ETCS Level 1 in the Context of Digital Interlocking Technology

Von der Fakultät für Bauingenieurwesen
der Rheinisch-Westfälischen Technischen Hochschule Aachen
zur Erlangung des akademischen Grades eines
Doktors der Ingenieurwissenschaften
genehmigte Dissertation

vorgelegt von

Peter Josef Laumen

Berichter: Univ.-Prof. Dr.-Ing. Nils Nießen
Univ.-Prof. Dr.-Ing. Birgit Milius
Dr.-Ing. Christoph Gralla

Tag der mündlichen Prüfung: 30. Juni 2023

Diese Dissertation ist auf den Internetseiten der Universitätsbibliothek online verfügbar.

Summary

Digitisation, as a major global trend, is also making its way into railway signalling technology. Many aspects of rail traffic are to be improved and optimised through digitisation. This ranges from big data for predictive maintenance to digital interlocking (IL) basing on IP networks. The European Train Control System (ETCS) should enable interoperable rail traffic throughout Europe as a standardised Automatic Train Protection (ATP) system. However, this also requires the definition of international and harmonised operating procedures. Each country has its own ATP system, making international traffic complex. On the one hand, drivers must be trained in the different systems and on the other hand, trains must be equipped with the various systems.

A lot of countries throughout Europe propose ETCS Level 2 as a target. ETCS Level 2 requires mobile radio communication. Therefore, the fundamentals of radio communication with its advantages and disadvantages are presented. Considering that a radio communication system such as the Global System for Mobile Communications - Rail (GSM-R) is a separate infrastructure, its technology is modernised in certain cycles. These cycles do not correspond to the long-term cycles of railway signalling technology. Migration concepts are necessary for an optimal transition between technologies.

ETCS has been specified by the European Union (EU). The development began in the late 1980s. There has not yet been a Europe-wide, comprehensive introduction. Only the states of Luxembourg and Switzerland have introduced ETCS in their whole network, Denmark is still in progress. Many research and implementation projects examine the migration to ETCS. Also the adaption of operating rules and improvement of safety systems (IL & ETCS) is in the focus of such research projects. The overall topic is the improvement of railway operations and increase of capacity.

Level 1 was initially considered as a level for migration to Level 2 or Level 3. The application of ETCS in this thesis discusses Level 1 Full Supervision (FS) as a full ETCS level.

This thesis considers the interaction of a digital IL and ETCS, focusing on Level 1. The digital IL bases on modern bus or network communication to further safety systems (level crossing, control system, RBC) and the field components (axle counter, signal, point). Cab-signalling is the fundament for modern railway operation. This makes fixed signals almost useless in means of safety function and allows savings in trackside equipment. A special feature is the telegram-based interface between the balises and the IL without the need of measuring the signal's lamp currents. The impact of the new digital and integrated IL architecture on operations is considered to evaluate the architecture. The advantages, especially of cab-signalling, are examined. Another advantage results from the innovative connection of the balises to the IL and the resulting high information density at the balise. The separation of shunting movements and train movements becomes obsolete, as pre-signalling is no longer required. Existing track section are used to set up additional blocks.

Minimum block lengths are not depending on the pre-signalling and braking distance due to cab-signalling. The new architecture also simplifies the connection of sidings.

The new architecture also impacts capacity. ETCS enables an increase in capacity by establishing multiple block sections, increasing the average speed and improving infill locations.

Further evaluation criteria are energy consumption, security, safety, economic efficiency and project planning. Improvements in all these areas results with the new architecture. The architecture designed for a decentralised IL topology will improve energy consumption and offer the minimal potential for security attacks. Fewer components are needed for communication (which reduces or does not increase energy consumption), and with minimal communication over open networks and greater use of closed networks, the need for security measures is reduced. In particular, the communication of the several components of the safey systems, i.e. the IL with the field elements, is handled via closed networks. Through the intelligent control of balises, groups of balises can be combined, which reduces the cost of trackside equipment.

Kurzfassung

Die Digitalisierung als ein bedeutender globaler Trend hält auch Einzug in die Signaltechnik. Viele Aspekte des Schienenbahnverkehrs sollen durch die Digitalisierung verbessert und optimiert werden. Dies reicht von Big Data zur prädiktiven Instandhaltung bis hin zur Vernetzung der Sicherungssysteme und Stelleinheiten über IP-Netzwerke. ETCS als Zugsicherungssystem soll einen europaweiten interoperablen Zugverkehr ermöglichen. Dazu ist es jedoch auch notwendig, internationale und harmonisierte Betriebsverfahren zu schaffen. Jedes Land hat seine eigenen Zugsicherungssysteme, was internationalen Verkehr aufwendig gestaltet. Zum einen müssen Triebfahrzeugführer in den verschiedenen Systemen geschult sein und zum anderen müssen die Züge mit den verschiedenen Systemen ausgestattet sein.

Da vielfach eine Zielarchitektur mit ETCS Level 2 angestrebt wird, werden die Grundlagen der Funktechnologie mit ihren Vor- und Nachteilen dargestellt. Dabei ist zu bedenken, dass ein Funksystem wie GSM-R eine eigene Infrastruktur ist. Ein solches System wird in entsprechenden Zyklen durch neue Technologien angepasst. Diese Zyklen entsprechen nicht den langlebigen Zyklen der Eisenbahnsicherungstechnik. Migrationskonzepte sind notwendig, um einen langen und aufwendigen Übergang zwischen den Technologien zu ermöglichen.

ETCS ist von der Europäischen Union als ein solches System spezifiziert worden. Die Entwicklung begann Ende der 80er Jahre. Eine europaweite, flächendeckende Einführung gab es bisher nicht. Lediglich die Staaten Luxemburg und Schweiz haben ETCS flachendeckend eingeführt, in Dänemark läuft aktuell der Rollout. Viele Forschungs- und Implementierungsprojekte untersuchen die Migration zu ETCS um ein möglichst optimales System zu installieren und an den vielfältigen Anforderungen anzupassen. Dabei wird ein verbesserter Bahnbetrieb und eine Erhöhung der Kapazität avisiert.

Der Level 1 war zunächst nur als Zwischenschritt einer Migration zu Level 2 oder Level 3 vorgesehen. Die Anwendung von ETCS in dieser Arbeit forciert den Level 1 im Modus FS als vollwertigen ETCS Level.

Diese Arbeit betrachtet die Interaktion von digitalem Stellwerk und ETCS mit einem Fokus auf Level 1. Als digitales Stellwerk wird dabei ein Stellwerk angenommen, welches auf telegrammbasierter Kommunikation zwischen allen Komponenten (Bahnübergang, Bediensystem, RBC, Feldkomponenten) basiert. Ob dabei IP-basierte Netzwerke oder Buskommunikation verwendet wird, ist im Rahmen dieser Arbeit von untergeordneter Bedeutung. Führerstandssignalisierung wird als Grundlage für einen modernen Bahnbetrieb festgelegt. Dadurch werden ortsfeste Signale nahezu bedeutungslos. Dies erlaubt Einsparungen in der streckenseitigen Ausrüstung. Die daraus resultierenden Rahmenbedingungen, insbesondere bei einer Anwendung von Level 1 FS werden dabei betrachtet. Ein besonderes Feature stellt die direkte Anbindung der Balisen an das Stellwerk dar, ohne Lampenströme der Signale zu messen.

Um die Architektur zu bewerten, werden die Auswirkungen der neuen digitalen und integrierten Stellwerksarchitektur auf den Betrieb betrachtet. Dabei werden die Vorteile, insbesondere der Führerstandssignalisierung, untersucht. Ein weiterer Vorteil ergibt sich aus der innovativen Anbindung der Balisen an das Stellwerk und der daraus resultierenden hohen Informationsdichte an der Balise. Die Trennung von Rangierfahrten und Zugfahrten wird obsolet, da die Vorsignalisierung entfällt. Vorhandene Freimeldeabschnitte können genutzt werden, um zusätzliche Blöcke einzurichten. Mindestblocklängen können aufgrund der Führerstandssignalisierung reduziert werden. Auch die Anbindung von Ausweichanschlussstellen wird durch die neue Architektur vereinfacht.

Eine weitere Betrachtung bezieht sich auf die Kapazität und Leistungsfähigkeit. Diese wird ebenfalls durch die neue Architektur gesteigert. Dies liegt jedoch nicht in der Anwendung von ETCS, sondern vielmehr in der Errichtung zusätzlicher Blockabschnitte, der Erhöhung der mittleren Geschwindigkeit und der Verbesserung der Infill-Standorte.

Weitere Bewertungkriterien sind der Energieverbrauch, IT-Security, signaltechnische Sicherheit, Wirtschaftlichkeit und Projektierung. In all diesen Bereichen ergeben sich durch die neue Architektur Verbessserungen. Die für eine dezentrale Stellwerkstopologie ausgelegte Architekture wird den Energieverbrauch verbessern und der IT-Security ein minimales Angriffspotential bieten. Weniger Komponenten für Kommunikation sind notwendig (was den Energieverbrauch reduziert, bzw. nicht erhöht) und mit einer minimalen Kommunikation über offenen Netze und stärkeren Einsatz von abgeschlossenen Netzen reduziert die Notwendigkeit für Cybersecurity. Insbesondere die Kommunikation der sicheren Elementen, d. h. der Stellwerke mit den Feldelementen wird über geschlossene Netze abgewickelt. Durch die intelligente Ansteuerung der Balisen, können Balisengruppen zusammengelegt und somit die Kosten für die Streckenausrüstung reduziert werden.

Acknowledgements

This thesis was written during my time at the Institut of Transport Science at the RWTH Aachen University. Such a thesis is seldom written without the support of friends, colleagues and family.

First, I would express my gratitude to my advisor Univ.-Prof. Dr.-Ing. Nils Nießen for supervising my thesis and his interest in this topic. He gave me a lot of freedom for my research. Furthermore, I was pleased to have the opportunity and honour to modernise the signalling lab. Both were challenging tasks that broadened my horizon.

I would like to thank Univ.-Prof. Dr.-Ing. Birgit Milius and Dr.-Ing. Christoph Gralla for supporting my thesis as a reviewer. Their interest in this topic and their advice lead me to consider and reflect on my ideas. It helped me to form a rounded picture of my thesis.

But all the interesting work was only possible with my colleagues at the VIA. Every day was a lot of fun. It was a pleasure for me to work with all of you. I have beautiful memories of joyful coffee breaks, bike tours, regular meetings in the Labyrint or Pontgarten, barbecue at the institute‘s point or carnival breakfast ... never forgetting the Martinique trip.

I thank my colleagues Marcel Schneider, Fabian Stoll, Albrecht Morast, and especially Nadine Friesen for sharing “Bureau 129”.

Alexander Große, Jürgen Jacobs, Tim Kipshagen, and Maximilian Kliem always had an open ear for critical discussions about signalling systems and the improvement of the signalling lab. Tobias Jacke, Norman Weik, and Christopher Wink supported me in the field of capacity analysis. Therefore, I thank you very much.

A warm thank you belongs to all my student researchers, bachelor and master thesis students. The modernisation of the signalling lab, further research projects and this thesis have only been possible with you. I was lucky enough to had many great students in the team - special thanks to Tobias Wall, who supported me in preparing this thesis.

Eventually, I thank my family for supporting me during my whole life. Growing up in a harmonic family is an excellent fundament and gave me the patience to focus on the thesis. Special thanks go to my father, who led me to the exciting field of signalling technology and gave me the idea for this topic.

Contents

Abbrevations

ATP Automatic Train Protection

ATO Automatic Train Operation

ATC Automatic Train Control

BCU Balise Control Unit

BTM Balise Transmission Module

CBI Computer Based Interlocking

CC Command & Control

CCS control, command and signalling

CFL Chemin de Fer Luxembourgois

COTS commercial off-the-shelf

DB AG Deutsche Bahn AG

DB Netz AG Deutsche Bahn Netz AG

DI Digital Interlocking

DMI Driver Machine Interface

DP Danger Point

DSD Digitale Schiene Deutschland

DZFS German Centre for Rail Traffic Research

EBD emergence braking deceleration

EBO Railway Construction and Operations Act

EIRENE eirene

EoA End of Authority

ERTMS European Traffic Management System

ETCS European Train Control System

EU European Union

EVC European Vital Computer

EVS EUREGIO Verkehrsschienennetz GmbH

FRMCS future railway mobile communication system

FSR functional system requirements

FS Full Supervision

GNSS Global Navigation Satellite System

GPRS general packet radio service

GSM-R Global System for Mobile Communications - Rail

GSM Global System for Mobile Communications

IL interlocking

IO input & output

IP Indication Point

LEU Lineside Electronic Unit

LoA Limit of Authority

LTE Long Term Evolution

LTE-R Long Term Evolution - Rail

LTM Loop Transmission System

LX level crossing

LZB Linienzugbeeinflussung

LRBG Last Relevant Balise Group

LS Limited Supervision

MA Movement Authority

MORANE Morane

NeuPro Neuausrichtung der Produktionstechnik

NTC National Train Control

OS On Sight

PM point machine

PT Post Trip

PZB punktförmige Zugbeeinflussung

RASTA Rail Safe Transport Application

RBC Radio Block Center

RIU Radio Infill Unit

SB Stand By

SBB Swiss Federal Railways

SBD service braking deceleration

SCI standard communication interface

SIL Safety Integrity Level

SH Shunting

SR Staff Responsible

SRS system requirement specification

SSP Static Speed Profile

STM Specific Transmission System

SvL Supervised Location

TDS train detection system

TEN Trans European Network

TETRA Terrestrial Trunked Radio

TMS Traffic Management System

TR Trip

TSI Technical Specification for Interoperability

TCC Train Control Center

TSR Temporary Speed Restriction

UMTS Universal Mobile Telecommunication System

VDE 8 Verkehrsprojekt Deutsche Einheit No. 8

Chapter 1

Introduction

Global trends like digitisation, ecology and connectivity change the people's way of life [1]. Urbanisation and ecology lead to a shift from individual traffic to public transport [2]. Especially in big cities, the demand for mass transport systems is very high. Individual traffic requires much space for parking and transport ways.

The railway plays an essential role as an efficient and environmentally friendly means of transport. The electrification of the railway started decades ago. The automotive industry discusses the aspect of electrification since years which is already reality for railways. Now, governmental activities focus on modernising the rail network and its digitisation after decades of pushing the automotive industry [3].

In the last century, there was a decrease in railway lines and a shift to motorised individual transport systems. Today, the reactivation of these lines is in progress [4]. Regional and secondary lines with low traffic density exploit and connect urban and rural areas.

There are many programmes in progress with a focus on digitisation to improve railways [5], [6], [7]. These programmes consider different aspects of the railway, including safety systems, management systems, and maintenance, for example. The main objective is a more robust railway network with a higher capacity and reduced life cycle costs [8].

A recurring mantra is that *digitisation makes everything better*. That includes full automation of train traffic and an improvement of capacity. Due to automation (automated trains), more control and safety systems are necessary on the train [9].

Developing a new and modern railway safety system requires considering a migration strategy. The (life)time constants of safety systems are long, leading to a long migration phase [10]. Migrating an extensive network like the German railway network with about 33.000 km is a process for decades. Therefore, the current systems must exist partly in parallel with intersections to the new systems.

However, digitisation only is not the final solution to cope with the demands. A new digital safety system improves operation and capacity in combination with European Train

Control System (ETCS) to a certain extend. But in the end, additional infrastructure is necessary to increase traffic. Digitisation and intelligent automation increase capacity and improve operation to a certain extent. [11].

1.1 Objective of this Thesis

This thesis outlines a new digital interlocking (IL) architecture. It focuses on an integrated European Train Control System (ETCS) and IL solution. An efficient and smart IL solution designed for regional lines.

The primary reasons for the new architecture are:

- Simple safety system (IL) without dependencies to further infrastructure systems like radio communication or Global Navigation Satellite System (GNSS).
- Applying cab-signalling and its features on regional lines by using the advantages of a continuous supervision and discrete transmission.
- Avoiding a trackside signalling system or at least simplifying it.

Hence, means of a high-performance block systems [12], [13] are applied to a regional architecture.

But not the level is relevant to improve operations – it is the mode. Trains operate in ETCS mode Full Supervision (FS) to achieve the benefits of cab-signalling.

Current ETCS applications need a Lineside Electronic Unit (LEU) or a Radio Block Center (RBC) to use ETCS. The IL itself does not know which Automatic Train Protection (ATP) systems are connected. Digitisation allows an integration that eliminates the resulting drawbacks of the side-by-side architecture. Commanding balises directly from the IL improves operation due to a higher information density.

1.2 Thesis Outline

At first, chapter 2 gives a historical overview on the railway safety systems to state the railway's current situation. Chapter 3 presents the *fundamentals* of railway safety systems with a focus on ETCS. Since radio communication, especially the Global System for Mobile Communications - Rail (GSM-R), is a core technology for ETCS Level 2 and Level 3, chapter 4 states the fundamentals of radio communication. Project examples, lessons learned, and current research activities are presented in chapter 5 and substantiate this thesis' topic.

Chapter 6 describes the new architecture. The impact on operations is outlined in chapter 7.

Capacity analysis is described in chapter 8 to justify statements concerning capacity. Considering further aspects, like energy, security, economic efficiency, project planning, and safety in the context of a safety system are described in chapter 9.

A summary and outlook conclude this thesis (chapter 11).

1.3 Definitions

In the context of this thesis, some definitions need to be mentioned for proper understanding. Due to a different usage or wording in different regions, the understanding may vary. This thesis relies on the the British way of speaking.

In rear / in advance of
If a train is waiting at a signal, the train is *in rear of the signal*. If the train drives and passes the signal, the train is *in advance of the signal*. The same applies to level crossing, e. g.

Balise Groups and Signals
Generally, a triangle in the track indicates a balise group. The triangle may point in or odd driving direction and in both directions (see figure 1.1). The same applies to the

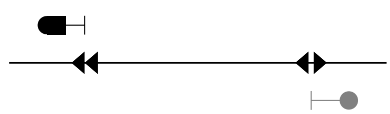


Figure 1.1: Classic balise group/signal vs new balise group/indication signal.

signals. A black signal refers to the classic signalling system. A grey signal with a filled circle on top is a simple signal (named indication signal [14]) for dispositive information with no safety relevance. It only indicates a valid Movement Authority (MA) in the balise group located at the signal.

The balise group with both triangles pointing in the same direction means a balise group connected to a signal containing information for one direction only. The new balise group refers to the new application of ETCS Level 1 explained in this thesis. The balise group may contain information for both driving directions depending on the locked route or operational situation. Details are explained in later chapters.

Profile Data
Mandatory for ETCS FS are several profile data. These data cover the Static Speed Profile (SSP), gradient profile, and Axle Load Speed Profile, e. g. Reffering to profile data means SSP and gradient profile.

LEU vs. BCU
An LEU refers to a classic ETCS setup with balise groups connected to a signal. The LEU derives the signal aspect and selects a predefined telegram. Opposed, the Balise Control Unit (BCU) is a type of LEU controlled by the IL and refers to the new architecture developed in this thesis. It is introduced in [15] and explains the connection of an LEU to the IL directly.

Wording
This thesis describes an IL which bases on cab-signalling. Hence, trackside signals are not necessary. To describe the location of the End of Authority (EoA) or the start of a train ride, sometimes the common signal location is used. This shall simplify the description of some use cases by using the well known wording concerning signal locations.

Chapter 2

Historic Background

The first German railway engine called “Adler” run on 07.12.1835. At that time, there was no interlocking to safeguard the infrastructure. Also, there was no train protection system to supervise the train driver and protect the train [16].

Operating rules have evolved with increasing rail traffic and the growing need for a safe train operation following accidents. More traffic requires more station tracks, and points are necessary to guide the trains into different tracks. Thinking about steam locomotives, they have to move to the other end of the train for changing the direction. The train drivers or track workers control the points. Improving railway operation requires a central control device to set the points in the correct positions [17]. That device is the IL. It fulfils two major tasks:

- Controlling infrastructure elements
- Safeguarding infrastructure to secure train movements

IL systems are the technical realisation of the operating rules. Enhanced operating rules lead to the development of technical features in the IL to ensure safety. The basic railway safety principles are presented in the following list [18], [19]:

- **Following protection** secures the trains sequence on the line. The commonly used method is block sections and a time distance between train runs is an often-used method for low-density lines. Realising moving block requires a reduction of block sections to an infinitesimal length. A train follows in the absolute braking distance, but, in principle, a relative braking distance is possible.
- **Opposite movement protection** secures a train against oncoming trains. It is comparable to the permission to enter a line with opposite movements.

- **Level crossing protection** secures the intersection of road and railway – the road traffic has to stop when a train approaches the level crossing (LX).
- **Flank protection** ensures a train movement against other movements running into the flank of the train. That avoids sideways movements of a train into another train.
- **Speed indication** gives the maximal permitted speed. The train driver must ensure to drive at the permitted speed.

These principles are realised in the technical dependencies of the IL. Speed supervision is mainly processed in the trainborne systems (in interaction with the trackside systems). Realising safety without technical systems is possible. The operating staff must apply the necessary rules to ensure safety. However, the safety level of an only rule-based operation is not that high as a technical realisation. A person is more prone to errors than a technical system [20], [21].

An IL protects train movements by locking points, checking track vacancy and controlling signals. The train movement itself is not supervised and protected. A train driver is instructed to stop at a stop signal. Suppose the train driver does not recognise that stop signal, so the rule is not obeyed. Protecting the train movements required the development of ATP systems. These systems supervise the train movement, and exceeding a threshold leads to an intervention. In Germany, a trainborne safety system is necessary for speeds above 50 km/h, but it also depends on line and traffic type [22]. Due to high speeds and the iron-iron contact between rail and wheel, long braking distance requires distant signals for a main signal's pre-indication [18], [23]. ATP systems ensure that the train driver does not miss the signals and intervene if the train driver fails to react. The main ATP system used in Germany is the punktförmige Zugbeeinflussung (PZB). That system was developed in the 1930th and named INDUSI as a predecessor of the PZB. It is decades old but provides an important safety level for the railway.

Figure 2.1 shows the principle of the IL and ATP system. The IL locks and safeguards the infrastructure, whereas the ATP systems safeguard the train movement. ATP systems are connected to a signal and derive the information from the signal aspect and transmit a corresponding information to the train. Integration of the ATP system into the IL is not necessary. The trackside ATP components transmit information about the current signal aspect to the trainborne ATP device, evaluating information. There is no interaction between IL and ATP. Mostly, there is no feedback from ATP to the IL. The IL does not know if an ATP system is connected to the IL. Even if an ATP system is connected to the IL, its type is unknown. The ATP system is only connected to the IL but not integrated.

2.1 Interlocking

The history of railway safety presents four generations of IL systems. The first generation of IL systems is the **mechanical interlocking** basing on mechanical dependencies be-

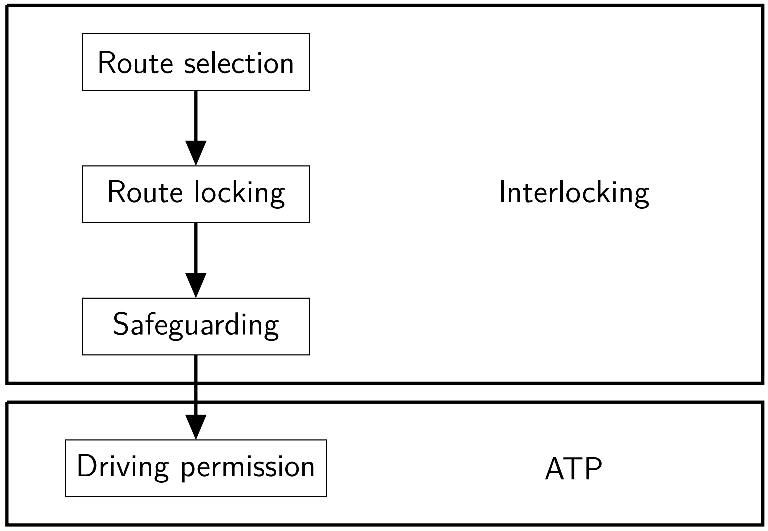


Figure 2.1: Process of locking a route and protecting a train with an ATP.

tween points, signals and locks. There are moveable bars that lock the signal if the points are in the correct position. Wire ropes connect signals and points to the appropriate levers. Every single step of the route setting process is operated manually. Moving point and signal levers is challenging and time-intensive work.

The **electromechanical interlocking** is the second generation of IL systems. Electrical motors substitute hard manual work for setting points and signals. Some mechanical levers are merged into one lever to increase efficiency. Hence, reducing the number of operational steps improves route setting time.

In Germany, mechanical and electromechanical IL systems base on visual track vacancy detection. The dispatcher is in charge of checking the track vacancy. The third generation, the **relay interlocking**, reveals this safety-critical process. Track circuits are introduced to check the track vacancy. The dispatcher is no longer in charge of a visual track vacancy check. This technical impact leads to a safety increase. The locking principle of some relay IL is model-driven. That is realised by connecting different functional relay groups according to the track layout. An operating panel operates the relay IL. For selecting a route, only two buttons are necessary: A start and a destination button. Setting points, locking, and checking track vacancy is processed automatically by the relay circuits. The relay IL is a revolution for safety and efficiency.

With the spreading of computer technology, also the IL systems were designed with micro computers. The fourth generation of IL systems is named **Computer Based Interlocking (CBI)**. Compared to the relay technology, the operation of a CBI is similar to a relay IL. Instead of operating by a special control panel, the CBI will use a controller desk for a computer with a monitor, mouse and keyboard to select a route or do other operational actions. Automatic control of an IL is possible so that the dispatcher performs a supervising function. However, if there is a malfunction, some special auxiliary operations are necessary. That requires a particular action of the dispatcher.

The controlled area of an IL increases with the development of the relay IL. A further increase is achieved with the CBI due to technological progress. The newer the technology, the fewer people are necessary for railway operation. [24], [23], [10]

A new generation is currently under development. This is the so called digital interlocking. However, the development is not yet complete and finished. Hence, this thesis disusses briefly a rough achritecture of an digital interlocking.

2.2 Automatic Train Protection

Opposed to an IL safeguarding the infrastructure, an ATP system safeguards the train movement. The main objective of ATP systems is to supervise the train movement. In Germany there is the PZB in operation, e. g.The scope of functionality reaches from simple warning systems to braking curve supervision. ATP systems supervise speed restrictions. A commonality is a connection to the trackside signals of the IL. The signal indication is evaluated, and the corresponding information is transmitted to the train. A restrictive signal indication activates a watchfulness check of the train driver or the braking curve's supervision. If the train driver does not react, the ATP system commands the emergency brake to stop the train. [25]

ATP systems are divided into conventional systems and high-speed systems. Both types have different requirements for the system itself [22]. Most ATP systems in the EU are different and not compatible. Some have a continuous transmission, and others have a discrete transmission at a certain track location. There are systems with continuous supervision of the train movement, and there are systems, which only supervise the train driver reaction (warning system) without protecting or commanding the train. Most systems supervise the braking curve or the speed reduction if the train approaches the main signal.

Historically, the ATP systems have been specified by each railway undertaking itself. Hence, every country has its own ATP system today. Figure 2.2 shows a map of the used ATP systems throughout Europe. The national impact is similar compared to the IL. In contrast to the IL, an ATP system is a technical interface between infrastructure and train. Hence, it is more in focus for interoperable train traffic than the IL's safety logic.

The different ATP throughout Europe have different safety levels. Countries with safety issues force a replacement of that ATP system. Such replacement requires a significant economic and logistic effort. A replacement with a European system is preferred to support international train traffic in means of interoperability. Also, the bigger market and long term availability of technical components is a significant advantage for ETCS. Furthermore, ETCS is introduced due to an European Union (EU) regulation.

Figure 2.2: ATP systems throughout Europe.

For international train traffic, such old technical interfaces are obstructive. It is similar to the gauge as well as the electrical power supply. These technical aspects have a huge impact on international railway traffic. If a train runs throughout Europe, more ATP systems are necessary. Today an international driving train needs different ATP systems, at least one for each country. Such an equipped train causes high costs. At the time, when the Class B systems were developed, the international rail traffic was not that important. The development of railway safety systems was a national interest, and international competition was nearly not existing. [26]

This issue leaded to the development of the European Train Control System (ETCS). ETCS is named the single (Class A, opposed to Class B) train control system in the EU. [26]

Migration to ETCS was mainly forced by the countries with safety issues as well as an old safety infrastructure. That requires a replacement with a new system or a modernisation of the existing systems.

Interoperability is the main reason for the development of ETCS, but it is not the main reason for the migration to ETCS. The replacement of such a safety system requires long term planning in logistics and funding.

Chapter 3

Fundamentals of Railway Safety Systems

This chapter presents briefly the fundamentals of railway safety systems.

ETCS, IL, and LX are the relevant safety systems considered in this thesis.

Railway business is currently in the change process of digitisation. Many systems are going to be connected to strengthen operations, maintenance and service. The so-called fifth generation of IL systems, the Digital Interlocking (DI), is introduced. The DI and ETCS as the single future train protection system are the core technology for railway's digitalisation.

3.1 ETCS - European Train Control System

ETCS is a part of the European Traffic Management System (ERTMS) divided into ATP/ATC systems (ETCS) and a communication system part (GSM-R). It is a technical system for an interoperable Automatic Train Control (ATC) system throughout the EU. The target of the system's design is technical interoperability and handling of different operating principles. Harmonisation of operating rules is not the main focus in connection with ETCS. The introduction of ETCS is driven and forced by the EU.

If not stated, the references for the description of ETCS are [27], [28], [29]. These references specify the different ETCS parts covering the system requirement specification, the balise specification and the functional specification. Also, relevant books like [18] and [23] are used.

3.1.1 Historic Development

At the end of the 1980s, the development of ETCS and GSM-R started. Legislative regulations and laws are necessary to introduce such an interoperable system throughout Europe. Some infrastructure managers introduce ETCS due to reasonable motivations like replacing old systems or increasing safey. Other infrastructure managers have no relevant reasons for migration to ETCS in their network because they do not have significant benefits due to ETCS. The benefits of introducing ETCS are different. Safety and capacity are the two main reasons to introduce ETCS. Safety was a reason for Switzerland to force the development of ERTMS instead of developing a national system to increase the Swiss railway network's safety.

The EU forces development and introduction of ETCS in the railway network with directive **96/48/EG** on the pan-European network on part for high-speed lines. Directive **2001/16/EG** covers the introduction of ERTMS on the conventional railway network. As seen in the directives, ETCS was a system dedicated to high-speed lines. An implementation of ETCS on the conventional network was considered years later [30]. Both directives merged into directive **2008/57/EG** for the high speed and conventional network.

Later this directive was expanded in **2013/9/EG**. This directive results in the regulation Technical Specification for Interoperability (TSI) **(EU) 2016/919**. The TSI is the specification for interoperable railway traffic in the EU and describes the properties of ETCS. The system requirement specification (SRS) for ETCS derive from the TSI. The basic requirements for ETCS specify in the different TSI, e. g.control, command and signalling (CCS). Defining the Class A train control system (ETCS) is the major scope of this directive. The TSI is valid for different subsystems of the railway network. These are

- infrastructure,
- energy,
- control, command, & signalling, and
- the train.

The specification for ETCS is described in different SUBSETs. SUBSET 026 is the SRS for ETCS and describes the system properties. The functional system requirements (FSR) in SUBSET 037 describe only the system's functions but not the technical realisation.

The current version of ETCS is Baseline 3 with version 3.6.0 of the SRS.

3.1.2 System Description

ETCS is a system divided into different subsystems. These are the trackside and trainborne subsystems.

Other systems, which are not a part of ETCS, are the train, the train driver, IL and management systems, for example. Defined ETCS interfaces are the driver interface, the train interface, and other trainborne interfaces (e. g., brake system). Interfaces to trackside systems like signals, IL or management systems are not defined and are not part of the SRS or other ETCS related specifications. All these ETCS specifications describe ETCS and GSM-R.

The SRS defines different levels for ETCS. An ETCS *Level* describes, for example, the technical equipment of a railway line and of the train concerning train detection and train integrity. Hence, ETCS is not only one system – it is a modular system that allows depicting several types of ATP and ATC systems [31].

Each level uses a specific procedure for data transmission. ETCS offers both punctual data transmission and continuous data transmission. It is possible to use ETCS for various operational situations. These different concepts are named MODE. There are modes for regular service and exceptional cases like System Failure or Unfitted.

