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ERTMS/ETCS Hybrid Level 3

Analysis of the overall challenges/limitations of ETCS Hybrid Level 3

TU Delft

Movares adviseurs & ingenieurs

ERTMS/ETCS Hybrid Level 3

Analysis of the overall challenges/limitations of ETCS Hybrid Level 3

by

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Cover image: Stop Marker Board (SMB) for ERTMS/ETCS Level 2 and Hybrid Level 3. Source: ProRail [26]

Preface

This thesis marks the final stage of my Master in Transport, Infrastructure and Logistics at Delft University of Technology. I experienced writing this thesis as a rollercoaster. Before I started working on my thesis, I was often told that this period is one of the most stressful of the study years. At the time, I thought that was fairly exaggerated, but now I understand what these people meant. Writing this thesis was quite an experience with highlights but also setbacks. My journey began with my keen interest in railways and discussions with Movares. The topic was quickly chosen, but establishing the research direction was stagnant. I had no previous experience in reliability studies. The lack of this experience caused my trajectory to take longer, but I am glad I chose the challenge. Another major change in my thesis took place later in the trajectory, which made me feel more personally comfortable with my research.

Writing the master thesis is an individual assignment, but without the guidance of a number of people, my journey would have been a lot harder. First, I would like to thank my two company supervisors Jack Raats and Laura Mattheeuwse for their guidance within Movares. Jack helped me with the technical aspects within the thesis and the weekly sparring sessions always gave me new insights. Laura left Movares halfway through my thesis, but made me feel welcome at Movares during the time she was there.

I would also like to thank my supervisors at TU Delft. I am grateful to Rob Goverde and Egidio Quaglietta for rail engineering advice and feedback on my papers. I would also like to thank Jan Anne Annema, as well as Egidio Quaglietta, for multiple conversations and guidance during my journey.

Finally, I would like to thank my family and my girlfriend. During the process of writing the thesis, it is very nice to have people around you who, without saying anything, realise how you feel and support you. I still have the affection with rail and will therefore enjoy continuing in the rail sector after graduation.

I hope my research can do its bit for the possible implementation of ETCS Hybrid Level 3.

Robin Dissel

Delft, 2023

Summary

In 2019, the Dutch government decided to gradually replace the old Automatische TreinBeïnvloeding (ATB) system and NS'54 multi-aspect fixed-block signalling system with ERTMS until 2050. As a result, the Ministry of Infrastructure and Water Management set up the ERTMS Programme and commissioned ProRail to realize the rollout. In Dutch vernacular, ERTMS is often used, but the system that replaces the legacy ATB is ETCS Level 2. This rollout of ETCS Level 2 in infrastructure is currently being done on 7 sections of track in collaboration with 5 engineering firms that form the knowledge alliance. Although the rollout of ETCS Level 2 in the Netherlands is still in progress, research into new ETCS variants is ongoing. One of these variants is ETCS Hybrid Level 3. In ETCS Hybrid Level 3, Virtual Sub-Section (VSS) are introduced, allowing smaller track sections without additional investment in Trackside Train Detection (TTD). The use of VSS requires a Train Integrity Monitoring (TIM) system in the train that monitors train integrity.

There are several studies showing that ETCS Hybrid Level 3 has a positive impact on rail capacity utilisation. For example, capacity studies have been done on Dutch rail corridors around Amsterdam and Utrecht, comparing ETCS Level 2 with ETCS Level 3 and the legacy ATB system [15][34]. Besides capacity, reducing TTD can lead to an improvement in infrastructure reliability. Although several studies have shown that ETCS Hybrid Level 3 is a capacity and reliability improvement on the currently rolling out ETCS Level 2, the ERTMS Programme does not include ETCS Hybrid Level 3. In addition, a research report by [33] on possible rail system jumps showed that including ETCS Hybrid Level 3 in the current ERTMS rollout is the most cost-efficient solution.

The reasons for not including ETCS Hybrid Level 3 in the ERTMS implementation and the impact of a possible implementation have not yet been investigated. It is important to find out what impact the implementation of ETCS Hybrid Level 3 has on: operation rules, strategy and stakeholders' responsibilities. The purpose of this study is therefore to answer the following main research question: What is the impact of implementing ETCS Hybrid level 3 to the operations on the Dutch rail network? To answer the research question, it is necessary to examine the differences with ETCS Level 2, how ETCS Hybrid Level 3 is viewed in the Dutch rail sector and what impact the addition of Train Integrity Monitoring (TIM) system has on reliability of the on-board system.

A literature review was done to investigate the changes in the transition from ETCS Level 2 to Hybrid Level 3, where these changes are taking place and which stakeholders are affected by the changes. The biggest changes taking place due to ETCS Hybrid Level 3 are the introduction of VSS and TIM. The new definition of VSS requires adaptation in the Radio Block Center (RBC), Interlocking (IXL) and user processes for degraded situations. These adjustments mostly concern the infrastructure manager ProRail, while the introduction of the TIM is the responsibility of rolling stock owners like NS.

Researching the views of concerned stakeholders on these modifications by ETCS Hybrid Level 3, was done through stakeholder interview. The semi-structured interviews with persons with positions within the stakeholders, were used for the data collection. The results show that there is a lot of uncertainty within the rail sector in terms of actual benefits, way of implementation and required steps for a possible implementation.

One of the required steps for the effective implementation of ETCS Hybrid Level 3 is the incorporation of a TIM functionalities in the passenger trains. The two TIM functionalities established in Subset-091 are: "Train Integrity" and "Train Length". To investigate the necessary reliability requirements, a follow-up study to the reliability analysis by Flammini et al. [14] was carried out. Through reverse engineering and the assumption that the TIM consists of the two functionalities for checking train integrity and train length, the result is that the reliability requirements of the two functionalities do not have to meet Safety Integrity Level 4 (SIL 4).

From the results of this study, it can be concluded that the implementation of ETCS Hybrid Level 3 will results in changes within the RBC, Interlocking, rolling stock and user processes. The scale of the

challenges that will occur by the implementation of ETCS Hybrid Level 3 depends on the implementation strategy that will be applied. Within the rail sector, there is much uncertainty as to what benefits are desired and feasible, and what implementation steps are required to achieve them. Interviews have shown that the technical challenge is in specifying the essential requirements of the TIM system. Besides the technical challenge, a possible implementation of ETCS Hybrid Level 3 will arise a significant challenge on an organisational level within the Dutch rail sector. This study recommends a development plan at rail sector level, establishing the necessary responsibilities and tasks of stakeholders. With the aim of having a clear and common vision on the choice that have to be made for a possible implementation of ETCS Hybrid Level 3.

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1 Introduction

According to the integral mobility analysis of the Ministry of Infrastructure and Water Management, passenger transportation is expected to grow 18 to 40 percent until 2040. For freight transport, the expected growth is as high as 32 to 55 percent until 2040 [20]. Rail innovations are needed to accommodate this growth. In a collaboration between the Ministry of Infrastructure and Water Management (I&W), provinces, metropolitan regions, transport operators and ProRail, the joint ambitions have been bundled in the Toekomstbeeld OV 2040 (The Future of Public Transport 2040) [25].

Currently, a combination of the NS'54 multi-aspect fixed-block signalling system and the Automatic Train Protection (ATP) Automatische TreinBeïnvloeding-Eerste Generatie (ATB-EG) is used on most of the Dutch main railway tracks. The ATB-EG system was implemented in the Netherlands from the 1960s until 1992 for all main railway lines and is at the end of its technological lifetime. Whereby the knowledge and expertise of the ATB system is also gradually disappearing within the market parties. In 2019, the Dutch government decided to replace the legacy ATB system with European Rail Traffic Management System (ERTMS) gradually until 2050 [19]. As a result, the ERTMS Program was set up by the Ministry of Infrastructure and Water Management and commissioned ProRail to realize this program. The introduction of ERTMS marks a switch from analogue to digital technology within the rail sector and will improve not only capacity but also the reliability of Dutch railway network [27]. The ERTMS Program contains the first phase of the national rollout of ETCS Level 2 through 2030. In Dutch vernacular, ERTMS is often used, but the system that replaces the legacy ATB is ETCS Level 2 baseline 3. Currently, the rail corridors: HSL-South, Betuweroute, Hanzelijn and corridor Amsterdam Bijlmer Arena - Utrecht are already equipped with ETCS Level 2. In early 2022, the contract for the first phase of the rollout of European Train Control System Level 2 (ETCS L2) in the Netherlands was awarded to Thales [28]. Besides the system delivery from Thales, ProRail has set up a knowledge alliance to realize the delivery of ETCS L2. The knowledge alliance consists of Arcadis, Movares, Nexus Rail, Royal HaskoningDHV and Sweco. Portions of Kijkhoek - Belgian Border (EKB), the Northern Lines (ENL), Hanzelijn Lelystad (EHL) and Schiphol - Amsterdam - Almere - Lelystad (ESAAL) corridors are divided among these engineering firms. This collaboration allows for open engineering, making it easier for the companies to exchange knowledge and experience between projects with both other engineering firms and ProRail. Although the rollout of ETCS Level 2 is still going on in the Netherlands, European Train Control System (ETCS) variants that go beyond Level 2 are being researched, and one such variant is ETCS Hybrid Level 3.

Studies on ETCS Hybrid Level 3 show that it has a positive impact on track capacity occupation compared to Level 2 and legacy ATB system. This included studies on the impact of ETCS Hybrid Level 3 on the capacity utilisation of Dutch rail corridors. But in the current rollout of ERTMS in the Netherlands, only ETCS Level 2 is being implemented. Why is ETCS Hybrid Level 3 not being considered when studies show the system has a beneficial impact on rail capacity consumption? Besides capacity, ETCS Hybrid Level 3 also provides the opportunity to improve the reliability of the rail infrastructure by reducing TTD. But that is only the impact on the infrastructure side of hybrid level 3. What the implementation of hybrid level 3 means for on-board reliability has not been studied. ETCS Hybrid Level 3 is not yet in operational use anywhere in Europe and is a not yet fully developed system. As a result, it is still unclear what the uncertainties are and what the reliability of the system depends on. Currently, Alstom is introducing Hybrid Level 3 on the French high-speed line between Paris and Lyon [2]. The difference between a single high-speed line and the Dutch main rail network is that over the high-speed line runs a more homogeneous rolling stock and on the Dutch network runs a wide variety of passenger trains and freight trains.

But why is the development of ETCS Hybrid Level 3 not being looked at for implementation in the Dutch ERTMS Programme. Therefore, this thesis will research the challenges/limitations of implementing ETCS Hybrid Level 3 in the rail sector. In order to identify the different stakeholders' reasons why ETCS Hybrid Level 3 should or should not be implemented.

1.1 Problem description

The Dutch rail network is a compact and busy network and the current ERTMS rollout is therefore a major task. But what are the reasons not to start developing ETCS Hybrid Level 3 for the Dutch rail network and integrate it into the current ERTMS Programme? And how long will it take to implement a system like ETCS Hybrid Level 3? Does the addition of the new ETCS Hybrid Level 3 components affect the reliability of the operation compared to Level 2? Or are the obstacles not at the technical level, but more at the organisational level between the stakeholders? These topics have not yet been explored in more detail in the existing literature and therefore constitute the knowledge gap that this thesis addresses.

1.2 Objective

Because ETCS Hybrid Level 3 is not yet a fully mature developed system, it is not yet known what the uncertainties are and where the reliability of the system depends most. A research report by TwynstraGudde [33] on the possible system jumps within the rail system showed that including Hybrid Level 3 in the current ERTMS rollout is the most cost-efficient solution [33]. Because the implementation of ETCS Hybrid Level 3 is most cost-efficient when combined with the rollout of the current ERTMS programme. Is it important to investigate what the changes in operation rules, regulations as well as stakeholder responsibilities are when introducing ETCS Hybrid Level 3. Therefore, the purpose of this thesis is to analyse the main challenges/limitations stakeholders see in the actual deployment of ETCS Hybrid Level 3 in terms of responsibilities, regulation changes, system reliability and strategy. In addition, the aim is to identify and propose possible technical solutions to enable implementation. In the thesis will be to identify the opinions and visions of the different stakeholders within the Dutch rail sector on ETCS hybrid level 3. This will identify stakeholders' reasons for and against the implementation of ETCS Hybrid Level 3, providing a clear overview of how ETCS Hybrid Level 3 can be possibly implemented in the Dutch rail network.

1.3 Research questions

The purpose of this research is to see what effect the implementation of ETCS Hybrid Level 3 has on the Dutch railway network. A new system like ETCS Hybrid Level 3 will introduce new components within the systems, which may cause changes that affect the current system. Therefore, the main research question is as follows:

'What are the main challenges and potential enablers to the deployment of ETCS Hybrid Level 3 on the Dutch rail network?'

To answer the main research question, the following sub-questions are composed:

1. What will be the changes to the subsystems and functional relations within ETCS Hybrid Level 3 with respect to Level 2?
2. What are stakeholders' visions in terms of strategy, responsibilities and timeline within the effective implementation of ETCS Hybrid Level 3?
3. What will be the effect of the new functionalities of ETCS Hybrid Level 3 to the reliability of the on-board system?

1.4 Scope

Within this project, the focus will be on ETCS Hybrid Level 3. In order to be able to evaluate this system properly, it is decided to make a comparison exclusively with ETCS Level 2. The choice for only ETCS Level 2 and no legacy national signalling systems is because the rollout of ETCS Level 2 has already started. This means that Level 2 is already seen as an improved system to ATB, making the comparison of ETCS Hybrid Level 3 with ATB redundant. Within this study, the focus is to understand the overall challenges/limitations of ETCS hybrid Level 3 obtained from stakeholder interviews and analyse potential technical enablers to overcome these challenges.

1.5 Report structure

To answer the main research question, the chapters have been divided in such a way that they each provide answers to the defined sub-questions (Figure 1.1). Chapter 2 explains the background of the Dutch rail sector and the safety/control systems. Chapter 3 contains the literature review of the research. This is partly explained by previous studies in the literature. Subsequently, chapter 3 discusses the methodology used for both general system analysis and technical system analysis. This covers methods and theory for the stakeholder interview and reliability methods used for calculations. Following the methodology, chapter 5 discusses the results of the general system analysis within the Dutch rail sector as a case study. Following that, chapter 6 elaborates on the results of the reliability analysis on the on-board system of passenger trains within hybrid level 3. Fllowing this, chapter 7 discusses the principles that emerged during the study. Finally, chapter 8 provides the answers to the research questions and recommendations for future research.

