its effects its operational performance. Delays due to onboard system failures were 91 events in total and the MTTF is found to be 0.01(0.01 years, i.e. one failure per roughly less than 4 days) using usage based analysis, which is relatively very high. This value was obtained from the 2016 historical data. A probability density function (pdf) of the onboard systems failure is shown in Figure 5.24, and it was done by the TRAIL simulation process.

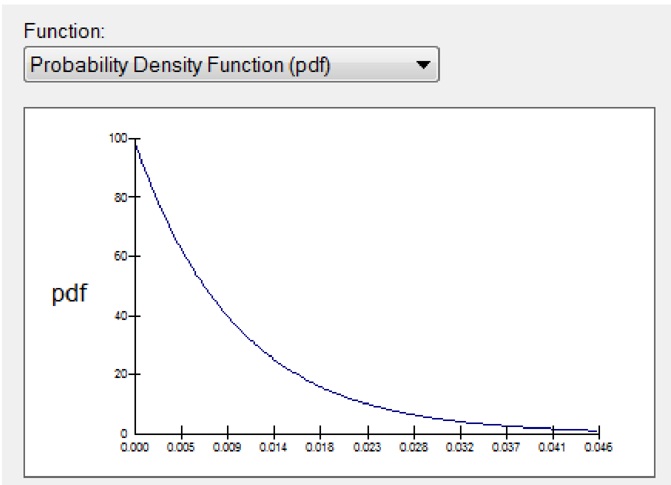

Figure 5.24 Probability density function (pdf) of onoard ssytem failures

In both the pdf and the repair distribution functions, the probability percentage is represented on vertical axis and corresponding time on horizontal axis. On performing the simulation, the probability of repair is determined for the onboard system failure as shown in Figure 5.25. It is approximately estimated from the repair distribution that the onboard system failures can be repaired upto 80% in 0.28 hours and 100% in 0.68 hours. The estimation might be quite deterministic because the failure referred here is in general onboard system failures retrieved from the 2016 failure data. However, there are several factors that cause onboard failures starting from an onboard card failures to human errors.

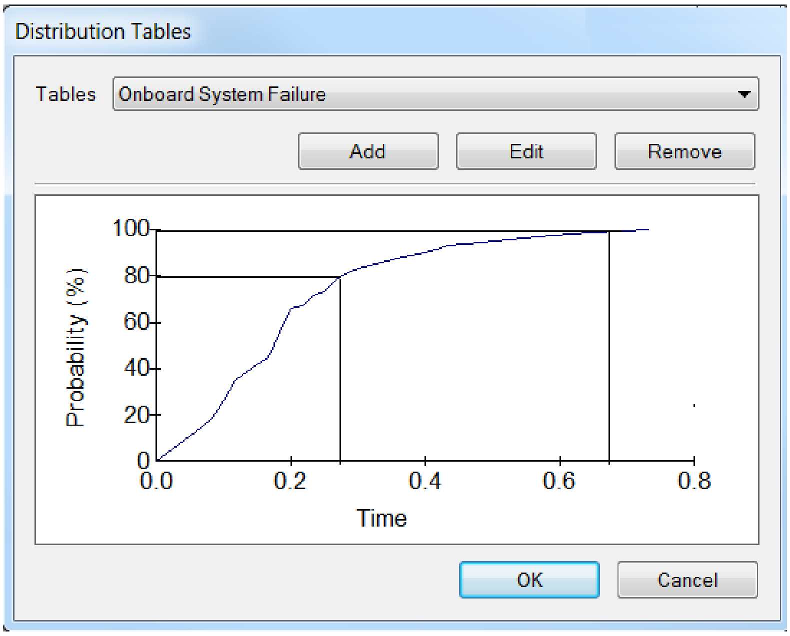

Figure 5.25 Repair strategy of onboard system failures

Section Operational Performance:

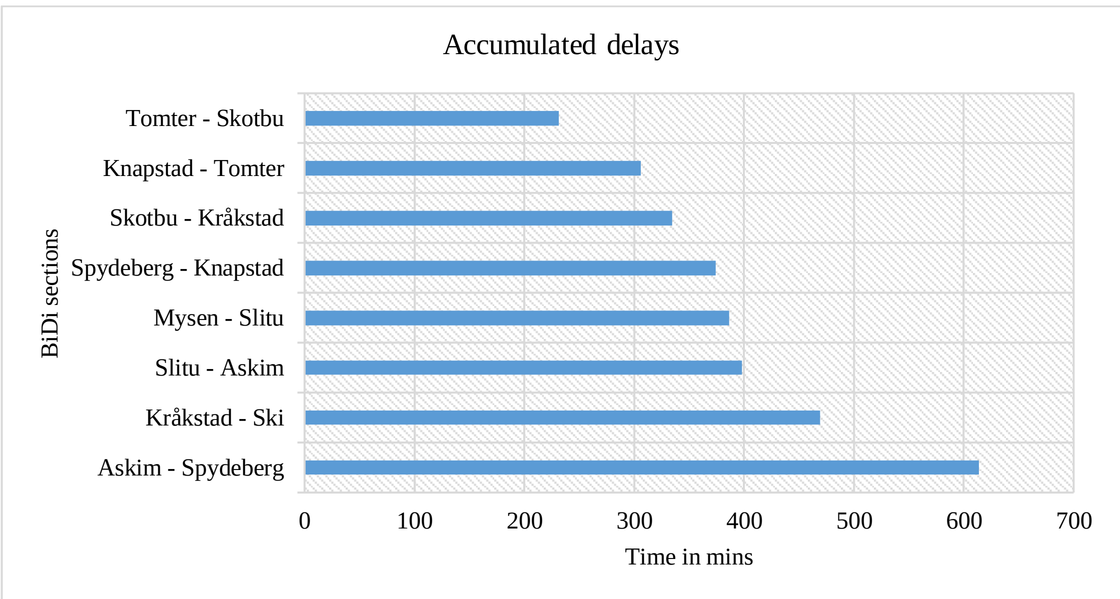

Figure 5.26 Time based model accumulated delays in BiDi sections

For different BiDi sections in the ØØL, accumulated delays from TRAIL simulation is presented in the above Figure 5.26, where the simulations were carried according to the set time table and speed profile. The BiDi section that generates the highest amount of delays is Askim to Spydeberg, followed by Kråkstad to Ski. All other sections are significantly contributing a similar amount of delays with wide variations when compared to the usage based analysis. A detailed discussion is made in Chapter 6 on the results obtained from simulations of all the models.

Services Availability Analysis:

The availability of trains at the stations is a key indicator of punctuality, and the availability assessment needs to consider several operational constraints like timings, previous train delays, maintenance, passenger errors, failures, weather conditions etc. TRAIL simulation performed here for the developed model has the ability to include all the above constraints. As discussed earlier in section 3.2, Bane NOR has set some project reliability requirements and in which availability of 99% is required for the trains to arrive at stations (not more than four minutes after the scheduled arrival).

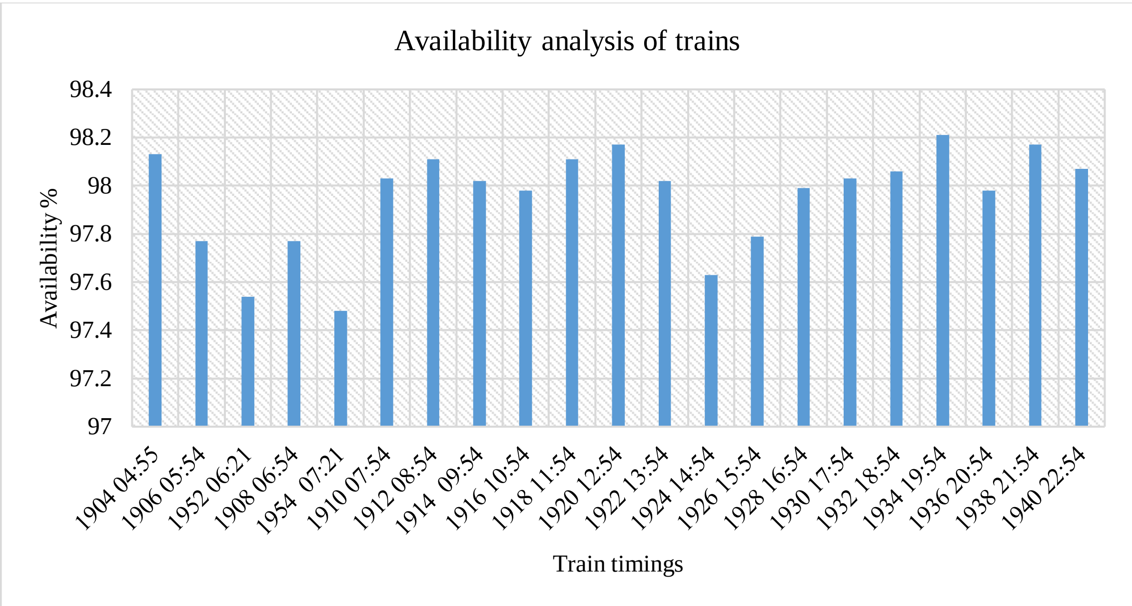

Figure 5.27 Train services analysis operating in Up direction from Mysen to Ski in ØØL