Trackside Subsystems

Two relevant trackside subsystems are balises and the RBC. Balises are necessary at all levels. They transmit the MA from track to train in Level 1. Level 2 and Level 3 requires balises as a position mark to the train. It is necessary to synchronise the train position detection via odometer in recent intervals due to wheel diameter inaccuracy. Euroloop and radio infill are infill devices which are rarely used and therefore of little importance.

The **balise** is the core element of trackside ETCS equipment. Level 1 uses transparent and fix data balises. Transparent data balises are connected to an LEU. A balise transmit at maximum 830 bit (useable bits). The maximum number of balises within a balise group is fixed at eight balises. Hence, the message's length, transmitted by a balise group, is at a maximum of 6.640 bit.

The **LEU** is a device that sends a telegram to a balise. The LEU evaluates a signal aspect by measuring the current of the single light points of the signal or the position of a mechanical signal component. A centralised LEU is possible, but an interface to the existing IL is necessary. That allows using more precise telegrams if more information is available.

Euroloop is an antenna for a local communication loop. It can be used for continuous data transmission from track to train, e. g. in a local area in rear of the signal. Used as an infill device, the upgrade of an MA in rear of a signal is possible. On the train, a special receiver is necessary to receive the Euroloop telegrams. The advantage of Euroloop is the upgrade of the MA continuously in braking distance to an EoA. The train can accelerate earlier and does not need to brake until reaching the EoA, where a new MA is transmitted. Using a balise group to upgrade the MA is only discrete and forces the train to stop if the signal is cleared after the train passes the last infill balise group. Corresponding to the infill by Euroloop an infill by GSM-R is possible. Therefore, a radio device, the **Radio Infill Unit (RIU)**, is needed. This device is connected to the trackside subsystems to select the message transmitted to the corresponding train.

The **RBC** is the core element used in Level 2 and Level 3. In general, the RBC is the ETCS centre, which connects the IL with the train. However, an RBC handles some safety operations concerning track vacancy detection, e. g. It acts as an ETCS centre of a railway line or the assigned control area.

The development of RBC bases on the relay IL technology. Usually, an RBC is connected to several IL. The information flow is from the IL to the RBC. Since the function's range is not specified, different setups and interfaces between IL and RBC are available.

Also, the method to create the telegrams is different. An RBC with a look-up-table and predefined telegrams is available [32], [33], as well as an RBC with a kind of generic telegram creation [34]. In both cases, ETCS is enabled due to the RBC and on the common IL logic. The RBC receives and handles messages sent by the train.

Level 2 and Level 3 base on radio communication via GSM-R. It is similar to Global System for Mobile Communications (GSM) but has more functions related to railway requirements. GSM-R uses different frequencies than GSM.

Trainborne Subsystems

The trainbornesystem is divided into the On-Board Unit and the trainborne GSM-R system. The On-Board Unit manages the interfaces to all train systems. A core component of the On-Board Unit is the European Vital Computer (EVC).

The GSM-R system establishes a connection to the Radio Block Center (RBC) (Level 2 and Level 3) or an RIU in Level 1 to receive and send data. Interface to the trackside subsystem is the **Balise Transmission Module (BTM)**, the **Loop Transmission System (LTM)** or a Specific Transmission System (STM) to connect a national ATP system to ETCS.

The **Driver Machine Interface (DMI)** realises data input and output. It combines the speedometer, train control, and track overview if available. Touch screen or buttons are used for data input or to confirm a message.

An essential function of ETCS is position determination. Measuring the wheel rotations realises path measurement.

3.1.3 Levels

ETCS defines several levels: Level 1, Level 2 and Level 3 are used for ETCS service. Level NTC is dedicated to lines with a class B ATP system. Level 0 describes a train ride on a track without ETCS equipment.

Level NTC
Level NTC describes a railway line equipped with a national ATP system. The train is equipped with ETCS and an STM to read the available Class B ATP system data. The STM transmits the national ATP data to ETCS, which is in charge of train control. Also, the DMI is used to display the national ATP data (see figure 3.1). Depending on the operating rules, the train driver must look at the trackside signals if necessary due to the national system.

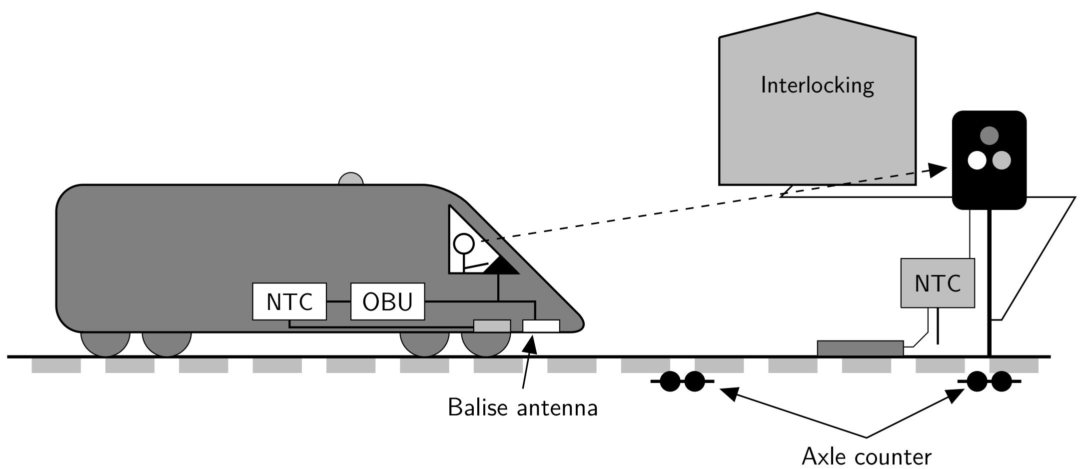


Figure 3.1: ETCS Level NTC.

Level 0
In level 0, the line is equipped with no ATP systems or with a Class B ATP system. The train is equipped with ETCS and a trainborne Class B system which is not connected to a trackside ETCS. In this case, ETCS supervises the train's maximum speed and the train is safeguarded with the Class B ATP system.

Level 1
The **LEU** is connected to a signal and evaluates the signal aspect by measuring lamp current, e. g.Depending on the signal aspect, the LEU selects a predefined telegram and transmits it to the balise. A transparent data balise is connected to an LEU that selects the message depending on the signal aspect. An interface to the IL is possible. Such a setup is named centralised LEU. Figure 3.2 shows the setup of Level 1. There is no interaction between the IL and ETCS itself. The LEU transmits the information of the signal aspect to the balise. Data transmission is unidirectional from IL (balise) to the train.

In general, balises are located at the signal locations and transmit the information given by the signal aspect. Additional infill balise group allow transmitting an upgrade if the signal switches its aspect. This feature is similar to the distant signal. For Level 1,

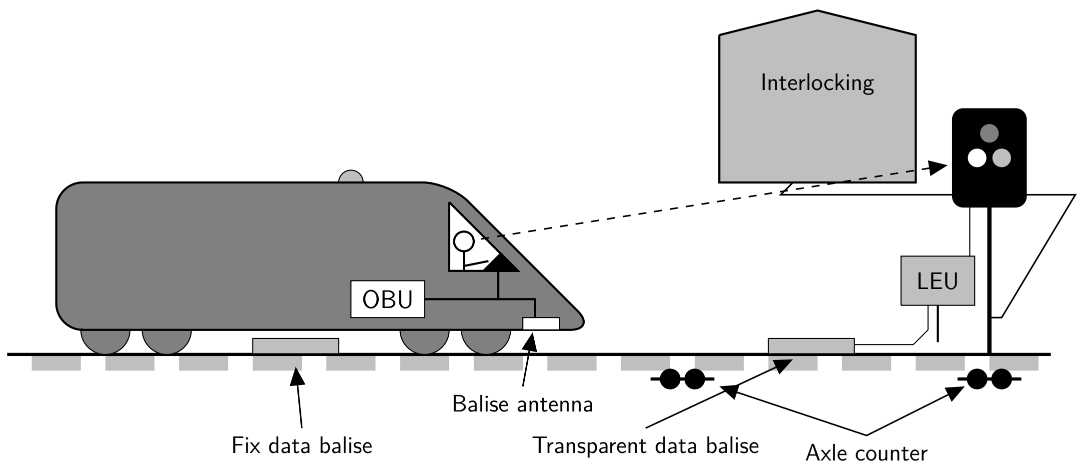


Figure 3.2: ETCS Level 1.

transparent data balises are used. Fixed data balises can be located everywhere since the data does not change during operation. Mainly, they transmit national values or a position update.

Level 2
In Level 2, Euroradio exchanges messages between IL/RBC and train. The transport technology is GSM-R. Level 2 provides continuous transmission of data. Transmission of messages is not limited to specific locations. Data transmission is bidirectional.

Passive balises are necessary for a position adjustment like in Level 1. Figure 3.3 shows the setup of a Level 2 line. Because of radio communication, GSM-R transmits the MA. Trackside signals are not necessary because the RBC transmits a new MA to the train. Due to continuous data transmission and cab-signalling, no trackside signals are necessary. The DMI displays the MA. A train detection system (TDS) is still necessary.

The RBC receives information from the IL about the locked routes and selects a predefined MA. After defining the packages, the message is transmitted to the train. Level 2 allows transmitting a message every time and every place independently from balise locations. Compared to Level 1, signals and LEU are not necessary due to GSM-R. A loss of radio communication during a train run is accepted, and a valid MA remains valid even if there is no active GSM-R connection. A new MA cannot be transmitted to the train without a radio-link, and a valid MA cannot be reduced.

Level 3
Level 3 is an extension of Level 2. If trains are equipped with an integrity check, no trackside TDS is necessary. The trains' position is calculated on-board with the odometer and the position adjustment via balises. Usage of Global Navigation Satellite System (GNSS) is possible. Although ETCS requires balise groups for position updates, GNSS can do without balises. However, to stay within the ETCS logic, ETCS messages need

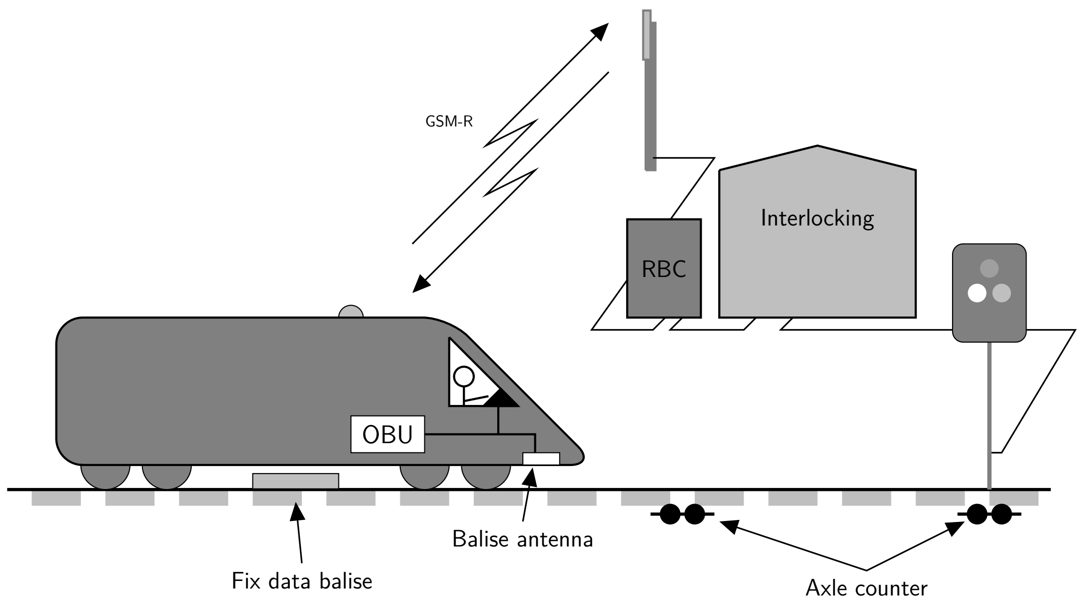


Figure 3.3: ETCS Level 2.

a balise as a reference. In this way, messages refer to a virtual balise group indicated by the virtual balise cover marker.

A Last Relevant Balise Group (LRBG) (reference balise group) is still necessary for the basic ETCS functionality.

Figure 3.4 shows the setup of Level 3. The remaining trackside components are points, LX and passive balise groups.

Since no trackside TDS is necessary, train movements in moving block are possible. ETCS supervises the train location and creates an MA up to the safe next train end, including a safety margin. Therefore, a train integrity check is necessary, which allows the train to report its completeness next to the location. The RBC estimates track vacancy due to the train position report. The IL is reduced to the locking of the moveable track elements.

Transition between Levels

The preferred level, which a train shall use, is given trackside. The packet Level Transition Order (LTO) gives the train a rule, which level is the preferred one. If there is only one level on the line, it is pretty simple.

If the line is equipped with several levels, the packet LTO defines the level used by the train. Hence, a train equipped for Level 1, Level 2, and Level 3 can be forced in Level 2 if the packet LTO defines Level 2 with the highest priority.

However, if Level 3 is the highest priority, Level 2 the second priority, and Level 1 the third priority, the train selects the level depending on its capability. A train without Level 3 equipment chooses Level 2 for the service, e. g.

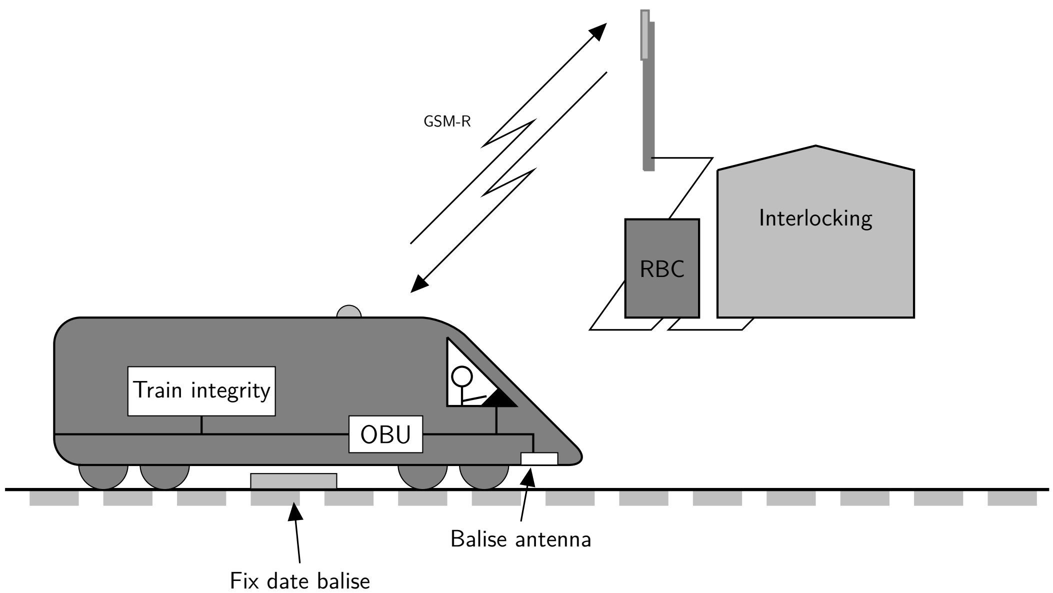


Figure 3.4: ETCS Level 3

If the line is equipped with several levels, the trains can be commanded at different levels individually. Therefore, defining a telegram with packet LTO depending on the individual train must be possible.

For the transition between the different levels, the trackside systems must provide the necessary information. That covers the dial-in for Level 2 and Level 3 or the correct information for Level NTC or Level 0. The MA must end at the correct locations or must be given in the correct order.

3.1.4 Modes

ETCS, as a technical system, handles different operating rules. Therefore, various modes are defined in the ETCS system requirement specification (SRS). Regular operating modes are Full Supervision (FS), Limited Supervision (LS), Shunting (SH), On Sight (OS), National Train Control (NTC), and Staff Responsible (SR). These modes perform regular train service, shunting movements and particular movements, e. g. movements into closed track sections.

Further modes are Unfitted, Sleeping, Stand By, Trip, Post Trip, System Failure, Isolation, No Power, Non Leading, and Reversing. These modes are not dedicated to a regular operation (train service) and cover different situations for standstill or a train service without ETCS supervision.

The driver can select some modes, but the trackside systems command some modes if the necessary conditions are met. The transition from each to each mode is not possible.

There are transition rules which define the allowed transitions. That is depending on the current mode and the operational requirements.

Details of the different modes are explained in the following:

FS - Full Supervision
In mode FS, the whole train movement is supervised by ETCS. The train driver does not select this mode. Entering FS is successful if all required data is available. The required data is the SSP, gradient profile, and the MA itself. The whole train must be in the given MA to finish switching to FS. If the train is not in FS, the DMI indicates ENTRY IN FULL SUPERVISION.

LS - Limited Supervision
Limited Supervision supervises only the braking curve in rear of a signal indicating stop. The train driver has to supervise the trackside signals. In mode LS, the ETCS On-Board Unit performs background supervision of the train. The infrastructure orders mode LS.

OS - On Sight
The mode OS is similar to FS concerning supervision. Divergently to FS, it is intended to enter an occupied track. OS is entered when the necessary information is available. That means a valid MA is available, but an additional packet defines the movement or a part of the movement as OS. The On-Board Unit supervises against a dynamic speed profile. The train driveris responsible for stopping in front of an obstacle. Compared to FS, the train movement itself is supervised to a ceiling speed limit.

SH - Shunting
SH is dedicated to shunting movements. The train is supervised to a speed limit – the shunting mode speed limit. The train can receive two lists of balise groups, balise groups that are not allowed to pass or balise groups allowed to pass. If no list is transmitted, all balise groups are allowed to pass. The shunting mode can be selected by the driver (at a standstill) or ordered by trackside. Communication to an RBC is not allowed during shunting movement. It is possible to enable communication to the RBC. An exchange of information with relevance for the shunting movement is not foreseen in SH.

In Level 2 and Level 3, the transition to SH needs authorisation. That is transmitted via GSM-R. In Level 1, there is no need for authorisation. If the driver switches to SH, no instance can authorize the transition. There is no communication channel to send the request to the infrastructure. If the trackside orders SH mode, the driver has to confirm the transition to SH. The On-Board Unit only supervises the shunting mode speed limit and the eventually given shunting border. The train driver is responsible for stopping the train rear of obstacles.

SR - Staff Responsible
SR is used for a train movement in an ETCS area under the responsibility of the train driver. The use of SR can be selected by the train driver or chosen by the On-Board Unit due to a failure, e. g.

In SR, the On-Board Unit supervises the train movement.

1. The national values define the SR speed limit.
2. A given distance to travel is supervised. Various aspects determine the distance.
3. A list with expected balise groups can be transmitted to the train.
4. A balise group with a message STOP IF IN STAFF RESPONSIBLE stops the train.
5. The On-Board Unit supervises the direction of the train movement.

SB - Stand By
Stand By (SB) is a default mode entered after the launch of the train. The On-Board Unit supervises the standstill of the train. A further mode is entered manually by the train driver. In SB, the On-Board Unit collects information for an ongoing mission.

TR - Trip
Trip (TR) commands the emergency brake until the train has come to a standstill. Then, TR supervises the standstill of the train. After confirmation of TR, the On-Board Unit switches to Post Trip (PT). The DMI shall indicate the reason for TR.

PT - Post Trip
The On-Board Unit enters PT if the train driver confirms mode TR. PT releases the brakes. No MA is available, but moving the train back in rear of a signal shall be possible.

Essential Functions of the On-Board Unit

The ETCS On-Board Unit intends to fulfil various functions.

- If balise groups are linked, they must be announced to the train. The On-Board Unit checks the linking consistency. That means that the estimated location of the balise groups is supervised. A not detected balise group within the expected balise group location window leads to a defined reaction. That can be an emergency brake or a notification to the train driver, for example.
- The On-Board Unit receives the messages of the balise group and proves them. The message is split into a telegram for each balise. If a balise telegram changes while the train passes the balise group, the message is not valid. The telegram header variable `NID_ID` is an ID to identify a message. If the message is changed, the ID must be changed, too. Otherwise, a wrong message is not detected.
- The On-Board Unit calculates the train position. Therefore, odometer and balise groups are necessary. The odometer has an inaccuracy, which requires a periodic position synchronisation at a balise group. Position synchronisation is required at approximately every kilometre.

- A major task of the On-Board Unit is the supervision of the train speed and position. ETCS is designed to supervise the train position and speed. GNSS can be used for positioning as well. The position of a train is connected to the LRBG. That is the balise group, the reference balise group for the MA or SSP, e. g. The modes FS and OS supervise the whole dynamic speed profile. In other modes, a ceiling speed is monitored to protect the train against exceeding that ceiling speed.

- The On-Board Unit calculates the Dynamic Speed Profile. The trackside given static speed profiles or restrictions do not consider the dynamic parameters of the train. Therefore, the On-Board Unit owns the train parameters and calculates the Dynamic Speed Profile to supervise the train movement.

Transition between Modes

Rules for switching the modes are defined. For example, to enter FS or OS, the train needs a valid MA, SSP and gradient profile. Without these data, the train with its whole length does not enter the mode FS. Hence, entering FS cannot be forced.

The modes FS, LS, OS and SR can be switched back and forth. SH, SB, TR and PT are necessary for the train movements. Figure 3.5 shows a simplified sketch of the defined transitions between the modes. A transition from SH to the four mentioned modes above is only possible via the intermediate mode SB. That requires a standstill of the train. A transition from SH directly to FS is not possible.

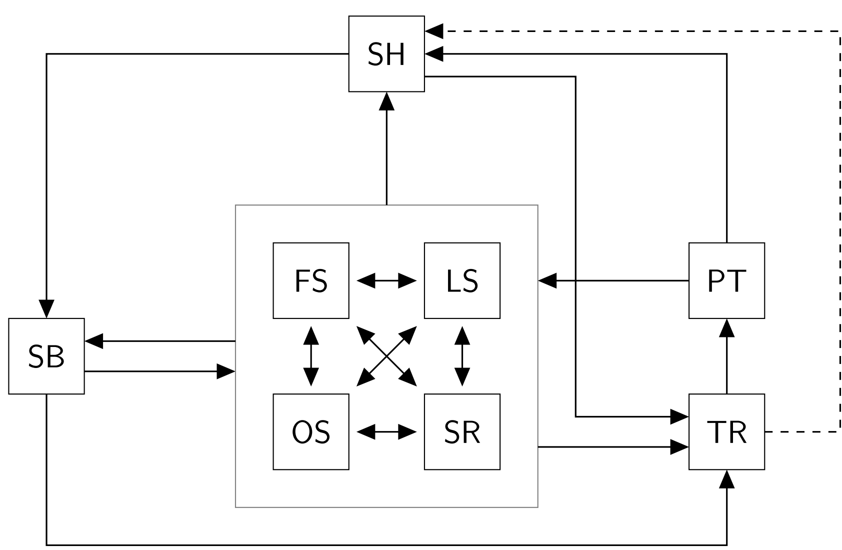


Figure 3.5: Transitions between selected modes.

The following list gives some facts about the transition to different modes:

- Entering FS
  If a valid MA, SSP and gradient profile is available, the train enters FS. The driver cannot select this mode.

- Entering OS
  The infrastructure commands OS. The train driver must acknowledge the transition to OS. PACKET 80 (Mode profile) initiates transmission to OS. A transition to OS is limited to a certain length. Afterwards, a transition back to FS, LS, SR or SH is possible.

- Entering LS
  LS is commanded by the infrastructure and must be acknowledged by the train driver.

- Entering SR
  Executing the override function transits the train into SR. Otherwise, SR is proposed to the driver if the train is in mode PT or SB.

- Entering SH
  The driver can select SH at a standstill. Otherwise, SH is commanded by the infrastructure via a balise or radio message.

- Entering SB
  SB is entered if the desk of the train is closed. If the train is in SH, selecting EXIT SHUNTING switches to SB when the train is at a standstill.

- Entering TR
  The train enters TR if (examples)

  - the train passes the EoA,
  - a speed limit is exceeded,
  - a linking reaction commands emergency brake,
  - a balise group with a STOP IF IN SHUNTING message,
  - a balise group, which is restricted for shunting movements, is passed.

- Entering PT
  If the driver acknowledges TR, the train enters PT.

The transitions between different modes must be taken into account if telegrams are created (predefined). Especially for ETCS Level 1, the transitions must be defined during project planning.

3.1.5 ETCS Language

ETCS allows transmitting messages from train to track or from track to train.

A Level 1 message consists of the same number of telegrams as balises are in the balise group. A message or a telegram consists of packages. A package is a set of variables grouped to a dedicated function like MA, gradient profile or text message. Packages merge different variables which contain the values to be transmitted. The size of the variables and the packages are different. A structure of the different elements of the language is shown in table 3.6.

<table>
<tr><td colspan="8">Message</td></tr>
<tr><td colspan="4">Telegram</td><td colspan="4">Telegram</td></tr>
<tr><td colspan="2">Packet</td><td colspan="2">Packet</td><td colspan="2">Packet</td><td colspan="2">Packet</td></tr>
<tr><td>Var</td><td>Var</td><td>Var</td><td>Var</td><td>Var</td><td>Var</td><td>Var</td><td>Var</td></tr>
</table>

Figure 3.6: Structure of ETCS language.

Movement Authority

The central function of ETCS operation is the MA. The MA describes the distance and the conditions, which a train is allowed to drive. The EoA indicates the point where the train has to stop. If the end of the MA is defined with speed unequal to zero, it is named Limit of Authority (LoA). For the length of the MA, a permitted speed V_{main} of the MA is defined. An MA is only valid if the SSP and the gradient profile cover the MA's whole length.

The SSP or Temporary Speed Restriction (TSR) reduces the speed given by the MA. The braking curves are calculated in the ETCS On-Board Unit. If a Danger Point (DP) is defined in the MA, the emergency braking curve will end at the DP. A Supervised Location (SvL) refers to the overlap of the route. It is a location beyond the DP and only valid for a certain time. In Level 1, the telegrams respective the message is predefined. The telegrams are saved in the LEU. A signal is used as an indicator to select the proper telegram. The MA is defined in PACKET 12.

Different sections can be defined, which has an impact on the length of the packet. The END SECTION is a mandatory section. Further sections are optional. A section can correspond to a locked route or a block section, for example.

Figure 3.7 shows the structure of an MA. As an example, two sections are drawn, an end section and an additional section.

Mandatory information is the distance, the speed at the end of the MA and the length of the overlap or the DP's distance.

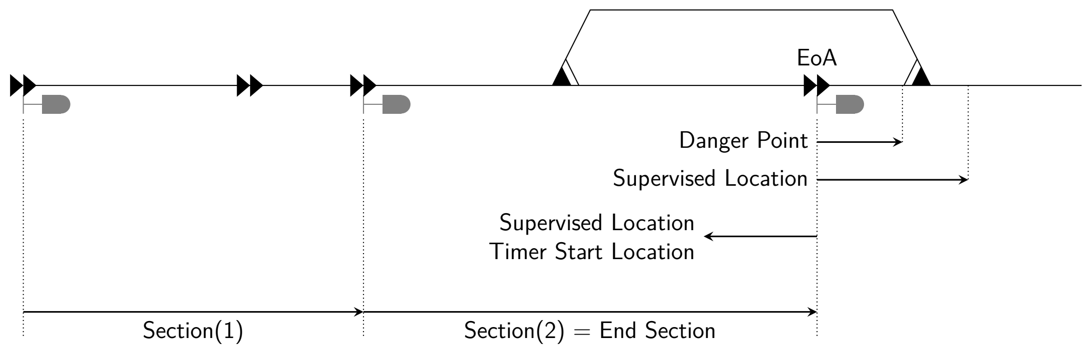


Figure 3.7: Structure of an MA.

Speed Profile

ETCS defines two basic speed profiles, the Most Restrictive Speed Profile and the Dynamic Speed Profile. The Most Restrictive Speed Profile is a mostly trackside given speed profile.

It is calculated by different packages which transmit a speed restriction to the train. The most important speed restrictions are the SSP and the TSR. Also, an *Axle Load Speed Profile* is available.

By taking the most restrictive speed of all given profiles and the maximum train speed (which can also be compared to the trackside given speed profiles), the Most Restrictive Speed Profile is calculated. Figure 3.8, shows the Most Restrictive Speed Profile. That figure shows the merge of SSP, TSR, and maximum train speed. The trains' On-Board Unit calculates the Most Restrictive Speed Profile. Hence, for each train, there can be a different Most Restrictive Speed Profile.

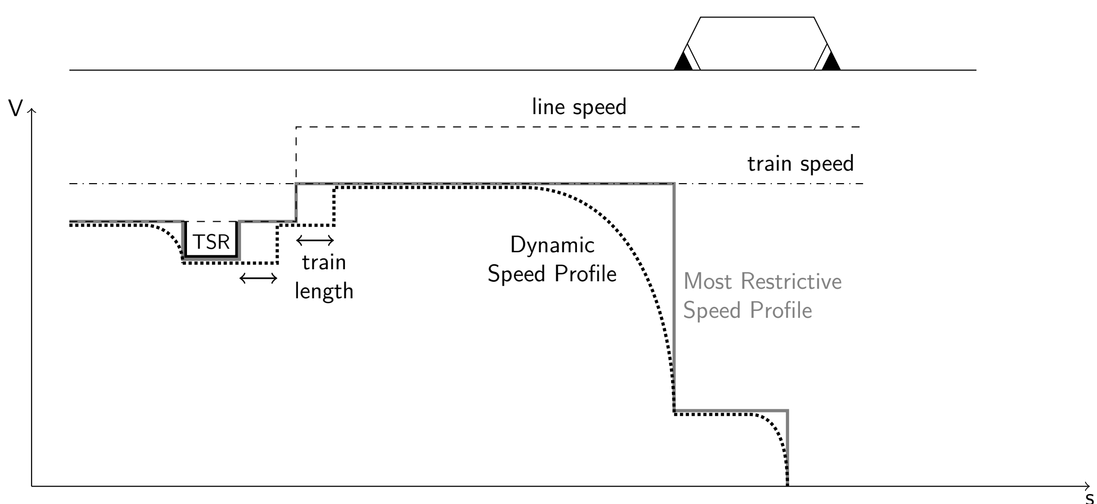


Figure 3.8: Principle of Most Restrictive Speed Profile and Dynamic Speed Profile.

The Dynamic Speed Profile is calculated with the Most Restrictive Speed Profile, considering the train and track properties. That means, the track conditions and gradient profile impact the braking distance and the braking properties of the train. Furthermore, the train length is considered as well. These relations are shown in figure 3.8. The current speed of the train is compared to the Dynamic Speed Profile. If the current speed exceeds the Dynamic Speed Profile a warning is displayed in the DMI, or the emergency brake is commanded, and the train switches to trip mode. The Most Restrictive Speed Profile is calculated by the On-Board Unit of the train and the trains parameter. Hence, for each train, there is an individual Dynamic Speed Profile.

To define and transmit the speed-related data, PACKET 27 (SSP) and PACKET 65 (TSR) are the most relevant packets. The speed profile limits the permitted tracksidespeed of the train. It is a fixed speed and ordered by the infrastructure. Modelling and implementing the correct speed profile is a task of the infrastructure.

Opposed to the SSP, which covers all static speed restrictions defined at project planning, the TSR defines a speed limits for non-permanent use. A change of the SSP is complex due to a new definition of packets and their approvement. The additional packet is simply integrated into the predefined telegrams. Also, mobile balises are used to integrate a TSR into an operating system. Furthermore, the TSR is valid in several modes, whereas the SSP is only valid in mode FS or OS.

The TSR defines a non-permanent speed restriction, e. g., for construction sites. PACKET 65 defines the TSR and transmits it to the train. A TSR is defined by

- the distance to the TSR,
- the length of the TSR, and
- the permitted speed of the TSR.

A TSR is marked with an ID. The ID allows revoking a prior given TSR. Therefore, PACKET 66 is introduced. This packet allows revoking a TSR independently of the TSR definition in PACKET 65. So, placing of the mobile balises allows limiting the TSR.

Gradient Profile

As well as the SSP, the gradient profile is necessary for a valid MA. PACKET 21 defines a gradient profile and transmits it to the train. PACKET 21 represents up to 33 gradient sections. Figure 3.9 illustrates the principle of a gradient profile. Each gradient is described by the distance (`D_GRADIENT`), the sign (`Q_GDIR`) and the gradient itself (`Q_A`). The distance of a gradient is an incremental value. That means the distances from the gradient section to the next gradient section is given and not the distance to the reference location (transmitting balise group).