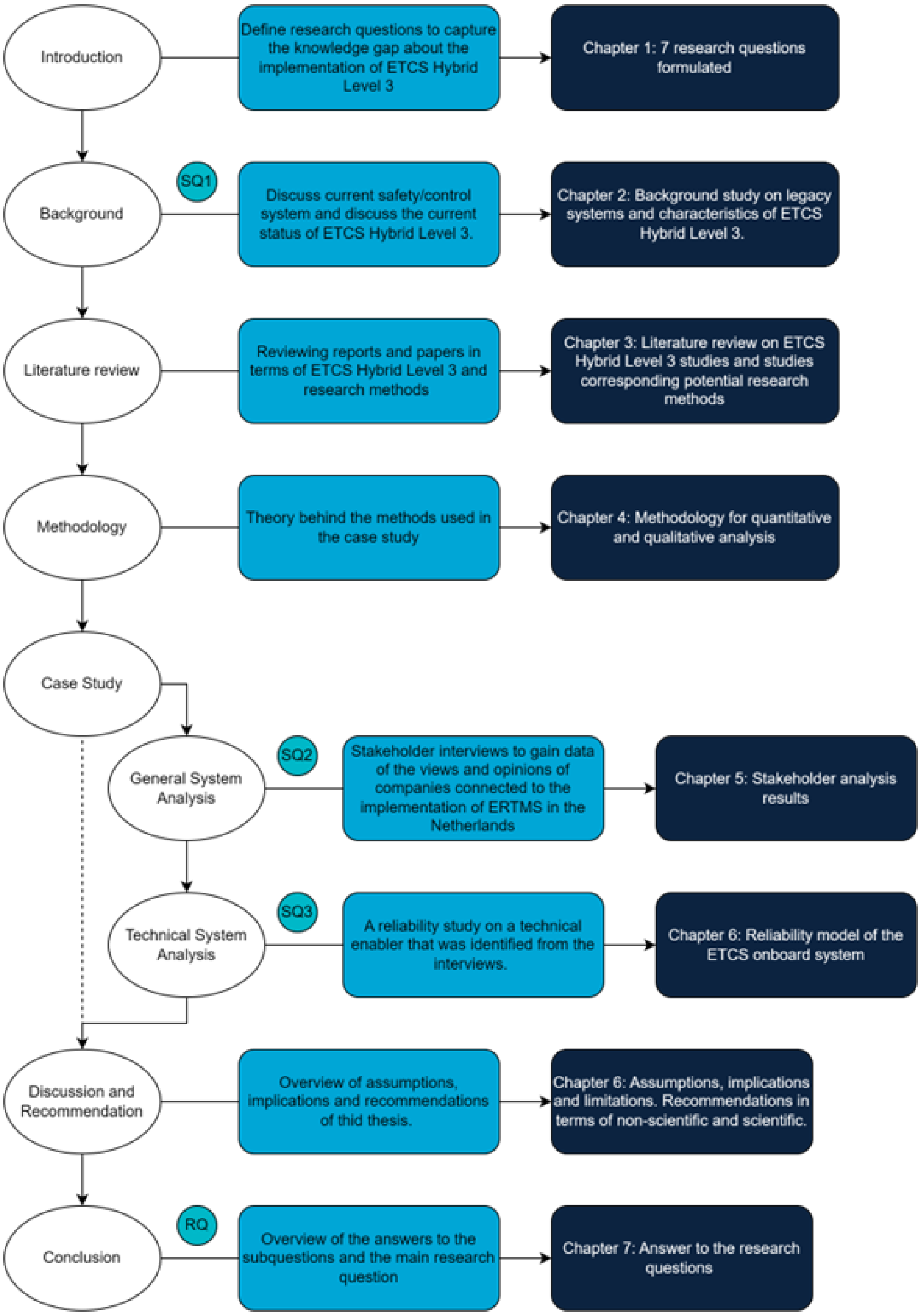

Figure 1.1: Thesis structure.

2 Background

This chapter covers the background information of the different train protection systems. First, the background of the older Dutch train protection system is presented. Then the system ERTMS with its levels and modes is discussed. Subsequently, the concept of ETCS Hybrid Level 3 and what this means for the various subsystems are reviewed. Finally, the stakeholders within the Dutch rail sector are explained.

2.1 Legacy train protection system

As described in the introduction to this thesis, ATB has been used as the ATP system in the Netherlands since the 1960s. The ATB system works in combination with the Dutch multi-aspect fixed-block signalling system. The ATB system with which the main network of the Dutch railway is equipped is Automatische TreinBeïnvloeding-Eerste Generatie (ATB-EG). Within this system, the track is split into fixed blocks where physical light signals are located at the beginning of each block along the track. Furthermore, communication about the maximum speed to the trains goes through coded track circuits. Downsides of NS'54/ATB-EG are that it has a limited speed supervision of only 5 speed steps (40, 60, 80, 130 and 140 km/h) and the system does not include full brake supervision. Besides ATB-EG, there are two other forms of ATB in the Netherlands, namely ATB-NG and ATB-vv. Even though Automatische TreinBeïnvloeding-Nieuwe Generatie (ATB-NG) is a system suitable for all railway lines, it is mainly used on regional lines in the Netherlands. With ATB-NG, there is intermittent communication through beacons. Through these beacons, the driving permission is transmitted to the train, which includes the maximum distance the train is allowed to travel and its associated maximum speed. As a result, ATB-NG includes braking curve monitoring. Automatische TreinBeïnvloeding-Verbeterde versie (ATB-Vv) is a supplement to ATB-EG. With ATB-Vv, a solution has been added to close the gap for train speed below 40 km/h. The additions for ATB-vv include 3 connected beacons placed in front of the corresponding signal [24]. The system monitors at each beacon whether the train can still stop within the relative distance in front of a stop signal with its current speed and braking behaviour. This ensures that ATB-vv contains braking curve monitoring for trains with a running speed of at most 40 km/h.

ATB systems belong to analogue train protection systems. For the next innovation step to digital track, ERTMS has been defined as a European standard.

2.2 European Rail Traffic Management System

European Rail Traffic Management System (ERTMS) aims to eliminate the technical conflicts caused by different national railway signalling systems in order to improve the interoperability of the European railway network. ERTMS is therefore stated as the European standard for the Control, Command and Signalling (CCS) system which create the opportunity for potential increasing safety and efficiency. The two main components of ERTMS are ETCS and Global System for Mobile Communications - Railway (GSM-R). In addition to these two systems, ERTMS also includes a Traffic Management Layer and operating rules. For the Traffic Management Layer, the plan was to establish specifications for a European Traffic Management Layer (ETML), but this component has not been developed to date. ETCS is the signalling and control component of ERTMS and specifications of system requirements of ETCS are set out in Subset-026 [12]. The ETCS architecture is divided into the On-Board Unit (OBU) and track-side subsystem. Where the RBC and IXL together the Central Safety System (CSS) is the main component within the track-side subsystem. The specifications of the GSM-R system cover the communication between the train and railway control centers. This includes voice communication and communication between the RBC and the radio module in the train.

2.2.1 Levels and Baselines/Versions

A fundamental concept of ETCS is the different levels. These levels were devised because of the wide variety of signalling systems within Europe. Within ETCS, the following levels can be distinguished:

- Level NTC
- Level 0
- Level 1
- Level 2
- Level 3

The following paragraphs highlight the different levels and Table 2.1 provides an overview of these different levels.

Level NTC
In the case of Level NTC, a train equipped with ERTMS runs on a track equipped with the national signalling system. This requires a Specific Transmission Module (STM) inside the train which provides the interface between the national ATP system infrastructure and the ETCS on-board equipment. As a result, supervision of speed and transmission of information takes place through the national signalling system. The STM module is country-specific, for example, a train must be equipped with an STM-ATB to operate in the Netherlands.

Level 0
When operating at level 0, no train control system is active. The maximum speed of the train is determined by maximum design speed of the train or the maximum permitted speed in an unfitted area. Besides this speed, the on-board equipment does not provide supervision. Therefore, apart from the current train speed, no supervisory information is displayed on the Driver Machine Interface (DMI). Operating under Level 0 in the Netherlands is therefore only allowed on decommissioned sections of track.

Level 1
Within the ETCS L1, ETCS operates as an intermittent ATP system. As a result, Level 1 is closest to the legacy national system ATB-NG. Here, a discontinuous information transfer takes place from fixed and switchable Eurobalises to the train. The difference between these types of balises are explained in subsection 2.2.3. The information transmitted from the Eurobalises on the track to the Balise Transmission module (BTM) is used to calculate braking curves and speed profiles. These are monitored inside the train, providing continuous supervision. Furthermore, no information transfer takes place to and from the track/shore via GSM-R. As a result, the train does not receive any new information between the balise groups. The Movement Authority (MA) for the train is generated by the Lineside Electronic Unit (LEU) connected to the balises and interlocking. As a result, the train receives new MA only when it passes over a balise. Within this level, both the DMI for cab signalling and the signals at the track are used. The fixed signals on the track indicate to the driver that a new MA is available in the scenario when the train has come to a stop in rear of the balises. A variation within this level is the addition of an infill loop, which allows the train to receive a new MA before it has passed the balise. This reduces unnecessary braking and thus allows the trains to run more efficiently. For train detection, track circuits or axle counters are used within this level.

Level 2
One step further is ETCS L2. Unlike Level 1, in ETCS L2 there is continuous information transfer via a GSM-R radio connection. This GSM-R connection provides a two-way communication between the European Vital Computer (EVC) and the RBC. Instead of the LEU, the MA is now provided by the RBC. In ETCS L2, fixed blocks are still used. But the trackside signals have been replaced by Stop Marker Board (SMB). These are placed at the end of each block section to which the MA is then connected. Replacing track-side signalling, ETCS L2 uses only in-cab signalling. This makes it possible for trains to run at a higher speed on the track because the driver is no longer limited by his sight distance. As in lower levels, the balises are mainly used provide information used as a reference point for the location of the train. This information is used to provide the position reports to the RBC. Between the balise groups, the location of the train is determined by the location of the last relevant balise group and the distance

traveled calculated by the odometer. When the train passes over a balise group again, the location is reset, and again reducing the accuracy error margin. To check for track section occupancy, axle counters or track circuits are still used in ETCS L2.

Level 3

European Train Control System Level 3 (ETCS L3) is like Level 2 a signalling and control system which uses radio communication via GSM-R. Also in this level, the Eurobalises have the function of mainly providing geo-reference information to the train. The MA is again provided by the RBC, but the difference with ETCS L2 is that it does not use fixed blocks where the TTD disappears. This is made possible by the addition of TIM system in the train. This system monitors the integrity of the train, and will add this information in the position report to the RBC so that the location of the front of the train and train length is known. The additon of TIM makes it possible to use moving blocks and/or virtual blocks. With moving blocks, an MA is given to the train depending on the position of the rear of the predecessor. This makes it possible to run trains with a shorter minimum headway behind preceding trains. When integer trains run on rail corridors where there is still TTD, Interlocking (IXL) will obtain track occupancy through the RBC instead of the TTD. When it is chosen to remove the TTD from the track, interlocking will depend entirely on the level 3 system for track occupancy. Because pure ETCS L3 is completely dependent on wireless communication via GSM-R, the completeness (integrity) of the train cannot be checked for trains without TIM. This makes it impossible to know for sure if all parts of the train have left the track without the presence of TTD.

Level	**Summary**
Level NTC	ATP provided by NTC. STM functions as interface between NTC and ETCS on-board equipment. DMI displays maximum speed allowed by NTC.
Level 0	No ATP system active. Maximum speed set bij National Value. No trackside train detection
Level 1	Fixed block sections with track-side signals. In-cab signalling in addition to the trackside signals. Discontinuous data exchange through balises. LEU provides MA to the balises. Train receives MA via BTM from balises
Level 2	Fixed block sections with SMBs. In-cab signalling only without track-side signals. Data exchange between RBC en EVC through GSM-R. Trackside train detection still present. Eurobalises transmit geo-reference information.
Level 3	Also in-cab signalling only. No trackside train detection. Train integrity monitoring by TIM. Possibility of moving block.

Table 2.1: ETCS Level overview

To get a harmonized European rail network, the ERTMS specifications have apply to all EU countries. The specifications are developed, but can still be updated with new versions. A consolidated version of a set of specifications is called a baseline. There are baselines for both the ETCS system and the GSM-R system. For the GSM-R, there is currently only one baseline (GSM-R B1). For ETCS there are currently 3 different baselines: B2, B3MR1 and B3R2. When modifications are made within a baseline, it is indicated by a release number. The number behind the Release (R) indicates which release number of the baseline it is. For smaller maintenance modifications, the letter M is used before the R. System Version (SV) are specified within a set of specifications. But SV are not associated with a specific set. An SV defines the mandatory technical functions involving interoperability between the ETCS on-board and trackside. So SV is a version of the ETCS Language identifying which functionalities can be used. Each baseline defines the specifications for Level 1, Level 2 and Level 3.

2.2.2 Modes

As discussed earlier, the use of TTD, trackside signals and GSM-R depends on the ETCS level. But in addition to the levels, the operating mode the train is in also affects the information exchange. The different modes are defined in Subset-26 by ERA * UNISIG * EEIG ERTMS USERS GROUP [12]. Of these, 5 are commonly used while running on operating track:

- FS (Full Supervision): All train and track data needed is available in de ETCS train equipment. The EVC fully supervises the train movement and the train has recieved a MA.
- LS (Limited Supervision): The Limited Supervision mode enables the train to be operated in areas where track-side signals are not fitted with LEU or connected to a RBC. In this situation ETCS does not have all trackside information. This mode can not be selected by the train driver and is only entered automatically by trackside. The ETCS on-board system is responsible for the background supervision of the train movement to the extent that the information is reported by the trackside equipement.
- OS (On Sight): Enables the train to enter a track section that could already be occupied by another train or obstruction. In this mode the driver is responsible for checking the occupancy of the track. The EVC supervises the the movement of the train against the dynamic speed profile.
- SR (Staff Responsible): This mode is used when the route is unknown for the system. The driver is allowed to move the train under his own responsibility in an ERTMS/ETCS equipped area. The ETCS equipment supervises the balise groups passed, the distance traveled and a certain ceiling speed.
- SN (National System): In SN mode the national system is able to access the ETCS equipment like: DMI, TIU and Odometer through the STM interface. the national system is responsible for all the train supervision, where ETCS on-board equipment has no functionality.