The availability of the all the trains at stations operated at different times in up direction from to Mysen to Ski is shown in Figure 5.27, and the average availability of trains at station is found to be 97.95 % which is almost 98 %. It can be seen noticed from the plot that the availability of the trains is reducing gradually from office starting hours like 07:54 am and shortage of availability at 14:54 hours which is general office closing hours. This indicates that during the peak hours the punctuality is affected severely due to heavy traffic in all the lines. From the analysis performed in this section, the results show that the time based analysis for the model developed are well inclined to the expected requirements theoretically.

Chapter 6

Discussion

The reliability modelling of the chosen ØØL pilot project was realized by using two software programs namely Relysism and TRAIL to evaluate the performance of ERTMS infrastructure components and their effect on the operating services. Both the program methods opted for modelling the ERTMS significantly follow the multi formalism modelling, in which methods like RBD, FMEA and FTA are adopted for relating component failures and their dependency. Along with the inputs from these methods, Monte Carlo simulations were carried out using programs to match with real-time operations. From the Bane NOR RAM analysis, it was observed that the reliability parameters like MTTF, MTTR and MTBF derived by them does not meet the RAM requirements specified by ERTMS user's group, this indicates that eventually the operating systems under these conditions might experience some immobilizing failures.

6.1 Interpretations

A model was developed using Relysim for a station and BiDi section assuming all station and BiDi's to be similar, and their ERTMS/ETCS infrastructure elements were distributed according to the layouts provided by Bane NOR. On performing discrete event simulations to the model in Relysim, it was deduced that interlocking failures, track failures and maintenance activities were causing the delays. Though there are many axle counters and balises having relatively high MTTF, their MTBF was found to be greater than interlocking and track failures. This show that the model has the capacity to evaluate the overall performance, and it requires precise information and improvement to the model developed. However, it is recognized that model is quite uncertain due to the fact that it does not count in many constraints like timetable, speeds, rolling stock, various stations etc. So to perform a reliability and analyses using Relysim, a thorough knowledge in usage of Relysim is required. In addition, timetable to the model is not fed and thus punctuality cannot be assessed here.

One of the main reason for using the TRAIL for modelling of ØØL pilot project is that it has the ability to include various factors that affect the railway operations such as infrastructure assets, maintenance, operations and timetable, which makes the model very precise. In the TRAIL, two models were implemented for the reliability, availability and punctuality assessment of ØØL pilot project by considering all the mentioned constraints. Initially a usage based analysis was done using the failure log obtained from Bane NOR, where these failures were distributed to different sections and 100 annual simulation were performed to assess the performance.

Some of the significant interpretations from TRAIL usage based analysis are,

- Though the number of ERTMS and non-ERTMS infrastructure failures are same as onboard failures, the simulations resulted that ERTMS failures are critical in instigating more delays.
- Due to the even distribution of all types of failures in different sections, the criticality of BiDi sections is ambiguous. However, the MTBF of onboard system and ERTMS are very low.
- From section operational performance, it was found that Askim - Spydeberg has the highest amount of delays followed by Kråkstad - Ski.

In order to have a model purely based on the system definition (ØØL pilot line) and ERTMS/ETCS infrastructure reliability parameters, a time based analysis was performed. This model developed was deterministic in nature because, it was precisely built on the relations between various system components and their corresponding failure events. The data was imported to the model and 100 annual simulations were executed in 40 minutes of time.

On simulating in TRAIL, the model automatically generates the train services according to the timetable and introduces events, failures, repairs and as a result it quantifies the delays and other reliability parameters. As the model is undergoing a dynamic analysis, the time based analysis can be regarded as more accurate. The analysis has revealed that,

- ERTMS failures are contributing to more delays in the sections Askim - Spydeberg followed by Kråkstad - Ski.
- The MTBF of ERTMS is low and continuously varying due to the infrastructure distribution at various BiDi sections. However, the range of values and trend followed is similar to the one obtained in usage based analysis.
- On comparing the BiDi section accumulated delays with delays from the usage based analysis, it was found that the same sections Askim - Spydeberg and Kråkstad - Ski are having the highest accumulated delays of all.
- Infrastructure evaluation shows that the balises, axle counters and interlocking are the key ERTMS components and their failures are causing the most delays.

Sections like Askim - Spydeberg and Kråkstad - Ski were assessed to have the highest number of ERTMS components failure and most delays of all BiDi sections are happening here. However, in reality Bane NOR has discovered that major delays are occurring at Askim, due to the number of crossings present in that region. From the Mysen - Slitu and Slitu - Askim sections if Slitu was removed, then analysis would incline more to the present day problems faced by Bane NOR because the sum of delays of both Mysen - Slitu and Slitu - Askim is greater than delay of all other BiDi sections.

When it comes to stations criticality again Mysen, Askim, Kråkstad and Ski are witnessed to have more delays due to ERTMS failures. Based on these observations, it can be suggested that to increase the availability and reliability of operations in the long run, Bane NOR has to set their maintenance crew readily available at Askim and Kråkstad stations such that they carry out the maintenance and repair process immediately after failure detection.

The ERTMS/ETCS infrastructure analysis in TRAIL also avails to make decision on where to place the components like balises and axle confuters. However, for this type of statistics the input to TRAIL has to be specified precisely for all the defined components and sections.

6.2 Model Validation

From the usage based and time based analysis interpretations mentioned above, the results obtained are reasonably similar for delay analysis, MTBF of the ERTMS systems and BiDi sections' criticality. Moreover, the overall KPI's (key performance indices) generated for both the models are almost equal, and are summarized in below Table 8. The overall availability for time based model is found to be 96.75% and it approximately matches with the estimated average availability of Mysen - Ski services performance which had 97.75%.

A small difference of 1% here is because of the overall availability considered both up and down services in the estimation. The number of delays and total train delays have near values and the reason for tiny variations is due to fact that the stations were not counted in the usage based analysis.

Table 8. Comparison of usage based and time based results

Model type	**Availability**	**Number of Delays**	**Total train delays**
Usage based	96.99 %	2.95 %	1231.1 +/- 162.29 minutes
Time based	96.75 %	3.12 %	1197.4 +/- 161.71 minutes

- The percentage of number of delays obtained from analysis seems to be very low and it is greater than the punctuality requirement of Bane NOR which is 90 %.
- Overall availability is short of 2 % than the required availability of Bane NOR.

Therefore, referring to all simulation results and comparing them with usage based model and reliability requirements defined by Bane NOR, the time based model developed in TRAIL can be validated with an optimistic view. The operational, infrastructure and services performance evaluation done in time based model is more practical and is possible to use these results as base for further decision making by Bane NOR. Further enhancement of the TRAIL model with more detailed subsystems information and breakdown of failures included in the model could evaluate the performance of the system in more detailed method.