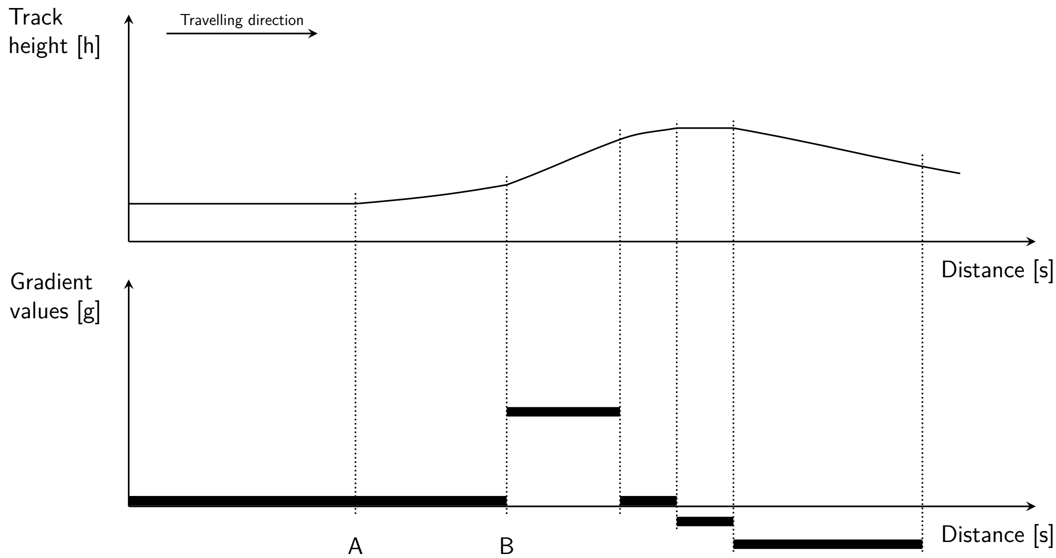


Figure 3.9: Visualisation of the gradient profile.

Linking

Balise groups are linked or unlinked.

- An unlinked balise group is evaluated independently of any linking information.
- A linked balise group is only evaluated if the balise group is announced as linked to the train.

When a balise group is marked as linked, and the train has no linking information for this balise group, the message is not evaluated. If a balise group consists of one balise only, linking applies a coordinate system to this balise group. That allows the train to evaluate the direction when passing the balise group. An additional balise is necessary if the length of transmitted packages requires a second balise.

Linking information are sent with PACKET 5 to the train. It consists of the distance to the balise group, the linked balise group's ID, the linking orientation, and the linking reaction. PACKET 5 links up to 33 balise groups.

Linking is relevant in the context of repositioning.

- If the exact route is not known, the infill reference location is not known.
- If this reference location (balise group) is unknown, the reference balise group cannot be linked to the train.

Therefore, a balise group for repositioning is linked with a range where the balise group is expected.

3.1.6 Capacity of Data Transmission

The described packets and profile data are transferred via balise groups to the train. The SRS defines a maximum number of eight balises within a balise group. Hence, eight telegrams are the maximum size of a Level 1 message. Each balise has a data space for 830 bit. The size of the maximum message length results to

$$8 \cdot 830\ bit = 6.640\ bit \tag{3.1}$$

The transmitted information must fit into this balise group. Otherwise, a transmission is not possible. The limiting factor is the packet length. It is not possible to separate one packet and distribute it onto two telegrams. It is challenging to use all the available data space of a balise respective a balise group.

Packet		**Size**	
#	Name	**min**	**max**
5	Linking	79	4.598
12	Movement Authority	51	2.628
21	Gradient Profile	54	798
27	Static Speed Profile	58	1.980
49	List of Balises for SH area	53	828
65	Temporary Speed Restriction	71	—
66	Temporary Speed Restriction Revocation	31	—
80	Mode Profile	110	—
88	Level Crossing	87	—
72	Plain Text Message	150	2.182

Table 3.1: Overview of maximum and minimum packet size.

Most packets have a variable part. Using sections or profile points increases the packet size. Table 3.1 gives an overview of the size of the different packets. Some packets have a size of more than 2000 bit. Since a balise can only transmit 830 bit, the packet size is limited. A reduction of the packet size to 830 bit at maximum is necessary. Otherwise, the packet cannot be transmitted.

3.1.7 Braking Curves and Capacity

ETCS defines two basic braking curves - the emergence braking deceleration (EBD) and the service braking deceleration (SBD) (see figure 3.10). The EBD bases on the SvL or DP. That corresponds to the overlap in advance of the route-target. The overlap depends on the Class B ATP. ETCS allows defining an overlap. The SBD bases on the EoA, which is the stop of a regular train movement. If the train driver does not follow the emergency braking intervention curve, the On-Board Unit commands the emergency brake. In this case, the train is allowed to stop at the DP or the SvL. According to the EBD and SBD, there are the corresponding intervention curves. This time considers the brake build-up time, whether the emergency brake or service brake is selected. Figure 3.10 shows simplified EBD and SBD braking curves.

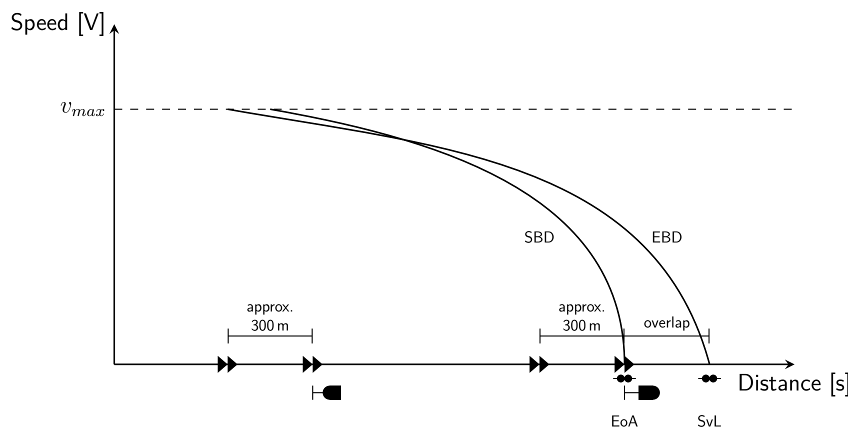


Figure 3.10: EBD and SBD.

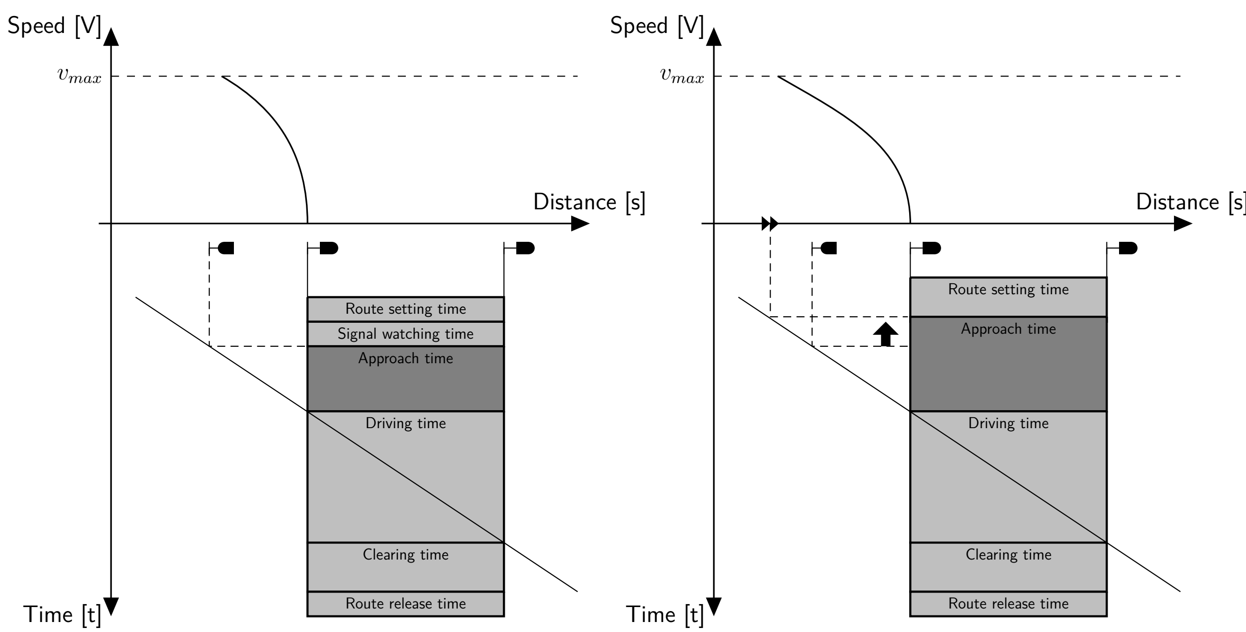


Figure 3.11: Impact on blocking time due to ETCS [35].

Since the EBD is the safe braking curve, the slope is smaller compared to the SBD. Figure 3.11 shows the blocking time for a running train with a Class B ATP systems and the blocking time for a train running with cab-signalling. This blocking time is the basis for the capacity calculation [36]. The supervised braking curve has an impact on the blocking time. For most Class B ATP systems, the braking supervision starts at the distant signal. Hence, the distance between the distant signal and the main signal is the reference for the approach time. For a train with continuous data transmission, the Indication Point (IP) is the reference location for the approach time. If the communication is punctual, the last balise group in rear of the IP is the reference for the approach time. The positioning of balise groups must be carefully considered. [37] presents the optimisation of balise group positioning for the railway network in Luxembourg. [38] gives further aspects for ETCS braking curves on the planning of infrastructure. For the route setting time, driving time, clearing time, and route release time, there is no difference to ETCS than Class B ATC.

[39] describes the impact of ETCS on the capacity for different ETCS level. The capacity analysis is carried out for *high-speed lines*, *main lines* and *regional lines*. Figure 3.12, 3.13, and 3.14 show the impact on the capacity of different line types and other setups. The reference value for the comparison of the impact is ETCS Level 1 FS.

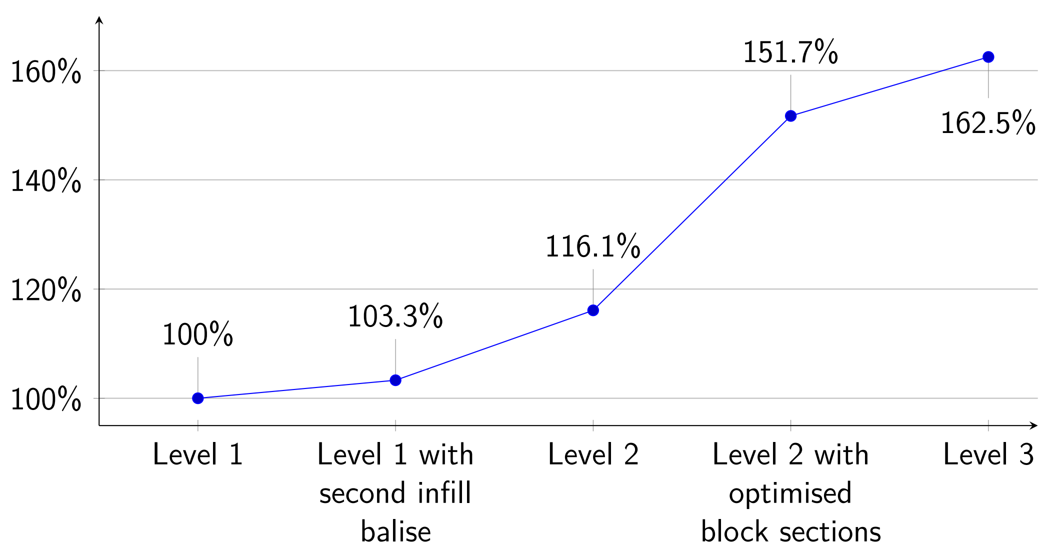


Figure 3.12: Capacity of ETCS on high-speed lines.

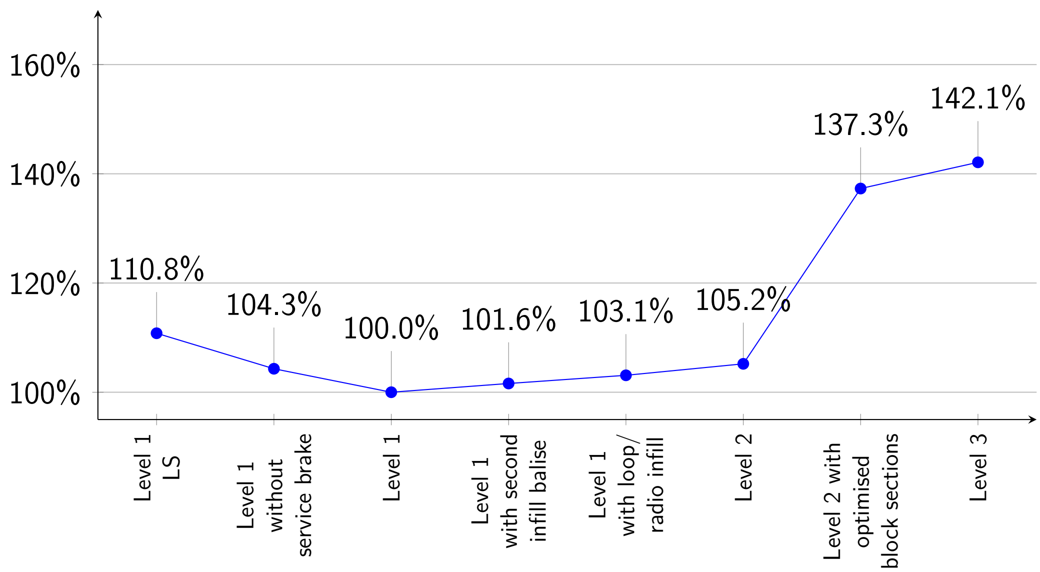


Figure 3.13: Capacity of ETCS on mainlines.

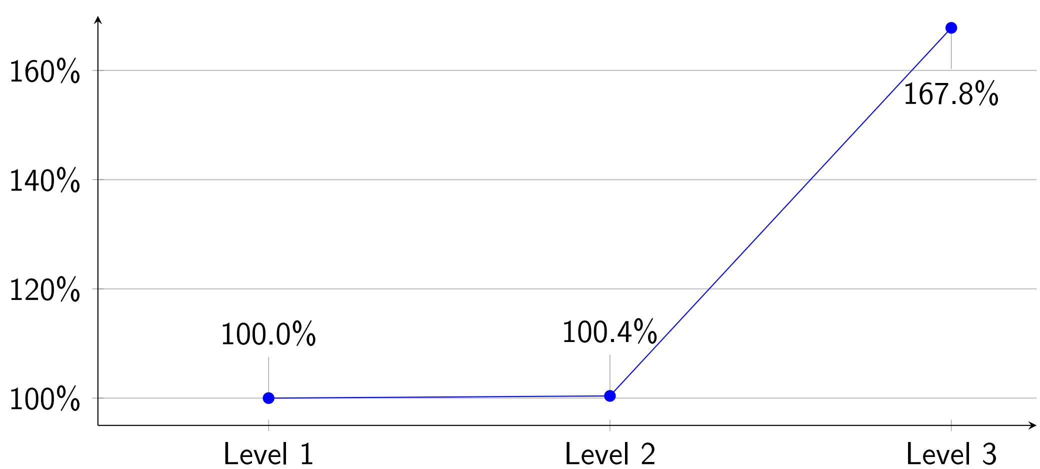


Figure 3.14: Capacity of ETCS on regional lines.

Following boundary conditions are applied to the calculations:

1. For high-speed line and mainline, a block length of 3 km is taken as a basis.
2. The regional line is modelled as a single track without any additional block sections.
3. On high-speed lines, only passenger trains are running.
4. Mainlines and regional lines have mixed traffic (passenger and cargo trains).
5. Optimised block sections are only applied to ETCS Level 2.

The capacity on **high-speed lines** is set to 100 % for ETCS Level 1 FS. For this setup, only one infill balise is assumed at the location of the distant signal. Capacity increases by 3 % with a second infill balise. With ETCS Level 2, the capacity increases by 16 % compared to the zero case. These three cases base on the same block sections. Suppose the block sections' length is optimised (adding more block sections), the capacity increases by 51 %. That relies on the block sections and not on ETCS itself. If ETCS Level 3 is applied to the line, the capacity increases to 62 %. The increase from Level 2 to Level 3 is only 7 %.

That means a Level 2 equipped network increases the capacity by 7 % if Level 3 is introduced.

For the **main lines** with mixed traffic, more use cases are applied to the capacity calculation. Without using the service brake, the capacity increases by 4 %. If Level 1 LS is used, capacity increases by 10 %. LS is comparable to the German PZB. A balise is located at the distant signal, starting braking curve supervision if the main signal is not cleared. ETCS Level 1 FS capacity with two infill balises, radio infill/loop infill and Level 2 increases about 1.6 %, 3.1 % and 5.2 %. A big increase of 37.3 % is achieved by optimising the block section – an increase that does not depend on ETCS itself. Level 3 increases by 42.1 % compared to the zero case. Compared to Level 2, the growth is only 3.4 %.

Only Level 1, Level 2, and Level 3 are considered for capacity calculation **on regional lines**. Level 1 is set to 100 %. For Level 2, the capacity increases by 0.4 %. For Level 3, the capacity increases by 67.8 %. Because of the missed block signals between the station on the single line, the continuous data transmission in Level 2 has no impact on a regional line's capacity. The impact of Level 3 depends on the moving block, which is available in Level 3. Regular operation on single lines, the crossing of trains limits and determines the capacity. Due to schedule independent capacity calculation, the use case of the following train pair and its headway is included in the calculation. Hence, the calculated (theoretical) capacity is higher compared to the capacity for the scheduled operation. The location of crossing stations impacts the capacity on the single line. A train waiting for the train in the opposite direction limits the capacity.

Two significant aspects of this study are:

1. Capacity increases if the number of block sections rises appropriately for the running trains on the line.
2. On a single line, the location and number of crossing stations is decisive.

3.2 Computer-Based Interlocking

The latest commercial IL generation is the CBI. It is a software-based system with no logic realised in electrical circuits. Its system architecture aligns with the three-tier model (see figure 3.15) of process control [18].

3.2.1 Interlocking Architecture

The **management layer** is used for the user interface and operational functions aside from safety functionality. The first controller desks for CBI are safe systems with high requirements to the hard and software. Modern CBI uses a process-oriented method to connect the controller desk to the CBI using only commercial-off-the-shelf components for the controller desk [40], [41]. In the case of auxiliary operation or fall-back mode, safety must be granted. The CBI controls a regular request for setting a route. Checking the conditions to set the requested route is performed in the CBI. Auxiliary operations bypass the safety logic of the CBI and hand over the responsibility to the controller. The dispatcher's desk must show the correct operational situation. The dispatcher's request to bypass safety features is checked and permitted in the CBI. The management layer covers several systems like train describer systems, automated route setting systems and the dispatcher's desk. These systems are non-vital because safety is not realised in the management layer. If dangerous inputs are sent to the CBI, these requests are denied.

The **safety layer** is the core of a CBI. There, safety logic is implemented. Orders of the management layer are verified and executed or rejected. For regular service, the CBI is in charge of responsibility. States of the different field elements are supervised to ensure safety for the locked routes and train movements.

The **field layer** connects the field components (signals, axle counters and points) to the safety layer. The field elements are supervised so that only safety-relevant events are transmitted to the safety layer. The field components themself handle processes that do not need interaction with the safety layer.

Interfaces between the layers are proprietary systems of the suppliers. The single standardised interface to a field element is the *four-wire point circuit*. This interface is an analogue interface developed to connect a point machine to the relay IL and the CBI [18]. Usually, it is not possible to use components of the different supplier in one CBI. The supplier-dependency is a big issue because all changes at a CBI must be handled by the supplier [42]. That causes high costs and is time-consuming due to approvals of the authority.

The interface problem arises from the transfer of relay functions to a software-based system. At first, the field elements remained analogue, and the safety logic only was adapted to a computer-based system. The logic and evaluation of the field elements are located centrally in the CBI. Later on, bus communication has been used in the CBI to connect the field components. That allows arranging a decentralised logic. The field components became intelligent and are able to pre-evaluate their information. Smart integration of LED signals was possible [43]. The LEDs are supervised, and if there has been a malfunction, the CBI gets information. In general, the former point-to-point connection has been replaced by a bus connection. Figure 3.16 shows the point-to-point connection of field elements and CBI [44].

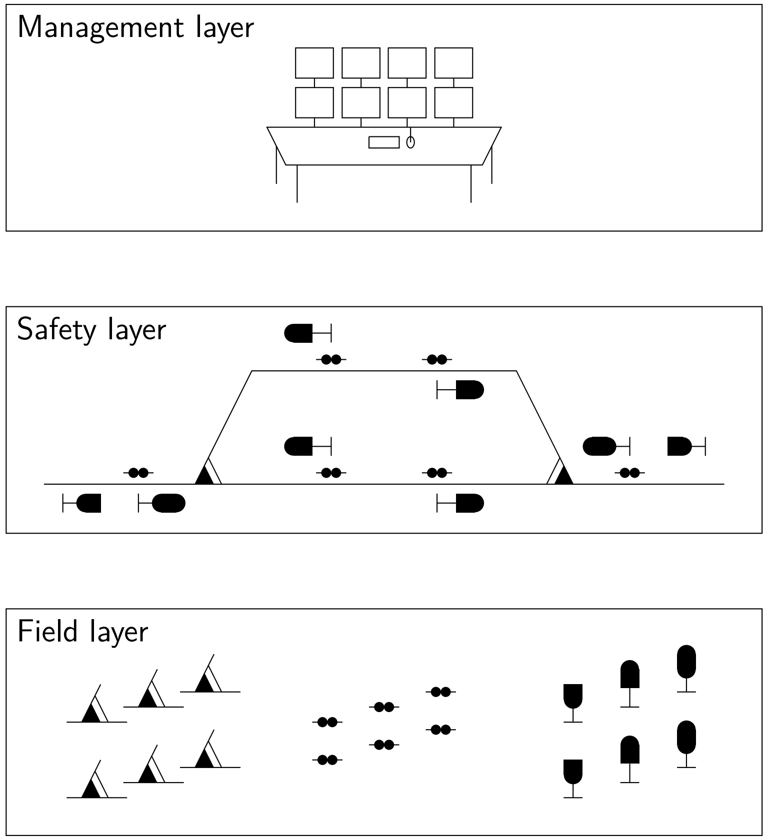


Figure 3.15: Architecture of a CBI.

The separation of energy and information due to the bus connection allows a longer transmission distance. The need for wires is minimised, which has an important impact on the costs of cabling. In addition to the exchange of information, the distribution of energy is necessary. Compared to the analogue transmission, only one bus cable for data transmission and one cable for energy distribution is needed. For means of redundancy, a double wired connection is necessary.

Neuausrichtung der Produktionstechnik (NeuPro) and EUlynx projects pursue the approach of connecting field components with bus technology [45]. It is the aim to standardise the interfaces. That shall improve operations, reduce investment and life-cycle-costs Figure 3.17 show a sketch of the NeuPro standard communication interface (SCI) [8], [46]. These are the interfaces to the field components and the system interfaces (controller desk – SCI-CC, the block interface – SCI-ILS, the LX interface – SCI-LX, and the interface to the RBC – SCI-RBC). The LX is on the same level as the field components. In principle, the LX is a safety system like the IL with its safety logic. The LX operates autonomous (depending on the operating principle) and does not need an IL interface.

A major aspect of digitisation is the transformation of processes and not (only) adopting new technology. Common CBI systems have vital field components, vital safety logic and

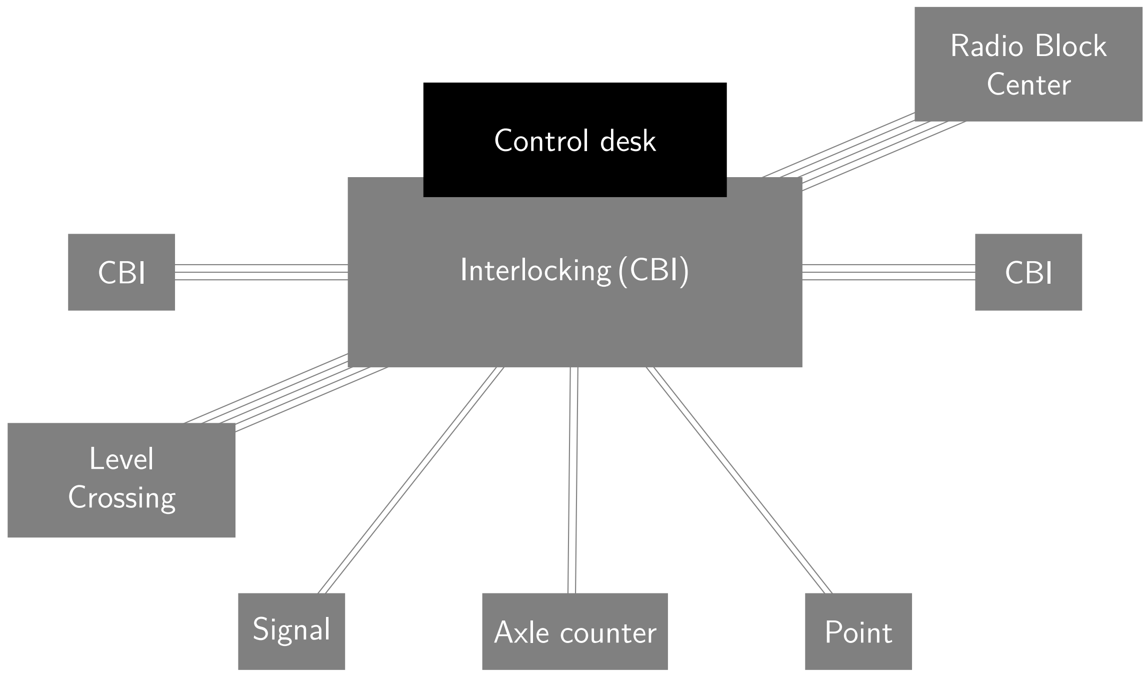


Figure 3.16: Interfaces of a common CBI with point-to-point connection of field components and other systems.

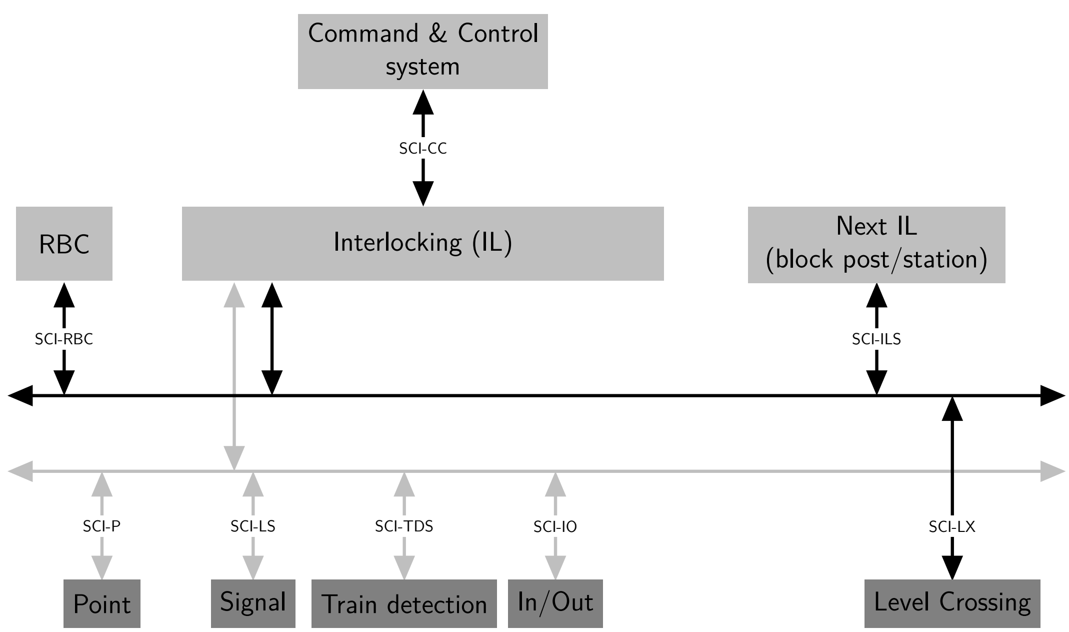


Figure 3.17: Interfaces of a new digital IL proposed by DB AG [46].

vital controller desks. All three layers of the presented IL structure are vital. However, safety is established in the safety logic (safety layer). The interaction with the field components must be a safe process. Hence, there is no need for a vital controller desk [47]. The new methods, described in [48] and [49], are implemented in the new standardised controller desk for DB AG [40].

For communication-based safety systems like the IL, the issue of security becomes relevant. On the one hand, IL ensures operational safety to the railway. On the other hand, communication-based systems must operate without disruptions due to communication errors or hacking. Both topics – safety and security – should be separated. If changes in operational safety are necessary, the security functions should not be affected. The objective of the security aspect is to achieve a safe system. If the IL is attacked, a safe state is necessary. Also, resilience behaviour is necessary. That means that the system can handle security issues by entering a safe state and return to operation after resolving the issue. [50]

3.2.2 Signalling

„Railway signals are the language of the IL“ is stated in [17]. That means the interface between IL and train or train driver is the signal. The train driver sees a signal and has to react properly.

Railway signals fulfil two tasks:

1. Signals indicate the driving permission if the section in advance of the train is clear and a route is locked.
2. Signals indicate the permitted speed to the train if the speed is lower than the line speed.

Instead of speed signalling, route signalling indicates the locked route, concluding the locked route's permitted speed.

Because of the long braking distances, the main signal needs a distant signal for a signal's aspect pre-indication. For speeds up to 160 km/h, the braking distance is estimated to 1 km. This long braking distance is caused by the iron contact between the rail and the wheel of the train. The friction is very low, which leads to an energy-efficient movement.

On regional lines, a reduction of the line speed leads to a reduction of the braking distance. It is allowed to reduce the distance between the distant signal and the main signal to 700 m or 400 m [51]. That is necessary for the suitable positioning of signals in stations on regional lines. To locate the exit signal's pre-indication at the home signal is only possible with a distance much shorter than 1000 m. The development of different signalling systems leads to a reduction of lamps and light points. That relies on the reduction of energy for the signal. The fewer lighting lamps are used, the less energy is required for the signal. A huge drop in energy is achieved by the implementation of LEDs [52].

3.3 Level Crossing

The basic principles of LX protection are similar around the world. The technical realisation and the legal framework may vary in different countries and infrastructure manager. This section bases mostly on the German rules for level crossing ([53], [54]). Also, an international view is taken into account [55], [56], [57].

An LX is a railway safety system similar to an IL from a technical point of view. The LX has its own safety logic and is independent of an IL. Like the IL, the LX safeguards the trackside field components to ensure a train's safe movement. The LX protects the train movement by stopping road traffic. As a junction of road and railway, different aspects are considered to design an LX system.

An LX causes a high risk for accidents [58]. The higher the speed, the worse the accident. Hence, LX are forbidden on high-speed lines. In some countries, the dismantling of LX is forced to reduce the number of LX. On regional lines, the LX will remain because the economic effort to dismantle the existing LX does not allow an economical and efficient railway line operation.

The safety level of an LX and an IL are the same. Both protect train movements along a railway line which requires the same safety level of the safety systems.

3.3.1 Principles of Level Crossing Protection

The major principles of LX protection are to guarantee the right of way of the train. Therefore, an approaching train must be recognised as timely by road traffic. A road user must be guaranteed a safe crossing of the railway track or a safe stop in front of the LX. There are different methods to realise this protection, and these vary from nation to nation and from infrastructure manager to infrastructure manager. Figure 3.18 gives an overview of the different types of LX protection. The general differentiation is in passive and active LX. Passive LX are LX without technical devices. Road used must recognise an approaching train by viewing. Active LX are LX with a technological system to indicate an approaching train and close the road with technological devices. This section describes the details of the different methods of technical protection.

A further classification of LX is the

- Roadside protection,
- Trackside protection,
- Surveillance, and
- Activation.