2.2.3 ETCS Hybrid Level 3

Due to the growing demand for capacity and the challenge of implementing TIM within all trains for ETCS level 3, an intermediate step has been designed in which both integer trains with TIM and non-integer trains without a TIM can operate on the track. The concept of ETCS Hybrid level 3 is the introduction of VSS. The fixed TTD blocks are divided into smaller virtual blocks. This allows trains equipped with TIM to run with a smaller minimum headway time, and the trains without TIM on-board can fall back to the underlying ETCS L2 fixed block sections with TTD. Within ETCS Hybrid Level 3, axle counters are used for TTD at the boundaries of the fixed block sections to provide the fall-back to ETCS level 2 for non-integer trains. As described in section 2.2, the ETCS system can be divided into 2 main subsystems: On-board system and Trackside system. This subsection explains the components within the two subsystems. It uses the glossary that has been defined in Subset-23 [11].

On-board components

European Vital Computer (EVC)
The heart of the ETCS on-board train equipment is the EVC. This component processes all information within the train and is therefore in communication with the other on-board train components. As shown in Figure 2.1, the train receives the MA through the Radio Transmission Module (RTM). With the MA and the entered train specifications, the EVC calculates the braking curves for the End of Authority (EoA). In addition to processing the incoming information, the EVC also monitors the dynamic speed profile of the train. Because this causes the EVC to be viewed as safety components, the EVC is built as a redundant system. This is often implemented as a 2 out of 3 system, where two EVC system-components must fail simultaneously before the train fails.

Radio Transmission Module (RTM)
The RTM is an on-board module that provides the bi-directional data exchange between the RBC and the on-board subsystem. The data send from track to train contains track description and MA and the data send form train to track is mainly a position report. The data report format send via RTM to the RBC is

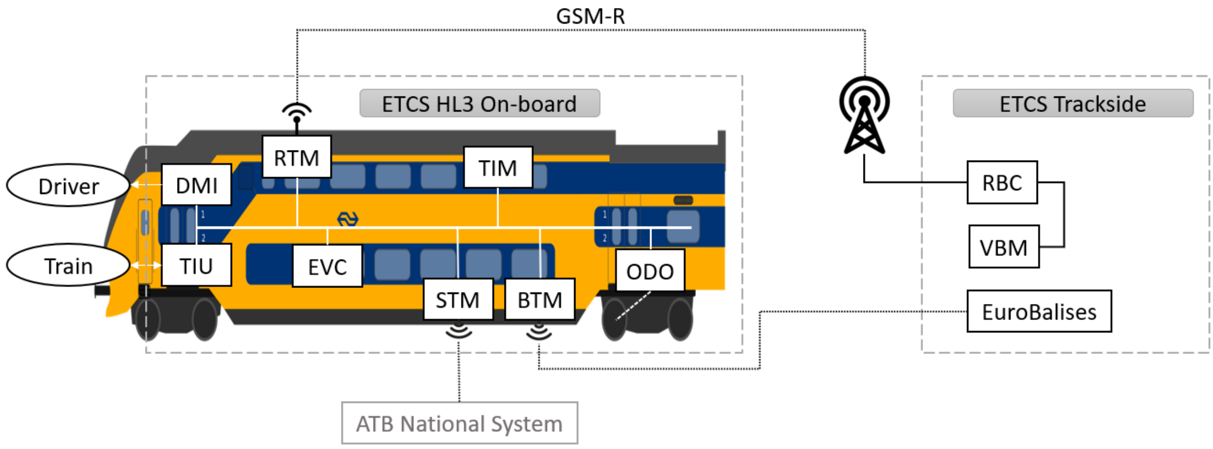

Figure 2.1: ETCS (Hybrid) Level 3 subsystems.

identical for train with TIM and without TIM, but for the train with TIM the train integrity and length are set to 1 for integer trains and 0 for non-integer trains.

Odometry System (ODO)
The odometer calculates the location of the train by means of a redundant system including a tachometer and a radar. Here the location is determined by the last transmitted location reference of the eurobalises in combination with the driven distance of the train. The system calculates the distance, acceleration and speed of the train and delivers this data to the EVC.

Balise Transmission module (BTM)
The intermittent communication from the track to the train goes through the BTM. This module send a tele-powering signal and energizes the eurobalise at the time of passing.

Driver Machine Interface (DMI)
The information interface between the train and the driver is provided by the DMI. This component shows the information about for example the track and movement authority in the cab. Here the driver can see the required brake behaviour and the maximum speed allowed of the track. Furthermore, the DMI allows the driver to input required data such as train length and selection of RBC in the situation of a moved train.

Train Interface Unit (TIU)
The communication between the ETCS on-board system and the rolling stock is provided through the TIU. Here the train transmits information about the direction of movement to the EVC, so that there is a possibility for the ETCS system to monitor the train for backward driving. Through the TIU, commands from the ETCS system are also given to the rolling stock. An example of a command given to the train via the TIU is the command to apply the brakes.

Specific Transmission Module (STM)
To ensure the interoperability of the train, the train is equipped with an STM. This module provides the interface between the ETCS on-board system and the track side data from a national ATP system. This makes it possible for a train with ETCS on-board equipment to communicate with another national ATP system as ATB. In this case, the STM transmits the ATB data from the balises or coded track circuit to the data that can be monitored by the ETCS equipment.

Train Integrity Monitoring (TIM)
One component which is introduced in European Train Control System Hybrid Level 3 (ETCS HL3) compared to ETCS L2 is the TIM. This system monitors the completeness of the train. The completeness of a train is defined as a train that is physically and continuously coupled together by couplers [17]. With the the completeness of the train and the entered train length, the position of the back of the train can be calculated. The information of completeness is transmitted to the EVC and is further transmitted to the RBC

via the GSM-R link. By the implementation of TIM, the train detection will shift from the infrastructure to the on-board system of the train.

Trackside subsystem

Eurobalises
In ETCS hybrid level 3, the main function of the eurobalises is to provide a geo-reference to the train. With which location delay caused by distance travelled measurement of odometry is reset by this geo-reference. The eurobalises are passive communication components mounted on the track and are not connected to a power supply. the balises are energized by the BTM the moment the train passes. When activated by the BTM, the balise will send out up-link data to the BTM.

Radio Block Center (RBC)
The RBC is a central safety unit that communicates with the trains via GSM-R, in which the rbc receives the train position report and sends movement authorities (Subset-023) [11]. The RBC is connected with the interlocking, requesting to the Interlocking (IXL) whether there is a safely set route for the train. When the route is secured, the RBC can transmit a Movement Authority (MA) to the train for that route. The RBC has supervision over a particular track area where more than 100 trains can be actively monitored. To make a safe transition for the train on a border of a track area, the RBC's of adjacent track areas are connected to each other. The communication between RBC's is needed when a train wants to move from one RBC track area to another RBC track area.

Global System for Mobile Communications - Railway (GSM-R)
An international standard has been introduced for the communication of trains within ERTMS: Global System for Mobile Communications - Railway (GSM-R). This is a mobile telecommunications specialised supplemented by railway-specific functions and is used for data exchange between the train and the RBC as well as voice communication between the driver and train control. Within this data exchange, from the train its location and completeness is relayed to the RBC, with the RBC sending back a movement authority when the route is secured. To enable this communication, the trains are equipped with a the previously mentioned modem: RTM. A train carries several of these modems to facilitate transitions between RBC regions. For an additional layer of security within this communication, a protocol called Euroradio has been implemented. This protocol has therefore been implemented on both the train side and the RBC.

System definitions

Compared to lower levels of safety systems, ETCS Hybrid Level 3 distinguishes between 3 types of trains: Integer, non-Integer and Non-ERTMS. The advantage of ETCS Hybrid Level 3is that integer trains can use virtual subsections (VSS). Because these VSS are not previously used in ETCS L2 and NTC, different principles apply. These principles are established in documents of EEIG ERTMS Users Group [10]. In the paper of Butler et al. [4] these principles are translated into a list of requirements that the safety system must meet to work. For example, the behavior of the VSS is explained in situations of a ghost or shadow train. The distinction between the first mentioned integer and non-integer trains, depends on the presence of a TIM. The aim is to minimise the amount of non-integrated trains on rail corridors where ETCS Hybrid Level 3 is operated. This quantity is important since non-integer trains have an impact on the capacity of the ETCS Hybrid level 3 track, because the non-integer trains occupy the entire fixed block.

Virtual Sub-Section (VSS)
With the implementation of TIM system to trains, the opportunity arises to implement the concept of virtual subsections. A virtual subsection represents part of a TTD block section. In the case of Hybrid level 3, the occupancy of virtual subsections will be determined by means of both TTD and the position/integrity of the train. Fixed virtual subsections allow integer trains to run closer together. This result can also be achieved with TTD block compaction, but with virtual block sections the required axle counters will not increase. A virtual subsection has 4 statuses it can have within ETCS hybrid level 3: Free, Occupied, Ambiguous and Unknown. Here, Ambiguous and Unknown are new compared to the status of a TTD block section. A subsection is Ambiguous when the trackside has position report information that a train is located on the VSS but does not know certain that there is not another train located in the rear of this train in the same VSS. In case of Unknown, trackside has no position report information that a train is located on the VSS

and so is not sure if the VSS is free. The definition of the VSS must be known in the IXL so that it can check which sections of track are occupied.

2.2.4 Stakeholders

Major modifications like the introduction of ETCS Hybrid Level 3 have implications for stakeholders in the rail sector. The introduction of ETCS HL3 will require adjustments on both the train side and the track side. In order to link the results to the actors at a later stage of this study, it is important to outline an overview of the most relevant stakeholders involved within the Dutch train network. This section lists the different stakeholders with their involvement.

ERA

At European level, the European Union Agency for Railways was set up in 2004. This agency is tasked with creating/maintaining a framework both technically and legally for a Single European Railway Area (SERA) covered by mandatory European laws. The ERA is in charge of specifications for ERTMS and, since 2019, is responsible for issuing safety certificates and approval for ERTMS equipment. To realize innovations like ETCS hybrid level 3, specifications of a new system has to be approved and maintained by the ERA. The technical specifications of the subsystems ETCS and GSM-R are defined in the Technical Specifications for Interoperability (TSI). The drafting of the TSI allows individual European countries to adhere to European specifications to ensure train safety/control system interoperability.

Ministry of Infrastructure and Water Management

The Ministry of Infrastructure and Water Management (I&W) is an organisational unit within the Dutch Government that is responsible for the quality of railways. The ministry is the organisation that commissioned the rollout of ERTMS in the Netherlands. This rollout is set out in European agreements, which require the Netherlands to equip its main rail corridors with ERTMS by 2031. With a follow-up step that by 2050 the rest of the main rail network must be equipped with ERTMS.

ProRail

The contract for the roll-out of ERTMS in the Netherlands issued by the Ministry of Infrastructure and Water Management to ProRail. This outsourcing means two assignments for Prorail. The first is for the independent component within Prorail: ERTMS Programme Directorate. This directorate is responsible by directing and coordinating the ERTMS roll-out across the entire rail network. In doing so, the Directorate reports directly to ProRail's Board of Directors and the Ministry of Infrastructure and Water Management. The coordination structure for the ERTMS deployment programme is shown in Figure 2.2. This shows that the ERTMS programme directorate coordinates across the various implementation divisions: ERTMS rollout within NS, Implementation ERTMS at equipment owners and transport operators and Implementation ERTMS in the rail infrastructure. The latter includes the second assignment ProRail has received from the ministry. Here, the implementation of ERTMS in the infrastructure is carried out by Implementation ERTMS ProRail (IEP). Unlike Programme Directorate ERTMS, Implementation ERTMS ProRail (IEP) is not an independent organisation and is a department of ProRail's line organisation. This department is responsible for implementing ERTMS within the track infrastructure and RBC.

NS

As mentioned earlier, the ERTMS Programme Directorate coordinates the roll-out of ERTMS across the entire rail network. In addition to adjustments to the network infrastructure, trains also need to be adapted to be able to run on ERTMS. As NS is the largest travel carrier in the Netherlands, the ERMTS@NS programme has been set up within NS. This organisation is responsible for making NS future-ready, which involves updating or modifying trains to make it possible for them to also operate under ERTMS. In addition

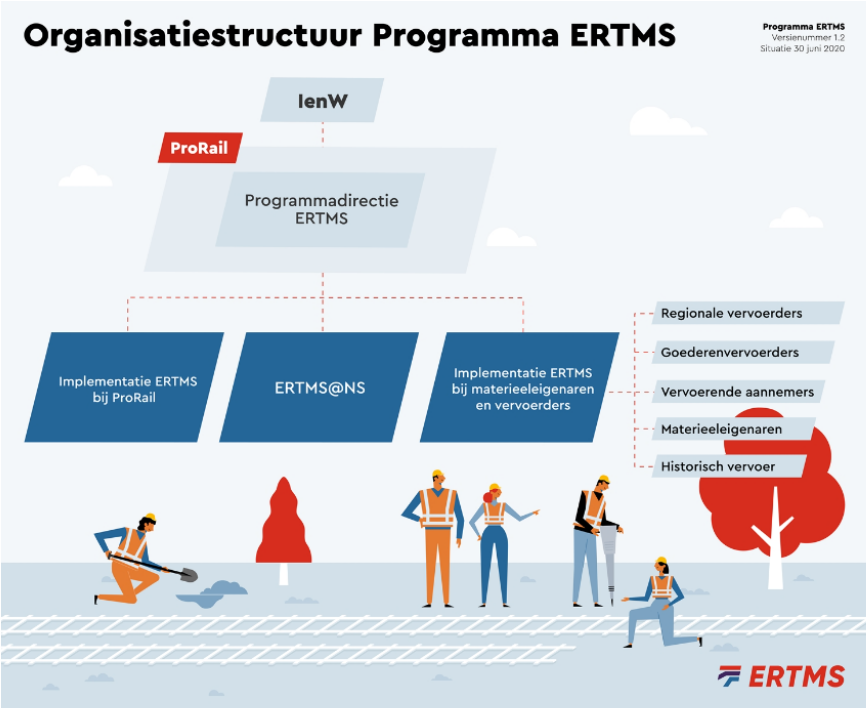

Figure 2.2: Organisation structure ERTMS roll-out. Source: Programma ERTMS [23].

to rolling stock adjustments, the ERTMS@NS, in collaboration with the rest of the NS organisation, prepares the adjustments for preparing a timetable that is ERTMS-proof. To prepare NS for the arrival of ERTMS, the organisation will have to train employees such as train drivers, planners and maintenance engineers for the new system.