6.3 Model Shortcomings

The time based model made in TRAIL is of major concern in the thesis because, it aims to design an arbitrary ØØL section in software and simulates based on the inputs given to it. This makes the model to be referred as a deterministic model. Though the model is well equipped with all major constraints, while some inputs were lacking or that were not taken into count in the model as follows,

- One main aspect of TRAIL is, how precisely the inputs are fed to TRAIL model that accurately the results are obtained as outputs. As there are several assumptions in the TRAIL time based model, some uncertainties might have crept in.
- Trains that are delayed usually have a property to speed up to arrive at the destination on schedule. However, this option is available in TRAIL, it was not included in the TRAIL model at this stage due to time constraints.
- The weather conditions, original delays due to other trains at starting stations is not considered in the analysis. It was presumed that at the origin station a train is always available.
- Although TRAIL has options like allocating maintenance resources, planning and maintenance crew availability, due to lack of data they were not given as inputs and the repair of failures were added as single values or MTTR
- Due to the limited time and limited access to TRAIL, an in-depth analysis was not performed for each of the failure.
- Disturbances and delays caused by passengers and human errors are not taken into analysis. Rather a high-level approach was taken where failures are broken down to ERTMS and non-ERTMS and onboard failures.

At a later stage, these could all be incorporated in the model to make it more detailed and obtain further information from the application.

Chapter 7

Conclusion

In this chapter the work accomplished and the results obtained in the thesis are summarized. Later based on the findings, some recommendations are proposed for further work and research.

7.1 Summary and Conclusions

The reliability assessment of complex dynamic systems is always challenging and similar system focused in this thesis is ERTMS/ETCS railway signaling system. Since the ERTMS/ETCS signaling operations are carried out by simultaneous coordination of several dissimilar and geographically distributed systems, it is regarded as a complex system. The thesis aims to perform reliability modelling of ERTMS/ETCS, in which all the effects of various factors like infrastructure, rolling stock, time table, maintenance resources, passengers etc. are considered to make the modelling dynamic and precise.

As a case study for reliability modelling and assessment of ERTMS/ETCS level 2 system, ØØL pilot line was chosen and studied with the help of Bane NOR. Later, a software called TRAIL developed by DNV GL was used to assess the ØØL pilot line, in which a time based model was developed and validated by comparing with the usage based model. The following conclusion were drawn while achieving the aim of the thesis,

A literature review was performed in section 4.1 to identify the appropriate methods for performing reliability modelling. Many authors have suggested different methods for ERTMS modelling in both conventional and simulation methods. ERTMS/ETCS system is considered to be a complex network and realization of such networks by a single method may not provide accurate evaluation. Therefore, multi formalism modelling approach was selected for modelling in the thesis. The main feature of multi formalism modelling is the capacity that it has to cope with the complexity of the system constraints and helps the users to analyze the performance in a convenient manner. It facilitates to use more simplified methods for different system analyses such as FMEA for failure mode analysis and FTA for failure dependency of various systems.

The multi formalism method is adopted for modelling because the use of traditional methods only such as RBD, FTA and FMEA for performance analysis is best suited for static system calculations rather than dynamic systems. If these conventional methods were used in railways, then they fail to provide the accurate analysis due to the continuous and large variations in operational strategies. As the thesis had adopted multi formalism modelling, FMEA, FTA and RBD were used as input source to the Monte Carlo simulations in which these traditional methods introduce the failures and their component dependency. The Monte Carlo discrete event simulations implemented using RelySim and TRAIL will virtually create real-time railway operations and all the components follow their statistical pattern of failure. Therefore, using software simulation process will consider the dynamics in operations and supports to perform realistic analysis.

As all the ERTMS railway projects are executed according to the CENELEC standard EN 50126, performing RAMS analysis is mandatory and reliability modelling could help to define the reliability requirements to various system components. For the ØØL pilot line, Bane NOR has defined MTTF's for various infrastructure systems and these are quite low compared to the ERTMS users' group requirements mentioned in section 5.2.2, which indicates that there are some chances that they will run into immobilizing service failures during operations in ØØL.

Relysim model developed in section 5.4.3, has the capacity to assess the system infrastructure performance by discrete event simulation process and determine the availability of various systems. It was found from Relysim simulation that partial interlocking fail, maintenance and track fracture will occur often and contribute to delays. However, Relysim analysis done in the thesis does not include the timetable and maintenance resources because of the inadequate information on usage of Relsyim. Thus, the model has some chances for uncertainty.

Unlike Relysim, TRAIL has all the features to develop a precise model and analyze the systems' performance. As discussed in section 5.5.4, TRAIL counts in the timetable, assets, routes, infrastructure and journeys, which on assigning will make the model self-reliant and on simulation it will result in close results as such to reality. The main attribute of TRAIL is its preciseness in outcomes, and this is mainly dependent on how well the model is established in TRAIL. Some of the outcomes of TRAIL simulation are infrastructure performances, unplanned delay timings, maintenance resources etc. In the thesis, a usage based and time based model were developed for the ØØL pilot line as a case study, where many assumptions were taken to build the models. Simulations and outcomes analyses was performed to these models, and it was found that the results of time based model are in line with usage based model and accordingly the time based model was validated with some approximations.

By simulating the ØØL time based model in TRAIL for 100 annual simulations, it was found that the stations and sections between Mysen, Askim, Spydeberg and Ski were having more delays due to ERTMS failures and having maintenance crew available at these stations could be possible measure to reduce the delays. The infrastructure performance analysis revealed that axle counters, balises and interlocking were more prone to fail frequently. Services availability analysis indicates that the trains in ØØL are punctual and are not meeting availability requirements of Bane NOR. It was found that the overall availability as 96.75% and punctuality to be 96.88% in the ØØL pilot line.

From the reliability modelling of ERTMS operated ØØL pilot line using TRAIL, it was able identify the stations and sections that were weaker, critical infrastructure elements, maintenance strategy, delays occurring and other reliability parameters of ØØL. Thus it can be concluded that TRAIL is a suitable method to performing reliability modelling and analyze any railway system. Since ØØL is a pilot project implemented by Bane NOR as a part of their ERTMS NI project, the results obtained from TRAIL model will certainly help to estimate the performance of ERTMS/ETCS system in other regions of Norway with some uncertainty. In addition, this analysis assists to predict and define the individual reliability parameters for various infrastructure elements such as axle counters, interlocking, balise etc, which later on can improve the overall reliability of operations.

7.2 Recommendations

The thesis primary objective was to perform reliability modelling of ERTMS/ETCS system and it was achieved using TRAIL software. Meanwhile the model was built on several assumptions, and more detailed work with further system breakdown and analysis is required to develop a precise model. In TRAIL, the time based model has an option to modify the model according to requirements and its simulation process supports to perform in depth RAM analysis to various systems. For further studies in this area of ERTMS/ETCS modelling, the developed method in TRAIL could be improved by taking into account the measures mentioned in the following two categories.

***Measures for Bane NOR*:**

1. At present Bane NOR has top-level criteria for train traffic such as overall availability, punctuality and regularity. In a similar way. Bane NOR could perform a thorough analysis for entire ERTMS infrastructure system and determine reliability and availability requirements for individual ERMTS system, such that a precise model can be developed. Example: setting up an availability target of 99% for RBC.
2. Some of the reliability parameters like MTBF assigned to different components are not meeting the requirements specified by ERTMS users' group, this can be developed by taking an expert judgement or analyzing the similar ERTMS operated lines in other neighboring regions.
3. The failure log used in usage based analysis prepared by Bane NOR was quite complex to analyze. The log may be categorized into delays due to initial failures, delays due to preceding train delays and type of infrastructure failures.

4. All the reliability parameters derived by Bane NOR such as MTTF, MTTR and MTBF were assumed to be exponentially distributed. Sometimes, in reality the infrastructure ageing may vary from system to system, so a thorough analysis could be done to find the type of ageing distribution in this case.
5. FMEA was done for the failure analysis of ERTMS system. However, using FMECA would have revealed the critical failures in initial analysis.

***Measures for TRAIL*:**

1. Multi formalism modelling approach adopted here has not counted for interdependency of different models and more research is required to understand the dependency.
2. In the TRAIL time based model, FTA used was developed by assuming that it was the same for all stations and the BiDi's. However, making different fault trees for every station and BiDi section will result in more exact analysis and this takes a long time to develop.
3. TRAIL has more features like conditional monitoring, considering weather conditions etc. that could also contribute to analyze the systems and take necessary actions for doing maintenance. Unfortunately, these factors were not possible to include in this thesis due to the limited access to TRAIL.
4. The delays at the starting station were ignored in the thesis due to lack of data. In order to do an inclusive analysis, these delays have to be included in the TRAIL time based analysis.