The **roadside protection** covers viewing zones and technical devices to close the road

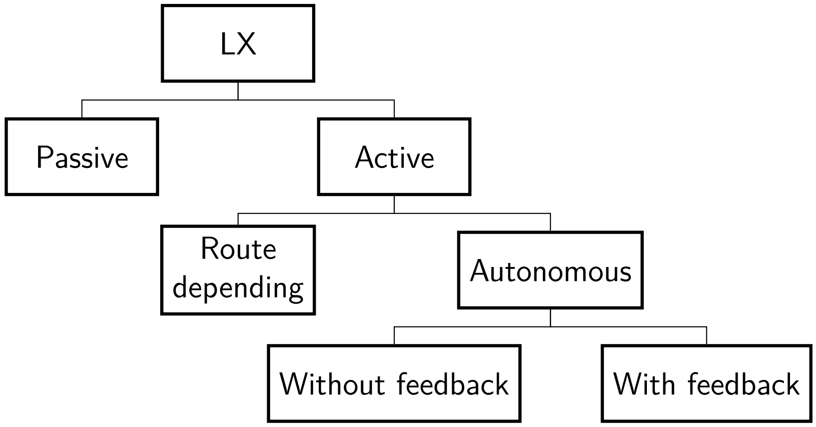


Figure 3.18: Classification of LX systems.

with traffic lights, half barriers or full barriers. Traffic lights are aligned to regular traffic lights without the green light. Only the yellow and red light remain. If the red light is on, the LX is closed. The traffic ligths vary in each country and must not be aligned to regular traffic lights as in Germany.

Barriers close the road physically. A road user can easily pass traffic lights, but a barrier must be bypassed. **Trackside protection** describes the process to stop or inform the train driverif the LX is not protected or in error mode. A trackside signal can be used, or the dispatcher's information (a call via train radio ,e. g.). Close connected to the trackside protection is the **surveillance**. That describes the supervision of the LX functionality. Different setups are possible: A supervision of the train driver, the dispatcher or an LX operator. **Activation** describes the procedure to activate the LX protection. A trigger of an approaching train or a locked route can activate the LX, for example.

These different categories are used to describe the different methods and variants of LX protection. The design of a technical LX system depends on the local conditions and the operational requirements:

- High road traffic density (or rail traffic density) requires a barrier (half barrier or full barrier closure). The more traffic, the higher the number of road users who have to wait at an LX.

- The duration of the road closing process is also relevant to choose the type of road protection. Suppose the road is closed too long, the probability of bypassing the barrier increases. Hence, a full closure is necessary to abandon bypassing the LX.

- If an LX is not in the vicinity of a station or block signals, it can be designed as an autonomous LX. This LX is supervised by the train driver and activated by the train.

- A reduction of the road closing time is achieved by monitoring the functionality and not the activation. That means the train driver has no feedback about the LX activation if the train passes the braking indication point. The dispatcher supervises functionality. Different approaches combine the surveillance with signalling so that a trackside signal does not indicate the activation and correct LX protection but only the functionality (readiness of activation). In this case, the signals are not locked with the barrier or the traffic lights.

3.3.2 ETCS and Level Crossing

In the first specifications of ETCS, the LX has been considered [59]. Balises with bidirectional communication were defined. The train could send information to the track. Also, communication via balises could trigger the activation of an LX.

A new release of the specifications removed the bidirectional communication and the integration of LX. With the release of Baseline 3 of the SRS, LX has introduced again [27]. Packed 88 was defined, which contains the protection status of an LX. Information about the procedure at a non-protected LX is included in the packet and supervised by the On-Board Unit.

In packet 88, the status of the level crossing is defined as PROTECTED or NOT PROTECTED. The intention of the exact meaning of protected is not defined. It can be interpreted as:

- The LX is activated, and the road is closed.
- The LX is ready for activation.

That allows implementing an LX with packet 88 in ETCS. The integration of LX in ETCS does not touch the described principles of LX protection.

Chapter 4

Radio Communication

Radio communication is an essential part of today's train traffic. In the last two decades, GSM-R was introduced for radio communication in the railway. The GSM technology is discontinued by the industry. There are different generations of successor technologies for mobile communication. The rollout of the latest technology – 5G – just started [60],[61]. The future radio communication system dedicated to the railway is under development. It is called the future railway mobile communication system (FRMCS).

Radio communication is used for voice communication between different railway units and data communication for safety and non-safety systems. Today's bandwidth limits are reached for some applications, so that a migration to a modern radio communication system is necessary.

This section describes the principles of radio communication and gives an overview of the different technologies. Furthermore, the railway specific functions are presented. The current development of FRMCS is outlined. An outlook on the future development, applications, and usage of radio communication is given.

This section is presented more in detail. Current trends depict a digital connected world where radio communcation is available everywhere. 5G is stated as the unique radio communication system, which solves all problems. Hence, a detailed view on the princiles is given.

4.1 History of Radio Communication

The first radio communication was established in 1919. Used frequencies were 4.2 MHz up to 10 MHz. The advantage of radio communication is the transmission of information without any wires. Each receiver in the dedicated range can participate in the communication. [62] The technical access cannot be denied because the radio waves cannot be shielded for a single user. Shielding must be created for an object or receiver itself, and it cannot be created generic for selected users.

Table 4.1 gives an overview of the different generations of radio communication technologies.

	Standard	**Network**	**Latency**	**Data Rate**	**Launch**
0G	—	analogue	—	—	1940
1G	B-/C-Net	analogue cellular	—	2.4 kbit/s	1972
2G	GSM	digital cellular	400 ms	40 kbit/s	1990
3G	UMTS	digital cellular	300 ms	384 kbit/s	2000
4G	LTE	digital cellular	15 - 50 ms	100 Mbit/s	2010
5G	5G	digital cellular	approx. 1 ms	600 Mbit/s	2019

Table 4.1: Overview of the different generation of radio communication and technologies [63], [64], [65].

Analogue radio communication is the first approach to mobile communication. Of course, it is dedicated to voice service only. Later on, the first mobile communication system in Germany was established and named *A-Netz*. Addressing a certain user was possible. [65]

Analogue cellular networks are the first radio communication network. In Germany, the so-called *B-Netz* and *C-Netz* are the first generation of cellular radio communication networks enabling mobile communication. Manual switching was not necessary. [64]

Global System for Mobile Communications (GSM) is the first digital radio communication system and analogue radio communication network's successor. New services like short message service (SMS) were introduced. GSM is a widespread radio communication standard. The lifetime of GSM is at the end because different successor technologies are available, which make GSM obsolete. [64]

3rd generation of radio communication systems is the **Universal Mobile Telecommunication System (UMTS)**. UMTS has a higher data rate compared to GSM. Transmission of voice and data is possible. The data rate allows the transmission of videos and messaging services. Access to the World Wide Web (WWW) is also possible.

The current standard for radio communication is **Long Term Evolution (LTE)**. The Data rate increases compared to 3G. The principle of enabling communication is still the same as UMTS. An exchange of radio communication technology is simply possible. Existing radio masts remain, but the corresponding LTE components replace some current components.

Mobile communication has a vast impact on human life. It reduces distances and allows the transport of data by long distances. With the introduction of smartphones and mobile internet, the use of information rises enormously. New business models are developed due to new communication opportunities. Digitisation is the buzzword that describes this megatrend.

Since 2016, the **5th generation (5G)** was developed and proposed as a change in radio communication paradigms. It is dedicated to fast, high capacity and low energy communication technology. 5G is not only dedicated to voice calls and message services. Also, data communication like web services and connecting machines (Internet of Things – IoT) is an objective of 5G [66], [67]. Suppliers recently launched the first devices on the market. [68]

[64] mentions the 6^{th} and 7^{th} generation (6G and 7G). Communication via satellites or GNSS satellites is introduced. That has a significant impact on the radio communication infrastructure. Hence, a shift from 5G to 6G or 7G is indicated in the following decades. The rollout of 5G is finished, and the successor technologies are available.

4.2 Technical Fundamentals

Some fundamentals present the complexity of building, controlling and maintaining a radio communication network. A radio communication network is an infrastructure itself. It is pretty easy to buy mobile communication devices and start talking. Different providers build radio communication networks and offer access to wireless communication. Currently, different network operators own and manage the network. They build and operate the network as a business model and corporate purpose. Minimum network size is necessary for an adequate and cost-efficient network operation.

Several technical aspects outline the issues concerning the usage within the railway. A communication link is a connection between a sender and a receiver. The physical bits are transmitted through the cable as a voltage or current signal in a wired network. Limiting parameters is the resistance of the cable, which corresponds to the length of the cable. A wired connection is much more straightforward than a wireless connection. The transmitting distance is depending on the resistance of the wire and the power of the sender. Both are calculated and defined because the transfer medium is well known.

In contrast to a wired connection, a wireless connection is more complex to establish. The sender does not know the location of the receiver and vice versa. It is necessary to send in all directions.

The energy emitted by the sender spreads onto a spheric surface, which leads to a cubic energy decrease with the distance. Assumed that the transmission of the radio waves is nearly plane, a quadratic reduction of the energy is possible. Hence, is the range of a radio mast doubled, fourth times the energy is necessary. Similar aspects apply to the carrier frequency. The higher the frequency, the less the range.

Different frequencies have a special characteristic that offers a wide range. For example, broadcast service uses low frequencies between 2 MHz and 30 MHz. These frequencies reflect at the ionosphere, which results in a wide range.

To visualise the range of a sender, figure 4.1 outlines the fundamental connection ranges. The described distances and areas are depending on the distance and from obstacles in the transmitting line.

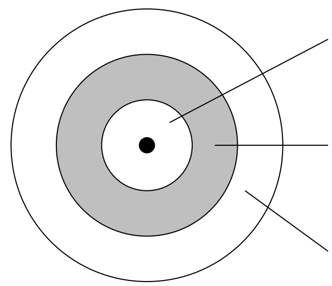


Figure 4.1: Wireless connection range [62].

The **transmission range** is the area where the communication is well working. The mobile device has no problems establishing communication. Errors are possible, but the error rate is meagre. The **detection range** indicates a sender that sends information, but the error rate is too high to establish communication. The **interference range** is the area where no sender is detectable. The receiver cannot recognise a signal because other signals and background noise interfere with it and overlay. The described ranges are not fixed and are depending on several local conditions. [62]

4.2.1 Bandwidth and Data Rate

Bandwidth and data rate are two key figures to describe a communication system. The Shannon-Hartley Theorem [69] describes the relation between bandwidth and data rate.

$$C = B \cdot log_2 \left(1 + \frac{S}{N}\right) \tag{4.1}$$

C is the channel capacity in $^{bit}/_{s}$, B is the bandwidth in Hz, S is the average received signal power, N is the average power of noise and interference, and S/N is the signal to noise ratio SNR.

This law indicates an increasing data rate by rising bandwidth. A higher carrier frequency allows sending more data because the higher frequency allows better data encoding. A bit, or generally a symbol, is better decoded if a carrier signal with a higher frequency is used. The Nyquist-Theorem states that at minimum, one wavelength is necessary to detect the frequency [70]. The shorter the wavelength, the faster a bit or symbol is transmitted. Figure 4.2 shows two different carrier frequencies. The higher the frequency, the more data is transmitted in a time slot.

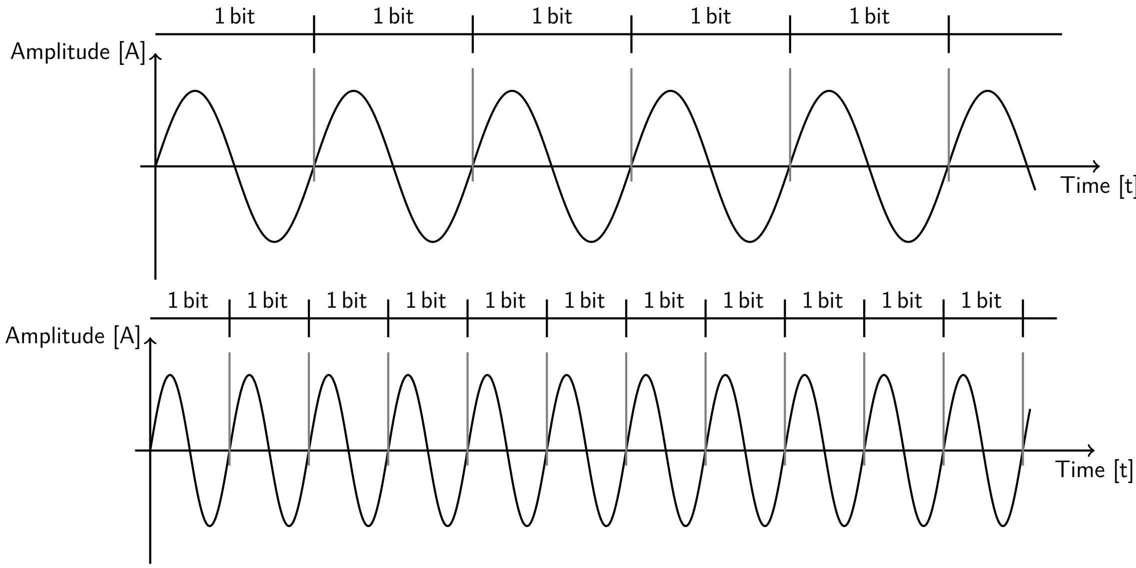


Figure 4.2: Bits in a carrier wave.

4.2.2 Network Access and Disruptions

Wireless communication is data transmission in an open network. Instead of cable bound communication networks, where wired, physical connections transmit information.

Everywhere in the range of the sender a receiver can receive the radio waves. It is not possible to exclude a user or a group from receiving the radio waves. Hence, radio communication networks require high-security standards. [62]

Radio transmission can be disturbed by a jammer, for example. The aim of a jammer is not the interception of the transmitted data. Still, the disruption of a connection causes issues. Of course, a wire can disrupt similarly, but this requires direct access to the wire. Depending on the safety precautions, the opportunity to disrupt communication is much higher for wireless communication systems.

4.2.3 Network Structure

A radio communication network is a wireless link between an antenna and a mobile device. The antenna is connected to a base station. The mobile part can be any device that can connect to the radio network. The data transfer from a base station to a mobile device is

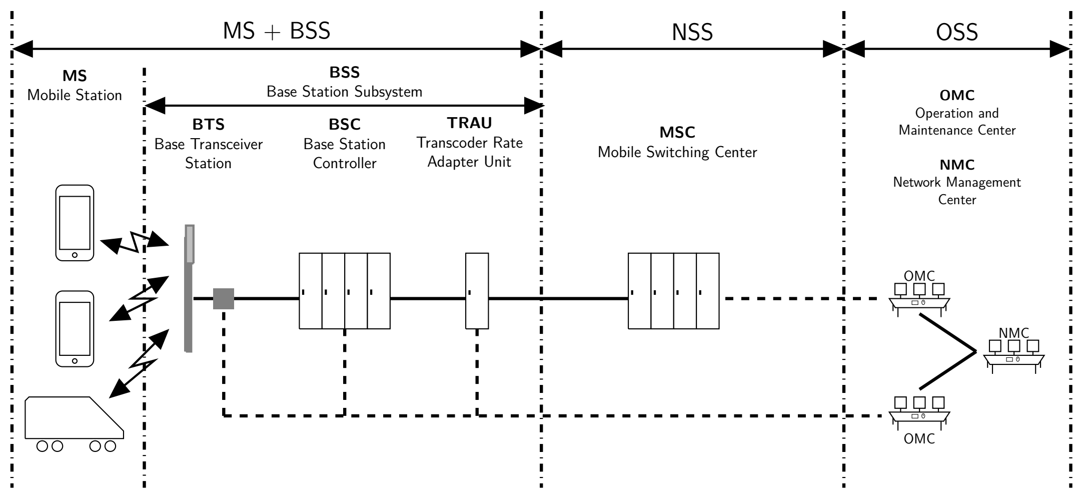


Figure 4.3: Radio communication network structure

called the DOWNLINK. The opposed transmission, from a mobile device to a base station, is called UPLINK.

A radio communication network consists of different subsystems. The Network Switching Subsystem (NSS) is the core element of the radio communication network. It represents the logic of communication – realising and managing the connections. The Base Station Sub System (BSS) is the access point for the network users. Antennas and the corresponding Base Transceiver Stations form the network cells. The Mobile Stations (MS) are the clients which communicate via the radio communication network. These can be mobile clients but also Fixed Terminal Stations using the GSM-R network. The Operation and Support Subsystem (OS) is dedicated to network control and management. The operators are located in this entity. In the case of disruptions, the OSS detects the errors and triggers maintenance.

Higher frequencies allow higher bandwidth what will increase the capacity of the radio communication network [63].

4.3 Radio Communication for Railway

In the late 80s, the first considerations for a new radio communication system for railways started. A study discussed the usage of the radio communication systems GSM or TETRA in railway applications. The authorities chose GSM because it was the only system in commercial use. At that time, the radio communication network throughout Europe based on GSM.

The used frequency bands for GSM-R are:

- Uplink: 876 MHz - 880 MHz
- Downlink: 921 MHz - 925 MHz

These are two frequency bands, each with a bandwidth of 4 MHz, below the corresponding GSM frequencies. 19 channels are available with a channel spacing of 200 kHz The expanded bandwidth (EGSM-R) uses the additional frequency band:

- Uplink: 873 MHz - 876 MHz
- Downlink: 918 MHz - 921 MHz

This frequency band offers 15 additional channels. [26]

The balise communication is radio communication as well. It is near field communication and not dedicated to long-distance transmission.

For the balise communication also an energy transmission for empowering the balises is necessary. So, there is an energy transmission (downlink, train to track) and a data transmission (uplink, track to train).

- Energy downlink: 27.095 MHz
- Data uplink: 3.951 MHz (logic 0) and 4.516 MHz (logic 1)

Crosstalk into a neighbour track is not allowed. Hence, the transmission range and direction must be precise and adjusted.

GSM-R Features

The railway GSM network is called GSM-R and contains special functions [71] like

- group calls,
- voice broadcast calls,
- railway emergency calls,
- functional numbering and
- location dependent addressing.

Even though GSM was selected for its availability and proved commercial-off-the-shelf products, some modifications were necessary for the application in railway. [71]

A train is called by a train number, independent of the telephone number of the mobile device itself. The functional number matches the device number. That principle helps to call a train driver without knowing who is on duty and without knowing the individual mobile device located on the train. A group call can address all trains on a line. All devices currently situated along the line are mapped to the line number. But GSM-R is not only used for voice calls. Since GSM-R replaced the ancient analogue radio communication system, it is also used for ETCS Level 2 and (in the future) for Level 3 and other data transmission.

The specification for the European GSM-R network was established in 1992. The Project EIRENE (European Integrated Railway Radio Enhanced Network) was a project to define and specify the functional and technical requirements for a European railway communication network. Since it was a European interest, EIRENE supports interoperable train traffic by providing European train radio communication. After successful testing and finalising the specification, the rollout started throughout Europe.

Communication Channels

GSM-R is a channel based communication system. That means communication between two devices uses the same channel during the whole communication time. For other devices, this channel is blocked at that time. For voice calls, that issue is not critical if all channels are blocked. But if a safety system cannot enable communication, the system reacts to a safe state, and the train cannot drive.

An ETCS Level 2 guided train requires permanent communication to the RBC. Therefore, a communication channel in a radio cell is blocked by the train. That reduces the capacity of radio communication significantly. GSM was extended with a general packet radio service (GPRS) to allow more communication links on a single channel to avoid this capacity issue. GPRS uses the communication channel only if data is transmitted. For the times without sending or receiving data, the communication is disabled. The classic GSM-R communication blocks a channel even if no data is transmitted. SUBSET 3.6.0 of the SRS introduces GPRS for GSM-R.

The current channel-based communication limits the number of trains in a radio cell. That is not a big issue on the line, but in nodes, the maximum number of trains exceeds fast.

Radio Coverage

GSM-R is used for two general purposes:

- Train radio and the
- Safety System ETCS.

The requirements are different for both applications. Due to GSM-R usage for communication in the safety system ETCS, certain conditions are placed on the radio coverage. A public network with its current setup concerning coverage does not fulfil the requirements of EIRENE.

But to achieve sufficient coverage of GSM-R for train radio, e. g., roaming to the public networks was introduced. That allows communication within line sections whithout GSM-R. An international roaming (within the GSM-R network) for international railway traffic is implemented as well.

4.4 Future Railway Mobile Communication System

As shown in section 4.1, technological progress is a lot faster than its infrastructure's life cycle. This issue is problematic if the mobile communication industry discontinues technology and stops the support of this technology. The 20 years old GSM-R technology is now replaced by one of the latest radio communication systems like 4G (e. g. LTE) or 5G. The project to define the successor systems is called FRMCS.

[72] presents the **Swiss Federal Railways (SBB)'s strategy for mobile communication systems**. The article and the presented approach shows the demands and issues of a radio communication infrastructure. The Swiss introduced GSM-R in 2004. Since the beginning, public roaming was used to increase the coverage of the radio network. For international train traffic, roaming with international GSM-R networks was introduced.

Swisscom announced to discontinue GSM in 2020. SBB planned to introduce FRMCS, but the specification is not released to develop the system and devices. In 2017, roaming with the fourth generation (LTE) started to cover GSM equipped lines when GSM is switched off. For the same reason, equipping some lines with GSM-R is planned. That is necessary to bridge the time from switching off GSM and launch of FRMCS. The industry announced the end of GSM-R support for 2030.

FRMCS defines and specifies the requirements of a future railway radio communication system. Instead of using a radio communication technology and adapt it with special functions (as performed with GSM-R), the intention of developing FRMCS is fundamentally different. It is stated that different radio communication systems can be used without modifications. FRMCS defines an application layer, which contains the railway specific functions. This procedure leads to the independence of the used radio communication technology itself. The railway specific functions are part of GSM-R itself. These features cannot be separated from GSM-R and used in different technology. Still, the same features can be implemented in another technology.

For FRMCS, it does not make any difference which radio communication technology is used. Future radio communication devices will be commercial-off-the-shelf products. FRMCS functions are an independent software feature. Figure 4.4 shows the general architecture of FRMCS.

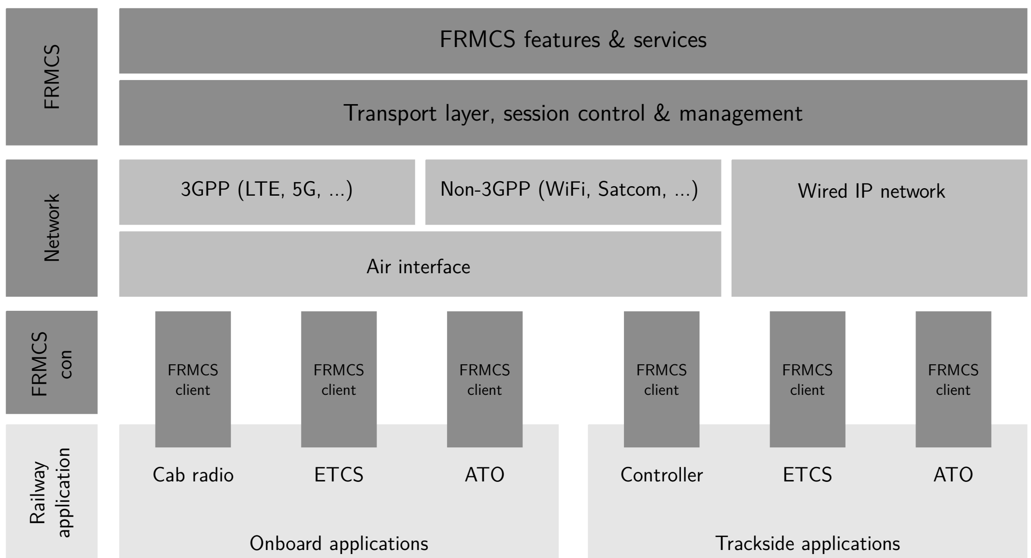


Figure 4.4: System architecture of FRMCS.

Trackside and trainborne clients communicate via wired and wireless communication. The different communication technologies can be different. These communication technologies provide access to the FRMCS system, which is a communication layer enabling communication between different clients.

Possible radio communication technologies are LTE or 5G. LTE is already installed, 5G is in the rollout progress. Both are networks without full coverage. The required number of masts are not installed yet.

Special railway communication networks are no alternative. Operating and maintaining a separate radio communication network like GSM-R gives experience. Especially, the decommissioning of technology, as outlined for 2G, is an example of a comprehensive solution. There have been considerations abort a Long Term Evolution - Rail (LTE-R) system, the GSM-R technology's successor. But this leads to the same individual solution as GSM-R.

The current media presence of 5G promises a universal radio communication system. It should be evaluated to use the newest technology for new radio communication, instead of an old technology like LTE, which the new 5G technology will succeed.

The following major parameters of radio communication are improved:

- Capacity
- Range
- Data rate
- Latency
- Energy consumption

The biggest issue is that all parameters concurrence with each other. It is not possible to achieve the maximum of all parameters within one setup. If speed and capacity are high, the range is short. To accomplish all parameters at maximum, a big effort of cost-intensive technical equipmentis necessary [73]. Different applications have their requirements on radio communication. Hence, 5G and FRMCS allow using harmonised network access for several users and applications [74].

A detailed view of the technology proves the suitability for railway use cases. A general issue on radio networks is, independent of the technology, open access. In contrast to wired networks, everybody can receive radio messages. Eavesdropping is not a problem since it is not safety-critical regarding its functionality, whereas jamming is a big problem. With small and cheap equipment, it is possible to install a jammer to emit an interfering signal. That interrupts the communication, and the system function is disturbed dangerously.

Compared to the development of GSM-R, the requirements of a new radio communication system are different. The need to transmit a lot of data is continuously increasing. In the early years of GSM-R, train radio only used it. Train radio means the communication between the train driver and the dispatcher and the train driver and shunting employees. Today‘s safety systems rely on a radio communication system to improve data capacity. With the overall digitisation, many more aspects arise and require a radio communication system, e. g.

- predictive maintenance,
- passenger information,
- train positioning,
- real-time monitoring, and
- safety systems.

Thus, the need for higher bandwidth and capacity must be considered in FRMCS.

Chapter 5

Problem Description

The previous chapters give an overview of the railway safety systems. The historical overview (chapter 2) describes the reasons for the current state of the railway network briefly. Years of development and gathering experience lead to systems like ETCS, CBI and GSM-R. Due to the long life cycles of the described systems, innovations require a lot of time from the idea to its implementation.

Basic principles of railway safety systems are not new. The IL and its principles are about 100 years old, ATP systems like INDUSI about 90 years old. The ETCS development started at the end of the 1980s and is about 30 years old [26]. A system that actually is called modern is still decades-old [24]. The first ideas, which are the basis for the development, base on relay safety systems.

While these systems have been developed, the technology around them changes enormously. Information technology changes very quickly and impacts railway safety systems [75], [76].

This chapter summarises the issues of the railway and gives an overview of ongoing projects and research. Finally, an approach to dealing with these issues is stated, which will be the basis for this thesis.

5.1 Challenges of the Railway Industry

The framework conditions for the railway are political and technical determined. Transport is a public task and needs the support of politics. Funding of road, rail or water traffic impacts the development of the modal split and the transport's medium acceptance [77]. The challenge to increase the rail's modal split requires the appropriate political responses [78].

Besides the political conditions, there are different technical and operational issues to discuss.

- Digitisation in railway offers new possibilities for operation, safety and maintenance [5].
- It is not appropriate to consider digitisation in means of replacing an existing system with a digital system. However, digitisation is about linking different systems and adjusting the processes.
- Rapid completion of infrastructure projects will be an essential pillar of future safety systems [10]. The digitised safety systems should allow for a quick realisation of the projects to enable the rollout.
- Improving the railway does not only yield to operations. Also sustainability and efficiency are considered as well.

Deutsche Bahn AG (DB AG) and SBB have developed digitisation projects to meet these challenges [5], [6]. Both projects have the same intention, but they are still different and pursue different strategies. The following listing gives an overview of the various topics and buzzwords of both projects.

Digitale Schiene Deutschland (DSD)

- Intelligent infrastructure
- Digital interlocking
- Low maintenance
- Real-time location
- Obstacle detection
- Digital control and safety technology

SmartRail 4.0

- A more robust timetable
- Increased capacity
- Increased safety
- Better customer service
- Stabilisation of system costs

These projects consider the whole railway system. Concerning the safety systems, both projects focus on the standardisation of interfaces for a simple connection of different subsystems. This thesis only focuses on safety systems. DSD focuses on technology, whereas SBB claims the new benefits to operational reasons to strengthen operation.

Several railway projects shall improve rail transport by increasing capacity and safety. These projects target high-speed traffic and main lines. Rural lines are not in the main focus of these projects. Modern, digital and connected systems shall use commercial off-the-shelf (COTS) products to reduce costs [79]. If possible, COTS shall also be used in vital systems if safety is granted.

The current system topology for the railway is heterogeneous. The different systems were developed independently of each other when connectivity was not an issue. Simple and smart interfaces were not available. Today, communication technology allows connecting different systems quite easy with standardised interfaces.

An interaction of ETCS and the IL is not focused in DSD. Opposed to DSD, SmartRail 4.0 proposes a complete integration of ETCS and the IL system and names it ETCS interlocking (EI). Whereas SmartRail 4.0 combines ETCS and IL in means of technology and operations, NeuPro (Neuausrichtung der Produktionstechnik, a subproject of DSD) considers and defines interfaces of the safety systems. [8], [80]

Depending on the ideas of a digital IL, a definition of a digital IL in the context of this thesis is stated:

> *A **digital IL** is close to a conventional CBI. It has standardised bus or network interfaces to other safety systems. Field elements are also connected via bus interfaces. Energy and data are transmitted separately.*

The main difference to other ideas of an digital IL is the standardisation of field components and the connection via network interfaces. In this thesis no standardised interfaces within the IL are proposed.

5.2 Lessons Learned

Since the development of ETCS started, a lot of experience is gathered. Each national railway undertaking gets in touch with ETCS and defines its national deployment plans [81]. The reasons to migrate to ETCS are different. The following listing gives a brief overview of the main reasons for the migration to ETCS [82].

- **Outdated Safety System**
  Old safety systems need spare parts and maintenance increases to achieve an adequate service. If the decision to modernise the safety systems must be taken, replacing a modern and interoperable system is advantageous. Countries with outdated IL push the migration to ETCS along with the modernisation of the IL.

- **Low Safety Level of the Class B ATP Systems**
  As described, there are Class B ATP systems with a low level of safety. They only warn the train driver if the train passes a stop signal or lacks safety for some operational situations. Deciding to replace the unsafe systems leads to the choice of ETCS because of its expected future availability and widespread use.

- **Interoperability**
  Interoperability is the main reason for the development of ETCS. It is a crucial

factor for trains and locomotives in international traffic. But, interoperability on its own is not a driver for migration due to multi system locomotives. Hence, no country migrates to ETCS only for interoperability. Meanwhile, EU law forces the migration of several lines, especially new construction lines, to equip with ETCS.

- **Network Size**
  The more extensive the network, the more time is necessary for migration to ETCS and the greater the effort. The time for parallel equipment must be well designed to reduce the struggle for the migration period.

- **Regulations and Law**
  The EU decided to use ETCS for new construction lines to fulfil the TSI. That forces an infrastructure manager to equip that line with ETCS. If trains run with the Class B systems, the line must be equipped with both systems in parallel.

There is not only one reason for migration. Mostly there are different reasons which lead to the migration to ETCS.

In addition to the general reasons, there are specific experiences gathered in various ETCS projects. These examples present pragmatic problems instead of theoretical problems.

Project examples

- **VDE 8**
  Verkehrsprojekt Deutsche Einheit No. 8 (VDE 8) is a project to connect Berlin with Munich by a high-speed line. It consists of new construction lines (VDE 8.1 and VDE 8.2) and existing lines that are upgraded (VDE 8.3). At the new constructed high-speed lines, ETCS Level 2 without signals is used. It is the first ETCS application in Germany of ETCS Level 2 without signals. Table 5.1 shows the number of IL, RBC and balises for project parts 1 and 2. The length of the line is given, too. Two interesting aspects are the number of RBC and IL and the number of balises. This gives an assumption about the technical effort of such a railway line. For the 300 km approx. 3.000 balises are used. If balise groups of two balises are assumed, there are about 4-5 balise groups each kilometre (9-10 balises each kilometre). This will be compared with the new architecture developed in this thesis.

Project Part	**Interlocking**	**RBC**	**Length [km]**	**Balises**
VDE.1	5	2	83 + 107	1.000
VDE.2	4	3	123	2.000
Sum	9	5	313	3.000

Table 5.1: Number of IL, RBC and balises on the VDE 8.1 and VDE 8.2.

- **High-speed Lines in Spain**
  Spain started early to implement ETCS on its high-speed lines [83]. An advantage was the new construction of high-speed lines with normal gauge instead of Iberian gauge. The high-speed lines are a separate network beside the existing network. The European law and the TSI forced implementation and usage of ETCS on these new construction lines. Two major topics are exciting in the Spanish ETCS implementation process:

  - Use of ETCS Level 1 for high-speed traffic and the
  - Participation of different supplier on a line to grant interoperability and prove interoperability independent of the suppliers.