Rolling stock owners and carriers

With the organisation set up within NS, the rolling stock managed by NS will be changed. Besides NS' rolling stock, there are many other trains using the tracks owned by other companies. First, there are the local train operators that facilitate regional lines via transport concession from provinces. The introduction of ERTMS may have an impact on these regional trains, requiring the regional operators to adjust their rolling stock. These adjustments will be compensated by the concession granters. After which, these concession providers can be compensated again by complying with the service obligations.

Not only passenger routes will be equipped with ERTMS. The corridors used for freight transport within Europe are also included in the ERTMS rollout in the Netherlands. here, the focus is on the sections belonging to the so-called TEN-T corridors. As with passenger trains, goods trains will also be fitted with on-board ETCS equipment to operate on the upgraded sections of track. This has implications for both freight operators and rolling stock owners. The cost of equipping locomotives with ETCS equipment is high, requiring the rolling stock owners to make a large investment to keep their rolling stock functioning. As compensation, these freight operators can appeal for CEF-subsidy. This financial aid is co-financed by the European Union. The total conversion costs will not be fully funded by the CEF-subsidy, so part of the costs will always be borne by the freight operators and equipment owners.

Track maintenance requires contractors to be able to access the track with their work trains. As a result, this rolling stock will also have to be equipped with ETCS equipment. Investigating the possibilities of financial support for this addition of ERTMS an the work trains, a market consultation via TenderNed has been launched by Programme Directorate ERTMS. It is therefore not yet clear how and by whom these costs will be financed.

Thales Netherlands

As mentioned earlier, Thales Netherlands is the trackside system supplier of ERTMS within the Netherlands. Thales Netherlands is a subsidiary of the global electronics company Thales Group. Within the ERTMS Programme, Thales is responsible for the CSS in infrastructure. Here, Thales takes care of the development, supply and maintenance of the safety systems and objects related to the ERTMS infrastructure. During this project, Thales works closely with ProRail to ensure the interface between the CSS and the rail infrastructure.

ERTMS Knowlegde Alliance

Besides the relation with Thales, ProRail has launched a cooperation contract with 5 engineering firms Arcadis, Movares, Nexus Rail, Royal HaskoningDHV and Sweco. This collaboration goes under the name of ERTMS Knowledge Alliance and aims to deliver ERTMS Level 2 in the Netherlands through "open engineering". Open engineering enables engineering companies to gain knowledge and experience with the implementation and application of ERTMS Level 2. As a result, the engineering companies are able to independently carry out projects within ERTMS from design to commissioning of the installations. By introducing the ERTMS Knowledge Alliance, an opportunity presents itself for ProRail to tender future projects on the ERTMS rail network. This will create healthy competition between engineering firms and ProRail will no longer depend solely on system supplier Thales.

2.3 Conclusion

The main operational difference from ETCS Level 2 is that under ETCS Hybrid Level 3, there is a variation in minimum headway times due to the combination of integer and non-integer trains on the track sections. Trains still operate on fixed blocks with TTD, but with Hybrid Level 3, these fixed blocks are now divided into virtual blocks. Operating with virtual blocks is only feasible if trains can monitor their integrity and train length. This monitoring is done through the TIM on board the train. Behind integer trains, the track can be cleared faster than behind non-integer trains. As a result, the availability of TIM in the relevant rolling stock must be taken into account during timetabling. The addition of virtual blocks does also open up the possibility of enlarging the fixed blocks. As the fixed blocks are made longer, the investment costs for e.g. axle counters will decrease. In contrast, if ERTMS Hybrid Level 3 fails, the minimum follow-up time will increase due to the larger fixed blocks.

In addition to the module that will monitor integrity, changes in track layout also take place. Here, the newly defined virtual blocks have to be integrated into the system. The most obvious choice is to incorporate this into the RBC and IXL. This requires a new software in the RBC and IXL in which the combined track layout of TTD and virtual blocks are defined. Introducing a new safety/control system happens in collaboration between the stakeholders involved. Within the Netherlands, there are many stakeholders in the ERTMS programme. These are stakeholders at different levels. At the top is the European organisation (ERA) in which the principles and specifications of the new ERTMS version must be established. This is necessary so that the national governing bodies (I&W) can carry out the roll-out of ERTMS according to European regulations. Besides the organisational institutions, the major stakeholders can be divided into three groups: the infrastructure (ProRail), the main carrier (NS) and regional carrier/equipment owners. Each of these three groups will be affected when implementing a new safety/control system.

3 Literature Review

This chapter contains the literature review of the different research studies related to this thesis. First, the papers on the impact of ETCS Hybrid Level 3 are discussed. Subsequently, the studies on the TIM are discussed. In addition to studies on the impact of ETCS, studies on the reliability of systems such as ETCS are reviewed.

3.0.1 ETCS Hybrid Level 3

Capacity assessments

Multiple studies show that Hybrid Level 3 provides a positive impact on the performance of the rail network. For instance, Jansen [15] conducted a capacity study for ETCS Hybrid Level 3 using microscopic simulation. In this study, in comparison to ATB-NG and ETCS L2, several variants of ETCS Hybrid Level 3 were considered. The study examined which VSS block length will provide minimum capacity consumption. Here a distinction was made between VSS of 500m or 100m and existing or reduced Track-side Train Detection. The results are that ETCS Hybrid Level 3 with VSS block lengths of 100 meters with existing track-bound train detection results in the lowest capacity consumption. The stations and railway have not been included in this study, which means that not all options for ETCS Hybrid Level 3 have been covered. However, a start has been made within this study into the impact of ETCS Hybrid Level 3 on technical interruptions as a result of the failure of trackside train detection (in this case axle-counters).

Similar to the paper of Jansen [15], Ranjbar et al. [29] also conducted a capacity study for ETCS Hybrid Level 3. In this study a micro simulation is conducted to assess the impact of ETCS Hybrid Level 3 versus the Swedish national legacy system ATC2 and ETCS L2. The fixed TTD blocks were remained unchanged, and in the ETCS Hybrid Level 3, VSS of 100 to 200 meters were used. It resulted in higher performance and capacity gains of respectively 14% and 9% compared to ATC2 and ETCS L2. This study is based on a static situation of a single track with heterogeneous train traffic. As a result, the study was conducted with a simplified situation compared to the rail network of the Netherlands.

In the paper by Vergroesen [34], a capacity study was conducted which tested the impact ETCS Hybrid Level 3 combined with Automatic Train Operation (ATO) on the capacity consumption. The results show that by adding ATO, there is a significant reduction in capacity consumption. The reduction is obtained by the fact that trains can brake later with ETCS Hybrid Level 3 in combination with ATO. As a result of ATO, the buffer time can be hypothesised to be reduced from 60 to 30 seconds, and will result in an even greater reduction in capacity consumption.

In all three papers [15][29] [34], research has been done with heterogeneous train traffic. The calculations for capacity consumption are therefore based on the assumption that all regular passenger trains are equipped with a train integrity module. As a result, the calculations are for the ultimately desired situation and do not provide a picture of the impact of ETCS Hybrid Level 3 in the transition years during implementation.

Implementation strategy

The research study by Westerhuis [35] investigates where the adaptability of ERTMS in the Netherlands can be strengthened while the operability level of the system remains at the same level. This study also examines the impact of the ETCS Hybrid Level 3 innovation. It is stated here that the implementation of ETCS Hybrid Level 3 does not have a high impact. The paper assumes that the passenger trains are already equipped with a TIM. The system within the passenger trains indeed knows that the train is complete, but this is not at the required safety level (SIL 4). The implementation of the TIM with the required security level can therefore have a major impact.

3.0.2 Train Integrity Monitoring (TIM)

The method by which the completeness and length of the train is checked depends on the situation. While the technical solution for TIM has been frequently imagined in papers, it has not yet been technically developed. Among the methods for a TIM, there is a clear difference in difficulty. The reasoning for this is that multiple unit trains have an electrical connection (BUS) running throughout the train, making it relatively easier to establish communication between the front and rear of the train. In contrast, the methods for freight trains are less easily feasible because freight trains do not contain electrical connections between the wagons. These wagons are connected only by mechanical coupling and a compressed air pipe used for braking. A method for digitising a goods train is to implement Digital Automatic Coupler (DAC) in the freight wagons. This coupler provide an electrical connection throughout the freight train [5]. There are studies that have examined the potential methods for integrity monitoring for freight trains. The methods in the following references are only examples for integrity monitoring and are not yet established technologies.

In the paper of Pradeep kumar et al. [22] a three certification way TIM is researched. Here the combination of satellite positioning, air pressure in brake pipe and speed/acceleration monitoring is used. By doing this three way certification, the probability of having a false parting train is reduced. The innovations use a module in the head and end of the train with a wireless communication interface. With these two communication interfaces the probability of no communication is reduced. Both modules on the head of the train and end of the train have transceivers to facilitate the communication. In the paper of Pradeep kumar et al. [22], the module end of the train is mounted on the last wagon and is battery powered and rechargeable by wind turbine. Every module has an individual identification number which is used to connect the Head of Train (HoT) with the correct End of Train (EoT) module. This will add an additional task for the train driver within the Start of Mission. Besides the two modules themselves, a device called Inertial Measurement Unit (IMU) must also be installed on the train. This device monitors the state of the two positioning modules, checking the distance and thus the length of the train between them.

Another method for monitoring train integrity is to use a Wireless Sensor Network (WSN). This method was explored in the papers of Scholten et al. [30]. In these papers, the method in which all wagons are equipped with their own wireless sensor node was investigated. These sensor nodes measure the movement of the individual wagons. Thus, the integrity of the train is monitored by checking the equality of movement of the different wagons of a train. In addition, the composition of the train, that is defined in the driver manifest, is checked with the topology established by the coordinator sensor node in the locomotive. This coordinator sensor built the topology by analysing the communication paths between the ordinary sensor nodes in the wagons. A disadvantage of this method is that each wagon would have to be equipped with a wireless module. These modules will then consist of a sensor type that detects movement, a power source and a communication module.

3.0.3 System reliability

There are multiple methods used in the literature to perform reliability analysis. Because ERTMS is a complex system, using only FTA or FMEA, will not be able to perform an accurate analysis when computing the whole system [1]. Therefore, some studies use bayesian networks in addition to these methods. STPA can also be used instead of the aforementioned methods when investigating the reliability of a complex system.

3.0.4 Fault Tree Analysis (FTA)

An example of the use of FTA can be seen in the paper by Flammini et al. [14]. This paper researched the reliability of the entire ERTMS/ETCS Level 2 system. For the ETCS on-board system, a standard FTA was used by Flammini et al. [14]. The results of the FTA were then used as input for the entire ERTMS/ETCS Level 2 system which was modelled using a Bayesian Network. Since the on-board system of the train in the paper of Flammini et al. [14] is not repairable on site, this gives the opportunity to be able to use a standard FTA.

3.0.5 Failure Mode and Effects Analysis (FMEA)

Whereas with FTA there is a clear binary choice between working and failing, with FMEA there is more consideration of the failure mode of the components. So one component can have different failure modes which can have different impacts to the systems. Within this analysis the failure modes are ranked. Like FTA, failure rates are also used in FMEA. The failure rates of components are linked to the different failure modes which can be determined by experience, history data or libraries. Besides FMEA, there is also a method called Failure Mode Effect & Criticality Analysis (FMECA). The difference with FMEA is that FMECA is more quantitative by calculating the risk contribution. An FMECA therefore takes into account how severe it is if a certain failure mode occurs. This is measured by a rating called Risk Priority Number (RPN). The failure modes are ranked by occurrence, detect-ability and severity. When multiplying these three ranks the RPN of the failure mode is calculated. Within the FMEA different categories of failures are defined as a results of failure modes. An FMEA can be used in two ways: the Top-Down approach and Bottum-up approach. The choice of method depends on whether the structure of the system is already defined or not. If the concept of the system is already defined, the Bottum-up approach method can be used, which looks at the component level and evaluates the effect of the failure modes of these components on the sub-systems. When the structure of the system is not yet defined, the Top-down approach is more appropriate and looks more globally at sub-system level instead of component level. The FMEA method is a good tool for determining the various failure modes, but lacks a strong redundancy tool. It is therefore preferable to draw up an FTA after an FMEA to analyse the dependency of the various components. This was therefore done in the paper by Kalvakunta [16] which used FMEA to identify the failure modes within the infrastructure systems. After which FTA was subsequently chosen to analyse the dependencies of the components within those systems.

3.0.6 Systems Theoretic Process Analysis (STPA)

When the reliability of a system needs to be calculated, but the system is so complex due to human errors or interactions between subsystems within the system, an FTA or an FMEA will not be sufficient. To test this interaction within the system, STPA is a method that can be used. STPA is a reliability method that makes it possible to find insufficient controls within the system. These can be dangerous situations caused by humar errors or interaction between different subsystems. For example, in the thesis by Aantjes [1], the STPA method was used to test reliability where the interaction between ETCS, train driver and dispatcher was defined.

4 Methodology

In this chapter, the methodology of this research is explained. The research in this thesis is divided into the general system analysis and the technical system analysis. The first part will explain the methodology for the general system analysis. That includes the set-up of questions for the interview, the agreements with candidates and data analysis. Moreover, the literature used for the interviews and the method is briefly elaborated. The following part is about the method used for the technical reliability research.

4.1 General system analysis

To obtain answers to research questions 2 and 3, a stakeholder analysis is carried out. To achieve the results to answer the research questions, the analysis is composed of several steps that together form a process. The methodology of this process is described in the next paragraph.

4.1.1 Process

By going through the stakeholder analysis process in a structured way, the desired outcomes of the different stakeholders will be better analysed. The process is divided into several steps and is shown in Figure 4.1.