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Acronyms

ATC	Automatic Train Control
ATP	Automatic Train Protection
Bane NOR	Norwegian National Rail Administration
BiDi	Bidirectional section
BN	Bayesian Network
BTM	Balise Transmission Module
CENELEC	European Committee for Electro technical Standardization
CPN	Colored Petri Net
CTMC	Continuous Time Markov Chains
DMI	Driver Machine Interface
EEC	European Economic Community
EEIG	European Economic Interest Group
ERA	European Rail Agency
ERRI	European Institute of Railway Research
ERTMS	European Rail Traffic Management System
ERTMS NI	ERTMS National Implementation project
ETCS	European Train Control System
ETML	European Traffic Management Layer
ETA	Event Tree Analysis
EVC	European Vital Computer
FMEA	Failure Modes Effects Analysis

FMECA	Failure Modes Effects and Criticality Analysis
FRACAS	Failure Reporting Analysis and Corrective Action System
FRS	Functional Requirement Specifications
FTA	Fault Tree Analysis
GSM-R	Global System for Mobile Communications – Railway
GSPN	Generalized Stochastic Petri Nets
HAZID	Hazard Identification
IXL	Interlocking System
LEU	Lineside Electronic Unit
LTM	Lineside Transmission Module
MLD	Mean Logistic Delay
MMI	Man Machine Interface
MTBF	Mean Time between Failures
MTTF	Mean Time to Failures
MTTR	Mean Time to Repair
NTC	National Train Control
NTNU	Norwegian University of Science and Technology
ODD	Odometer on Train
ØØL	Østfoldbanen Østre Linje
PN	Petri Nets
PDF	Probability Distribution Function
RAMS	Reliability Availability Maintainability and Safety
RAM	Reliability Availability Maintainability Analysis
RCM	Reliability Centered Maintenance
RBC	Radio Block Center
RBD	Reliability Block Diagram

RFT	Repairable Fault Tree
RPN	Risk Priority Number
RTM	Radio Transmission Module
SPN	Stochastic Petri Nets
SRS	Safety Requirements Specifications
TIU	Train Interface Unit
TRAIL	Transport Reliability Availability and Infrastructure Logistic simulator
TSI	Technical Specifications for Interoperability
WAN	Wide Area Network

Appendix A

FMEA of ERTMS/ETCS infrastructure components

Description of unit			Description of failure			Effect of failure		Risk reducing measures
Item	Function	Operational mode	Failure mode	Failure cause or mechanism	Detection of failure	On the subsystem	On the system function	
Point	Switch trains from one track to other	Control the track	Control over straight track but not on switching	Fails to receive the signal from interlocking	Alarm or manual check	Remains in straight track position	Train can collide with other trains on same track	Regular maintenance and check
			Control over switching but not on straight track	Fails to receive the signal from interlocking	Alarm or manual check	Track remains in deviation position	Train can collide with other trains on same track	Regular maintenance and check
			No Control	Covered by ice and failure in interlocking signals	Alarm or manual check	Track cannot be controlled to on position	Train may collide with other trains	Heating the system and regular checking
Axle Counters	Count the number of wheels in and out of a section	Detect the track occupancy	Failure of axle counter at a location	Axle counter sensor failure	Red signal in section	Fails to count and send data	Train stops and delays in arrival	Regular maintenance
				Ice accumulated on axle counter	Red signal	Fails to count	Delay due to train stop	De-icing and regular checks
			Reset request	Counting error	Wrong axle count		Train stops for signal	Regular checks and replacement

Interlocking	Send data for signal control	Controls the track occupancy	Interlocking processors down	Software or hardware fail	Train blocked in a section	Wrong signalling	Block the train before a point	Using high reliable components
GSM - R	Provides communication media between train and RBC	Transmit signals and information to and from train	Central failure impacting all stations	Software or hardware system failure	Directly checking for signals	Affects the information flow	Train stops and waits for movement authority	Must have redundant systems
			Decentral failure at two or more stations	Transmitting or receiving failure	Directly checking for signals	Not receiving signals	Train is blocked and waiting for movement authority	Must be provided with redundant systems
Balise	Detects train position	Train speed and position is send to RBC	Balise dead or fail	Balise antenna fail	Automatic by not detecting train	Fails to detect train position	Train passes over balise but fails to receive signal further	Proper maintenance and checks
				Balise covered by ice	Unable to detect train	Fails to detect train position	Fails to transmit signals to RBC	De-icing and regular checks
RBC	Manage the interlocking and signals	Transmit and receive information via GSM-R	RBC down	Power failure	Automatic when there are no signals transmitted	Internal systems fail to function	Train stops and waits for movement authority from RBC	Arrange redundant power supply and maintain
				Other system software and hardware failure	Automatic when RBC do not transmit or receive	Internal system fails to function	Train stops and waits for movement authority from RBC	Use of reliable and redundant systems
Track	Movement of the train	Supports to run the train smoothly	Long or minor damage (fracture)	Wear out and other factors	Manual checks		Derailment if undetected. Train delays in if detected	Regular check and proper maintenance

Appendix B

Inputs for modelling of ERTMS/ETCS operated ØØL pilot line.

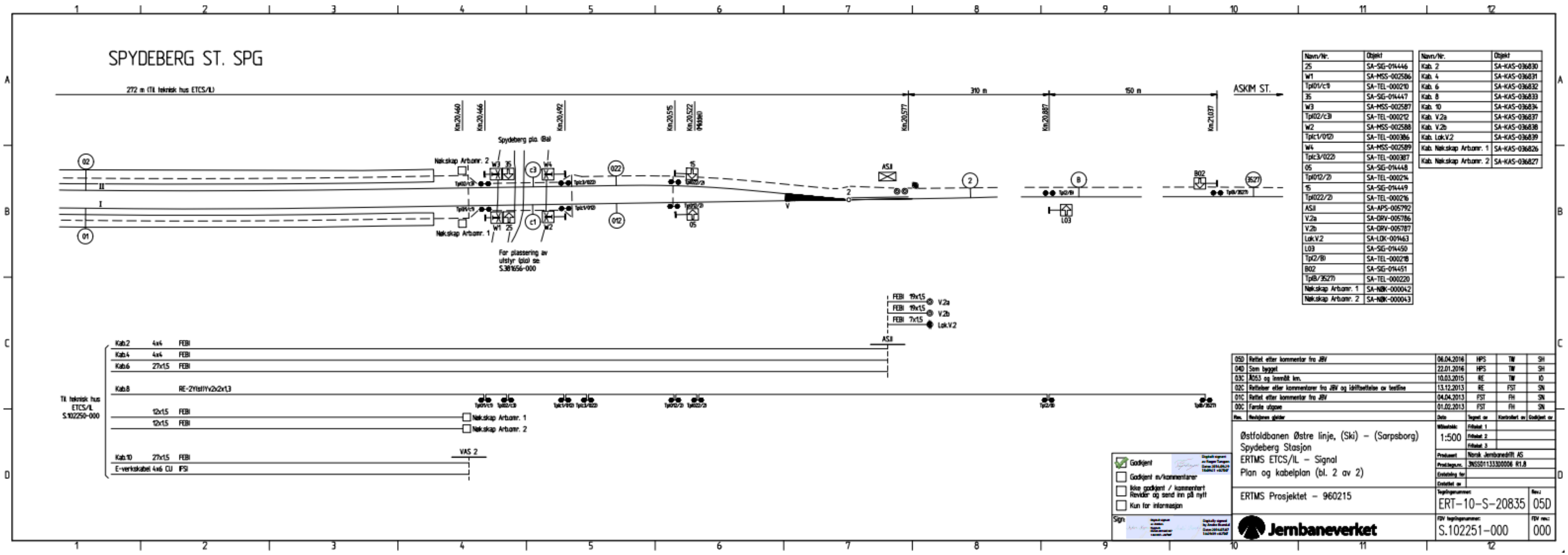


Figure B.1 Layout of cable plan at the exit of Spydeberg station

The above layout in Figure B shows the cable plan of the Spydeberg station exit, where the two platforms are merging to a single line by a point and proceeding towards Askim station. In the layout, the axle counters are seen at various points in the form of two adjacent black circles. Likewise, all the sections from Ski to Mysen were studied and the various components such as balise groups, axle counters, interlocking and points present along the line is presented in the below Table B.1.