  On high-speed lines in Spain, ETCS Level 1 is used for railway operation. FS enables cab-signalling, which is mandatory for high-speed traffic. The decision for Level 1 was made because Level 2 had not yet been validated. After validation, Level 2 is accepted and installed on the high-speed lines with high reliability of service. [84]

- **Basel Station**
  Station Basel Bad is located in Germany at the border to Switzerland and France. It is equipped with ETCS and the common German PZB. A big issue is the data capacity of the radio communication for ETCS Level 2 trains. The number of trains, which can drive simultaneously with ETCS Level 2 in the same area, is limited to three trains. The reduced number of frequencies is a reason due to the border to France and Switzerland. A state treaty regulates the allocation of the allowed frequencies to the different nations in the border region. [85]

  A further issue is the transition to ETCS and the dial-in to the German GSM-R network. Fix data balise groups trigger this transition when the balise group is passed. There is no dependency to the operational situation. Even if a shunting service pass the balise group, the dial-in is triggered [85]. Operating a radio communication network is generally a complex task [86].

- **ETCS Level 1 FS in Luxembourg**
  Luxembourg is one of the few countries that have already migrated the entire network to ETCS [87]. The target setup is ETCS Level 1 FS. That is very interesting because other countries focus on applying ETCS Level 2 and ETCS Level 1 LS. The implementation of ETCS and the use of Level 1 requires a revision of the operating rules for ETCS [14].

  The balise group's location is not fix and depends on the IP of the different trains in service and the local profile data like the gradient profile, e. g. [37]. National values and train parameters influence these locations.

- **ERTMS Regional (Sweden)**
  ERTMS Regional is a project to apply ETCS Level 3 on regional lines. To take

account of the reduced requirements on regional lines, a new concept basing on ETCS Level 3 was designed. A big issue of the classic architecture is the many subsystems and the effort for cabling all trackside components. The safety system ERTMS Regional defines a Train Control Centre (TCC) which is a merge of IL and RBC. Complete radio coverage is not necessary for this architecture. That means, train service in moving block is not possible because each train position is not continuously known in the TCC. Dispatching functions are also integrated into the new TCC. Radio communication is also used to connect the different field elements and the train. Axle counters for train detection are only used at necessary locations, e. g. for tracks with shunting service. Otherwise, Level 3 features are used for train detection. GNSS is not necessary. Only an odometer is used for position estimation. Pilot projects have been commissioned in Sweden. However, ERTMS Regional has not been applied on a large scale. Figure 5.1 shows the system structure of ERTMS Regional. [88], [89]

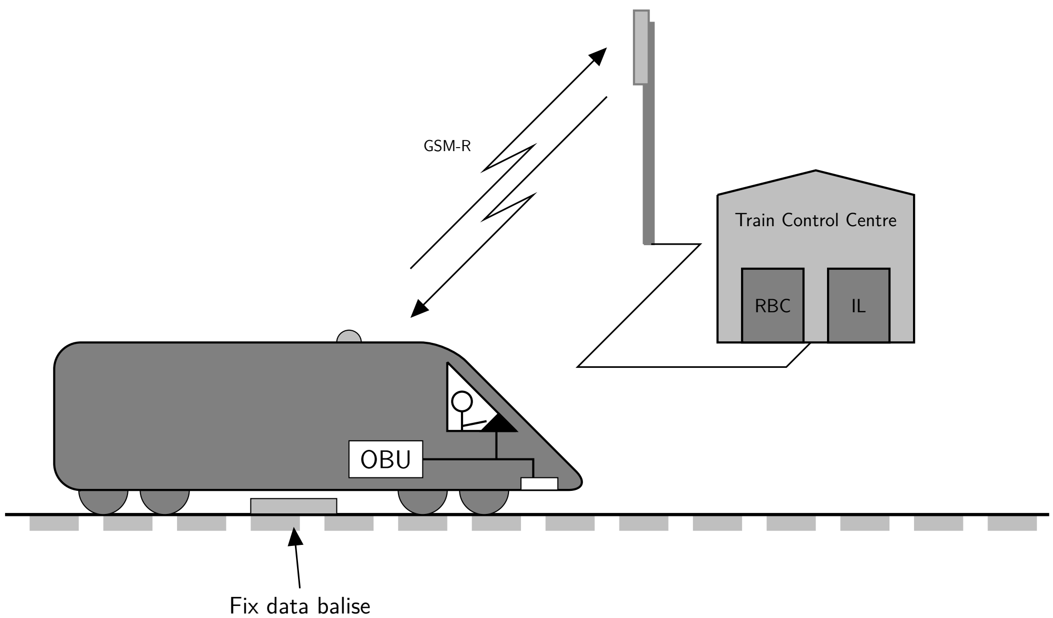


Figure 5.1: ERTMS Regional system structure (Sweden).

- **ERTMS Level 3 Regional (Italy)**
  Following the example of ERTMS Regional in Sweden, a similar system is considered in Italy. The proposed system is different from the Swedish approach. First, the trackside components are reduced to a minimum. Axle counters for track vacancy are neglected due to a trainborne position detection, position report and integrity check.

  A further approach is the use of a special feature of ETCS. That is the use of *Virtual Balise Cover Markers*. If the train uses GNSS for train detection, the balises are virtualised. This feature allows the use of the same ETCS principles, based on balise locations and references without using physical balises. Figure 5.2 shows the system structure of the Italian ERTMS Level 3 Regional solution. [90]

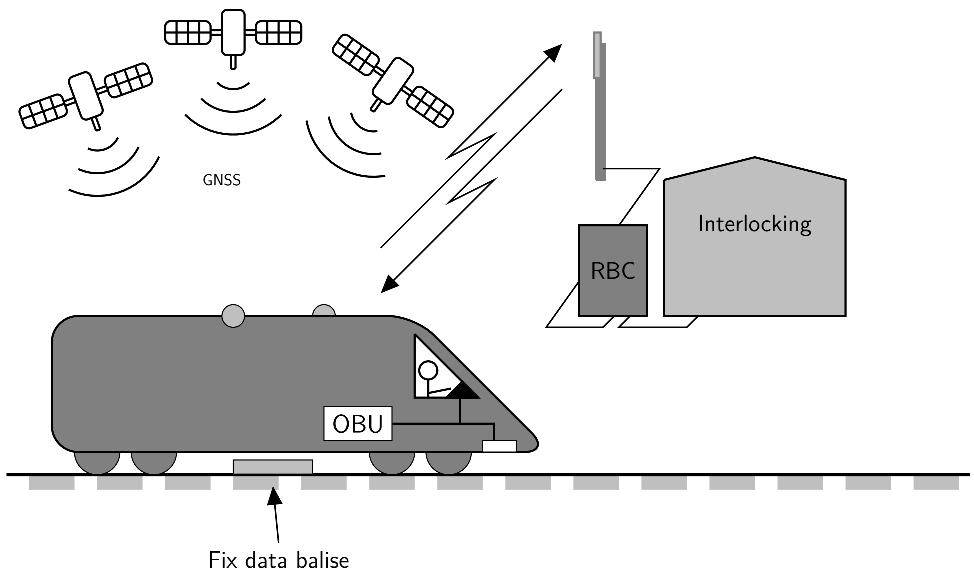


Figure 5.2: ERTMS Level 3 Regional system structure (Italy).

5.3 Research Topics

Besides the running ETCS migration projects, the development and improvement of ETCS and its application is not finished. Research is still going on. ETCS is not a static system that is 30 years old and has not been further developed in recent decades. There are lots of aspects to improve. The focus of development is the interaction with other systems, which was not focused in the early years of ETCS. Also, the topic of digitisation and resulting opportunities were not regarded years ago. In the following, a few projects are presented which focus on improving ETCS:

- **Capacity of ETCS Level 2 lines**
  [91] describes a reduced capacity due to ETCS Level 2. ETCS braking curves are more restrictive compared to most Class B ATP systems. Increasing capacity is not only depending on the applied ATP system. Also, the block sections and the overlap (especially for ETCS) significantly impact on the capacity. Adoption of the block sections is necessary, as well as precise modelling of trackside profiles. This requires a knowledge of the ETCS braking models and their parametrisation. [92]

- **Shunting with ETCS**
  [93], [94] and [95] give a detailed overview of shunting in ETCS. Level 2 needs interaction between IL and RBC. The IL locks a shunting route, and the RBC must confirm the shunting route because the RBC manages the communication to the trains. The IL still safeguards the shunting route. The train is commanded to SH, and only a speed limit is supervised on the train.

  If a train switches to mode SH, the communication link to the RBC is closed. It is impossible to send information about a locked shunting route or the shunting movement's target to the train via GSM-R. Also, the train's position report is not sent by the train. To transmit information from track to train, balises can be used, e. g., they transmit a list of balises (which are allowed or forbidden to pass).

  In Level 3, shunting is not possible. There is no trackside track vacancy detection, and a position report from train to track (RBC) is not specified for SH mode. A shunting area can only cover the whole shunting tracks. That reduces capacity when this shunting area blocks station tracks or prevents flank protection for train service.

  Shunting service can only performed in mode FS or OS. But this limits the flexibility of the shunting service.

- **ETCS and Level Crossing**
  LX are rarely integrated into ETCS. They have been regarded in the first specification [96] but dropped later on. With the release of Baseline 3, they have been reintroduced by the definition of Packet 88. In [97], the integration of LX into ETCS and the resulting benefits are described. Also, the bidirectional communication in Level 2 is outlined with the expected impact on LX operation. Integration of LX does not only affect the train operation, but also the road closing time is affected. A smart integration reduces the road closing time, whereas a poor integration may increase the road closing time.

- **Sekundärbahn**
  A current research project is Sekundärbahn. [98] presents the concept for safeguarding railway vehicles. It is similar to the ERTMS Regional concepts in Sweden or Italy. But it focuses a migration from trackside safety systems onto the railway vehicle. That means the trackside safety equipment is reduced to the moveable track elements like points and LX. Train detection is realised via GNSS and handled trainborne. Routes and the necessary position of points, e. g., are requested by the train. To enable interoperability, ETCS is used.

- **ETCS Level 3 Hybrid**
  Constraints of the current infrastructure and train equipment do not allow to drive in Level 3 with moving block. Therefore, all trains need an integrity check.

  Using the advantages of moving block in parallel to block sections (mixed traffic of Level 2 and Level 3 trains) is proposed and called Level 3 hybrid. This setup allows

Level 3 trains to run in moving block, whereas trains run in block distances in a common Level 2. Two Level 3 trains following each other run in braking distance. A Level 2 train runs in block distance independently which train is ahead. This principle is similar to the Linienzugbeeinflussung (LZB) CIR-ELKE, which allows running LZB trains in shorter LZB blocks and common trains in the block distance depending on trackside signalling [35].

- **ETCS Level 4**
  An interesting research paper [99] discusses the proposal of ETCS Level 4. Level 4 takes a relative braking distance into account. Today, railway operation assumes that a train stops immediately as the worst scenario. A route and an MA is only allowed in the whole clear track. A reservation of a track section in a temporal dimension is not allowed. The assumption that a track becomes clear in a certain time slot is not processed. Allowing train service in relative braking distance increases capacity because the headway is reduced. That topic is still a theoretical aspect but shows the demand to improve operation and increase capacity.

Besides these research topics and project examples, there are still further research activities focusing on the railway. EU projects like *Shift2Rail*, the German Centre for Rail Traffic Research (DZFS), and the universities are research institutions for rail research projects. These research activities do not focus on current projects where ETCS applies on a line or network. Furthermore, current issues are analysed, processes and applications of ETCS in the future are discussed. The specification of ETCS with its advantages and disadvantages is not questioned. Several PhD theses and research projects concern migration strategies to optimise the long process from a Class B ATP to ETCS [100], [101], [102]. Some PhD theses and research projects discuss technical ETCS topics like braking curves or a setup for regional lines [92], [103], [104]

Studies on capacity and improvement of operations with ETCS compare all ETCS levels but consider Level 1 only with a trackside signalling system. No research puts a focus on ETCS Level 1 FS. That is due the wrong image of ETCS Level 1. It is seen as a setup for the migration to Level 2 or Level 3. Furthermore, Level 1 is thought to trackside signalling in parallel to cab-signalling. A system without radio communication seems to be old fashioned and not modern because it does not use radio communication systems.

5.4 Approach

The presented projects, lessons learned, and research topics summarise several issues of current safety systems, ETCS projects and the demand for new features to improve railway operation. There are a lot of ideas to solve the issues. But most ideas are relating to a phrase: Higher, faster and wider. Driven by the industry and mega trends such as connectivity (Industry 4.0) and digitisation, wireless communication, as used in Level 2 or trainborne train detection for moving block in Level 3, becomes popular.

In this thesis, the approach for ETCS Level 1 FS is put on a smart and pragmatic solution. Improvement of operation is essential for the railway safety system. Operations include a capacity analysis to evaluate the impact on the operation. Also, topics like safety, economic, project planning, security, and energy are important. These are parameters, which are improved with the new architecture.

The target of this thesis is an improved ETCS Level 1 application, which is designed in the context of digital IL. The architecture is dedicated to regional lines. Operational requirements are different to mainlines and high-speed line.

In the following, there are issues & challenges summarised, which are derived in the previous chapters. Then, short approaches are stated, how this thesis will solve these issues & challenges.

Communication

- Issues & Challenges

  Comprehensive radio coverage is not granted everywhere. Although politics promise a complete coverage, the technical realisation is doubtful and takes a long time for realisation [105], [106]. Expanding radio communication is simple in urbanised areas but not in rural areas. Higher frequencies used for the latest radio communication technologies leads to a reduced range of radio masts. That acts contrary to the promised radio communication expansion. Using the same frequencies do not allow a higher capacity.

  There is a significant issue for railway infrastructure operators: They must operate their own GSM-R network for voice communication. And within ETCS, it is necessary for data communication for Level 2 and Level 3. Operating a radio network is much more than building a radio mast. Furthermore, it also covers operation and maintaining the radio network backbone. A small infrastructure manager cannot handle such tasks.

  The experience of the last decades shows that an integration of railway features into an infrastructure technology like GSM (radio communication) leads to direct dependencies to that technology. When that technology changes due to drivers from other industries (e. g., radio communication industry), the railway must follow or needs to pay for customised service and maintenance. Currently, the introduction of FRMCS is forced as a successor of GSM-R. That enables communication via the common radio communication technologies as a special communication layer, but the physical transmission systems must still be available.

A further aspect of radio communication is security. Radio communication is an intrinsic open network. It is not possible to shield and protect physically from unauthorised access.

- Approach

  The new architecture does not depend on a radio communication system to achieve independence from the radio communication systems. That is why ETCS Level 1 is preferred, especially on regional lines.

Operation

- Issues & Challenges

  A big issue is the restrictive braking model of ETCS. Capacity decreases in ETCS FS due to longer approach times compared to some Class B ATP systems. The capacity analysis presented in chapter 3 shows a reduced capacity for ETCS Level 1 applications compared to the conventional ATP system (PZB) [92]. Depending on this capacity analysis, Level 3 provides a significantly increased capacity due to moving block.

  ETCS Level 2 FS with cab-signalling enables high-capacity block and shorter block sections as the braking distance without complex signalling systems. That is not possible with conventional signalling systems.

  Classic ETCS Level 1 application have drawbacks concerning mode transitions. Balise groups are commanded via the signals. As presented in Basel Bad, there are situations where a fix data balise triggers a mode transition, which does not match the desired operational situations. In this case, a route depending mode transition or dial-in would be necessary. On the other side, shunting service in mode SH and with Level 2 has disadvantages. The movement area cannot be limited exactly to the train because no communication is open. If a train is in SH, the connection to an RBC is terminated.

  The common IL setup does not allow to lock routes into an occupied track. Also, high-capacity block sections are handled only with a certain ATP system connected to the IL. On regional lines, ATP systems with cab-signalling are not used commonly. Advantages of route locking philosophies that allow shorter block sections than braking distance or entering an occupied track section (except shunting routes) are not defined.

  Train service in fall-back mode is hard to handle with classic ETCS Level 1. The substitution or caution signal does not allow to derive the locked route belonging to the signal aspect. Thus, only a restrictive train service is possible. Shunting service has the same issue – the shunting signal does not allow to derive the locked shunting route. This information is still available in the IL but not in the signal.

- Approach

  Commanding the balise groups directly by the IL allows a route sensitive telegram definition. Not only for regular train service, also in fall-back mode and for shunting service. The advantages of cab-signalling allow a shorter block length because no trackside pre-indication and speed indication is necessary. The basic principles of locking a route do not change due to ETCS.

Economic

- Issues & Challenges

  Some aspects are cost-driving issues of classic safety systems.

  Personnel effort for the operation of outdated IL is very high [10]. If each station (IL) needs one or more dispatcher, it is very cost-intensive. Also, maintenance for such safety systems and recruiting and training of personnel for old technologies is very hard.

  Regarding the investment cost, the number of components is a cost-driving factor [107]. Due to the small quantity of the components compared to other industries, railway is no market driving industry. Hence, the hardware costs do not decrease with the number of components due to scale effects.

  The architecture impacts the number of components. Some architectures are presented in this section. To achieve functions like centralised safety logic with mandatory network communication, the components for this network communication will rise. Using open and standardised interfaces between the IL and its field components requires a universal communication interface and standardised interfaces within the safety system itself. For this case, each single subsystem like a field element must be vital itself. Opposed, an integrated solution with proprietary interfaces between the IL and its field components allows a smart interaction between these systems.

  A further aspect is energy consumption. The more active components are necessary, the more energy is necessary.

- Approach

  The idea of this new architecture is a smart and integrated architecture. Using cab-signalling reduces the number of components (signals). The number of connection in an open network is reduced to a minimum for avoiding security issues.

The overall target is a smart system architecture, which relies on a simple system without dependencies on other infrastructure systems. Pragmatical approaches and considerations are taken to design such a system. The new architecture is dedicated to regional and secondary lines instead of mainlines and high-speed lines. The presented topics are summarised in the following listing.

Issues and Challenges

- Shunting in classic ETCS applications
- Fixed minimum bock length
- No comprehensive radio coverage
- Mostly static ETCS Level 1 messages
- Cost efficient solution
- Robustness with respect to operation

Approach

- No GSM-R dependency in the safety system
- Balises commanded by the IL directly
- Generic and model-driven route logic and ETCS logic
- FS with cab-signalling
- Exploiting FS features in a dynamic ETCS Level 1.

Besides the presented approaches, pragmatical issues must be considered for designing a safety system architecture.

A safety system must be cost-efficient. Regional lines with a low traffic density cannot be operated if the infrastructure is not affordable. A simple structure is necessary without special features necessary on main and high-speed lines [108]. Route pricing on regional lines with a low traffic density requires a cost-efficient infrastructure. High-density lines, which allow an adequate revenue due to train service, enable the use of complex safety system for generating more traffic rather than the required capacity.

Using ETCS Level 1 calls for a rethinking of Level 1. In the past, Level 1 was designed to connect to old safety systems in means of migration and not to digital IL. It was not intended as a target state for a railway network.

Finally, the features and range of ETCS Level 1 increases. Figure 5.3 shows this effect. The axis show length of block sections to the type of signalling (trackside to cab-signalling). The intermediate positions of the y-axis describe systems, which base on trackside signalling but also have elements of cab-signalling on the train. The x-axis describes the possible block length for the regarded systems. Applying ETCS Level 1 without trackside signalling and digital IL pushes Level 1 up to Level 2. The range of an integrated ETCS Level 1 architecture is much more higher than an Level 1 architecture, which depends on a trackside signalling system.

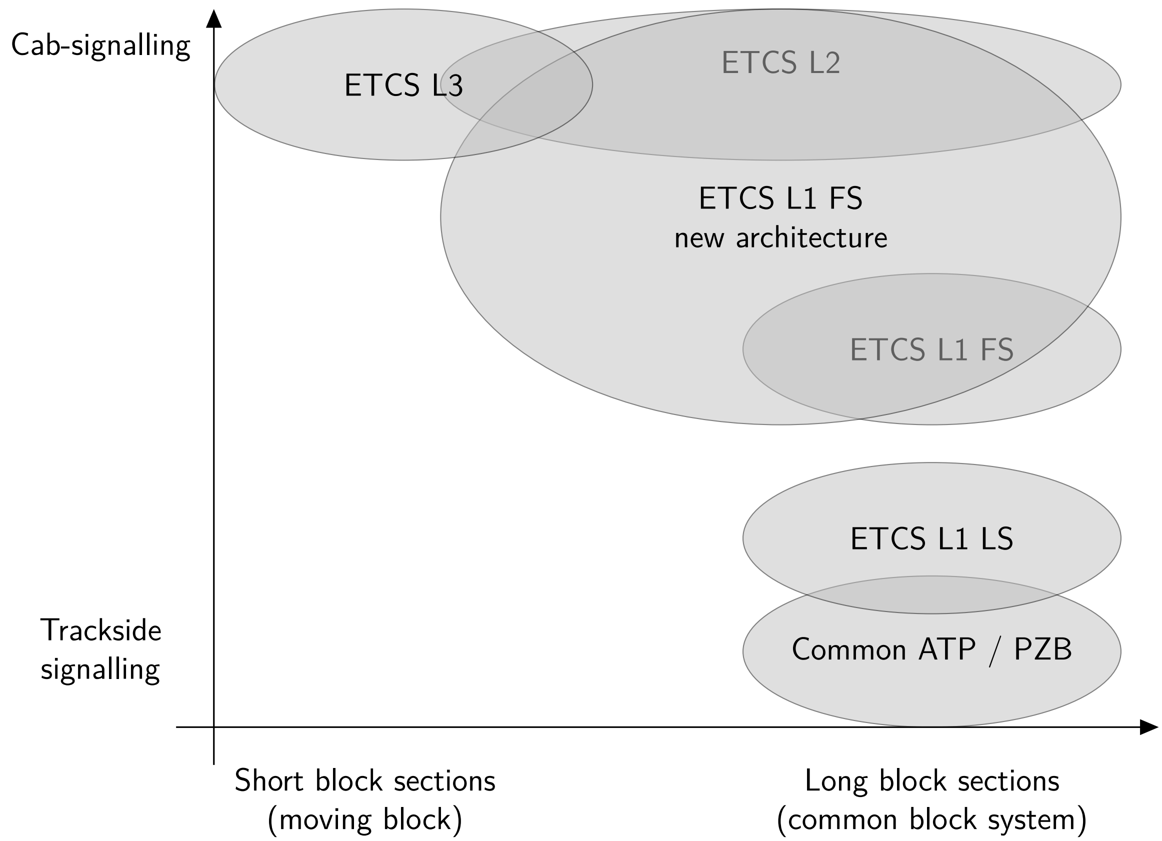


Figure 5.3: Categorisation of different ETCS solutions (own graphic).

Chapter 6

Integrated Interlocking and ETCS Architecture

A new IL architecture must improve the railway system as a whole. However, it is not the IL itself to be improved. Furthermore, it is the integration and combination of ETCS and IL. Integration and optimisation are necessary to achieve a more safe, reliable, economical and efficient railway system.

This chapter describes a new architecture of a digital IL with integrated ETCS functionality. ETCS is no longer a separate subsystem connected to the IL. The route logic focuses on safeguarding the trackside components, whereas ETCS safeguards the train movement itself. Defining routes in the context of ETCS simplifies the route logic. Integrating ETCS into the safety logic basing on a generic route logic offers new ways to define routes. An integrated system enables new approaches for train detection. The presented ETCS logic and route logic improve capacity and safety by complementing their features.

6.1 System Structure

The general system structure of the new architecture is similar to typical CBI. This structure aligns with the three tier-model presented in chapter 3. A focus is on the safety level, which contains the safety logic. The field level and safety level have vital functionality, whereas the management level is non-vital [48], [40]. The communication between all three levels performs via bus or network connections.

The system's structure describes the major components of the new architecture. Most components are well known, but some details may vary from the common meaning and definition. The historical development of these systems justifies this.

Figure 6.1 shows the structure of the whole architecture. The components of this architecture are explained briefly for the context used in this thesis. Some functions may vary

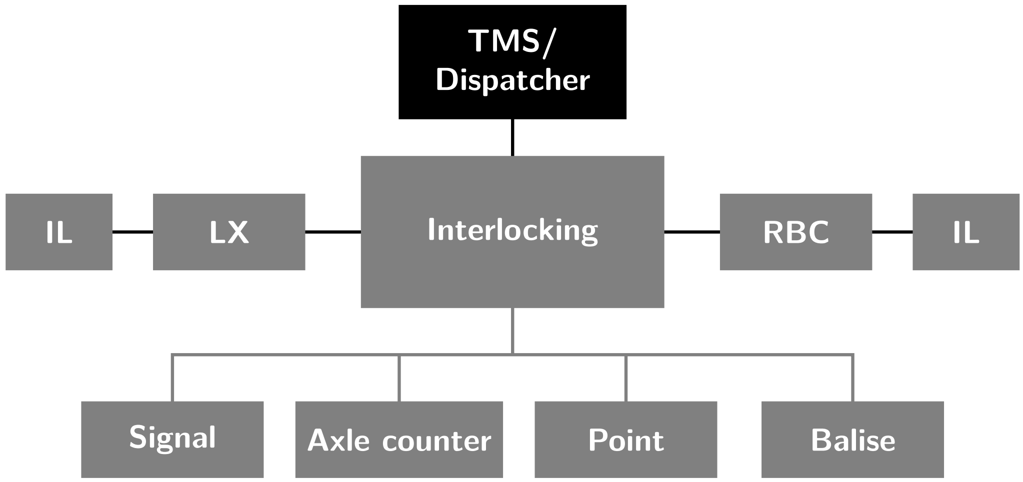


Figure 6.1: Overview of the new architecture and its connections to field elements and safety systems on the line.

to the usual meaning and an improved meaning in the new architecture. The black lines depict a network-based connection between the safety systems along a railway line in this figure. These safety systems are safe on their own, and the system interfaces between these single safety systems (IL, LX, dispatcher, RBC) are standardised in certain means. The block connection or the Hp and Fü interface between IL and LX are standardised as well (only as relay interface, not as telegram based communication) [109]. The grey lines depict a bus communication of a restricted local area network only for the field elements of the IL. Historically, field elements are connected directly to the IL. Today, the IL is only available with the field components of the same supplier. Because of the restricted connection between IL and field elements, there are no IT security issues. The interface is completely controlled and designed by the supplier and can be adjusted to further needs when it is necessary.

- **Traffic Management System**
  The Traffic Management System (TMS) is not described in detail in this thesis because the focus lies on the safety-relevant system. In this thesis, the TMS is regarded as a management system and fulfils tasks that several existing systems can process. As an example, a train describer system is given. The TMS can request a route for a train movement, and if this route cannot be locked, the IL declines this request. Also, an LX can be triggered in dependency of a train describer system to optimise the road closing time.

- **Level Crossing**
  The LX is more integrated into the IL and ETCS than in common applications. Instead of safeguarding road and rail intersection, only some IL features are handed over to the LX. Alternatively, the IL uses some LX components (e.g., the level

crossings axle counters). But, concerning ETCS, the LX is not only integrated into the IL and ETCS. The LX is used as a hub to connect balises and send messages.

- **Dispatcher**
  The function of the dispatcher adapts to the particular requirements of the new architecture. An input panel for routes and the IL's common operation remains but extends to functions for ETCS. These may be functions for adding a TSR to a line section or handling ETCS in fall-back mode. The dispatcher station is a non-vital system like the TMS. Both are management systems, but a dispatcher is authorised to perform auxiliary actions. Therefore, a special process is enabled to guarantee safety [48].

- **Interlocking**
  This thesis addresses the changes in the IL.

- **Radio Block Center**
  In common RBC's and Level 2 or Level 3 applications, the RBC takes safety functions for ETCS. Position report of the trains is handled. Messages are selected and send to the train depending on the locked route and the operational situation. In this thesis, the RBC is reduced to an interface for transmitting ETCS messages from track to train and vice versa. The RBC only manages the communication to the train with the relevant security aspects, but it does not provide any safety-relevant logic. In some special applications, the RBC takes safety functions. That is necessary if an old IL, like relay IL, is connected to an RBC. The new architecture strictly separates: The IL is responsible for safety, and the RBC is only a communication interface.

- **Field Components**
  Field components are axle counters, points, signals and balises. Axle counters and points are not affected by the new architecture. The balises are used as described in the specification [29]. The interface between balise and IL is a BCU as introduced in [14] and [15]. This BCU does not contain any logic. It is a hub to connect balises to the IL. Opposed to the BCU, a common LEU is connected to a signal and taps the lamp currents. The new name highlights the differences between a common LEU and the new one. Due to FS and cab-signalling used in the new architecture, trackside signals are not necessary. But if a train waits at the EoA a trackside signal is helpful, to transmit the infomation about a valid MA to the train driver. In this case, the signalling systems has no safety function. Safety is handled by ETCS.

Figure 6.2 sketches the safety level of the new architecture. The safety level contains only the safety-relevant functions. Other functions relating to the management, e.g. scheduling, are not located at the safety level. In the new architecture, the *route logic* exists next to the new *ETCS logic*. Both rely on each other. The route logic is regarded as the basis of safeguarding train movements by securing the infrastructure. ETCS acts only on a safe driveway respective a route. The *ETCS logic* covers the functions to calculate the ETCS informations and parameters for the selected route. This covers also the generation of telegrams for the dedicated balise groups. The functions for *track vacancy detection* are also located in the IL itself. The *block communication* is expanded to a general interface between IL for a safe exchange of data. Differences between station and line (block system) disappear due to full train detection by track sections. A *data model* contains the individual data which is used by the different generic modules.

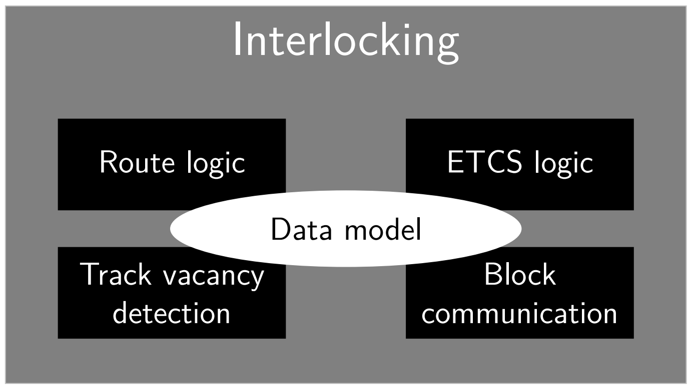


Figure 6.2: Sketch of the new safety architecture.

6.1.1 Integration of Level Crossing

The new architecture requires integration of LX into the IL and an adaption to ETCS. Three different approaches exist to connect an LX to the IL. Different advantages result from the integration of LX into the IL. Axle counters are used to activate and deactivate an LX [110], but the IL also uses them to define block sections. Existing LX with vehicle sensors can still be used in this architecture but limit the new architecture's benefits. There is also expected to be an increase in capacity, which is analysed in this thesis. Figure 6.3 shows these approaches.

1. The left-hand side presents the simple replacement of a common LX signal by a balise. There is no integration of LX into the IL.

2. The middle figure shows the integration of the LX via the IL. This approach bases on the exchange of LX data to the IL. It is comparable to the common existing LX interfaces.

3. On the right-hand side, the LX is upgraded with IL functionality. Not only LX information is exchanged but also IL and ETCS information. The LX can use axle counters of the IL for activation and deactivation.

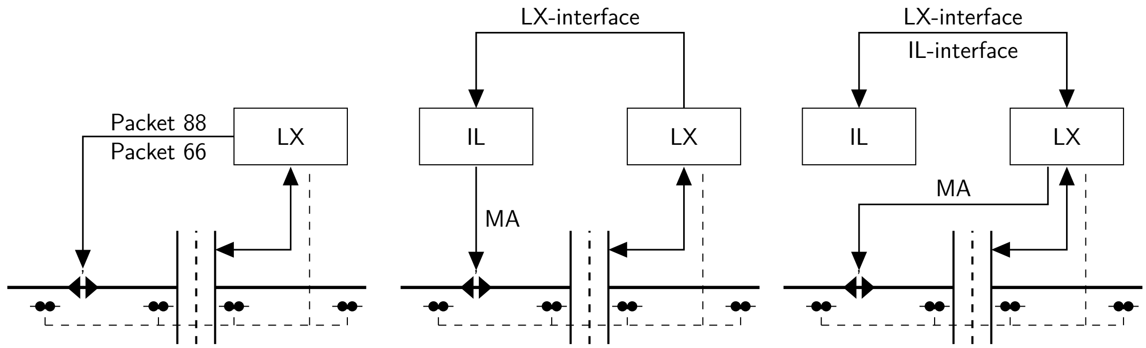


Figure 6.3: Three topologies to integrate a level crossing into the new architecture.