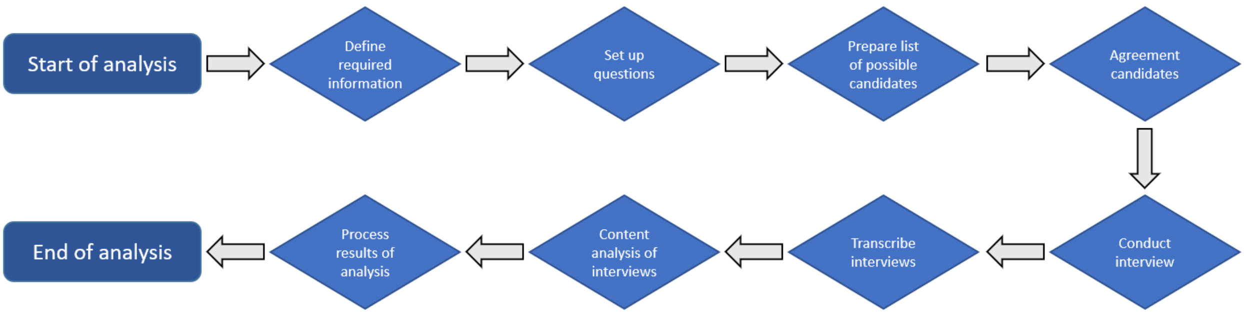

Figure 4.1: Process of stakeholder analyse. Source: [31]

This section will explain for each step what there is the goal and what needs to be done to achieve that goal.

Define required information
As a start of the process, the definition of the required information is needed. Within this study, interviewing the stakeholders aims to find out what image the stakeholders have of a new signalling/control system like ETCS Hybrid Level 3. Therefore, the required and desired information for the interviews are the opinions and accompanying justifications of the stakeholders as to how they see shifts in roles, responsibilities and policy by implementing ETCS Hybrid Level 3.

Set-up questions
A good structure of questions is necessary to obtain the desired information. When building an interview, the choice of structure is important. The choice of structure depends on the purpose of the interview. The different variants are:

- Structured interview
- Semi-structured interview

- Unstructured interview

In a structured interview, all the questions are predetermined and there will be no deviation from them. As a result, the order of the questions and the amount of questions will be fixed and there is no option for further questions from the interviewee. the advantage of asking the same set of questions is being able to analyse the data more efficiently. An unstructured interview is the most flexible structure for an interview. Here, there is room for spontaneity on the part of the interviewer, where the next questions can depend on the answer of the previous question. This allows for a deeper interview. But on the other hand, data collection and analysis become more complex. A combination of the two structures is a semi-structured interview. In this structure, the questions are fixed prior to the interview, but there is room for the interviewer to ask further questions on certain topics.

For the stakeholder analysis, a semi-structured interview is used. This enable the possibility for additional questions arising from previously conducted interviews through the Delphi method. The basic structure of the interview consists of the following 7 questions (Appendix A):

- Question 1: Can you give a brief description about yourself and your position within the rail sector?
- Question 2: What is your involvement with ERTMS on the Dutch rail network?
- Question 3: To what extent are you familiar with the ERTMS/ETCS Hybrid Level 3 concept? And what is your take on this new concept?
- Question 4: Do you see ERTMS/ETCS Hybrid Level 3 as an improvement system over ERTMS/ETCS Level 2?
- Question 5: What is your view on the cost shifts between ProRail and the rolling stock owners?
- Question 6: What do you consider to be the other critical constraints or issues that need to be addressed in terms of current roles, responsibilities and policies to enable seamless adoption of Hybrid Level 3?
- Question 7: How much time do you think is realistically needed to implement ERTMS/ETCS Hybrid Level 3 in practice based on the necessary adjustments in policy, regulation and stakeholder roles?

Questions 1 to 4 serve as a measurement for the candidate's expertise and position. As candidates are asked to answer from their position, asking their position within the stakeholder is important. Following this, it is necessary to establish in advance what the candidate's knowledge of ETCS Hybrid Level 3 is, so that the answers to the following questions depend on the candidate's expertise.

Questions 5 to 7 aim to obtain information to answer sub-question 2 of this thesis. In addition to the 7 pre-determined questions, additional questions were included in the interview depending on the stakeholder.

Interview candidates and agreements
The stakeholders included in the interviews and within the case study belong to the Dutch rail sector are explained in section 2.2.4. As the scope of the thesis is the Dutch rail sector, the ERA is not included in the stakeholder analysis. In advance of the interviews, stakeholders have been divided into 3 groups (Table 4.1).

Organisation	**Rolling Stock**	**Infrastructure**
Ministry I&W	ERTMS@NS	ProRail (IEP)
Prog. ERTMS	MRCE	Movares
	Rail Good/ WHB Rail	Thales

Table 4.1: Corresponding stakeholder groups

It is expected that stakeholders within the groups will have some degree of comparative expressions. The first group is the organisational group including the Ministry of Infrastructure & Water Management and the ERTMS Programme Directorate. These organisations are on top of the stakeholders as principal and regulator. Among them, the implementation of ERTMS can be divided into ERTMS implementation within rolling stock and infrastructure. Stakeholders categorised to the rolling stock group are: NS, MRCE and management-consultant companies. NS is the largest carrier on the Dutch rail network. In addition, MRCE was chosen to be included in this thesis because it is one of the largest locomotive leasing companies in Europe. Although under ETCS Hybrid Level 3 there is no obligation to equip freight locomotives with a TIM, these companies like MRCE will experience the effects of a new system. Last of the group are rail management companies, which represent freight operator groups in the rollout of ERTMS. For the infrastructure group, the following stakeholder are interviewed: ProRail, Thales and Movares. ProRail (IEP) is the responsible party for the implementation of ERTMS on the Dutch rail infrastructure. The party to which ProRail has outsourced the delivery of the ERTMS system is Thales. This company is responsible for the delivery and implementation of the new system. Movares is also involved in this implementation through the Knowledge Alliance and is therefore also an important party within the infrastructure group.

The selection for candidates within the stakeholders was done on the basis of their function within the respective company. In addition, new candidates emerged from interviews that were conducted. Prior to the interview, a consent form will be handed out to the candidates to establish what may be shared and in what manner. Collecting the candidates' answers can be done in several ways. The most obvious method is to record the interview so that post-interview transcription of the interview can be processed. This is possible only if there is permission from the candidate to record the interview. Another method is to take notes during the interview to elaborate post-interview the notes according to perception of the interviewer. This can lead to inaccuracies in collecting the results of the interview, which can make the analysis more inaccurate.

Transcription interview
Transcription is often seen as an at task to be done behind the scenes rather than a way of studying the data. The paper by Oliver et al. [21] identifies the various obstacles and opportunities of interview transcription. This clearly distinguishes between two dominant modes: Natural and denatural transcription. In natural transcription, every expression made is described in as much detail as possible. The advantages of this mode are that natural transcription: not only records verbatim conversations but also expressions sigh body language and actions. The unnatural method describes the interview word for word but omits everything else to make the text fluent. In this thesis, the unnatural method is chosen, as expressions are not applicable when establishing the views. As a result, in this thesis the interview is written out word for word, but in a way that the text flows more fluent.

Data analysis
The groups that are defined in this research are "Organisation", "Rolling Stock" and "Infrastructure". The stakeholders were divided into the groups according to their corresponding answers. With the analysis of the data, it is interesting to see whether these expectations are correct. And whether there are new groups will differ in opinions about ETCS Hybrid Level 3. Because stakeholders' answers for different questions may be consistent. When analysing the transcripts, the whole transcription is analysed first before conclusions are established. This avoids making misinterpretations by analysing data that has been taken out of context.

Implementing ETCS Hybrid Level 3 depends on many stakeholders. This creates the necessary complex policy decisions in the rail sector. The Delphi method is a theory that can be used to find out what decisions need to be made within the rail sector to achieve the implementation of ETCS Hybrid Level 3. The Delphi method focuses on a solution that exists from the research field. The Delphi method is often used for in-depth interviews where stakeholders from different disciplines interact with each other [3]. During the stakeholder analysis, feedback is used to take the findings of previous interviews into account in the subsequent interviews.

Results processing
With the different visions on ETCS Hybrid level 3, a overview will be made with every stakeholder. For each topic/barrier discussed, the different views of stakeholders are explained in the corresponding sections. The results of these topics are compiled into conclusion and recommendations.

4.1.2 Validity and reliability

The validity and reliability of the results when conducting a qualitative study are of great importance. Where validity refers to the credibility of the study, while reliability refers to the consistency of the study [32].

In the stakeholder analysis, semi-structural interviews are used, where the candidate was free to answer the questions without being influenced by the interviewer. The transcripts were corrected and approved by the candidates after the interview, so there is no erroneous information in the data. This allows the data from the results to be taken as valid. In contrast, the analysis of the data was done by only the researcher himself. Thus, the interpretation is of a single person and thus may affect validity. The validity of the results also depends on the size of the group of candidates. This validity increases as the group of candidates per stakeholder increases and the results can be generalised across the group. In this study, some stakeholders interviewed only 1 candidate, which raises the question of the generality of their responses. The reliability of the results depends on the analysis of the results. Since only the researcher analysed the data, there is more chance of misinterpretations. Even though the process of stakeholder analysis was explained in detail step by step, the repeatability of the study is questionable. This is because the study deals with an changing rail sector, so the probability is that different answers could be given to the interviews if they were conducted at different times.

4.2 Technical system analysis

The implementation of ETCS Hybrid Level 3 may affect the reliability of the railway network. Whether there is a change in reliability and in what magnitude it occurs can be researched using several methods. This section discuss method that is used to analyse the reliability of technical enablers within the implementation of ETCS Hybrid Level 3.

The focus of the first section will be on what reliability means within a rail system. This will include definitions of system reliability within this thesis. Subsequently, the method used in this thesis is provided

4.2.1 Railway system reliability definitions

European Committee for Electrotechnical Standardization (CENELEC) has prepared and published a European standard in the field of electrical engineering. One section of this standardisation is NEN-EN 50126-1 CENELEC [7], which defines the Specification and Demonstration of Reliability, Availability, Maintainability and Safety (RAMS). These standards are the standards that specifications for implementing ERTMS must meet. For the specifications of RAMS, EEIG ERTMS Users Group has produced the document: ERTMS/ETCS RAMS Requirements Specification EEIG ERTMS Users Group [9]. These specifications are based on EN-50126. The definition of reliability used in both documents is as follows: Ability to perform as required, without failure, for a given time interval, under given conditions. In addition to the specifications for reliability, the specifications of availability, maintainability and safety are taken into account in a RAMS analysis. But within this thesis, only reliability is included in the scope. Reliability can be expressed in different ways. For instance, the reliability of components can be expressed in Mean Time Between Failure (MTBF). This is the time between two moments of failure. The time required to repair the system or component is expressed in Mean Time To Repair (MTTR). Both MTBF and MTTR are often expressed in hours. The time a component is actually in operational status is the difference between MTBF and MTTR.

In this thesis, reliability is measured as a failure rate of the ETCS on-board system of the train. The decision to take trackside and interaction out of scope is that they cannot be defined in a standard FTA. The use of failure rates thus analyses the unreliability of different components. The failure rates in this thesis are defined as the inverse MTBF, and has a unit failure per hour. Within the reliability engineering, the progression of the failure rate over time is represented in a bathtub graph as shown in Figure 4.2.

The bathtub curve (Figure 4.2) is divided into 3 phases. The first phase is the Infant mortality phase, in which the probability of failure is high due to manufacture defect or misuse of the component. As time passes, you enter the second phase of the bathtub curve. This phase is the Normal Life phase where the failure rate is considered constant. At the end of the life cycle, the failure rate increases. This is the End of Life phase, where the failure rate is increased by wear out. For the failure rate of the components in this thesis, the failure rates are considered constant and only the Normal life phase is taken into account. The following two assumptions are made in this thesis:

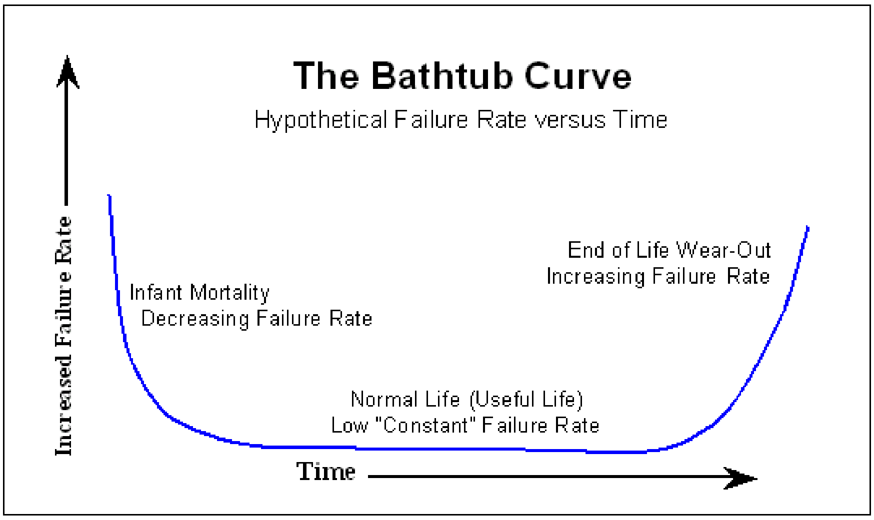

Figure 4.2: Hypothetical failure rate versus time. Source: Wilkins [36].

- By testing the system components intensively and training users before putting them into operation, it is assumed that the Infant Mortality phase can be disregarded.
- By maintaining a proper maintenance regime, components will be repaired or replaced before they enter the End of Life phase. And can therefore be assumed to disregard the End of Life phase.

Besides the failure of a system, the RAMS Requirements Specification [9] also distinguishes between different failure categories. There are three categories in total: Significant failure, major failure and minor failure.

4.2.2 Reliability method

In this thesis, the influence of ETCS Hybrid Level 3 on the on-board subsystem is specifically investigated. The literature review revealed that FTA is a good and passable method for calculating the reliability of a simplified system. Therefore, this thesis chose to use the FTA method to analyse the reliability of the ETCS Hybrid Level 3.