Table B.1 ERTMS/ETCS components distributed from Ski to Mysen

Location	**Balise Groups**	**Axle Counters**	**Interlocking**	**Points**
Ski station	13	4	5	3
Ski - Kråkstad BiDi	7	5	5	0
Kråkstad station	16	11	6	3
Kråkstad - Tomter BiDi	6	6	5	0
Skotbu	2	2	2	0
Tomter Station	15	10	4	2
Tomter - Spydeberg BiDi	9	6	6	0
Knapstad	0	2	2	0
Spydeberg Station	14	10	4	2
Spydeberg - Askim BiDi	7	6	6	0
Askim Station	18	8	6	3
Askim - Mysen BiDi	7	4	8	0
Slitu	2	4	2	0
Mysen Station	25	18	10	6

The average number of components present in the area of a station:

- Balise groups are approximated to 12
- Axle counters are approximated to 10
- Interlocking are 5

The average number of components present in the BiDi (bidirectional) section:

- Balise groups are approximated to 7
- Axle counters are approximated to 5
- Interlocking are 6

Points are always present at the entrance and exit of stations and at crossings. Therefore, generally it is assumed that there are two points at station. This may change if the station has different number of platforms. RBC and GSM-R is present all over the ØØL pilot line.

The corresponding MTTF (TBE) and MTTR (duration) of the down events used in the Relysim model are obtained from Table 6, and changed accordingly for a station and BiDi section based on the derived average number of components. The input to Relysim model's down events is given according to the Table B.2.

Table B.2 Input reliability parameters to Relysim.

Location/Area	Node/Block	Down Events	MTTF (hours)	MTTR (hours)
General	Start node	RBC Down	4.40E+05	8
		GSM-R fail	1.75E+05	5
		Maintenance	8.76E+03	1
		Track fracture	3.65E+05	2.5
Station/ Platform/ BiDi	Balise	Balise fail	3.67E+04	12
	Axle Counter	Axle counter fail	2.20E+04	40
		Axle counter reset	8.76E+03	0.25
	Interlocking	Interlocking fail	1.10E+05	4
		Partial fail	1.43E+03	4
	Point	Point fail	5.00E+04	4

As shown in Figure B.2, a point failure is defined in the Relysim event builder with an exponential distribution having MTTF of 50000 hours and MTTR of 4 hours. Similarly, other events are defined in the event builder for each block.

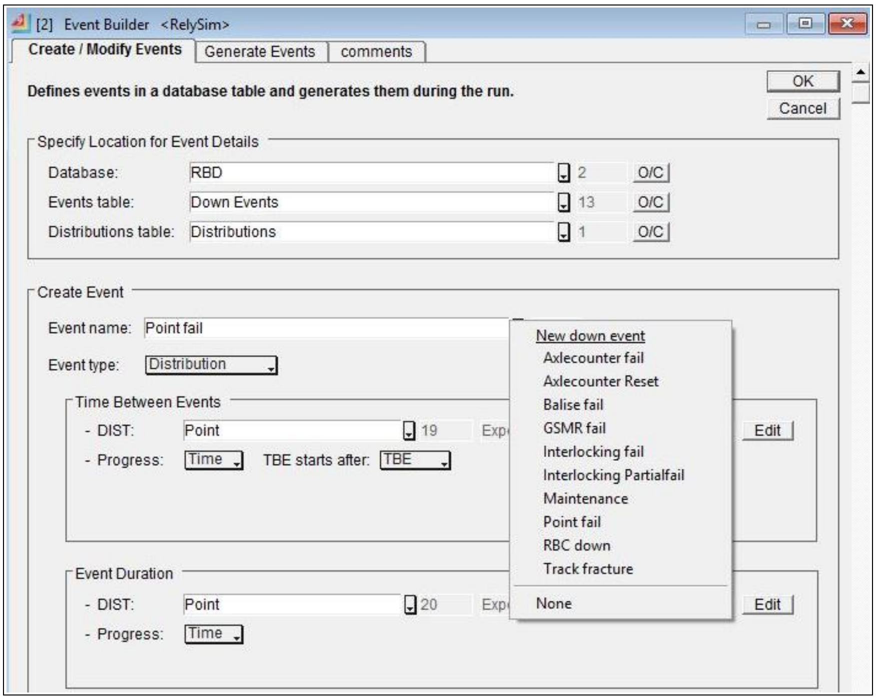


Figure B.2 Event builder in Relysim representing the definition of down events and their distribution

After developing the Relysim model and defining down events to all the ERTMS/ETCS components, the simulation is set up as shown in below Figure B.3. It was decided to run the simulations for a period of 1 year and 1000 runs.

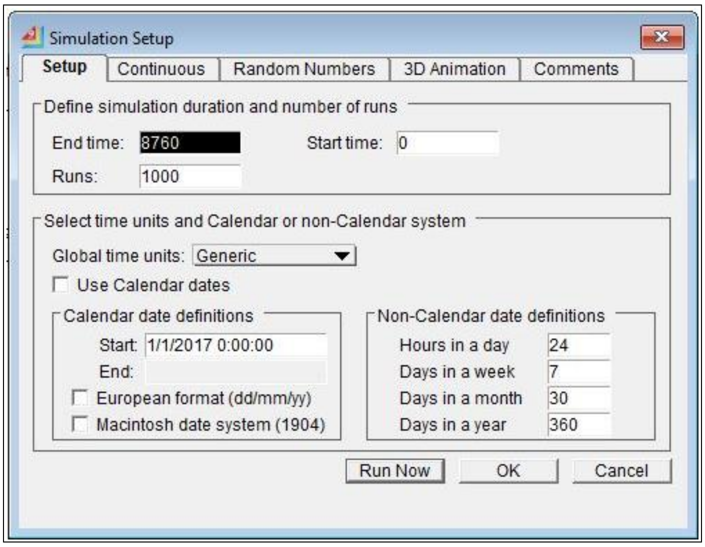


Figure B.3 Simulation set up in Relysim for the developed model

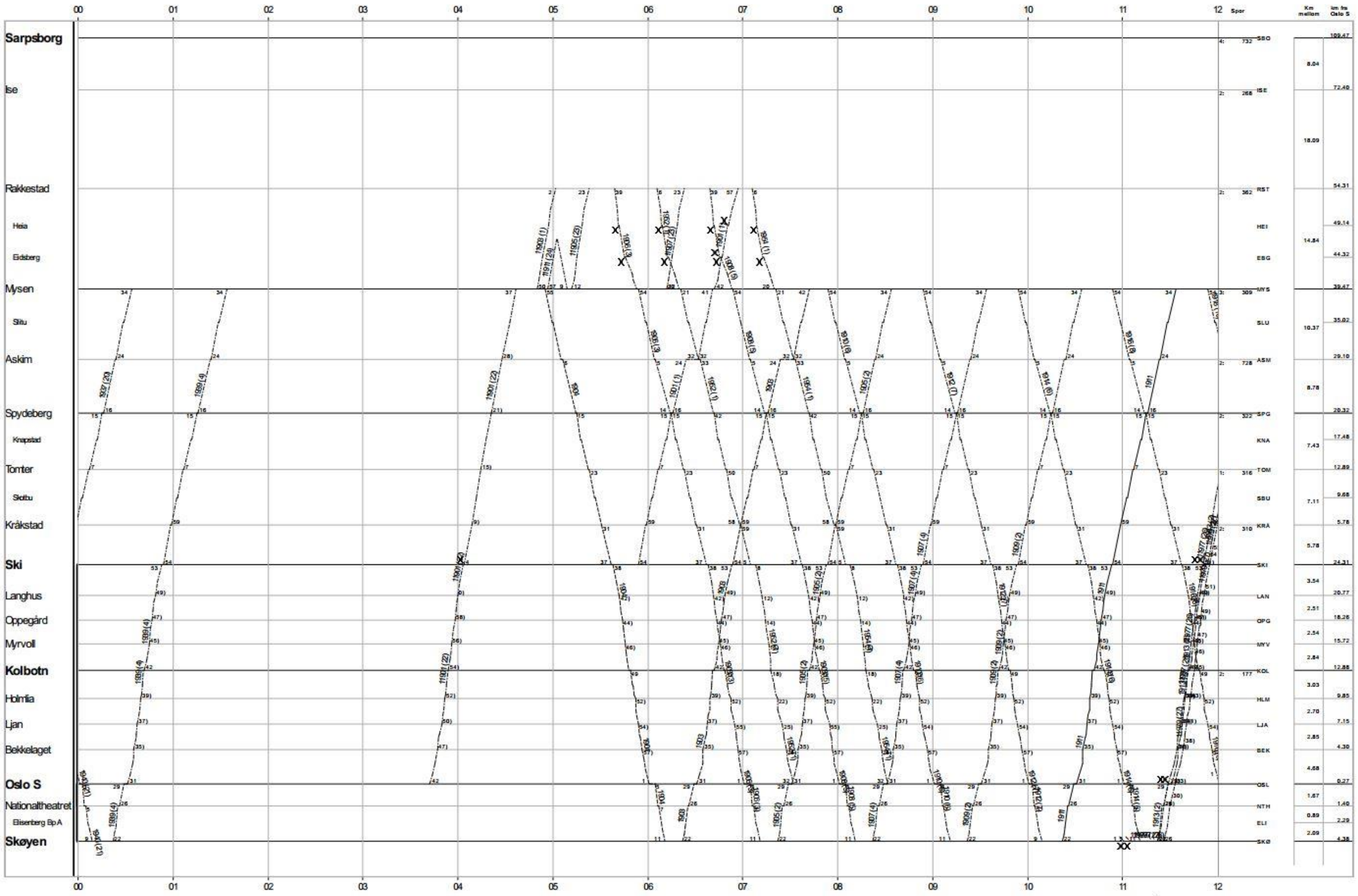
The result obtained by performing the simulation in Relysim for 1 year (8760 hours) and 1000 runs is shown in below Table B.3. It is estimated from analysis that reliability of interlocking partial fail, track and maintenance is very less, whereas for GSM-R and RBC it is found to be high. Also it can be interpreted that axle counters, balises, interlocking and point system are relatively less reliable. Therefore, it is important to do analysis and define high reliability parameters to systems, and procure such components.