Topology 1 (left-hand side)

Packet 88 or Packet 66 are used for integrating the LX into an MA. It is not an integration of the LX status information or functions into an IL. In this concept, the LX remains autonomous, and no interface to the IL is necessary. From an operational point of view, the IL has no access to the LX and its functionality. That is not a proposed setup for the new architecture. The definition of an MA in the IL is not possible. Topology 1 does not connect the LX to the interlocking. The LX itself handles the ETCS relevant information without interaction with the IL. The protection state of the LX is evaluated and sent to the train. Packet 66 and 67 or packet 88 are created by the IL and transmitted at the balise group connected to the LX.

Topology 2 (middle)

This approach relies on existing interfaces that connects LX and IL. For example, the SCI-LX is used but not limited to this functionality. The interface should be designed to improve railway operation and reduction of road closing time. Topology 2 supports integration into the safety logic of the IL. The LX is integrated as a route depending LX or still acts as an autonomous LX without route dependency. As an autonomous LX with an interface to the IL, the protection state's supervision and general functionality are integrated into ETCS. The LX is not in charge of creating ETCS telegrams and commanding balise groups. The IL processes this.

Topology 3 (right-hand side)

The LX acts as a common LX but obtains IL functionality. A further interface allows the IL to send ETCS telegrams to the LX, which forwards them to the balise group. Axle counters, used by the LX for train detection, are used to define additional block sections. The ETCS telegrams can be processed in the IL or in the LX itself. That depends on the operational boundary conditions and the implemented process. Topology 3 is a complete integration of LX into ETCS. The LX sends its status information to the IL. A further interface allows using the LX as a hub for ETCS balises. The IL sends ETCS telegrams to the LX, and the LX distributes them to the balise groups connected to the LX. An ETCS logic is not necessary on the LX if the IL itself handles this process. An advantage of topology 3, compared to topology 2, is the use of axle counters in the ILs route logic. Implementing an interface allows the IL to define additional block sections. That improves operation and capacity, but no additional axle counters are necessary. Only the range of application expands.

The presented topologies have different advantages and disadvantages. Table 6.1 gives an overview of the different advantages and disadvantages.

Advantage	**Disadvantage**
Topology no. 1	
Simple integration of LX into ETCS	Additional balise groups are necessary. No synergy effects with balise groups in the immediate vicinity.
Topology no. 2	
No ETCS logic necessary in the LX.	The IL uses the available balise groups to transmit the necessary ETCS information of the LX protection state. If the LX is turned off, the balise groups cannot be used.
Smart integration of LX into ETCS	
Topology no. 3	
Additional block sections increase capacity and improve operation.	Additional interface is necessary.
Smart integration of LX into ETCS	If the LX is turned off, the axle counters cannot be commanded by the IL via the LX.

Table 6.1: Advantages and disadvantages of the different LX topologies.

Trains are running in ETCS FS. Topology 1 is suitable for the fast integration of an LX into ETCS. The LX needs an ETCS module, which evaluates the LX protection state and translates it into ETCS telegrams. Topology 2 is a smart integration of an LX to ETCS by connecting the LX with the IL. The IL handles ETCS, and the LX is responsible for the closing of the road. The available balise groups are used but an optimal position of the balise group for the application for the LX is not important. Topology 3 expands the LX with IL features to use the available axle counters. However, handling these axle counters via the LX is not suitable if the LX is turned off for maintenance or if an error occurs. To avoid this issue, the axle counters are connected to the IL directly. The LX has access to the axle counters and connects to them via an interface. This topology has the advantage that the IL commands the axle counters every time, even if the LX is turned off. The LX receives the axle counter information via the special interface. Operation of the LX is not affected, and only the way of the information is different. Figure 6.4 sketches the adopted topology.

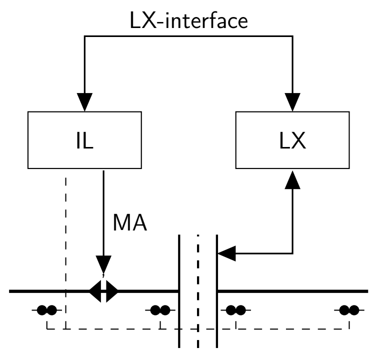


Figure 6.4: Adopted topology 2 with axle counters connected to the IL.

The proposed topology is topology 2. That topology provides a smart and simple integration of LX into an ETCS environment. Topology 3 is helpful if additional block sections are necessary. It is more complex but very innovative.

6.1.2 Transmission of ETCS Messages

ETCS offers two major ways to transmit messages to the train. The messages are transmitted via

- balise or
- RBC.

Euroloop and Radio-Infill are only available for infill messages and are not considered in the new architecture. Only balises are used for transmitting infill information.

Figure 6.5 shows two ways to transmit messages from IL to the train. The new architecture is designed for ETCS Level 1, and the main transmission medium is the balise. But, in this section, the RBC is discussed briefly and an approach to integrate it into the new architecture. The new architecture is also usable for ETCS Level 2. In this level, the RBC is the transmission medium for the ETCS messages.

The new architecture handles the process of telegram creation itself in the ETCS logic. This process is independent of a dedicated level. The RBC does not need safety logic related functions. In the new architecture, the RBC is simply a radio communication device. It only manages the communication between train and track. Communication-related ETCS features (technical aspects) are still handled in the RBC, but no railway safety features are located in the RBC. For example, position reports from the trains are received by the RBC and forwarded to the IL, which evaluates the position report. Enabling the communication from RBC to train is handled but the RBC itself. Also, the switch to another RBC is managed by the RBC. There is a strict separation between communication, railway safety and operation.

Contrary to classic ETCS applications, it is not the RBC that is in charge of defining clear and occupied track sections.

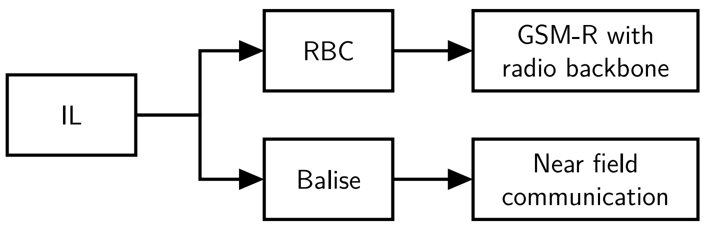


Figure 6.5: Different ways to transmit an MA.

As presented in chapter 4, radio communication technology changes faster than the long life cycles of railway safety technology are adapted. Using higher frequencies, the range of a radio transmitter is reduced. More radio masts are necessary, or the range of an RBC is reduced. A further limitation of the RBC is the maximum number of trains handled at the same time. That number is approximately 60 trains [111]. Approaches like E-GSM-R, GPRS or FRMCS do not solve the issues (see section 4). Considering two aspects outlines this purpose:

1. Higher frequencies require more radio masts to achieve the same range for the RBC. If the decentral architecture is applied to the RBC-setup, each station and each IL will have their own RBC. Since it is only the adapter to the radio communication, it is not that complex and expensive device as a common RBC with safety functions. The functionality will be similar to the RIU, the radio infill device in ETCS Level 1. This device still enables communication in Level 1. In principle, there is no operational difference to the RBC, which is reduced to a communication device.

2. A classic RBC contains a safety logic to evaluate the input of different IL technologies. The new architecture contains the logic for MA creation, and it is not a relevant task for the RBC any more. Whether the MA is transmitted via balises or GSM-R is of little importance.

6.1.3 Line Topology

IL's architecture impacts the whole topology of the IL and field elements along a railway line. A discussion of the structure of an entire line and the interaction with safety subsystems is also necessary. In this thesis, a decentral setup of IL is proposed. Therefore, each station has its own IL. Field components like axle counters, signals, balises and points are connected to the IL directly via bus or network communication. No open networks or radio communication systems are used for communication between field components and route logic. Interfaces to further safety systems like the RBC, LX or IL are standardised to achieve a simple connection of these systems. Figure 6.6 shows this topology.

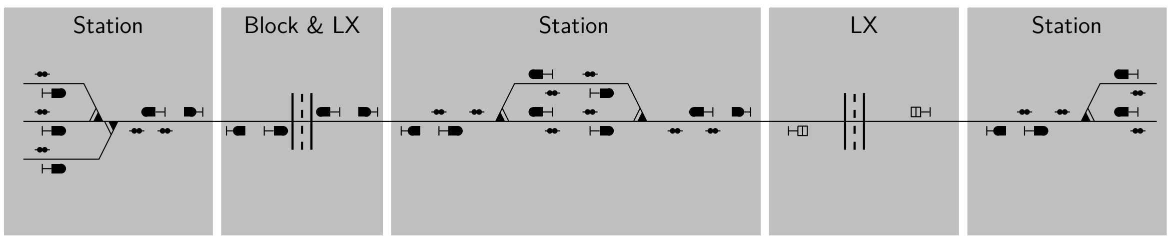


Figure 6.6: Topology of a railway line.

Each operating post along the line has its safety systems. These are an IL or an LX. An IL is used for safeguarding and controlling a station or a block post and sidings and junctions. Each IL or LX is safe even if the connection to a TMS or the controller desk is interrupted. Secure communication between IL (and LX) to the field components is safe and only available in the immediate local vicinity. The dispatcher does not control the field components directly. A request is sent to the IL, and then the IL submits or rejects the request. Hence, only the IL of the operating post commands the field elements. The guideline for this approach is described as *safety, where safety is necessary* [47]. A centralised topology is not proposed in this thesis because the effort for communication increases. This and further aspects are discussed in the following chapters.

The operation of such IL systems is described in [49], [112]. The differentiation between safe communication and process-oriented communication is introduced.

6.2 Route Logic

The route logic is a central element of the new architecture. This section describes the features of the proposed route logic. Presented ideas for the route logic are dedicated to ETCS Level 1. Basic principles can still be used for Level 2 and Level 3. Further considerations concerning the radio communication are necessary for Level 2 and Level 3. The new aspect is a complete model-based route logic and ETCS logic. The route locking process is combined with ETCS features. ETCS is used in mode FS, which enables cab-signalling. Trackside signals are no longer required for safeguarding train movements. [113]

An indication about a locked route and a valid MA in a balise group is outlined. The basic principles of safeguarding train movements are adapted to cab-signalling and ETCS.

6.2.1 Railway Signalling

The transmission from signal to train driver is still analogue. Most ATP systems have an interface to trackside signals which evaluate the signal aspect, and send information to the train. However, if no cab-signalling is used, the train driver must look at the signal and perceive the information. In the new architecture, balises are commanded by the IL directly. Hence, trackside signals are not necessary for ETCS Level 1 FS. Trackside signals and cab-signalling are redundant because there are two ways to transmit information from track to train driver. The vocabulary and the information content of ETCS messages are significantly higher than with common trackside signals. ETCS messages are much better suited to transmit safety-relevant information. They can still indicate a new MA in the balise ahead or other information to the train driver [114]. Therefore, a vital signal is not necessary.

The migration from trackside signals to cab-signalling has an impact on the realisation of the basic safety principles:

- Signal dependency and
- Flank protection.

Signal dependency describes the locking between the moveable route elements (points and LX) and the signal. Only if these elements are locked, the signal can be cleared. If ETCS is used without signals, putting the MA into the balise group is equivalent to clearing a signal. To specify this, instead of clearing the signal, the ETCS telegrams must be created and transmitted to the balises. If the message is available in the balise group, the route is in the same state as if the signal would be cleared.

The valid message in the balise group is the permission for a train to drive. It is signalled in the drivers cab (cab-signalling) which makes a signal or a cleared signal as part of the route logic unnecessary. Giving the dispositive information that a valid MA is in the balise group has no impact on the permission to drive.

> *If an MA is put into the balise group or the RBC, the moveable route elements must be locked. While the MA is available in the balise group or RBC, the moveable route elements must remain locked.*

Flank protection is affected due to cab-signalling. Hence, flank protection with points or derailer is not focussed. Realising flank protection without signals must be handled in ETCS. Common signals are not available in the new architecture. The DMI indicates the limit of permitted movement.

Flank protection in means of light protection aims to stop each train passing the dedicated signal at stop. A balise must stop each train passing the balise group. It is only possible to stop an actively operated train in mode FS, LS, SR, OS or SH. Other modes are not used for train movements.

> *Instead of using a signal to ensure flank protection, a balise group ensures flank protection.*

In the new architecture, a signal may exist, but it has no safety relevance.

Both topics, signal dependency and flank protection are independent of ETCS. That issue occurs if signalling moves from track to train – trackside signalling versus cab-signalling.

In Level 2, transmitting an MA to the train is not bound to the train position and available balises. The train driver receives an indication on the DMI if a new MA is available. In Level 1, it is necessary to inform the train driver if a valid MA is in the next balise to increase the performance. If no indication about a valid MA is given to the train driver, the train will not drive. Therefore, an indication is necessary. That is necessary when the train does not receive an infill in time. Information about a valid MA is not vital. The ETCS On-Board Unit stops the train if the train passes a balise without valid MA. If the train driver receives wrong information to pass the balise, ETCS acts as a safety system and stops the train. The indication to start driving can be transmitted

- by a simple (non-vital) signal,
- a call of the dispatcher or other means of communication,
- an automated SMS or another message via the public radio communication system or
- information via GSM-R.

These procedures are categorised in manual and automated transmission. Using a signal, an SMS or any other text message, this process can be automatised. A function is necessary, which evaluates the locked routes. As opposed to the automated procedures, a manual triggering of the dispatcher is possible. The dispatcher can call the train driver if a new MA is available. However, sending a text message can be triggered manually.

A simple signal does not need to fulfil the requirements of a safe railway signal. No supervision of signal function is necessary. It only needs a lamp that indicates that a valid MA is available in the balise. If the lamp is broken or the signal has a malfunction, the train will not drive or is stopped at the balise without a valid MA.

For example, a call via train radio of the dispatcher is possible, but calling every train that waits at the EoA challenges the dispatcher. The normal case should be an upgrade at an infill balise that the train will not reach the EoA. Passing the last infill balise without an upgrade is possible. For this case, informing the train driver about a valid MA in the next balise is necessary.

Furthermore, a management system or the dispatcher can send automated information via GSM-R, train radio or other systems to the train driver. IL's relevant information is provided, but another system is in charge of the non-vital features at the management level. Such a process can be automatised, and a message is send triggered by a locked route. The IL must know if a train is entering the locked route or heading onto the cleared signal. Information about a locked route is filtered. For the only case that a train has passed the last infill balise group without an upgrade, information is sent. That reduces the number of messages received by the train driver.

For the new architecture, a new type of trackside signal can be used. Such a type of signal is introduced in Luxembourg [111] and called *indication signal*. Next to the operational purpose, trackside signals are also helpful for operation in a degraded mode. The train driver can react on the signal aspect if the trainborne ETCS is not working. Opposed to the classic railway signal, this indication signal is not locked to the route. Figure 6.7 shows the schematic symbols of the classic signal (the German KS-Signal) and the new indication signal.

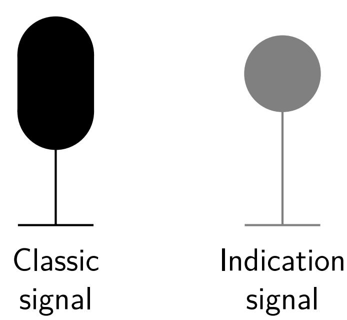


Figure 6.7: Symbols of the signals.

6.2.2 Model-based ETCS Route Logic

The route logic of the new architecture is different from the common CBI. Routes are not predefined. Therefore, the routes are determined model-based in the IL at runtime. The model depicts the track topology. For usage in the safety logic, a vital model is necessary.

The relay IL of type *Spurplan* has the first model-based safety logic [18]. In [115], [116], [117] and [118] also different kinds of model-based route logic are proposed. A model-based route logic is common in all systems, but all proposals rely on a radio communication like ETCS Level 2 or Level 3 environment with an integrated train detection. Level 1 is not considered.

A generic algorithm seeks the driveway in the model between the start and target element at runtime. The safety logic proves the validity of the driveway and locks the relevant elements. The algorithm must be well tested and approved. In common CBI, the start and target elements are signals and line target elements. Now, no signals are necessary for the route logic. A new definition of start and target element is necessary. Since the route logic defines a route as a coherent list of track sections, the start and target elements for a route are the track sections' endpoints. This principle is similar to a partly route release. A detachment from the conventional way of thinking with trackside signals is necessary. The route consists of a sequence of track sections and points. If these track sections are clear and the points locked in the correct position, the route is locked, and the MA is created. Such a route can be a part of a route in the classic way of thinking. Over-lap and the flank protection elements of the route are defined in a similar procedure.

As described, the usage of ETCS with the new architecture offers more start and target elements, which impacts operational flexibility. In principle, each balise group can be used as a start or target element for a route. The location of these balise groups is the start and target locations for the routes - the end points of the track sections.

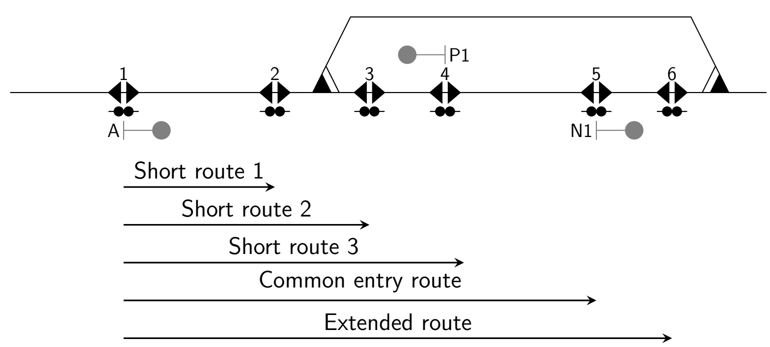


Figure 6.8: Different routes in a station for given track sections.

Figure 6.8 shows a station with different balise locations, which are depending on the axle counter locations. Balise groups number 1, 4 and 5 are available due to the signal located in a common station with trackside signals. There are operational issues for this location. Balise groups number 2, 3 and 6 are additional balise groups located at the end of a track section. This allows using each end of a track section as an EoA. The sketched routes indicate the principle of the dynamic route logic at the example of entry routes. Exit routes or routes within the station can apply the same principle. Because of cab-signalling, a minimum distance between two signals is not necessary. That allows a reduction of the route length. Depending on the algorithm, the different sketched routes can be implemented as a route or an automated and subsequently expanding route. The route is selected from start to target location, and only the clear track sections (between balise group) are locked. If an occupied track section is cleared by a train in advance, the route (more precise: the track section) is locked, and the MA is expanded.

Common routes are planned with an overlap. With ETCS FS, an overlap is not necessary. A fixed DP can be defined for an MA to increase capacity in means of reduced approach time. With ETCS the entry speed must not be limited due to a short overlap because the braking distance is calculated for the certain case with the target at the EoA. For an early locking of a route (occupied overlap, e. g.), an MA without DP or SvL can be defined.

Following routes can be locked:

- The overlap of the home signal and further track sections (short route 1 and 2).
- A route from the home signal to the exit signal of the opposite direction (short route 3).[1]
- The common entry route.
- An extended route from the home signal to the end of the overlap of the exit signal.

In general, the available track sections are locked individually and depending on the operational requirements. Start and target elements of a route are balises and not the (obsolete) signals.

In common IL systems, there is a differentiation between

- train route and
- shunting route.

The difference is the non-existent flank protection for shunting routes [18]. Moreover, a shunting route is only available within a station, whereas a train route directs from a line into a station and vice versa. As already mentioned, the new route logic does not need differentiation between station and line. The only differentiation of the type of movement is processed in ETCS and not in the route logic. Route elements are locked independently of the dedicated train movement. The IL only safeguards the trackside sections, which are necessary to perform the train movements. ETCS functions are not implemented in the route logic. However, the rules for locking the trackside elements are still defined concerning cab-signalling. Differentiation between different ETCS modes for a train movement is an ETCS feature and handled in the ETCS logic. Depending on the locked route elements and the elements' state, a decent ETCS mode is selected to perform the movement.

[1]There are no signals necessary in the new architecture. The mentioned home signal and exit signal refer to the corresponding location, where the ETCS messages are transmitted.

6.3 Train Detection

For safeguarding train movements, an efficient and smart train detection system is necessary. Train detection is divided into vital train detection and non-vital train localisation.

Vital train detection is used for safe train detection and provides the route logic with track occupancy information. Non-vital train localisation is used for dispositive features like passenger information or train run supervision. A fault in non-vital train localisation does not cause hazardous situations. Therefore, non-vital train localisation is not suitable for safety functions.

6.3.1 Vital Train Detection

In common IL systems, track circuits and axle counter circuits are used for vital train detection. GNSS or a train position report (ETCS Level 3) are also used for train detection. Chapter 5 presents different systems where GNSS serves a precise train detection in an IL system for vital train detection. There are various aspects to evaluate and design a train detection system (e.g.):

- Cost
- Components
- Availability
- Precision

In the new architecture, vital train detection is realised by using axle counters. No additional systems like GNSS are used. For example, GNSS is an infrastructure in itself. An additional trainborne system is necessary to estimate the train position and evaluate this information about track vacancy. The train detection must be a vital system to fulfil the conditions according to Safety Integrity Level (SIL) 4 [119]. GNSS is not granted at every place around the world. Problems occur in tunnels, valleys and in urban areas where tall buildings cause reflections [120]. These reflections lead to multipath propagation and result in a false position detection at the receiver. Sensor fusion is required to design a vital GNSS receiver for usage in railways safety systems. GNSS is used in combination with the odometer of the train [121].

A position report from the train requires communication from train to track. This architecture is dedicated to Level 1, and communication from train to track via balise is not provided. In early SRS of ETCS, a bidirectional communication via balises was defined. But in later versions, this feature was removed since it has not been used [96].

The new architecture is not dedicated to operate with moving blocks. Level 1 is in focus which relies on fix block sections. However, due to the new features, the number of block sections may increase, leading to an increase in capacity.

6.3.2 Non-vital Train Localisation

Opposed to vital train detection, a non-vital train localisation is introduced as a new architecture's feature. Non-vital train localisation describes the detection of a train for dispositive purposes only. That system is not used for safety functions like track vacancy detection.

The balise specification [29] defines an *Interface C*. This interface provides information because a passing train empowers the balise. It is not granted that the train reads the telegram. It is necessary for the BCU (or for the LEU) that the telegram is not changed while a train empowers the balise. That information is interpreted for train localisation. It is assumed that the train is at the balise group, and the train's position is detected. For a vital function, this *assumed* train position is not usable. There are different non-vital functions (located at the management level), requiring an IL position input. The IL provides train position information to different railway systems. This dispositive information is used for:

- Passenger information systems [122], [123]
- Train describer systems [124]
- Lei-Dis [125]

In common CBI the *signal stop event* is used in connected dispositive systems. The described non-vital train localisation sends information of every passed balise location to further systems. It is not only the passed main signal which is used for triggering the location information. So, this interface is adopted to its transmitted information. It is not only the signal stop event – it is the *passing a balise event*. Since no signals are necessary for the new architecture, there is no signal stop event. Usually, there are more balise in the track compared to the number of signals. The result is an improvement of the train localisation as well as the accuracy of the connected systems.

A trainborne train integrity check and its transmission to the track enables the IL to transform the non-vital train detection to a vital train detection [126]. In the context of this thesis, a train integrity check is not considered. That would be an interesting topic for bidirectional communication via balises and moving block applications. Both are not provided in Level 1 with the current specification. A trainborne train integrity check is necessary if the trackside track vacancy detection is no longer required to reduce the trackside components.

6.4 ETCS Logic

A further element of the new architecture is the generic ETCS logic. The ETCS logic creates the MA and the profile data. In the second step, the corresponding telegrams and messages are created. This is processed at runtime of the IL.

As outlined in section 6.2, the route logic and ETCS logic interact. The ETCS logic responds to the route logic if an MA is created and available in the balise group. In typical ETCS Level 1 applications, telegrams are predefined in the LEU and selected from the current signal aspect. Hence, signals are not locked in the new architecture because they are reduced to a simplyfied indication signal. The signal's safety function moves to ETCS. The availability of the MA in the balise group is the safety-relevant part, which must be supervised in the IL. So, the ETCS logic is an additional function within this safety system. The information of the route locking are evaluated to generate the ETCS data and telegrams.

The new architecture's ETCS logic bases on the route logic. The creation of ETCS telegrams is triggered if a route is locked. Two statements define the differences between route logic and ETCS logic:

- *The **route logic** defines the driveway for the train and safeguards the trackside elements.*
- *The **ETCS logic** describes the train's driveway and safeguards the train movement due to the trainborne ETCS subsystem.*

There are still more tasks for the ETCS logic. The ETCS logic calculates profile data (gradient profile and SSP, e. g.), linking information, the MA itself, and further data transmitted to the train based on the route logic. However, the packets for the route are created and the flank protection is handled. Clearing of a signal is replaced by the creating and loading the MA into the balise group. Therefore, the ETCS logic's response to the route logic is required. Figure 6.9 shows a basic flow chart of the ETCS logic. Both tasks, creating the MA and realising flank protection, are sketched as two different branches. Both branches depict the definition of profile data and the MA itself. Afterwards, the creation of telegrams is the process that finally results in telegrams and messages. The previously defined profile data and the MA are transferred to the physical ETCS telegrams, transmitted to the train.

The ETCS logic receives input from the route logic. There is also an optional input from train detection and input from the dispatcher. This input is not necessary for the safety functionality but may improve operation. Figure 6.10 gives an overview of the described input instances of the ETCS logic. In addition to the route logic input, operational systems like a TMS impact non-vital aspects of the MA. That input is used to change the profile data (SSP, gradient profile, e. g.) or create packets without affecting safety.

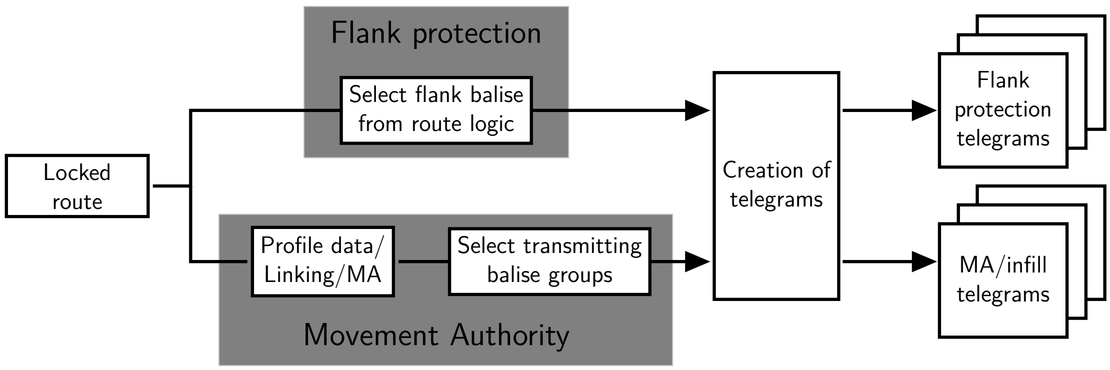


Figure 6.9: Defining the necessary ETCS information for the MA and flank protection.

The safe ETCS logic uses information from the non-vital TMS or further systems of the management level. That input has an impact on the operation but not on the safety. Handling non-vital information in a safety system is new. Similar ideas are described in the Swiss smartrail 4.0 project, where the TMS calculates the ETCS MA and further information and the IL only checks the information.

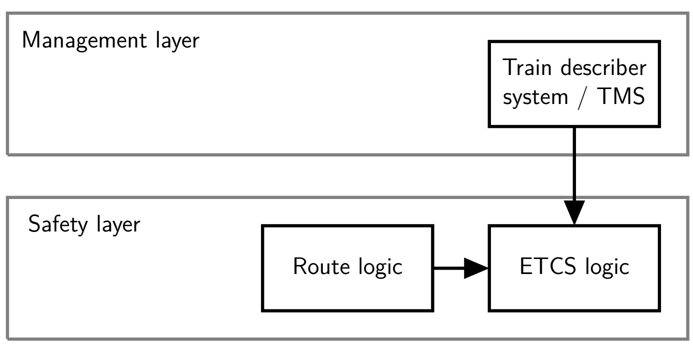


Figure 6.10: Input for ETCS logic.

An example of this operational information is the selection of the transmitting balise groups. Compared to classic ETCS applications, the balise groups are not linked to a signal in the new architecture and commanded individually. Hence, the transmitted information is not only depending on the state of the locked route. Furthermore, the operational situation and the train location are considered for selecting the balise groups to transmit the relevant packets. Selection of a location (balise group) to transmit a regular MA should consider the case of an emergency stop and entering TR. The new architecture allows using the infill balise group (in classic thinking) to transmit a regular

MA. That allows the train to enter FS earlier, and the train is allowed to drive at a higher speed.

6.4.1 Train Movements

The primary purpose of ETCS is to safeguard train movements. As outlined in chapter 3, the modes FS, LS, OS and SH are the regular operation modes. SR is an interim mode to enter one of the regular modes.

Mode	**Movement**
FS	Regular train movement.
FS	Provision movement into a free track.
OS or SH	Shunting into an occupied track.
SH	Shunting in a marshalling yard or siding if the direction must be changed often.
OS, SH or FS	Service movement onto the line, a siding e. g.
SR	Movements if no transition to ETCS is possible or transition not finished.
LS	Movements with trackside signals and missing profile data (ordered from infrastructure).

Table 6.2: Modes for different train movements.

As listed in table 6.2, several modes are used for various situations. Common IL distinguishes between regular routes and shunting routes. This is justified in signalling, locking and safety reasons. In the new architecture, locking and signalling are simplified due to ETCS. The ETCS logic is responsible for safeguarding the train movement.

In the new architecture, SR should not be used to perform train movements. SR intends to be used for interim movements from the *start of mission* until entry in FS, OS or SH. Mode LS is not regarded in this thesis, but the architecture can create and define telegrams for LS, principally.

OS is predestined to perform movements in degraded mode. This principle of selecting the ETCS mode in dependency to the route elements' state applies to fall-back operation. If a route cannot guarantee flank protection, the movement can be processed in a different ETCS mode or reduced speed. The mode OS is applied to an area or a track or route section. OS contains all MA relevant information, a switch to FS after passing the restricted area is possible.

The mode is not derived only from the generic algorithm. The dispatcher can select a mode as well. If the route elements' state is not sufficient, the dispatcher has to select a certain mode. An additional input of the dispatcher can switch the mode instead of using a default mode.

The default mode for train movements is FS. All movements are performed in this mode, regardless of the purpose for which the movement is intended. Also, a movement into a shunting track is performed in FS. If the target track is not clear, the mode OS is chosen by the ETCS logic. The ETCS logic defines the relevant parameters for

- Static Speed Profile,
- Gradient Profile,
- Linking,
- Level Crossing and
- the MA.

These are the essential parameters to safeguard train movements. A more operational impact have text messages which are sent to the train. These provide a train driver with additional information for special situations. For example, if an LX is in error mode, a text message informs the train driver and gives information about a special action for securing the LX in a fall-back mode. These text messages are not safty relevant but provide the train driver with additional information which could also be transmitted via voice communication.

If there is an issue in route locking, for example, the route supervision is not in place, the dispatcher must confirm the issue for processing the train movement in a degraded mode. The ETCS logic supervises the route logic and the locking state to define the proper ETCS data.

The ETCS logic realises the following features:

- Defining the route related profile data.
- Evaluate the operational situation.
- Evaluate user input data.
- Define the MA.

6.4.2 Flank Protection

Flank protection realised by points and derailers is still preferred. But there are topologies where flank protection is realised by A prohibition leading to the exclusion of routes. Therefore, signals are locked in a stop position.

In the new architecture, operation with classic trackside signals is replaced by cab-signalling. Flank protection realised by trackside signals is no longer available. Now, the relevant trackside component is the balise group. The ETCS logic's response is necessary for the route logic if the balise group contains a flank protection content. This is the same process as locking a signal for flank protection.

For realising flank protection, the balise must transmit restrictive telegrams which stop moving trains. Different packets are necessary:

- Packet 132 (Danger for Shunting information) stops trains in mode SH.
- Packet 137 (Stop if in Staff Responsible) stops trains in mode SR.
- Trains in mode FS, OS or LS are stopped by sending a restrictive MA (Packet 12 with $V_{target} = 0\,{}^{km}/_{h}$ and distance $d = 0\,m$, e. g.)