Fault Tree Analysis (FTA)
FTA is a deductive analyses what focus on a single undesired event. The FTA is looking at the cause of a hazard, and is a top-down analysis where it looks from the top event down to the cause at the lower component levels. The single undesired event within this method is defined as Top-Event (System Failure). This defined Top-Event is further composed of one or more subsystem events. Whereby these in turn may be further built up from underlying subsystems or ultimately Basic-Events (Component Failure). This branching from the Top-Event to the Basic-Events therefore forms the Failure Tree. The various events are connected by so-called Gates. The two most standard gates used are And Gates and Or Gates. With an And Gate, the output of the gate is calculated by multiplying the probabilistic failure rates of the inputs. An Or gate, on the other hand, takes the sum of the probabilistic failure rates of the inputs. In addition to these two gates, there is also the Voter Gate, which is used when a subsystem fails only when N number of inputs drop out of the M total. Thus, to calculate a 2 out of 3 Voter Gate, the following calculation applies: output = a*b + a*c + b*c. In the variables a,b and c in the equation are input failure data of the underlying events. There are theoretically more types of gates, but in this thesis only these three gates are relevant. The input parameters of components needed to calculate the FTA are defined as Failure Rate or MTTF. These are constant exponentially distributed failure rates. The FTA is a binary method and distinguishes between 2 states: the system is working as it should (output = 0) or the system is failing (output = 1). Besides the reliability of the Top-Event, an FTA can also calculate the influence of the individual components on this reliability. This is done using Fussel-Vesely. This value shows per basic event how much influence it has on the reliability of the Top-Event.

Reverse Engineering
The FTA analysis is a root cause analysis. The failure behaviour of the Top-Event is computed using the failure rates of the underlying components in the Fault Tree. ETCS Hybrid Level is a concept system and the failure data of the new components within the ETCS Hybrid Level 3 system are not available. To calculate failure data of the new components of a system, reverse engineering is used in this thesis. The purpose of the reverse engineering process is to abstract data specific from the original model that can be used to compute the required data of new objects or systems components [18].

4.3 Conclusion

In order to identify stakeholders' views, a structured stakeholder analysis process was chosen in this thesis. This involves semi-structural interviews in combination with a simplified version of the Delphi method. Chapter 5 applies this method to the Dutch rail sector as a case study.

Successively to the stakeholder analysis, the reliability of the on-board system is examined. In this thesis, the on-board functions in an FTA, as a top-down analysis can be used to see what causes the failure of a top event. Due to the lack of data for the newly introduced components of the TIM system, reverse engineering is used. This technical analysis is elaborated on the ETCS on-board system in Chapter 6.

5 General system analysis results

This chapter applies the stakeholder analysis methodology to the Dutch rail sector as a case study. First, the candidates of the interviews are explained. Following this, the results of the interviews are discussed by topic. In the results, reference is made to the reports of the interviews. Finally, the conclusions and recommendations of the results are discussed.

Stakeholder	**Code name**
Ministry of Infrastructure and Water Management	**M**
Candidate 1	M1
ERTMS Progamme Direction	**E**
Candidate 1	E1
Candidate 2	E2
Candidate 3	E3
ProRail	**P**
Candidate 1	P1
Candidate 2	P2
Candidate 3	P3
Candidate 4	P4
Candidate 5	P5
Candidate 6	P6
Suppliers	**S**
Candidate 1	S1
Engineering consultancies	**C**
Candidate 1	C1
Candidate 2	C2
Rolling stock Owners/Railway undertaking	**R**
Candidate 1	R1
Candidate 2	R2
Candidate 3	R3
Candidate 4	R4
Candidate 5	R5

Table 5.1: Overview of codenames per stakeholder.

5.1 Interview candidates

If possible, multiple candidates were interviewed for each stakeholder. Interviewing multiple individuals within a stakeholder allows for clearer distinction between personal opinions and views of the stakeholder. Table 5.1 shows how many candidates were interviewed for each stakeholder in this thesis.

5.2 Interview results

The results of the interviews were processed in the form of transcripts. After processing the interviews, the transcripts were analysed. In this section, the responses of the candidates are identified. subsequently, the challenges/limitations emerged from the interviews are discussed.

5.2.1 Categorized analysis

During the analysis, 3 categories were drawn up: Advantages of ETCS Hybrid Level 3, possible implementation barriers and implementation perspective of ETCS Hybrid Level 3. Within the categories, the various points of view were defined as subcategories. The categories and associated subcategories are shown in tables and explained.

Benefits ETCS Hybrid Level 3

	M1	**E1**	**E2**	**E3**	**P1**	**P2**	**P3**	**P4**	**P6**	**S1**	**C1**	**C2**	**R1**	**R2**	**R3**	**R5**
Capacity improvement	x			x			x	x		x	x			x		
Reliability improvement				x			x	x	x							
Cost reduction	x			x					x		x				x	
Robustness enhancement							x	x		x	x	x	x	x	x	x
Train Control improvement														x		
Flexibility enhancement							x	x						x		

Table 5.2: Identified benefits of ETCS Hybrid Level 3

The results of the interviews show that there are different opinions among stakeholders about the actual benefits of ETCS Hybrid Level 3. For example, NS indicates that the main benefits of ETCS Hybrid Level 3 are the capacity gains and the real benefits are going to come from ERTMS. While NS sees the capacity gain as the main benefits, an Expert Group at ProRail looks instead at the gains in robustness and reliability. Subsequently, several interviews revealed that the capacity gains achievable with ETCS Hybrid Level 3 are also achievable with the current ETCS Level 2. As a result, a ProRail project manager and external consultant, for instance, do not see ETCS Hybrid Level 3 as a capacity improvement but as a cost-saving opportunity. This is because the same block density can be achieved with both ETCS Hybrid Level 3 and ETCS Level 2, only with ETCS Hybrid Level 3 this can be done with possibly less track-bound train detection. The difference in opinions on the advantages of ETCS Hybrid Level 3 creates a difference in views on the required trajectory for the effective implementation of ETCS Hybrid Level 3. NS, for instance, does not see the implementation of ETCS Hybrid Level 3 happening in the short term because it is not feasible to equip the entire rolling stock with TIM. For this, the size of the rolling stock is too small to deliver the required punctuality. This is a non-feasible step, and stems from their idea that the capacity benefits of ETCS Hybrid Level 3 are only there when the whole of the rolling stock is equipped with a TIM. This is different with the view on implementation from ProRail. Where it looks at an effective ETCS Hybrid Level 3 in gradual steps.

Potential barriers of ETCS Hybrid Level 3

	M1	E1	E2	E3	P1	P2	P3	P4	P5	P6	S1	C1	C2	R1	R2	R3	R4	R5
Waiting for motivation from the sector	x	x	x												x			
HL3 transport-level design										x	x				x			
Old GSM-R system																x		x
Lack of sector harmonisation	x			x			x	x	x								x	
Rolling stock retrofit				x				x		x					x			
Lack of business case																x	x	x
Lack of European harmonisation												x				x	x	x
Political decision-making									x	x					x			

Table 5.3: Identified potential barriers of the implementation of ETCS Hybrid Level 3

Implementing a new system creates certain barriers. There are also barriers during the current roll-out of ETCS Level 2. But looking at Table 5.3, it is clear that there is a large spread between the different stakeholders. This makes it clear that the candidates from the freight rail sector are very focused on harmonization with the adjacent ETCS systems. For example, they want a system that is interoperable with the system in Germany. In addition to striving for harmonization, they also see the retrofit of rolling stock as a major barrier. This barrier is also recognized by NS candidates, among others. Only NS looks at it from an availability point of view, while the freight operators mainly see the barrier financially. In addition, it is also clear that organizations such as the Ministry of Infrastructure and Water Management and ERTMS Program Management see the barriers among the stakeholders themselves. It is indicated that a system such as ETCS Hybrid Level 3 will only be developed and included in the agenda, if the sector indicates that they need it and are ready for it. Because the motivation has to come from the sector. And at the moment this motivation is not yet there among the stakeholders. While stakeholders from the sector indicate that no steps can be taken until agreements have been made from the Ministry at sector level. And without these agreements, the stakeholders have no guidance and will not take the first steps.

The Ministry of I&W mentioned in the interview that the stakeholders in the Dutch rail sector are closely linked. This makes it important and necessary to take an optimal decision at sector level. Implementing ETCS Hybrid Level 3 mainly requires adjustments in RBC, Interlocking, rolling stock and user processes. According to ProRail Traffic Control, adapting the user processes is doable and achievable in a time frame of about three-quarters of a year. Further adjustments in RBC, Interlocking and rolling stock, depend on the type of implementation strategy of ETCS Hybrid Level 3. This strategy should be determined at sector level. In order to take the decision at sector level, clarity is needed on the feasibility of implementing ETCS Hybrid Level 3. Experts from ProRail have indicated that implementation at the track-side is technically feasible. This also emerged in the interview with Thales, with consideration that cooperation between RBC, Interlocking and Traffic Management System should be carefully considered. NS has indicated that equipping the entire rolling stock before 2035 is not feasible. The shortage of available trains equipped with TIM, is seen as a barrier to the implementation of ETCS Hybrid Level 3 in the short term. To experience the actual capacity benefits of ETCS Hybrid Level 3, this is indeed a requirement.

Implementation perspective of ETCS Hybrid Level 3

In line with the previous two categories, the positions of the various candidates are spread. This strong spread in the perspective of the implementation of ETCS Hybrid Level 3 is a limitation on the development. For example, the candidates from the ministry and program management are of the opinion that the current roll-out of ETCS Level 2 must first run smoothly before you can think about implementing a new system. On the other hand, candidates from ProRail are of the opinion that the adjustments for ETCS Hybrid

	M1	E1	E2	E3	P1	P2	P3	P4	P5	P6	C1	C2	R1	R2	R3	R4	R5
After rollout ETCS Level 2	x	x	x	x							x	x		x			
Combined with current roll-out					x	x	x	x	x			x					
Merged with FRMCS				x									x	x	x		x
Interoperable with current B3R2															x	x	x
Cooperating with neighboring countries				x											x	x	x

Table 5.4: Identified implementation perspectives of ETCS Hybrid Level 3

Level 3 within the infrastructure are not major and can be included in the roll-out. In the transition from ATB to ERTMS, dual-signalling was used in the Netherlands. This kind of principle can also be used in the rollout of ETCS Hybrid Level 3, leaving the current ETCS Level 2 infrastructure intact. With the implementation of ETCS Hybrid Level 3 systems in the RBC and interlocking, a so-called ”dual-train detection” is created. Although the timetable cannot be optimised due to the lack of sufficient integer trains, a robustness improvement of the network can take place with an increase in integer trains. With this implementation strategy, you lower the threshold for rolling out ETCS Hybrid Level 3, allowing the update in the RBC and Interlocking to be included in the existing contract with Thales. In doing so, it is necessary to impose requirements on the carriers, to ensure the incorporation of TIM in new train series. Candidates from rolling stock owners see an implementation of ETCS Hybrid Level 3 only happen in combination with another innovation step that allows the retrofit of the rolling stock to be combined. This difference in vision about the method of implementation creates a lack of clarity within the rail sector. Because of the adjustments to both trackside and rolling stock, the Ministry of Infrastructure and Water Management have look at the financial balance of the concessions within the rail sector.

5.2.2 Challenges/limitations

Besides the categories within which the candidates had different views, certain interesting topics emerged during the interviews. In this section, the topics are analysed. The topics that emerged most often throughout the interviews are:

- The reliability requirement of the TIM within the rolling stock.
- GSM-R
- Sectoral decision-making

Reliability requirement TIM
Besides the ambiguity about the actual benefits of ETCS Hybrid Level 3, the stakeholder analysis also identified ambiguity in the area of reliability. To operate effectively under ETCS Hybrid Level 3, you need trains with integrity. This integrity is guaranteed through an on-board TIM. In the Netherlands, a given punctuality is required. This punctuality has to do with the reliability of rolling stock, infrastructure, staff competence and adjustment. NS has indicated that there is ambiguity about the required reliability for the integer trains. This ambiguity prevents NS from properly drafting the specifications of the TIM in trains and thus implementing it in the trains. In contrast, Subset-091 specifies which requirements the TIM functionalities must meet. This lack of clarity on what requirements or specifications are needed for TIM to be implemented ensures that TIM functionality is still not present in the new train series as well. While Railmap 4.0 states that trains that will remain in service for a long period of time will also be equipped with the Train Integrity Functions (TIF) of TIM when ERTMS is installed.

Update GSM-R
Communication between the train and trackside is via GSM-R in the current rollout of ERTMS. With ETCS Hybrid Level 3, the train integrity information in the position report is sent to the RBC. Whether

an older system like GSM-R is an obstacle to implementing ETCS Hybrid Level 3 is something different stakeholders disagree on. An ERTMS consultant indicated that it is not wise to implement ETCS Hybrid Level 3 with GSM-R and this system jump only happen in combination with the 5G FRMCS system jump. Experts within ProRail do not see this as a good argument because ETCS Hybrid Level 3 does not demand any additional capacity/availability required from GSM-R compared to ETCS Level 2. The position report remains the same size and the report is sent at the same time. Even though a new communication system like FRMCS is desirable, it is not necessary for the implementation of ETCS Hybrid Level 3. NS did indicate that it sees the system leap FRMCS as an opportunity to build the TIM into the existing rolling stock at the same time as FRMCS.

Organization
The Ministry of Infrastructure and Water Management (I&W) indicates that it is not entirely clear to them what the actual technical requirements are for implementing ETCS Hybrid Level 3 in comparison with ETCS Level 2. Since the Ministry, together with the State Secretary, is the principal of the ERTMS Programme, it is important to have clarity on the impact of the implementation of ETCS Hybrid Level 3. As the Ministry of I&W is at a distance from the rail sector, they are not in a position to decide on their own whether ETCS Hybrid Level 3 should be included in the ERTMS Programme. The Ministry of I&W is of the opinion that the rail sector should instead provide evidence that a system like ETCS Hybrid Level 3 is a feasible and substantiated gamechanger so that it can be managed and responsibly implemented. In addition, it becomes clear from the interviews that due to lack of decision at sector level, stakeholders are pointing at each other for the first step. This is also where the ERTMS Programme Directorate sees its role, to start discussions to make a decision at sector level. There is still a clear difference within the sector as to whether the implementation of ETCS Hybrid Level 3 is technically possible. Here, IEP says that due to previous tests in England, it is clear to them that ETCS Hybrid Level 3 in the track-side is technically possible. But you can only go up to a certain Technology Readiness Level (TRL) and that is TRL 8. After that, you have to take the step to request/order it. The interviews with ProRail often reveal that they have heard from the suppliers, either formally or informally, that the RBC and Interlocking modifications are technically possible. In the interviews with the transport operators, these views did not emerge. Here, it was not indicated by the transport operators that the question was directed towards the suppliers, so the ambiguity about the technical feasibility within the train remains with these stakeholders.