Table B.3 Relysim simulation result and Reliability of ETCS components

Row Labels	**Total MTTF (hours)**	**Reliability**
Axle Counter Fail	52920.15	0.85
Axle Counter Reset	60892.31	0.86
Balise Fail	52025.78	0.85
GSM-R Fail	158790.72	0.95
Interlocking Fail	209723.67	0.96
Interlocking Partial Fail	18809.52	0.63
Maintenance	18494.97	0.62
Point Fail	60289.02	0.86
RBC Down	74346.36	0.98
Track Fracture	15732.68	0.57
Overall System	**1391125.19**	**0.99**

Appendix C

The timetable input to TRAIL is taken from the ØØL pilot line graphic route timetable shown below.



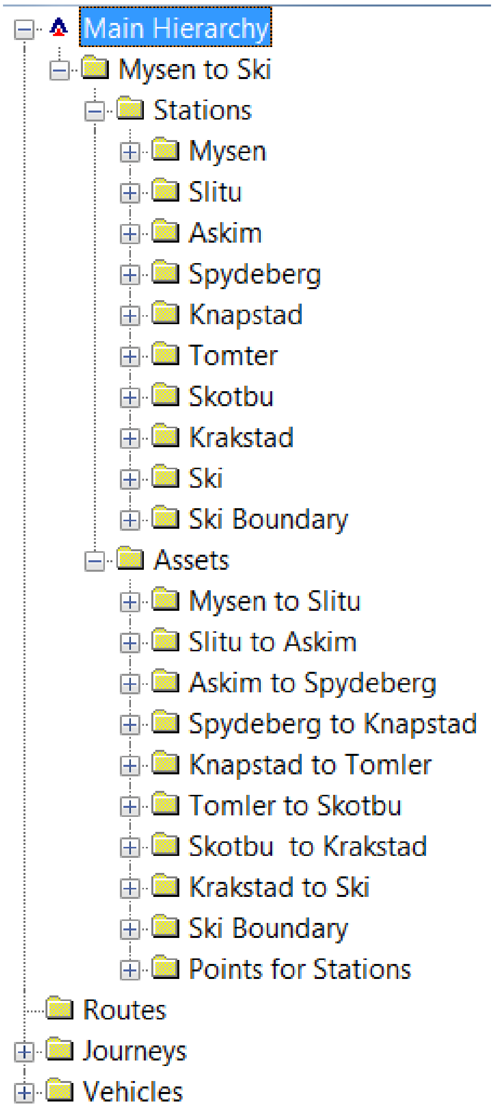
The timetable of downwards journeys from Ski to Mysen in the ØØL line are tabulated below and these were given as input to TRAIL for both usage and time based analysis. The timetable is adopted from the above graphic route timetable and similarly extracted for the upwards journeys from Mysen to Ski.

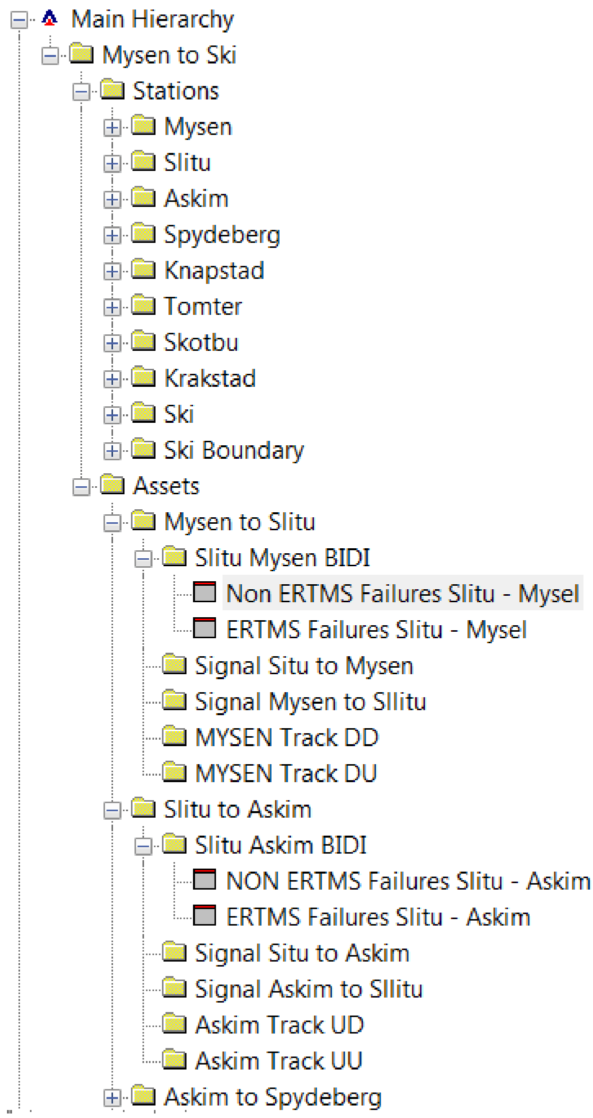
Journeys->Ski To Ise (Down)

Description	Frequency	Frequency Units	Peak	Weeks	Start Time
1901 (1) Ski to Mysen (Down) A 05:54	1	Days	Yes	1 - 52	05:52:59
1903 Ski to Mysen (Down) A 06:54	1	Days	Yes	1 - 52	06:52:59
1905 (2) Ski to Mysen (Down) A 07:54	1	Days	Yes	1 - 52	07:52:59
1907 (4) Ski to Mysen (Down) A 08:54	1	Days	Yes	1 - 52	08:52:59
1909 (2) Ski to Mysen (Down) A 09:54	1	Days	Yes	1 - 52	09:52:59
1911 Ski to Mysen (Down) A 10:54	1	Days	Yes	1 - 52	10:52:59
1915 Ski to Mysen (Down) A 12:54	1	Days	Yes	1 - 52	12:52:59
1917 (9) Ski to Mysen (Down) A 13:54	1	Days	Yes	1 - 52	13:52:59
1919 Ski to Mysen (Down) A 14:54	1	Days	Yes	1 - 52	14:52:59
1921 Ski to Mysen (Down) A 15:54	1	Days	Yes	1 - 52	15:52:59
1923 (11) Ski to Mysen (Down) A 16:54	1	Days	Yes	1 - 52	16:52:59
1925 (12) Ski to Mysen (Down) A 17:54	1	Days	Yes	1 - 52	17:52:59
1927 (13) Ski to Mysen (Down) A 18:54	1	Days	Yes	1 - 52	18:52:59
1929 (15) Ski to Mysen (Down) A 19:54	1	Days	Yes	1 - 52	19:52:59
1931 (13) Ski to Mysen (Down) A 20:54	1	Days	Yes	1 - 52	20:52:59
1933 (`15) Ski to Mysen (Down) A 21:54	1	Days	Yes	1 - 52	21:52:59
1935 (13) Ski to Mysen (Down) A 22:54	1	Days	Yes	1 - 52	22:52:59
1937 (20) Ski to Mysen (Down) A 23:54	1	Days	Yes	1 - 52	23:52:59
1939 (4) Ski to Mysen (Down) A 00:53	1	Days	Yes	1 - 52	00:52:59
1951 (1) Ski to Mysen (Down) A 15:22	1	Days	Yes	1 - 52	15:20:59
1953 (1) Ski to Mysen (Down) A 16:22	1	Days	Yes	1 - 52	16:20:59