Other modes are not relevant because these are not used to operate a train actively.

Flank protection is also realised dynamically. In [127], the speed depending flank protection is explained. If track-based flank protection is not possible due to the topology, the route's speed is reduced to handle the safety level. This is similar to the non-existing flank protection on shunting routes. Then speed reduction is necessary, if not all points realise track-based flank protection and no other flank protecting elements are available.

6.4.3 Creation of Telegrams

Now, a detailed look at the creation of telegrams is given. Previous sections outline the general aspects of performing movements. However, more important is the definition of the profile data for creating the telegrams. In the new architecture, a decision is taken at which balise group the data is transmitted. Classic ETCS Level 1 applications are quite simple due to a connection of the LEU to the signal. The transmission of telegrams is bound to the signal location. If the balises are commanded independently of a signal, every telegram can be transmitted at every balise group. Technically, there is no limit, but there are operational restrictions.

Figure 6.11 sketches the process to create the telegrams. These telegrams contain the packets, which are derived from the defined profile data. The packets for the physical MA and the corresponding packets like linking and gradient profile, for example, are mentioned. The process of creating the telegrams takes the position of balise group into account. For the definition of the profile data and further input data, the validity of the data must be granted. The safe process of creating the telegrams bases on the profile data. Selecting the transmitting balise groups depends on the operational situation. In classic thinking, the start of the route and the target of the route define the balise groups in the train's path. The TMS or the dispatcher may select the transmitting balise groups

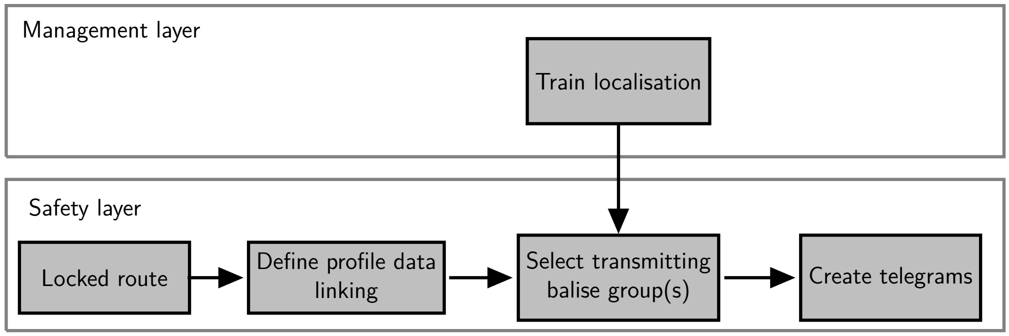


Figure 6.11: Process of the ETCS logic for creating telegrams.

due to some special situations not covered by the IL's safety process. In such a case, the non-vital train localisation supports the dispatcher or gives an input to the TMS to select the proper balise groups and improve operation. Non-vital impact refers to:

- Selecting a balise group for transmission.
- Reduction of speed for different purposes.
- Enabling braking of the train for a regular stop (EoA at the platform). The MA is defined with the EoA at the balise group in advance of the platform (formerly the exit signal location). But, by entering the station when the braking already started, the MA is extended. Therefore, the following section must be clear. This indication is not relevant for a continuous driving and an optimal utilisation of the capacity. Hence, the indication does not reduce capacity because the train must stop as scheduled.

Profile Data

ETCS defines several packets to describe the track properties. Two mandatory track properties are the SSP and the gradient profile. Figure 6.12 shows the SSP as an example for profile data. The SSP is sketched for an MA from signal A (balise group 1) to signal

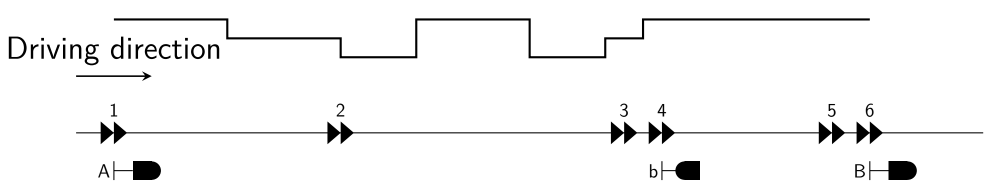


Figure 6.12: SSP (profile date) in a classic ETCS application.

B (balise group 6). SSP, gradient profile and MA are transmitted at balise group 1. It is possible to adjust the profile data and distribute its transmission to other balise groups.

This procedure allows saving data space. Figure 6.13 shows a distributed transmission of profile data. There, balise group 1 transmits the reduced profile data. The dashed profile

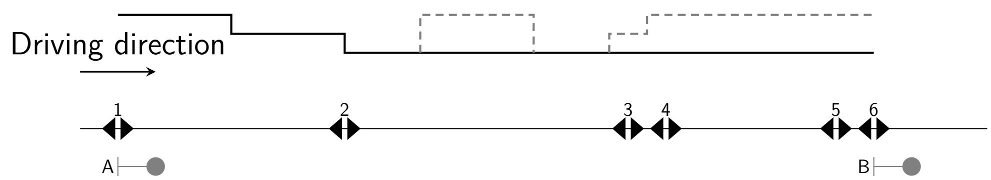


Figure 6.13: Distribution of SSP (profile data) on two balise group.

data is transmitted at balise group 2. This profile increases the speed, so braking curves are not considered. The gradient profile can use the same principle. It must be valid or more restrictive but can be changed or upgraded at a different location.

ETCS offers TSR in addition to the SSP. The TSR is transmitted with additional and moveable balise groups in classic applications. The new architecture allows integrating the TSR in common balise groups and adding unlinked balise groups to the track for construction sites. Figure 6.14 shows the setup with additional balise groups. Balise

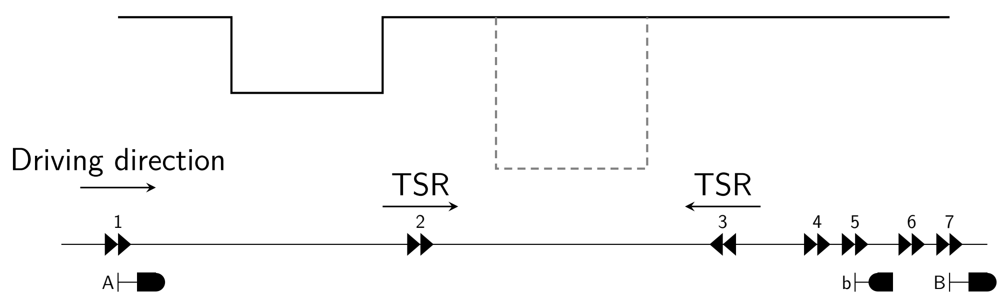


Figure 6.14: Classic application of a TSR.

groups 2 and 3 transmit the message for the TSR. These balise groups only transmit the TSR. The new architecture enables different approaches to handle a TSR. Figure 6.15 shows a similar example by using the available balise groups for the common signalling equipment. The TSR is transmitted at balise group 1 and 2. By creating an MA, the

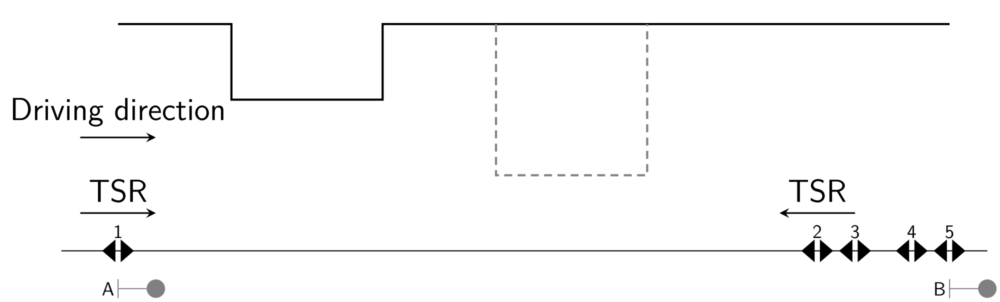


Figure 6.15: Dynamic TSR.

TSR is added to the message and transmitted to the train without using additional balise groups. If the TSR is used temporarily, it is defined only for the time slots where the TSR is active. Also, it is possible to change the SSP to implement the speed restriction by changing the SSP. Hence, an extra packet for transmitting the TSR is not necessary. Both procedures lead to the same result. Adopting the SSP reduced the necessary data space in a balise group.

Entering a TSR to the IL requires a special process:

- The input of the TSR must be safe. A change of the entered data must be avoided.
- The TSR can be valid in certain time slots which an authorised user must enter.
- A TSR cannot increase the maximum permitted speed given by the speed profile of the track.

The algorithm evaluates the speed relevant entries of the data model. Integration of the TSR into the SSP or a separate definition of a TSR packet depends on the operational requirements. The operational requirements are depending on the dedicated services and used modes. Shunting service requires TSR packets, whereas a service in FS can use the SSP with the integrated speed reduction.

Linking

The new architecture simplifies linking. There are no setups, where a complex situation occurs due to the signalling system because of cab-signalling, e. g. Each balise is known and considered in the linking. Trackside signalling is not necessary, except some signals for indicating a valid MA or shunting, e. g.

Transmitting infill information is possible at each balise location in the track because the route is known. In classic ETCS applications, linking is not possible in all track locations. If the distant signal of the exit signal is not known and the distant signal aspect does not allow to conclude the exit route, no infill is possible.

The new architecture allows linking of all balise groups. The route logic and ETCS logic know the whole driveway and the available balise groups. Hence, all balise groups in the driveway are linked. That allows every balise group to transmit infill information to the train. Also, a missing or defect balise group is detected if a linking reaction is defined, which leads to a reaction. A defect balise group is recognised if no data is transmitted to the train, and the train does not get an upgrade of the MA.

Level Crossing

In the new architecture, LX is consequently connected and integrated into the IL. The IL knows each state of the relevant LX. Two principles to handle LX are

- Packet 88: Level Crossing and
- Integration into the MA.

Using Packet 88 is a simple integration of an LX into ETCS. Packet 88 enables the smart handling of LX without feedback to the train driver. These LX are connected to the IL, which monitors functionality. In case of an LX error, the dispatcher is responsible for informing the train driver to stop. The LX is activated and monitored in the same process, but feedback to the train driver is introduced. The ETCS logic creates the packet and uses a balise at least in the longest braking distance to the LX to transmit the packet to the train. In this case, packet 88 transmits the functionality to the train and not the protection state. This process is similar to the LX supervision signal, which indicates the LX functionality instead of the protection state.

Common LX with feedback to the train driver is handled with the same procedure and packet 88. These LX are equipped with a remote interface, and an existing balise for transmitting the packet is selected.

The integration into the MA is a smart solution if there is a kind of route dependency. If a route is locked, the MA is generated up to the LX. The train can start driving while the LX performs the activation procedure. If the LX is protected, the MA is upgraded. This principle, connected with the dynamic activation and deactivation of the LX train detector, enables a simple realisation of special operating cases of an LX. For example, if a shunting movement heads in the LX direction, the activation sensor is disabled if the shunting movement does not pass the LX. Depending on the train's mode, the driveway's balise groups contain restrictive packets to stop the train before reaching the unprotected LX.

Stopping at the LX with an MA requires a definition of the overlap or Danger Point. Figure 6.17 shows two variants, one with overlap and one without an overlap. Restrictive braking curves lead to a longer approach distance for the LX.

For the case that the LX is in error mode, the MA is not extended. The train must stop in front of the LX. After activating the LX auxiliary protection, the train can drive, but still, an MA is needed. Figure 6.17 shows this principle to handle an LX that is in error mode or still not protected. The train's speed is reduced to 10 km/h or 20 km/h, for example. In advance of the LX, the reduced speed is revoked.

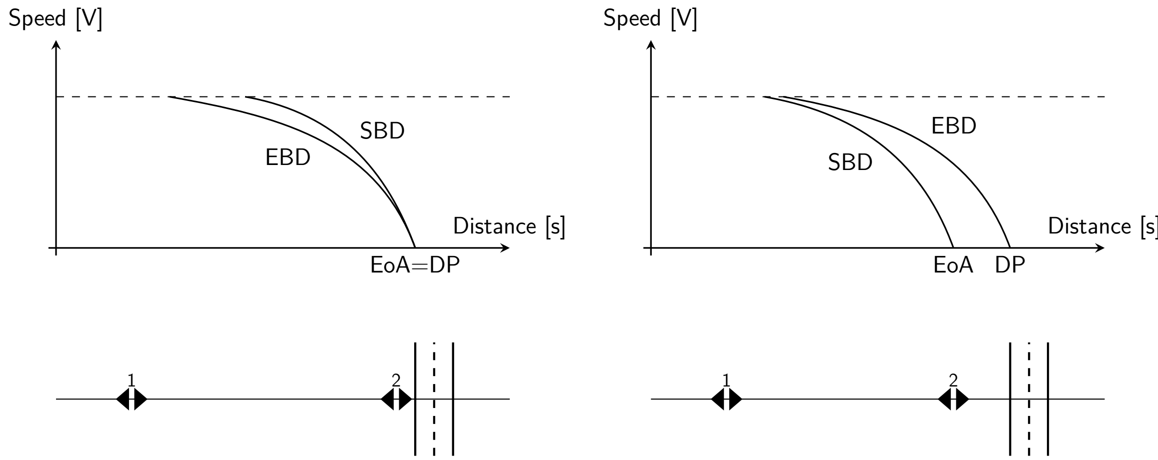


Figure 6.16: LX and overlap.

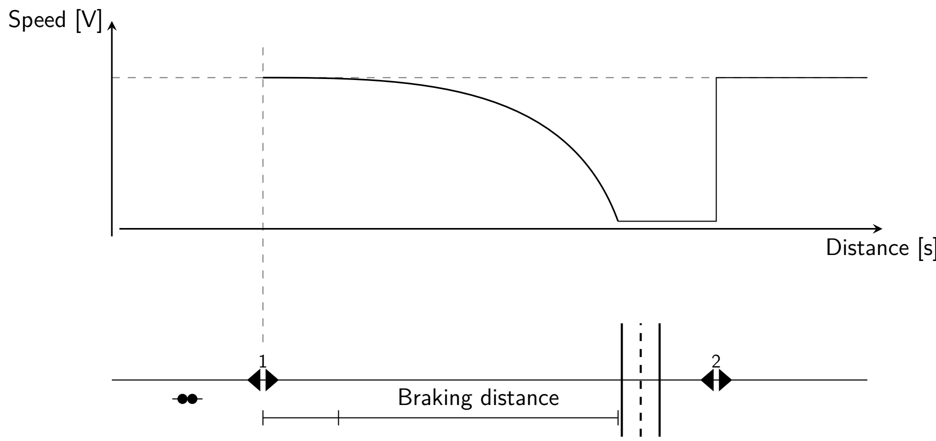


Figure 6.17: LX as a target of a MA.

Movement Authority

The MA is the counterpart of the locked route. If the route is locked, the train needs the MA or corresponding ETCS information, which permits a movement. In general, this is an MA, but also a shunting movement in mode SH is possible. In classic applications of ETCS Level 1, the coverage of an MA is identical to the locked route. That is simply depending on the information provided by the signal.

The new architecture allows a more dynamic creation of the MA. It is not necessary to define the MA with the same length of the route. The MA is segmented, and a shorter MA covers a part of the locked route.

The information transmitted in a balise group is not linked to a signal. This information is related to the locked route, but theoretically, any information can be transmitted at a balise group. Balises transmit much more information than classic ETCS Level 1 applications due to the IL's direct connection. The separation of the infill balise group and „normal“ balise group is not clear because every balise group can transmit infill information (valid at a reference balise group) and regular information (valid at the transmitting balise group).

The MA contains a few parameters which depict the locked route. These are the length of the route itself, the overlap or the danger point, and the permitted speed. Different sections of the MA are not regarded in this thesis.

- The overlap is derived from the locked track sections in advance of the target of the route.
- The length of the MA is the distance from the transmitting balise group to the target element of the balise group.
- The permitted speed is less important because the speed profile offers precise and detailed speed information.

A feature of the new architecture is the segmentation of profile data and the segmentation of the whole MA. Figure 6.18 shows a segmented MA.

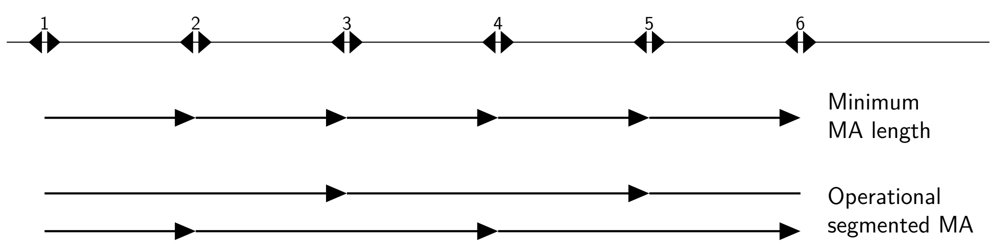


Figure 6.18: Segmentation of the Movement Authority.

Each MA covers the distance to the next balise group. No infill balise groups are available. From an operational point of view, a more rough segmentation is preferred. The train shall not enter a braking process to achieve a harmonic ride. This leads to a rule that the next MA (or the corresponding infill) must be transmitted before the current MA's indication point is reached. In this example, the MA is transmitted at every second balise group. Otherwise, the MA has a length that covers the distance between three balise groups.

The route divided into several single MAs. Classic applications require to transmit the MA at the balise group located at the corresponding signal location. The necessary information is available only at the signal. The new architecture has no restraints concerning the transmitting balise group. That allows splitting the MA into several shorter MA. Profile data with many profile points require a higher data space.

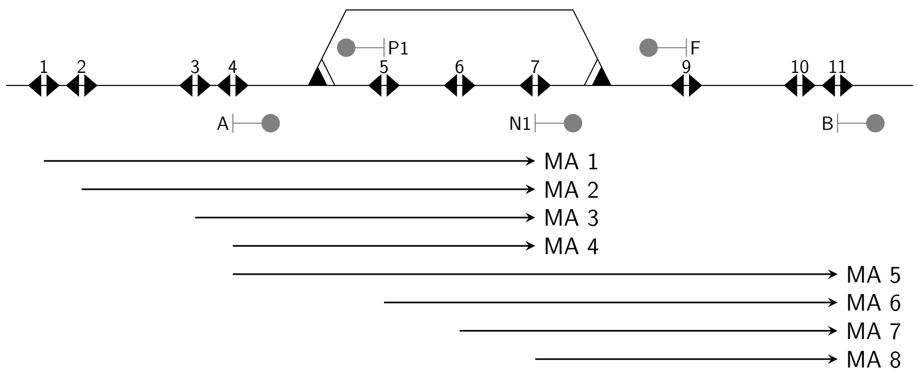


Figure 6.19: Transmission of a new MA instead of using infill functionality.

An MA can be created for every balise group. Figure 6.19 shows the different MA for two block sections. The MA for every balise group covers the profile data from the balise group location to the location of the EoA. If the train position is supervised via balise groups, it is possible to use only the balise group for transmitting the MA, which is passed by the train next.

- MA 1 to MA 4 describes four entry routes that have location *N1* as their target.
- MA 5 describes an MA covering the entry route and exit route with location *B* as their target.
- MA 6 to MA 8 describe three exit routes that have location *B* as their target.

In the MA calculation process, the balise group in the route of the train must be considered. A calculation of an MA for every balise group requires more computer power than calculating only one MA and transmitting this MA via infill or at the balise group passed by the train next.

Infill

Instead of defining an MA for every individual balise group, infill can transmit the MA and profile data. Each balise group can transmit regular profile data or the MA and the corresponding infill information in the new architecture.

The infill balises are located in rear of the distant signal or between the distant and main signal (see Figure 6.20). Infill balise groups in the classic setup still contain the same information. All infill balise groups of a signal transmit the same MA to the reference balise group at the main signal. The infill balise groups are circled together in Figure 6.20.

The new architecture allows addressing all infill balises independently. Every infill balise group is enabled to transmit different information. Figure 6.21 shows this setup. Each

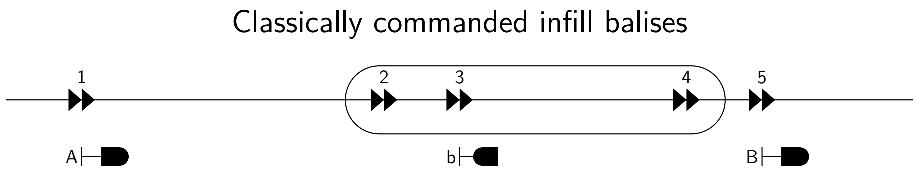


Figure 6.20: Transmitting infill data – classic.

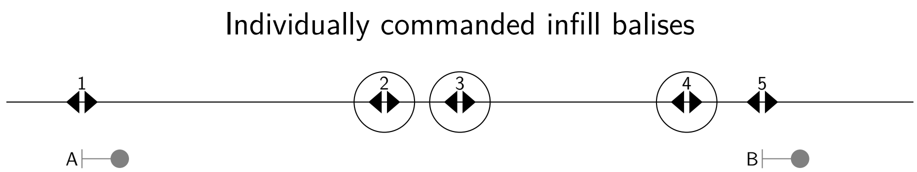


Figure 6.21: Transmitting infill data – dynamic.

circled balise groups are commanded independently by the IL. These balise groups are infill balise groups because they are not at the end of a track section. Transmission of infill data is not limited to the three marked infill balise groups. Balise number 1 in figure 6.21 can transmit infill data. If signal B is cleared, balise group 1 transmits the infill information.

The new architecture offers a new feature. If train localisation via balises is enabled only one balise group is necessary to transmit the dedicated message. This means that infill balise groups must not contain the same information. Each balise is commanded individually, so there is no need for each infill balise group to transmit the same telegram. Figure 6.22 shows this principle. Only balise group number 3 transmits the message for

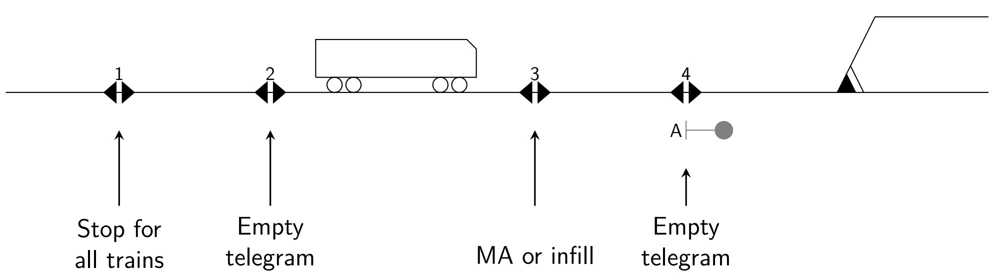


Figure 6.22: Sending telegram depending on train position.

the new MA. Balise group number 1 transmits restrictive information which stops a running train compared to a stop signal. Balise group number 2 and 4 transmit a default telegram.

Instead of using three identical or individual balise groups for transmitting infill data, the balise group, next passed by the train, transmits the message.

Fitting of Telegrams

The new architecture creates the telegrams at runtime. There are no predefined telegrams. Hence, the capacity of the balise groups is taken into account. In chapter 3, the size of some packets is presented. Depending on the profile data, the size may exceed the capacity of a balise. If the profile data does not fit into a balise or a whole balise group, the data must be distributed to different balise groups. For this purpose, the different presented methods of using infill or handling the profile data can be used. These are summarised below:

- Segmentation of the profile data and transmission of segmented data at several balise groups.
- Transmission as distributed infill information to a dedicated reference balise group.
- Reduction of the packet length by adjusting the profile data. The profile data is changed to restrictive values. Restrictive values do not change safety.

6.5 Data Management

This section describes the requirements of data management. It is not only data saving itself. Modelling the necessary data and separating different models for route logic and ETCS logic is described. A further data model is necessary for the project and technology-specific data.

The main focus is put on the arrangement of data models in different IL. Because of the block between two IL or stations, the profile data, e. g. and further data must be available in both corresponding IL. Redundancy must be avoided, and the architecture must ensure the same data availability in each assigned IL.

The transition between a classic (static) ETCS station and a dynamic ETCS station is regarded also.

The new architecture's dynamic features shall be applied to the line, even if an ancient IL is connected to a dynamic IL.

6.5.1 Data Model

Common IL use a look-up table for the route logic and definition of the individual routes. The same is used in the RBC for the ETCS packets [34]. 6.23 shows a static model. This model represents the common applications based on a predefined set of telegrams and

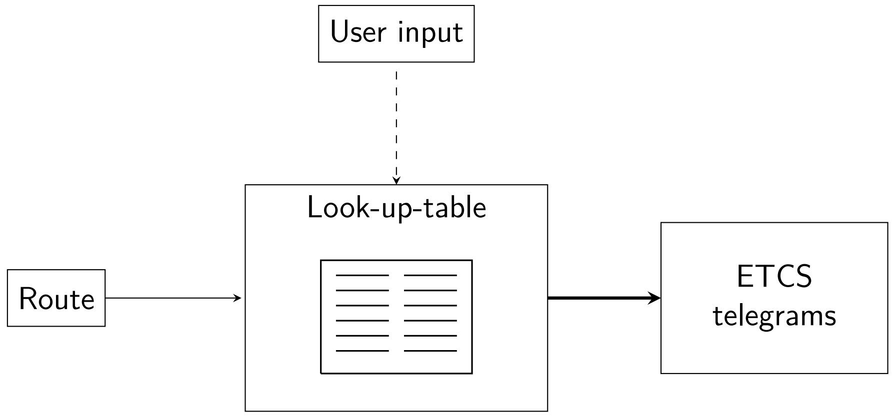


Figure 6.23: Overall process of the algorithm with predefined ETCS telegrams.

static information. The corresponding message is selected in a look-up table depending on the locked route and the operational situation.

For particular action, an input of the dispatcher is necessary. Therefore, predefined packets are created at project time for every possible user input. The more variants or special actions are necessary, the higher the effort to create and approve the packets.

The new architecture does not base on static and predefined telegrams. Dynamic features need a generic and flexible algorithm basing on a data model. Look-up tables are not suitable for this purpose. Therefore, a data model that contains the necessary data to define the ETCS packets or lock a route is required. Different approaches to model these data are available. The RailTopoModel and the Node Edge Model (NEM) are introduced in [128]. Both models are dedicated to model a railway topology. They base on a node edge model. As opposed to modelling the topology, there are approaches to digitise the whole dataset of IL‘s life cycle process [129]. Modelling of the track topology is only a part of the entire life cycle process.

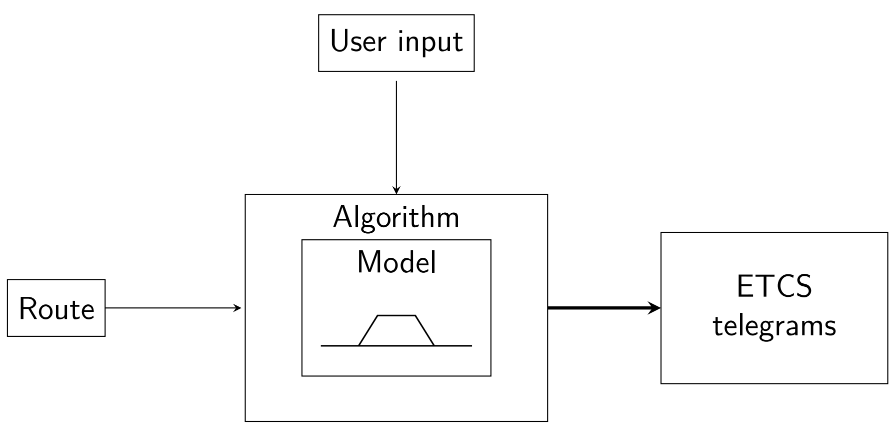


Figure 6.24: Overall process of the algorithm with dynamic ETCS logic.

A data model allows the creation of telegrams at runtime of the IL. No predefined telegrams are necessary. Figure 6.24 shows the proposed principle with a data model as a core element of the new IL architecture. A model of the infrastructure topology replaces the look-up table.

For achieving a modularisation of the IL itself, two separate models are proposed. The data model for route logic and ETCS logic are separated. This allows a simple exchange of data models between IL systems for the ETCS algorithm. Interaction between route logic and ETCS logic is necessary, and so the models are used in parallel and must be compliant. States of the infrastructure elements map into the ETCS model. Both models contain different data. For the route logic these are:

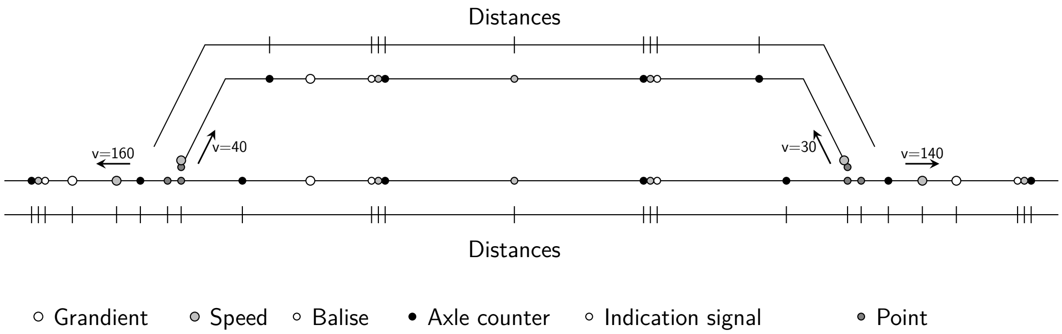
- Start and target elements of a route,
- Axle counters,
- Points,
- Balise group locations,
- Block adapter as a communication interface to further IL.

The ETCS model contains the ETCS relevant information:

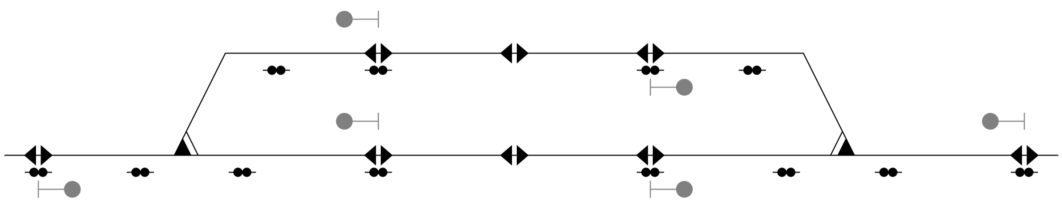
- Balise group locations and balise group related data like ID, linking, distances, orientation, e. g.,
- Speed limitations,
- Gradient profile,
- Location to switch the mode or level,
- Track conditions.

The route model and the ETCS model are abstract models which cover the railway topology. These models base on the *Spurplan*, which depicts the railway topology. However, there are still project data necessary that connect the data models with the physical components. To connect the physical components to the IL, enabling communication is necessary. These project data are technology depending, and the supplier is in charge of defining these data. It is impossible to add additional field components to the IL without changing the project data, route model and ETCS model.

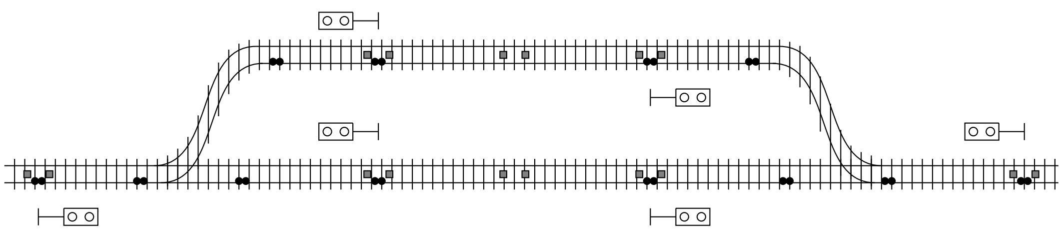
Figure 6.25 shows the three data models. The physical layer depicts the project data at the bottom (Figure 6.25(c)) of the figure and shows the physical infrastructure. This contains the axle counter, balises, points and signals. Also, the necessary communication



(a) Etcs model



(b) Route model



(c) Field elements

Figure 6.25: Overview of the data models for ETCS logic, route logic, and the field elements.

devices and modules in the IL belong to this data model. The route model (Figure 6.25(b)) represents the sketch of the infrastructure with the relevant IL components for defining and supervising the routes. This model is independent of the physical connection of the elements and has a generic character. However, this model must fit the physical elements connected to the IL. On top, the ETCS model is located (Figure 6.25(a)). This model contains all relevant data for the ETCS logic. Especially, the distances between the nodes are marked. A change in the physical components needs to adopt the route model and the ETCS model.