5.3 Conclusions

The results of the interviews show that within the Dutch rail sector, stakeholders agree that ETCS Hybrid Level 3 is an improvement on ETCS Level 2. What exactly this benefits entails does vary from one stakeholder to another. The difference in views on the benefits, may result in different views on the feasibility of implementing ETCS Hybrid Level 3. As a result, there is an unclear picture at sector level on what the requirements are for effective implementation of ETCS Hybrid Level 3. The lack of clarity and disparity in the visions of different stakeholders in reflected in the underlying technical topics such as: TIM, GSM-R and VSS. Without clarity on the necessary steps for implementing ETCS Hybrid Level 3, stakeholders remain wait-and-see and no investments are made in the new ETCS system.

6 Technical system analysis results

The general system analysis showed that there is uncertainty about the required reliability of the new on-board TIM system. In this chapter, a Fault Tree Analysis (FTA) and reverse engineering are used to investigate the reliability requirements for the TIM functionalities. First, the model used in the analysis is explained. Next, the data used for the study are discussed. And finally, the results and conclusion are given.

6.1 Reliability model

To research the reliability of the new TIM functionalities, this study made use of the reliability study from the paper by Flammini et al. [14]. In this paper, an FTA was used to calculate the required reliability of the ETCS Level 2 on-board system. The model used in the paper by Flammini et al. [14] is shown in Figure 6.1. The ETCS on-board system is divided into different ETCS components with their corresponding function. The structure of the basic FTA of ETCS Level 2 is based on redundancy within the ETCS on-board components. The model therefore uses AND gates for each component, so that a failure of a single component does not directly imply a failure of the on-board system.

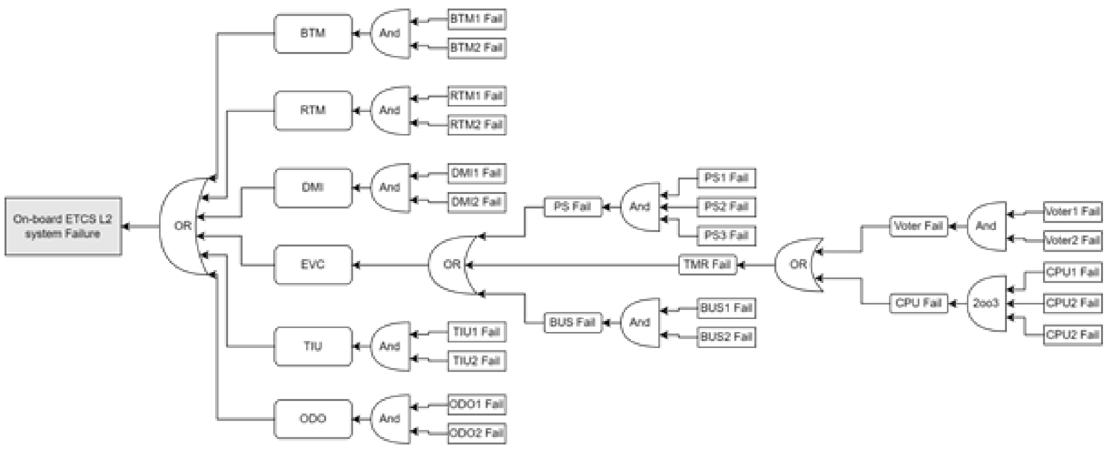

Figure 6.1: FTA model ETCS Level 2 on-board system. Source: Flammini et al. [14].

The new TIM functionalities introduced with ETCS Hybrid Level 3 are: confirm train length and confirm train integrity. The requirement of Subset-091 [13] states that these two functionalities are independent of each other. As the two TIM functionalities are still a concept that are not proven, no reliability data is available. In addition, there are also no studies proving that the two functionalities are actually independent of each other within the ETCS Hybrid Level 3.

The reliability analysis in this thesis uses reverse engineering, investigating what reliability the TIM functionalities must meet. The requirement in this thesis is that the reliability of the ETCS Hybrid Level 3 on-board system must remain equal to the reliability of the ETCS Level 2 on-board system. Because in this thesis is assumed that, in worst case, the new ETCS Hybrid Level 3 system should have equal reliability to the current ETCS Level 2 system.

6.2 Failure rate data

The operational failure data of the ETCS on-board subsystem modules are not available for this study. In this thesis, the use of the requirements defined in the RAMS Requirements Specification [8] was therefore chosen. The requirements are the maximum threshold (shown in Table 6.1) values beyond which should not be exceeded. Using these requirements creates worst-case reliability within the limits of RAM specifications. When designing the modules for operation purposes, it is likely to have lower failure data then the requirements assumed in this thesis.

Module	Failure Rate [1/hr]
BTM	<1E-08
RTM	<1E-06
DMI	<1E-07
TIU	<1E-07
ODO	<1E-07

Table 6.1: Unreliability specifications. Source: [8]

6.2.1 Basis model verification

As has been described by Carson [6], verification is important for the correctness of your model. The verification for the correct basis FTA model was done by using the existing ETCS Level 2 FTA model from the paper by Flammini et al. [14]. To enable verification of the model, the same reliability software is used: Symbolic Hierarchical Automated Reliability and Performance Evaluator (SHARPE). This reliability software was developed at Duke University and allows the average failure probability of the top event to be calculated using exponentially-distributed failure probabilities of the basic events. For the verification of the basic model, the same data input (Table 6.1) as the paper by Flammini et al. [14] is used to recalculate the results.

Using the ETCS Level 2 FTA model (Figure 6.1) and the input data from Table 6.1, the result is an MTBF of $6.4766 * 10^4$ for the reliability of the ETCS Level 2 on-board system. This reliability corresponds to the original result from the paper by Flammini et al. [14]. This confirms that the basis of the FTA is modelled correctly.

6.3 Reliability results

As explained earlier, reverse engineering is used to calculate the required reliability of the TIM functionalities. For the reliability of the ETCS Hybrid Level 3 on-board system, the same MTBF value ($6.4576 * 10^4$ [h]) is used as for ETCS Level 2. Because the independence of the two functionalities has not yet been firmly proven in the literature, the failure probabilities for the two functionalities Train Integrity and Train Length have been calculated twice. As by the paper of Flammini et al. [14], redundancy has been assumed within the components.

The first model for the ETCS Hybrid Level 3 on-board system is shown in Figure 6.2. This is based on the independence of the two TIM functionalities. To model this in the FTA model, an AND gate is used within the TIM component. Here, both functionalities must fail simultaneously before the subsystem fails.

The results of the TIM functionalities are shown in Table 6.2 and are expressed in terms of failure rates. This refers to the maximum allowable unreliability with the given system MTBF of $6.4766 * 10^4$ hours.

In the second FTA model of ETCS Hybrid Level 3, the functionalities Train Integrity and Train length are defined as dependent. In the FTA model an OR gate is used. Because of this, the failure of either of the two functionalities results in the failure of the on-board system. The FTA model is shown in Figure 6.3.

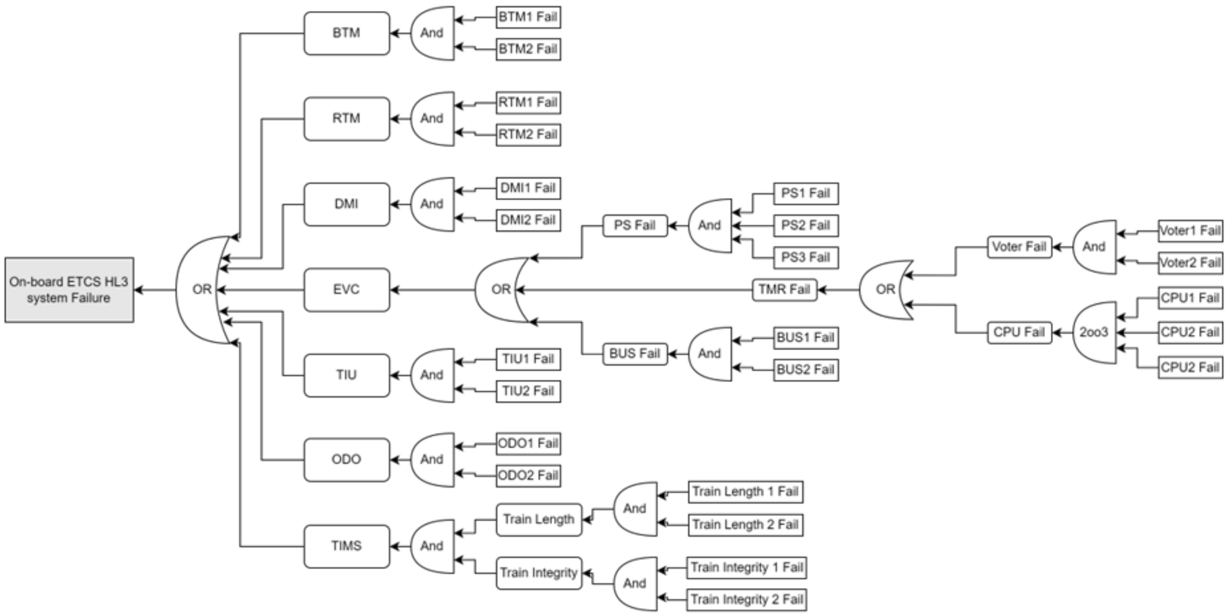

Figure 6.2: FTA model of ETCS Hybrid Level 3 on-board system (And gate)

funtion	**Failure Rate [1/hr]**
TIM module	2.2122E-05
Train Length Fail	3.8566E-02
Train integrity Fail	3.8566E-02

Table 6.2: Unreliability specifications TIM functionalities (And gate)

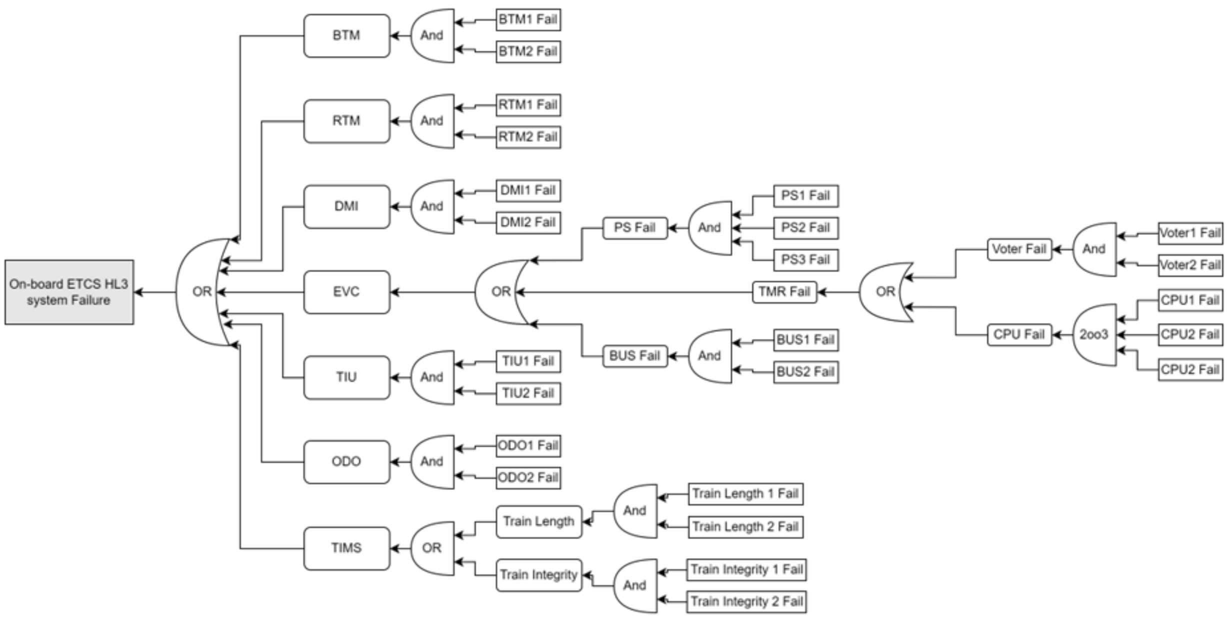

Figure 6.3: FTA model of ETCS Hybrid Level 3 on-board system (Or gate)

The results of the TIM functionalities are shown in Table 6.3 and are expressed in terms of failure rates.

This refers to the maximum allowable unreliability with the given system MTBF of $6.4766 * 10^4$ hours.

funtion	**Failure Rate [1/hr]**
TIM module	2.2122E-05
Train Length Fail	1.0517E-03
Train integrity Fail	1.0517E-03

Table 6.3: Unreliability specifications TIM functionalities (Or gate)

6.4 Conclusion

With the assumption that the MTBF of the ETCS Level 2 on-board system remains the same with the ETCS Hybrid Level 3 on-board system, the analysis showed that obtaining train integrity could have a maximum failure rate of $2.2122 * 10^{-05}$ per hour. The failure rates depend on the relationship between the two functionalities. The results showed that the maximum allowable failure rate is higher when independence between the Train Integrity and Train Length functionalities is assumed. The maximum allowable failure rates of the functionalities Train Integrity and Train length are $1.0517 * 10^{-03}$ per hour. But when the two functionalities are considered independent on each other, the maximum allowable failure rate is $3.8566*10^{-02}$ per hour. This means that within an on-board system with independence between the Train Integrity function and Train Length function, a higher failure rate is tolerable without degrading the failure rate of the ETCS on-board system compared to ETCS Level 2. When the failure rates are compared with the Safety Integrity Levels, it can be seen that the failure rates of the two functionalities in the best situation are well below the SIL 1 ($> 10^{-05}$) level.

7 Discussion and Recommendation

This chapter provides the implications and limitations of the different results within this thesis. Following that, recommendations for future research are discussed.

7.1 Discussion

The literature study showed what the differences are when moving from ETCS Level 2 to ETCS Hybrid Level 3. The results from the literature clearly showed in which subsystems the biggest adjustments take place. The differences were treated in a global manner, without going into technical design, for instance. These technical specifications were not drawn up either and are liberties given to the suppliers of the systems.

This study showed through stakeholder analysis what vision the dutch rail sector has on the implementation of ETCS Hybrid Level 3. Using a semi-structured interview, certain individuals within the stakeholder were asked about their views on topics such as cost shifts, responsibilities and implementation strategy. The companies included as stakeholders in the study were based on the organisational structure of ERTMS rollout in the Netherlands. In the process of selecting the right candidates, this thesis looked at the candidate's position in the respective company. To optimise the validation of the results, a minimum of 2 people per stakeholder was adopted with the preparation of the candidate list. In retrospect, the study failed to find at least two candidates for each stakeholder who have knowledge of both the current ERTMS rollout in the Netherlands and the ETCS Hybrid Level 3 concept. Because ETCS Hybrid Level 3 is still in development, there was also resistance to finding candidates within the suppliers. In this market, information is easily sensitive and it has been experienced that companies prefer to keep their cards close to their chests.