Appendix D

The main hierarchy of defining the systems in TRAIL model for the usage based analysis is shown below:





The mean delays due to various system failures obtained from the usage based model simulation is shown in the following table and a plot is made in section 5.5.4.1 Figure 5.14.

Table D.1 System failure types and corresponding delays

System Failures	**Mean Delay (minutes)**
Onboard	1231.20
ERTMS	1777.74
Non-ERTMS	757.36

Section reliability performance is done to usage based model of ØØL developed in TRAIL and was simulated for 100 runs for 1 year. Different BiDi sections and their corresponding MTBF of various types of system failures are presented in the following Table D.2 and graphically represented in section 5.5.4.1 Figure 5.16.

Table D.2 BiDi sections of ØØL and their corresponding MTBF (hours) for various types of failures

Location	**Onboard MTBF**	**ERTMS MTBF**	**non-ERTMS MTBF**
Mysen - Slitu	93.67	925.43	3012.41
Slitu - Askim	93.67	900.61	3452.91
Askim - Spydeberg	93.67	885.99	3131.18
Spydeberg - Knapstad	93.67	930.35	3372.94
Knapstad - Tomter	93.67	896.92	3360.00
Tomter - Skotbu	93.67	875.35	3200.06
Skotbu - Kråkstad	93.67	912.84	3494.40
Kråkstad - Ski	93.67	920.56	3296.66

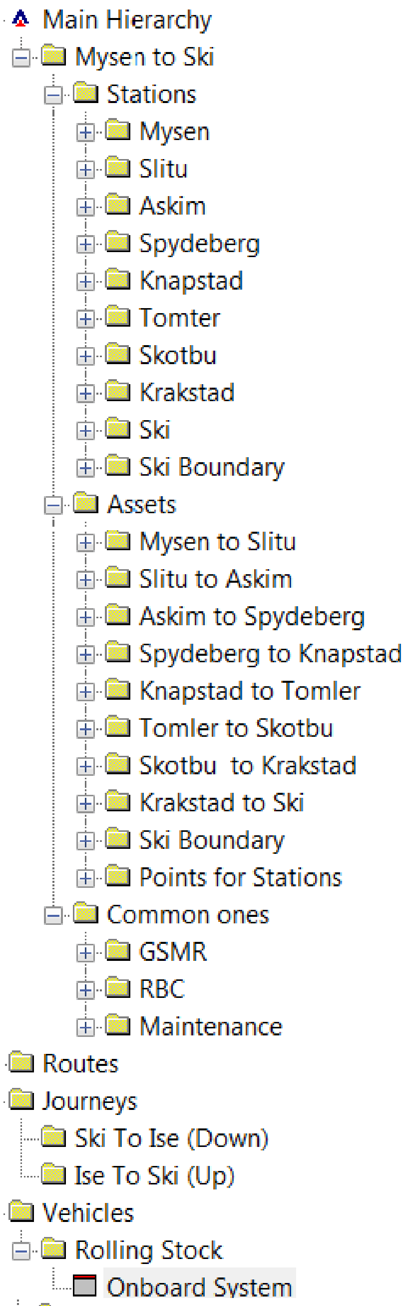
BiDi sections operational performance is evaluated from the developed usage based model and the outcome of accumulated delays for all BiDi sections is shown in below Table D.3 and a plot is illustrated in section 5.5.4.1 Figure 5.17.

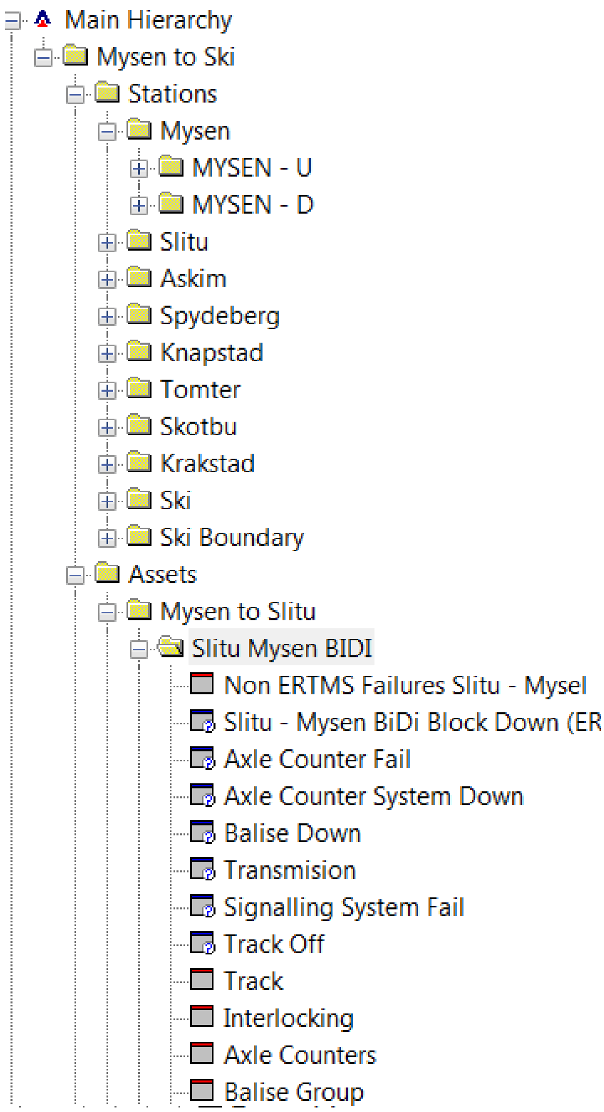
Table D.3 Accumulated delays in BiDi sections of ØØL

BiDi Section	**Accumulated Delays (mins)**
Askim - Spydeberg	359.37
Kråkstad - Ski	333.84
Knapstad - Tomter	327.48
Spydeberg - Knapstad	324.67
Mysen - Slitu	306.03
Skotbu - Kråkstad	301.45
Slitu - Askim	291.72
Tomter - Skotbu	290.79

Appendix E

The hierarchy of the systems defined in TRAIL for a time based analysis is shown below.





The fault trees developed for stations and BiDi sections are realized in TRAIL. The top event of BiDi section fault tree is train blocking in the BiDi section and this can occur if any of failure events such as track off, signaling system fail and maintenance takes place. As an example, Slitu - Mysen BiDi section and how the top event is realized in TRAIL is shown in below Figure E.1.

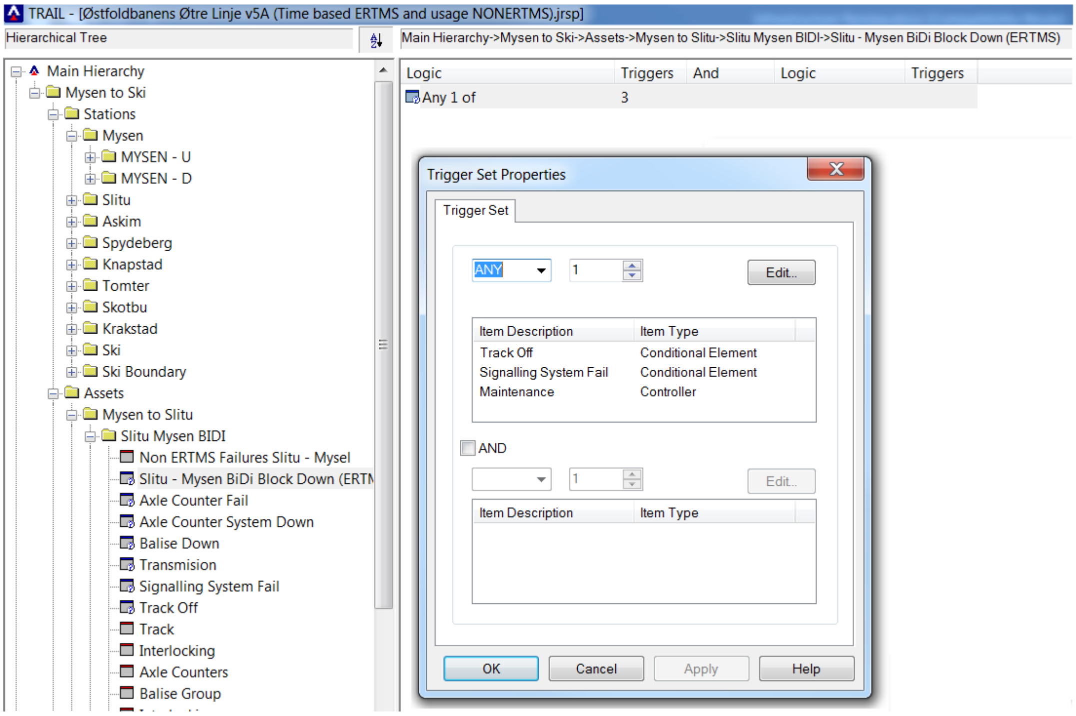


Figure E.1 Realization of fault tree in TRAIL with setup of triggering events

The choice of selecting the simulation process for 100 annual simulation is that the mean delays due to failures is almost constant after 55 runs. From the below Figure E.2, it can be observed that after 55 simulations to 100 simulations the average delays is constant with 12229.5 minutes. Therefore, the model developed was run for 100 simulations and 8760 hours.

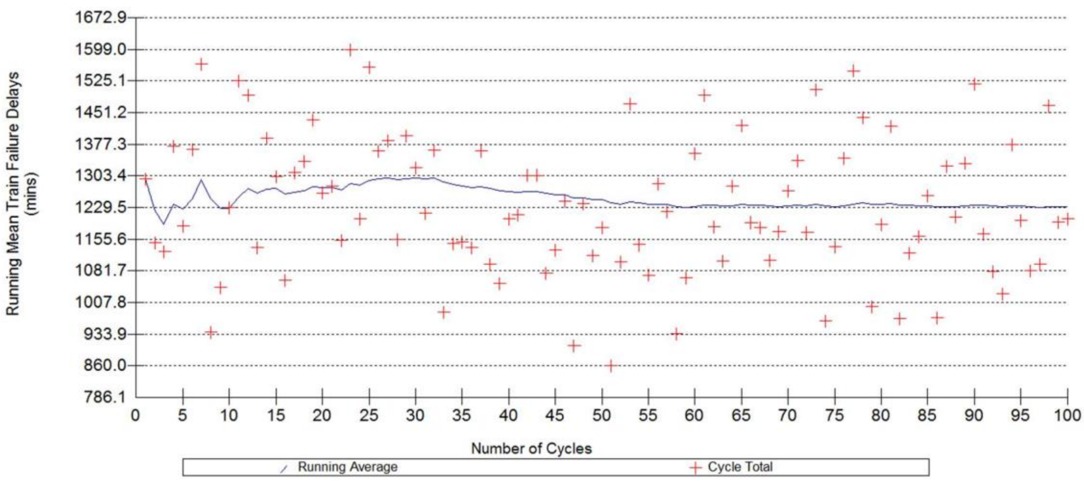


Figure E.2 Number of simulations and its corresponding mean delays

The time based model developed in TRAIL above is simulated for 100 runs for 1 year. The outcome of the analysis used to determine which type of failures are causing more delays in both BiDi sections and stations. Table E.1 and E.2 shows the results obtained for delays due to failures for BiDi section and station, and are plotted in section 5.5.4.2 Figure 5.20 and Figure 5.21.

Table E.1. BiDi section delays and causing failure types

Location	**ERTMS failure Delays (mins)**	**non-ERTMS failure Delays (mins)**
Tomter - Skotbu	147.85	76.33
Knapstad - Tomter	201.70	95.65
Skotbu - Kråkstad	239.00	87.50
Spydeberg - Knapstad	259.35	89.25
Mysen - Slitu	304.39	98.96
Slitu - Askim	311.86	80.00
Kråkstad - Ski	398.70	109.52
Askim - Spydeberg	515.34	120.4

Table E.2. Station Up and Down delays due to ERTMS failures

Stations	**ERTMS failures Down-track**	**ERTMS failures Up-track**
Tomter	90.26	80.72
Spydeberg	90.46	99.04
Kråkstad	138.16	95.68
Askim	146.86	112.11
Ski	166.99	73.53
Mysen	216.95	249.66

A section reliability performance is done based on the result obtained from simulation of time based model of ØØL. The failure types are categorized into onboard, ERTMS and non-ERTMS and their MTBF in each BiDi section are tabulated below in Table E.3 and plotted in section 5.5.4.2 Figure 5.22. The onboard and non-ERTMS failures are taken form usage based analysis.

Table E.3. ØØL BiDi sections and their corresponding MTBF (hours) for various types of failures

BiDi Section	**Onboard MTBF**	**ERTMS MTBF**	**non-ERTMS MTBF**
Askim - Spydeberg	95.86	779.301	3271.96
Kråkstad - Ski	95.86	921.513	3701.71

Mysen - Slitu	95.86	1110.04	3247.60
Slitu - Askim	95.86	1180.53	3372.93
Spydeberg - Knapstad	95.86	1371.43	3012.40
Skotbu - Kråkstad	95.86	1399.99	3097.92
Knapstad - Tomter	95.86	1551.68	3131.18
Tomter - Skotbu	95.86	1839.09	3399.14

Table E.4 ERTMS infrastructure systems and their failure occurrences.

ERTMS system	**Number of failures**
Axle Counters	94
Balise Group	128
GSMR	2
Interlocking	71
Maintenance	2
Points	25
RBC	2
Track	24

Infrastructure performance obtained from time based model simulation is shown in Table E.4 and plotted in section 5.5.4.2 Figure 5.23, where various ERTMS infrastructure system and their number of failures encountered for each system in a year are recorded.

Total accumulated delays in different BiDi sections of ØØL due to all the failures occurred during operations are tabulated below in Table E.5 and plotted in section 5.5.4.2 Figure 5.26. Later, these are compared with results of usage based analysis for model validation.

Table E.5 Accumulated delays in BiDi sections of ØØL

Location	**Accumulated Delays (mins)**
Askim - Spydeberg	613.72
Kråkstad - Ski	469.18
Slitu - Askim	397.91
Mysen - Slitu	386.16
Spydeberg - Knapstad	373.95
Skotbu - Kråkstad	334.77
Knapstad - Tomter	305.82
Tomter - Skotbu	231.31

Availability analysis of trains running from Mysen to Ski in up direction of ØØL is obtained from TRAIL time based model simulation. The results are shown in Table E.6 and discussed in detailed in section 5.5.4.2 Figure 5.27. Furthermore, this type of analysis can be performed for other direction in ØØL pilot line.

Table E.6 Availability analysis of train operating in Up direction of ØØL

Train number and Time	**Availability percentage**
1904 04:55	98.13
1906 05:54	97.77
1952 06:21	97.54
1908 06:54	97.77
1954 07:21	97.48
1910 07:54	98.03
1912 08:54	98.11
1914 09:54	98.02
1916 10:54	97.98
1918 11:54	98.11
1920 12:54	98.17
1922 13:54	98.02
1924 14:54	97.63
1926 15:54	97.79
1928 16:54	97.99
1930 17:54	98.03
1932 18:54	98.06
1934 19:54	98.21
1936 20:54	97.98
1938 21:54	98.17
1940 22:54	98.07