Although the candidates were asked to answer the questions from their positions, there is a possibility that subjective answers were given during the interview. In addition, the limited number of candidates among certain stakeholders make it difficult to generalise the answers for each stakeholder.

During the interview, the Delphi method was used to verify certain stakeholders' findings with other stakeholders. To apply the Delphi method comprehensively, multiple iteration phases are needed where you can question stakeholders several times. Due to the drafted schedule of this thesis, a simplified version of the Delphi method was chosen to still capture certain topics from different perspectives. To analyse the data obtained by the interviews, transcription parsing was chosen in this study. In retrospect, this process could have been faster and automated by using code.

One issue that emerged from the stakeholder analysis was the incorporation of the TIM into rolling stock. According to certain stakeholders, the specifications needed to design these functionalities were not available or clear. Therefore, this thesis opted for a reliability analysis that looked at the allowable unreliability of the TIM functionalities. This analysis used an existing reliability study for ETCS Level 2 done by Flammini et al. [14]. Due to the lack of substantiated literature, it is not known whether the functionalities within the TIM can be considered dependent or independent of each other. In this thesis, the maximum allowable failure rate has therefore been calculated for both cases. The results showed that according to the calculations, an independence between the two functionalities resulted in a higher allowable failure rate compared to dependence between the Train Integrity and Train Length. A simplified representation of the TIM module was used in this analysis. To what extent the magnitude of the calculated failure probability values are realistic with the actual safety requirement. Because the TIM is a safety-critical function, which have to meet the safety requirement of SIL 4. This contradicts the results from the analysis where the TIM module has a maximum allowable failure rate of $2.2122 * 10^{-05}$ (SIL 1). The results of the analysis where the two functionalities of the TIM are below the requirements of SIL 1 ($> 10^{-05}$)comes from the fact that the TIM module from the FTA results in a safety requirement of SIL 1. This can be investigated in future research, how it affects the failure rates of the two functionalities if the TIM module is defined as a SIL 4 system.

7.2 Recommendations

7.2.1 Dutch rails sector

It emerged from this thesis that ETCS Hybrid Level 3 is a desirable system within the Dutch rail sector. The stakeholder analysis resulted in a first overview of the findings of the different stakeholders. A following step to this thesis is therefore a further stakeholder analysis, in which the results of this research are included in the interviews. As a result, an extensive Delphi method can be used to create a clear picture of the possibilities in the implementation of ETCS hybrid Level 3. In addition, it is recommended to include other carriers outside NS in further research.

To decide whether the implementation of ETCS Hybrid Level 3 is the next innovation for the Dutch rail network, discussions between stakeholders must be initiated. These discussions should identify the desired benefits of ETCS Hybrid Level 3 for the rail operator and at what point in time certain benefits can be realised. The decision should identify the steps to be taken in the process towards effective implementation. These conversations will need to establish whether implementing ETCS Hybrid Level 3 is feasible and desirable within the sector. And clear agreements will have to be made when the choice is made to implement ETCS Hybrid Level 3, in order to eliminate the ambiguity that currently exists within the sector.

The recommendation is therefore for the rail sector to enter into discussions to first draw up a plan to substantiate the requirements and cost overview for the implementation of ETCS Hybrid Level 3. This will ensure that the Ministry of Infrastructure and Public Works has a picture of the technical, financial and organisational content of the roll-out. And can process this into a decision on scope change. With a good overview provided by the rail sector, the ministry is able to take a decision on the implementation of ETCS Hybrid Level 3.

7.2.2 Movares

The interviews have shown that the implementation of ETCS Hybrid Level 3 in the future is generally viewed positively. A recommendation for Movares is therefore to invest in understanding future security systems such as ETCS Hybrid Level 3 in order to have knowledge for future projects. This shows that Movares is investing in the future looking at solutions with a more sustainable perspective.
Although it is still unclear whether ETCS Hybrid Level 3 will really be implemented, a recommendation for Movares is to invest in the knowledge about ETCS Hybrid Level 3. In order to fulfil an active advisory role in the discussions around this topic.

7.2.3 Scientific

One concept that came out of the interviews as a result is dual-train detection. Here, the current ETCS Level 2 infrastructure will remain intact and the ETCS Hybrid Level 3 software update will be implemented in the RBC and Interlocking. An interesting topic for a future study, is to investigate the tipping point in this concept. This is the point at which sufficient integer trains are available so that optimisation in timetabling and reducing TDD can apply.

For the reliability of the TIM functionalities, there is an opportunity for a more extensive research. The scope of this study was specifically on the ETCS on-board system. Here, for future research, a more comprehensive FTA can be prepared that includes the functionalities of both trackside, on-board and communication. This can create a more realistic outcome at system level of ETCS Hybrid Level 3.

8 Conslusions

This chapter contains the conclusions of the research. First, the answers to the sub-questions are given. Finally, answers to the main research question as provided.

Sub-question 1: What will be the changes to the subsystems and functional relations within ETCS Hybrid Level 3 with respect to ETCS Level 2?

In 2019, the decision was taken to roll out ERTMS in the Netherlands. The Dutch Government has chosen to implement ETCS Level 2 whereby the communication between the train and the track is via GSM-R. The detection of trains under ETCS Level 2 is done by axle counters installed in the track.

With the transition to ETCS Hybrid Level 3, it becomes possible to reduce the number of axle counters in the track by using on-board train detection. On-board train detection is ensured by means of two additional functionalities: Train length and train integrity. These new functionalities within the train are called the TIM. In ETCS Level 2, the two variables are already included in the position report, but are declared as not defined.

The introduction of on-board train detection creates a distinction in the rolling stock between integer trains and non-integer trains. With the presence of the TIM, it is possible to apply block compaction without building additional TTD in the track. The existing track blocks are divided into smaller virtual blocks called Virtual Sub-Section (VSS). This VSS is the main change between ETCS Level 2 and ETCS Hybrid Level 3. Besides the two known block statuses (available and occupied), ETCS Hybrid Level 3 introduces Unknown and Ambiguous statuses in the VSS.

To answer this sub-question, the main adjustments are the introduction of VSS and the associated changes required in the RBC, Interlocking, user processes and the implementations of onboard train detection by using TIM.

Sub-question 2: What are stakeholders' visions in terms of strategy, responsibilities and timeline within the effective implementation of ETCS Hybrid Level 3?

Throughout the rail sector, the various stakeholders agree that ETCS Hybrid Level 3 provides benefits over ETCS Level 2, but the difference is in the kind of benefit the stakeholder recognises in ETCS Hybrid Level 3. There is no common vision within the sector of what kind of advantages ETCS Hybrid Level 3 has in terms of reliability, capacity or readjustment. This also affects stakeholder views on the possible implementation of ETCS Hybrid Level 3.

The strategy for implementing ETCS Hybrid Level 3 strongly depends on the stakeholders' perception of effective implementation. For example, NS believe effective ETCS Hybrid Level 3 only when there are enough integer trains equiped with TIM. And to start equipping trains with TIM, they say a design should be made at sector level on the reliability of the entire rail network. Such a design will clarify the rolling stock reliability required.

Confidence in ETCS Hybrid Level 3 also varies within the sector. The difference in confidence comes from a lack of knowledge about what is actually technically required to implement ETCS Hybrid Level 3. As a result, when asked about the estimated time needed for the implementation of ETCS Hybrid Level 3, stakeholders are reluctant to respond. The biggest advantage of ETCS Hybrid Level 3 is seen as the decrease in TTD and increase in reliability. This advantage is simultaneously its biggest pitfall. This creates a lack of clarity in possible implementation strategies where, for example, a dual-train detection system could be introduced as an intermediate step.

In terms of responsibilities, the various stakeholders do not foresee any shifts compared to ETCS Level 2. The ERTMS Programme Directorate sees its role as leader in the discussions with the stakeholders to gain clarity within the rail sector, in order to take a sector decision on possible implementation of ETCS Hybrid Level 3.

Sub-question 3: What will be the effect of the new functionalities of ETCS Hybrid Level 3 to the reliability of the on-board system?

An important step towards ETCS Hybrid Level 3 is equipping trains with TIM. As defined in this thesis, the TIM contains two functionalities: "Train Integrity" and "Train Length". Since the TIM acts as train detection, the two new functionalities be a part of safety-critical functions. As a result, the new functions must meet a certain SIL level. The stakeholder analysis revealed that the equipment owner is unclear about the reliability requirements for the new systems. In contrast, the requirements for the "Train Length" and "Train Integrity" functions were drafted in Subset-091. This design with the two functionalities has not been substantiated in the literature. Therefore, both dependence and independence between the two functionalities have been considered in this thesis. Results from the FTA of ETCS Hybrid Level 3 showed that broadcasting a confirmed train length should have a maximum failure probability of $2.2122 * 10^{-05}$ and is higher than SIL 4. But by assuming that the underlying functions "Train Integrity" and "Train Length" operate independently, the failure probabilities are only $3.8566 * 10^{-02}$. This ensures that the two individual TIM functions need to meet lower reliability requirement compared with dependency between the two functionalities ($1.0517 * 10^{-03}$).

Main research question: What are the main challenges and potential enablers to the deployment of ETCS Hybrid Level 3 on the Dutch rail network?

The challenges/limitations of ETCS Hybrid Level 3 on the operations of the Dutch rail network, depends on the chosen implementation strategy. Implementing ETCS Hybrid Level 3 requires adjustments in RBC, Interlocking, rolling stock and user processes. For the user processes, mainly adjustments/additions are needed for operation in degraded situation. In RBC and Interlocking, a new system update needs to be made in which the operation with VSS is defined. According to ProRail, the RBC and Interlocking modifications are considered feasible and are not seen as a significant challenge in implementing ETCS Hybrid Level 3. Moreover, installation of TIM in passenger trains is required to use VSS.

This thesis has shown that it is technically possible to implement ETCS Hybrid Level 3. However, a direct effective implementation of ETCS Hybrid Level 3 with capacity improvement and reduction of TTD has too big of an impact on the Dutch rail network. This major step is not feasible when looking at the required rolling stock which has to be equipped with a TIM. This makes it unfeasible for NS to convert all their trains and still deliver the required punctuality. A gradual implementation would have a lesser impact on operations. Dual-Train Detection is a concept for this which can be applied. Here, the designed ETCS Level 2 infrastructure will remain intact and an updated ETCS hybrid Level 3 RBC and Interlocking will be applied as a first step. The impact of this implementation, beyond the first phase of drafting user processes and design rules, has little impact on the operation of the current Dutch railway network. This will require agreements to be made at sector level about investing in rolling stock and drawing up a development plan. The biggest challenge of the implementation of ETCS Hybrid Level 3 is organisational. Here, stakeholders such as the Ministry of Infrastructure and Water Management, ProRail and NS will have to make agreements to draw up a clear case for an potential implementation of ETCS Hybrid Level 3.

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Appendix A: Information Document

To allow stakeholders to prepare for the interview, this information sheet was sent to each stakeholder. This information sheet contains a small introduction to the thesis and a selection of prepared questions that are the same for each stakeholder.

1 Information Document

1.1 Introduction

This interview is part of my Thesis project for the Master Transport, Infrastructure & Logistics at Delft University of Technology. In this project, I am conducting research into the impact of the train safety/control system ERTMS/ETCS Hybrid Level 3. Currently, the parties involved are busy rolling out ERTMS/ETCS Level 2, and this research tries to shed light on what the impact of a choice for immediate implementation of ERTMS/ETCS Hybrid Level 3 would be. The first part of the study consists of a quantitative research of the failure probabilities of the new ETCS system (Level 2 vs Hybrid Level 3). For this part, a reliability method called "Fault Tree Analysis" (FTA) is used. For the second part, through this interview, a qualitative research is conducted into insights/possible barriers at the organisational level. Here, I interview various actors within the ERTMS field with the aim of identifying how ERTMS/ETCS Hybrid Level 3 is considered in practice.

To be able to analyse the results post-interview, I would like to record the interviews. In addition, I would like to write out the interviews in order to then analyse and compare the answers. To avoid discussion afterwards, I would like to check with you in advance about this whether this is acceptable to you. This will include an agreement on whether and how the interview transcript may be shared in my report.

1.2 Questions

The interview is semi-structured. This leaves room for me to be able to ask further questions on topics that come up during the interview, in addition to the fixed questions. The selection of fixed questions, consists of the following questions:

Question 1: Can you give a brief description about yourself and your position within the rail sector?
Question 2: What is your involvement with ERTMS on the Dutch rail network?

Question 3: To what extent are you familiar with the ERTMS/ETCS Hybrid Level 3 concept? And what is your take on this new concept?
Question 4: Do you see ERTMS/ETCS Hybrid Level 3 as an improvement system over ERTMS/ETCS Level 2?

When implementing ERTMS/ETCS Hybrid Level 3, there will be a shift in costs. Infrastructure investments decrease for the reduction of Trackside Train Detection. But due to the increase in functionalities within the on-board system of the train, investment costs for the on-board systems will increase.

Question 5: What is your view on these cost shifts between ProRail and the equipment owners?

Besides the shifts in costs, there will also be shifts/changes in the roles and responsibilities of stakeholders. An example for this is the required upgrade of the track description section in the EVC to account for Virtual Sub-sections. Apart from additional costs for software updates and maintenance costs, this could also entail greater safety responsibilities for railway companies/rolling stock owners.

Question 6: How do you look at this example? Do you agree with these shifts?
Question 7: What do you think are the other critical constraints or issues that need to be addressed in terms of current roles, responsibilities and policies to enable seamless implementation of Hybrid Level 3?

The study "Systeemsprongen Spoorsysteem" by TwynstraGudde/Movares/Sweco/Dialogic and TU Eindhoven, showed that of the various system jumps, implementing ERTMS/ETCS Hybrid Level 3 is the most economical solution. Here, it is possible to achieve effectiveness gains when the implementation is combined with the current roll-out of ERTMS in the Netherlands.

Question 8: How much time do you think is realistically needed to implement ERTMS/ETCS Hybrid Level 3 in practice based on the necessary adjustments in policy, regulation and stakeholder roles?