To enable dynamic features of the new architecture, some parameters of the ETCS logic are changed at runtime. Adding field components requires a change of the project data. It is impossible to change the track topology without changing the connected field components (e. g. adding tracks, points, track sections). The only model which can be changed at runtime is the ETCS data model. Speed restrictions can be added to the data model. Depending on the process and the role of the user, more or less data is handled. Reducing the permitted speed is not that critical as increasing a speed limit or deleting a speed restriction.

Mandatory for the data models is a safe data set. This can be compared to the SAFE-TOPO in the project SmartRail 4.0 of the SBB [6].

6.5.2 Central versus Decentral Data Management

ETCS data model and route logic data model are different. The ETCS model is not restricted to a station, whereas a route logic model only covers its moveable track elements. That illustrates in the example of a single line. Figure 6.26 shows a single line with a station at both ends. The route logic safeguards the moveable track elements.

The block system processes the opposite movement and following movement protection. The block sections are handled like track sections in a station. Securing a block section uses a block route as in modern block systems. The necessary axle counters are assigned to a single IL, but an exchange of axle counter information is established for generating the necessary train detection information. Securing the train service within the block sections is processed by ETCS.

Figure 6.26 shows both MA, which cover the same area of the line. The routes onto the line of both stations do not overlap. That depicts the challenge in the ETCS data model. Both IL need data that must be available in both (all relevant) IL.

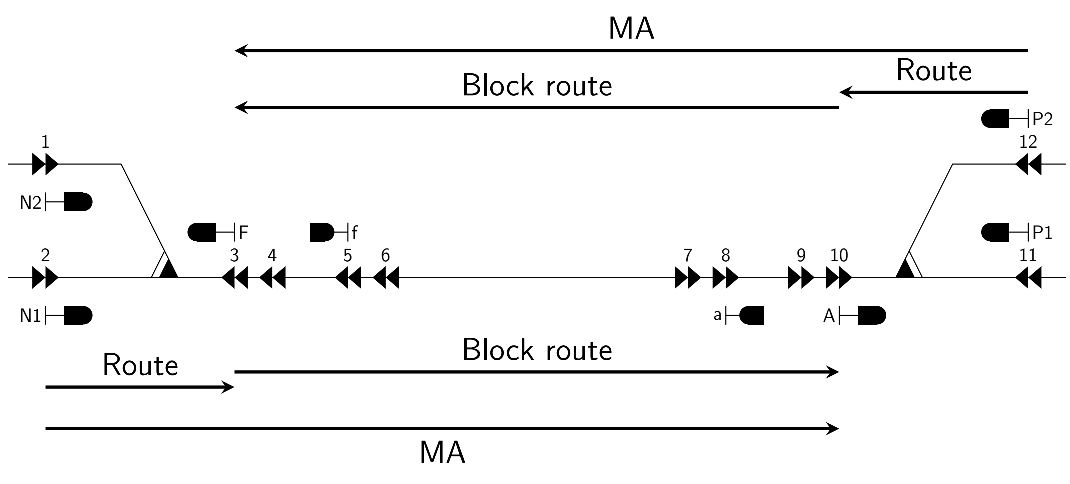


Figure 6.26: Overlap of ETCS data on the line

Data should not be saved twice in two IL. That causes redundancy.

Changing data at runtime (Entering a speed restriction, e. g.) requires a knowledge of this process in all entities, which generate packets and telegrams that cover this area. If a TSR is added to the line between both IL, both IL must create the MA (and profile data) with the correct data.

The ETCS data model can be saved in every IL covering the dedicated area or a central device to save the data. This central storage is a kind of ETCS or line centre for the corresponding railway line or part of a line.

As outlined in the following, a central and decentral architecture is possible. Furthermore, it distinguishes between a data model and a database. The data model returns the corresponding telegrams for a route. That means, the IL does not generate the telegrams for the certain block section. The database hands over the whole model to an IL. Then, the IL creates the telegrams on its own. In this case, both corresponding IL contain the same part of the data model, but the corresponding IL receives the model from the IL and not with the project data.

The main challenge is a safe and non-redundant data model to avoid conflicting states of multiple lapping models. If the data model is changed at runtime, the data model's distribution to different IL must be ensured. That is possible by using checksums of the data model, e. g.

1. **Central Data Model**
   Central data management relies on a central instance where the ETCS data are saved. Every IL requests the ETCS data to create the messages and telegrams. If the data are changed at runtime, the central model is changed. That guarantees that no redundancy occurs. Figure 6.27 shows the principle of this structure. IL exchange block information between themselves. The IL request ETCS data at the line centre. By sending route and block data to the ETCS line centre, the relevant data for creating messages and telegrams return to the IL. For example, an IL creates an MA for the train run from IL A to IL B. IL A creates the MA with an EoA at the home signal of station B. If the home signal indicates proceed, IL A can create an MA which has the EoA at the exit signal of station B. That means IL A safeguards the train movement in station A and the block section up to station B's home signal. For this case, IL A needs ETCS data for the line section between IL A and B. IL A can create an MA covering a route in IL B. To receive the necessary ETCS data from the line centre, an approval of IL B is necessary. Validation of the locked route is necessary for releasing the data.

2. **Central Database**
   The acquisition of the relevant ETCS data in the line centre requires a high data transport between line centre and IL. The IL acquires a part of the data model in the line centre to reduce data exchange. The modelled data for the dedicated station, including line sections up to the next IL, are sent to the IL. At runtime, the data model is available in the IL to create the necessary packets. Figure 6.28 shows the setup. IL A can only create an MA in station A or up to the home signal of station B. Creating an MA for other areas is not possible.

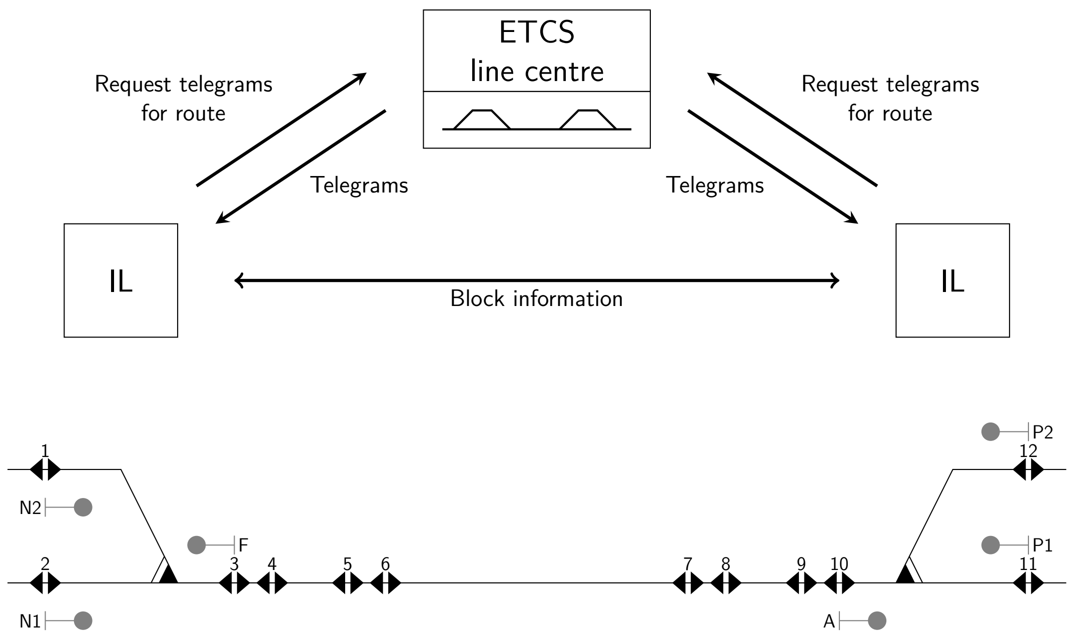


Figure 6.27: Centralised data model.

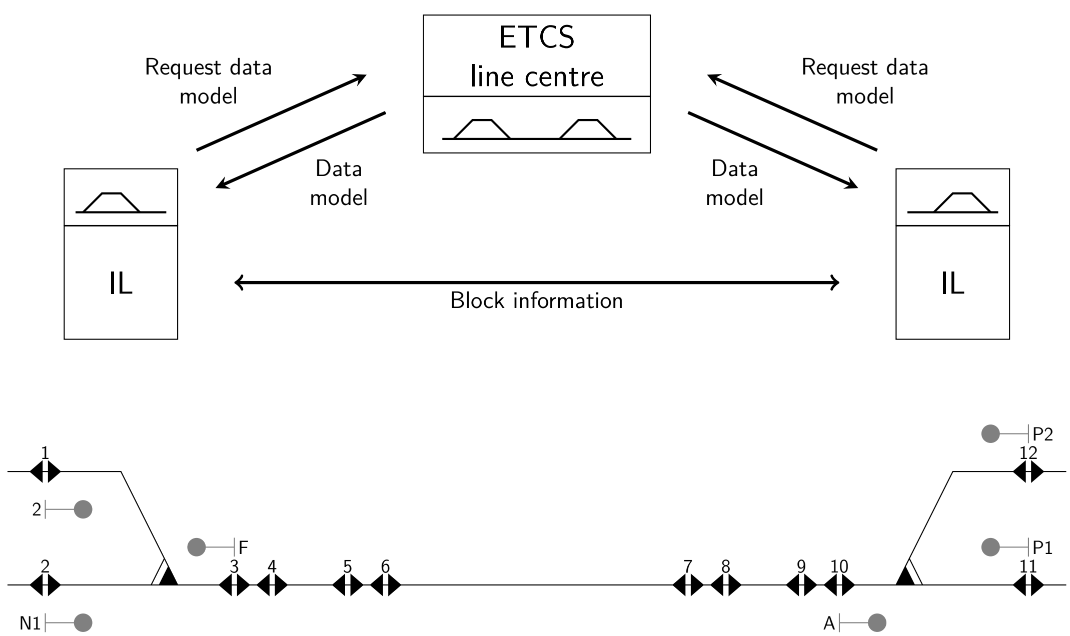


Figure 6.28: Centralised database.

For this setup with lapping models in the adjoining IL, managing the decentral models is necessary. If the ETCS data model is changed, the line centre must inform the relevant IL systems about the change in the data model. The IL must regularly check the model's validity in the line centre to avoid a lost connection to the line centre.

3. **Decentral Database**
Decentral data management bases on data storage in each IL. Each IL has a data model for a fixed area. No models are lapping. The model can cover a whole line between two IL but also a part of the line.

For creating a message, the adjoining IL acquires the relevant data. That is necessary for creating a message up to the home signal of a station. Creating a message for a route in the corresponding IL is also possible.

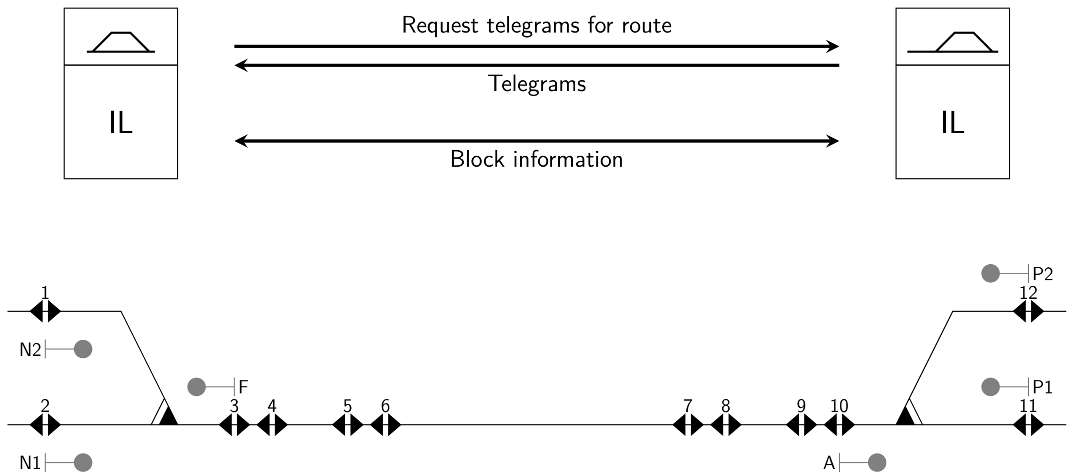


Figure 6.29: Decentralised data model.

IL A acquires ETCS data in IL B for creating messages. The same principle is applied if a block post, respective the corresponding axle counters which separate the several sections on the line, is in between both IL. Figure 6.29 shows this topology without a line centre.

4. **Decentral Data Model**
A complete decentral setup is shown in 6.30. An IL has a data model for a dedicated area like setup no. 3. The difference is the data exchange to adjoining IL: Both IL exchange model data only for a defined intersection. If the intersection is in the middle of a line, both IL have to create a message for one train movement. As presented in 6.30, IL A creates an MA for the area of IL A, and the intersection to IL B. IL B creates the MA from the end of the intersection area up to the home signal of station B.

The data transmission is minimal compared to other setups. A change in a data model is also handled in the intersection area.

Four different setups for data management are outlined. All the presented data management concepts have their advantages and disadvantages.

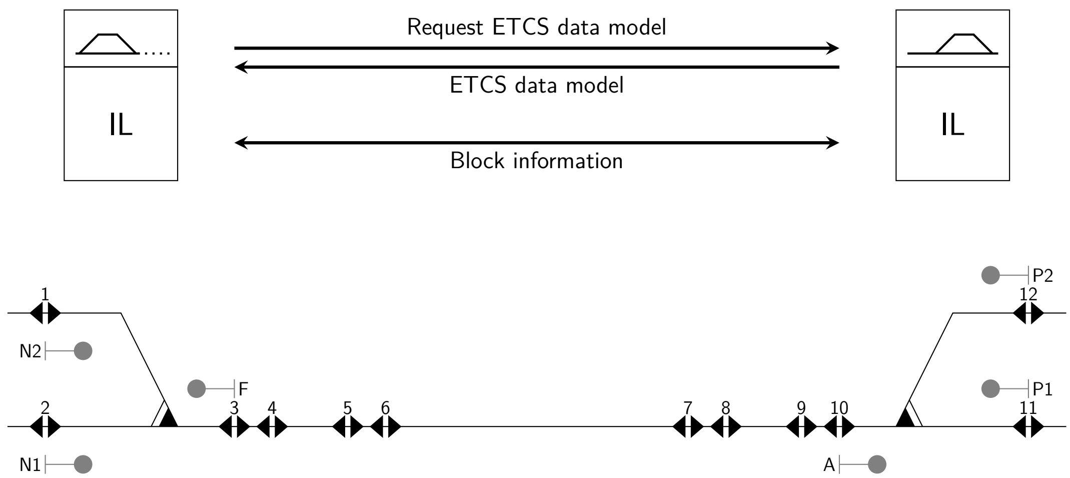


Figure 6.30: Decentralised database.

- Centralised setups require a data link to the line centre. An additional entity of the safety systems is necessary, which is not available today. It is comparable to the RBC, which can cover more IL.
- Decentral setups exchange data between the IL.
- Exchanging a data model reduced the data exchange at runtime of the IL. Therefore it must ensure that a change of the database is transmitted to the distributed model.

This thesis proposes the decentral database because it is close to the current IL architecture, and the data transmission is minimal at runtime. Only the block information exchanges between the IL at runtime, the data model is only exchanged once at runtime or if the data model is changed at runtime.

6.5.3 Transition between Dynamic and Static ETCS

In the previous sections, the exchange of data between different IL is presented. It is assumed that both IL are equipped with the same and new architecture and have an interface to exchange necessary ETCS data. However, there are lines with a common IL and a static ETCS application and an IL with the new architecture for migration.

If a TSR is added to a line, the new architecture will create the telegrams with the new data set. But, the common IL, equipped with a static ETCS Level 1, must change the telegrams inside LEU. This process is not automatised because there is no communication channel from the IL to the LEU, allowing to program the LEU.

Full usage of the presented dynamic ETCS Level 1 application's advantages needs to adopt the common, already with static ETCS equipped IL with an adapter. A block adapter like it is available in common CBI can handle this [130], [131]. This adapter is located in the common IL and realises block information exchange between an IL with the new architecture and a common CBI or previous IL generations. The presented block adapter can connect to the old IL like mechanical and electromechanical IL. Therefore, the block adapter needs a connection to the signal aspect for an adequate evaluation of the block information. For interaction with the new architecture, this block adapter is expanded by an ETCS module, which contains the necessary data for creating profile data of the line. To integrate the dynamic ETCS data into the ETCS equipment, the relevant balise groups are equipped with an additional balise connected to the new block adapter. All relevant ETCS data are projected in this balise. The block adapter needs a connection to the signals and the locked route for the block information. There are no changes necessary for the ETCS integration itself.

Figure 6.31 shows this setup for a station with the dynamic ETCS and the station with a common IL without dynamic ETCS. The balise group in the common IL are expanded with a grey balise which represents the dynamic balise.

The balise group for the exit signals and the home signal are equipped with the additional balise. Two cases are considered:

1. A train stopping at the station.
2. A train running through the station with maximum speed.

For both cases, the dynamic profile data must be available in time. The transmitted data must be available on the train before braking starts. Otherwise, the train enters TR mode. Depending on the transmitted data, two balise in the group would be in most cases sufficient.

Finally, both IL lock the route and created the MA up to the other station's home signal. From the home signal on, each IL takes responsibility.

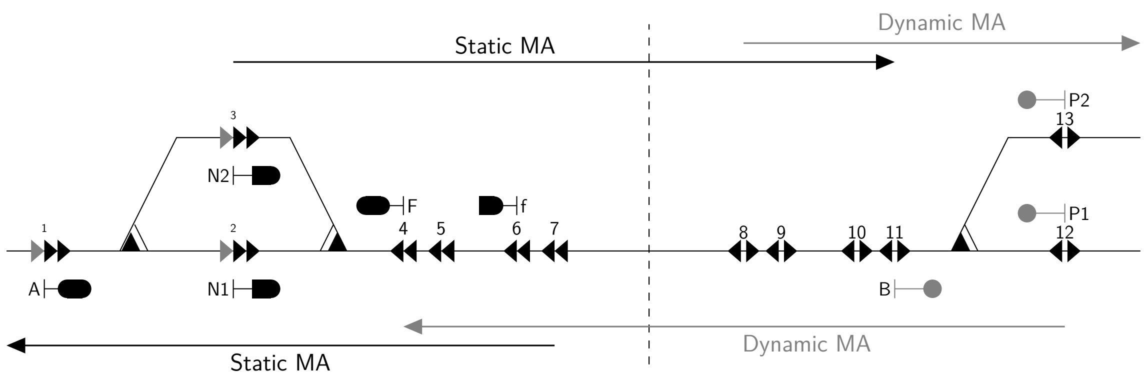


Figure 6.31: Transition from static to dynamic ETCS architecture with supervision gap.

Chapter 7

Impact on Operations

The most important aspect of the new architecture is the impact on operations. Different operational aspects may change due to the presented architecture. The driving time of a train, the headway time on a line and the delay propagation are the common evaluation parameters. Also, an operational impact is seen for LX. The road closing time is an essential parameter for the acceptance of an LX.

7.1 Driving Time

The new architecture offers two principles to reduce driving time. Increasing the track speed and using the exact speed profiles increases the average train speed.

7.1.1 Track and Train Speed

Constructional and signalling issues limit the maximum track speed. In Germany, the limit of track speed exceptional high-speed lines is 160 km/h. As mentioned in chapter 3, this speed limit depends on the train's braking power and the defined distance between the distant signal and the main signal. Cargo trains have a reduced speed due to a lack of braking power [51], [18]. Longer braking distances are necessary, which requires the adjustment of the location of the distant signals. The new architecture allows operating cargo trains at higher speeds due to cab-signalling.

Now, cab-signalling is not depending on trackside signals and the given signal distances. Brake application points are indicated on the DMI and are independent of the transmission of an existing MA upgrade. The distinction between conventional train with ATP basing on trackside signals and high-speed train with ATC is not present in the new architecture. ETCS FS enables this impact. There is no technical reason to limit the speed to 160 km/h due to cab-signalling. Higher track speed leads to a shorter driving time.

Speed [km/h]	160	170	180	190	200
Time [s]	22.5	21.18	20	18.95	18

Table 7.1: Driving time for different line speeds at a distance of 1 km
.

The technical limitation of the line speed to 160 km/h is justified in the Railway Construction and Operations Act (EBO) [22]. This limitation is for trains with discrete ATP systems like PZB. Applying ETCS in mode FS provides continuous supervision of the train, so the rule of the EBO must be questioned. For trains operating in FS with cab-signalling, the limitation to 160 km/h is no longer necessary. The differentiation to the high-speed traffic disappears. However, increasing the permitted speed on existing lines must be evaluated. Constructional boundaries may allow a higher speed. Applying the new architecture can upgrade the line. Commonly, there is not a speed restriction for a new construction line with a speed range between 160 km/h and 200 km/h. No additional safety systems like LZB in Germany are necessary. Applying the same idea to regional lines with a shorter braking distance allows increased line speed. This topic requires an adjustment of the design rules for railway lines.

The impact on the driving time is presented in the following. If a train runs at a constant speed, the travelled distance is calculated to

$$s = \frac{t}{v} \tag{7.1}$$

The resulting times are shown in table 7.1. The impact of a higher line speed is not that much. Increasing the speed by 40 km/h from 160 km/h to 200 km/h reduces the driving time by about 4.5 s and increases the braking distance, but in ETCS, the braking distance is individual for each train and the given national values.

The benefits of an increasing track speed and the new architecture have to be considered against different backgrounds:

- Formerly conventional trains can drive at higher speed on a high-speed line due to cab-signalling. A requirement is the legal admissibility of point-to-point train control systems. The technical and legal realisation is shown in Spain where trains with ETCS Level 1 drive up to 280 km/h.
- Table 7.1 shows the driving time for a distance of 1 km. The longer the line, the greater the time saved.
- Even small time savings can lead to a more stable timetable. A small reduction of the blocking time is important. There are projects to save a few seconds to increase capacity, especially in stations [132].

- ETCS FS removes the distinction between conventional and high-speed lines. Common Class B systems are mostly separated for the conventional network and high-speed lines. Principally, each ETCS equipped train runs on each line equipped with ETCS independent of the maximum speed. Operation in Level 1 or Level 2 FS is similar. Data transmission is different from what requires informing the train driver about a valid MA in the next balise group.
- Also, there is an increase in line speed on regional lines which was limited due to the reduced distant signal distance. If cab-signalling is available due to ETCS Level 1 FS, there is no need to use a reduced distant signal distance. Signals, and especially distant signals, are not necessary.

  Depending on the topology of a reginal line and the settlement area, the distance between stops varies. If the train drives with reduced speed because of the reduced distant signal distance, driving time and perhaps capacity is wasted.

ETCS enables these benefits due to cab-signalling and the continuous supervision, and discrete information transmission from track to train.

7.1.2 Exact Speed Profile

In common ETCS Level 1 applications, the MA is derived from the signal aspect. However, a signal aspect does not indicate the locked route. If many tracks with different signal locations and similar speeds are available, it is not possible to derive the locked route. Only a restrictive MA is transmitted to the train. Even route signalling systems do not indicate the precise target track [19]. Only at block signals and its corresponding MA it is obviously. If different routes of a signal have different length, the transmission of a restrictive MA is necessary. A restrictive speed and length are defined in the MA.

Figure 7.1 shows a station track with four tracks. The point speeds ($60\,{}^{km}/_{h}$ and $65\,{}^{km}/_{h}$) are given in the figure.

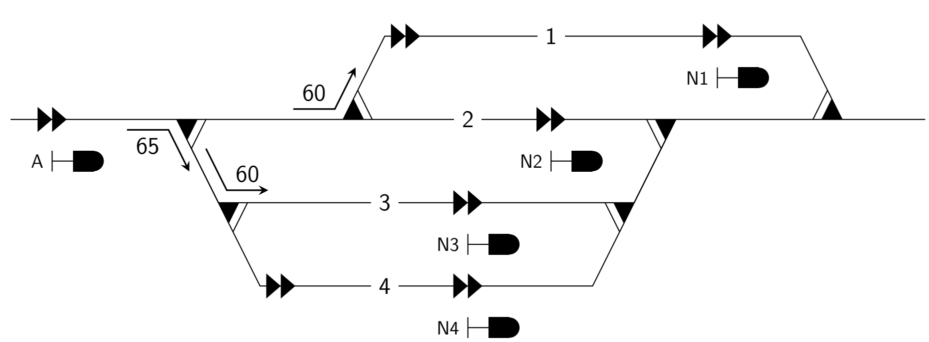


Figure 7.1: Classic MA with repositioning

The point speeds are signalled via ETCS. With trackside signalling, only speeds in multiples of ten are signalled. ETCS allows a more precise signalling. Trackside signalling reduces a theoretical speed of 59 km/h to 50 km/h whereas ETCS reduces the speed to 55 km/h.

Another issue is repositioning. If the train enters track number 1 up to signal *N1*, the MA is defined with a length to reach signal *N3* or *N4*. A repositioning balise in track number 1 changes the length of the MA to reach signal *N1*. If the permitted speed of the point for entering track number 1 would be 80 km/h no repositioning balise is necessary because the signal aspect allows identifying of the route target.

That reduces the train's speed because the On-Board Unit calculates the speed supervision for the reduced length. If the repositioning information is received, the supervision speed is adapted.

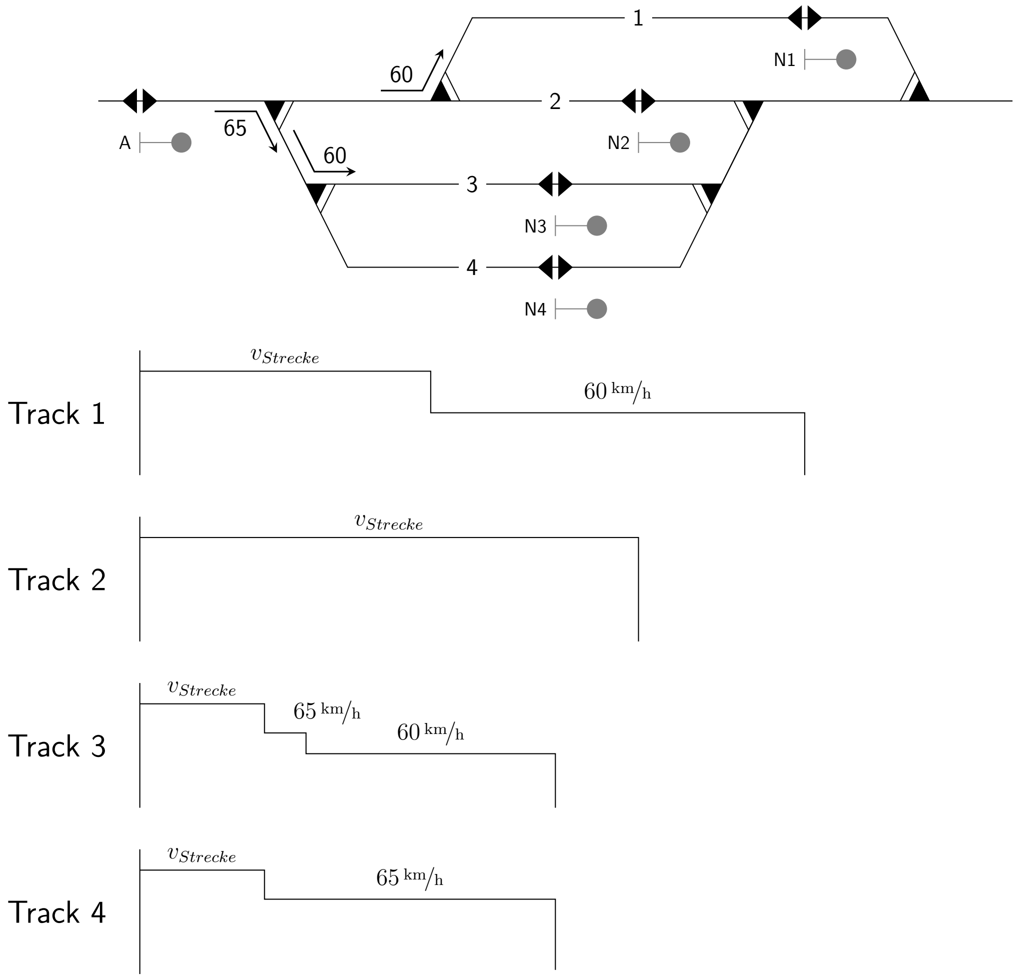


Figure 7.2: Classic MA without repositioning

The ETCS logic of the new architecture knows the locked route. All information about the different route elements is available. The MA is created for each locked route at runtime. Repositioning is unnecessary, and the train's average speed by entering the station is higher than in classic applications. Figure 7.2 shows the different speed profiles for the four entry routes of the sketched station and the restrictive profile for entering track number 1, 3 and 4.

The most significant influence shows the profile for track number 1. The point for entering track number 1 is located behind the first point in the driveway. The first point in the driveway is passed in the straight track, and no speed limit is necessary.

The impact on driving speed depends on the track topology. When entering track number 1, the braking curve starts later by the distance between both points. The impact is high if there are more tracks with the same speed and different target distances. Only one track with a short distance between both signals forces a restrictive MA. That reduces the average speed of the train. Hence, the new architecture creates an individual MA for each route. This MA ends at the dedicated location. The average speed for the entry movement increases [133].

7.1.3 Infill

Infill locations have an impact on capacity. [134] describes the impact of the number of infill locations on the capacity of a point-to-point transmission system. The point-to-point transmission is compared concerning a continuous transmission like ETCS Level 2. A high number of infill locations allows a fast upgrade of the current MA. Hence, the average speed increases because the train accelerates earlier or drives a longer distance with a higher speed. This leads to an increase in capacity. The number of 5 infill locations provide almost the same capacity compared to Level 2 accordingly [134]. It is assumed that the infill locations are located in the braking distance to the EoA. Hence, it is not valid for the whole speed range. This fact depends on the latency of the radio communication system compared to the distance of the infill balise groups in the braking distance. Of course, a higher number of infill locations requires a higher number of balise groups.

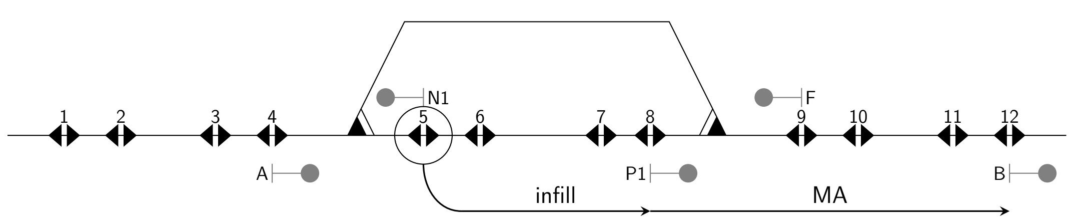


Figure 7.3: Additional Infill balise groups

The new architecture allows using every balise group to transmit telegrams independently from the location. Balise groups dedicated to the opposite direction are used to transmit infill information for the nominal direction. Figure 7.3 shows the setup of a small station. The balise group of signal *P1* is used as an infill location for signal *N1*. This principle can be used at various locations and still in every station. However, it is not limited to stations. On the line, a balise group dedicated to the opposite movement direction is used in the same way.

Additional balise groups for transmitting infill information increases capacity. The upgrade of an MA is performed earlier, and the setup of the line is suitable for more train types with different braking properties. Otherwise, due to the use of existing balise groups, the number of mounted infill balise groups can be reduced because their location is identical or close to the location of the existing balise groups.

7.1.4 Shunting Movements

Not only regular train movements are speed up. Also, shunting movements are speed up due to the new architecture. FS and OS can perform shunting movements. It is not mandatory to use mode SH. If regular shunting movements are processed in SH, the speed is not increased. Hence, regular shunting has no impact on operations. Only safety rises. Using modes like FS or OS needs a connection to a train movement in FS. These are provision movements, for example, and no movements in marshalling yards.

Provision Movement

Provision movements are movements to prepare a train movement. A train is moved from a shunting track, like storage sidings, into a station track. The new architecture knows the exact route for the provision movement, or in general: The shunting movement. If a balise is available, an MA for the provision movement in mode FS is transmitted to the train. Hence, the trainborne ETCS safeguards the train movement, and higher speeds are allowed. Figure 7.4 shows an example of a provision movement. Movement number 1 moves the train from station track 3 into shunting track 11. Opposed, movement number 2 is a provision movement that starts in shunting track 10 and moves the train into station track 2. There, the train run starts, and the train is already in mode FS. This procedure is only possible if the train is travelling in or coming from direction *A*.

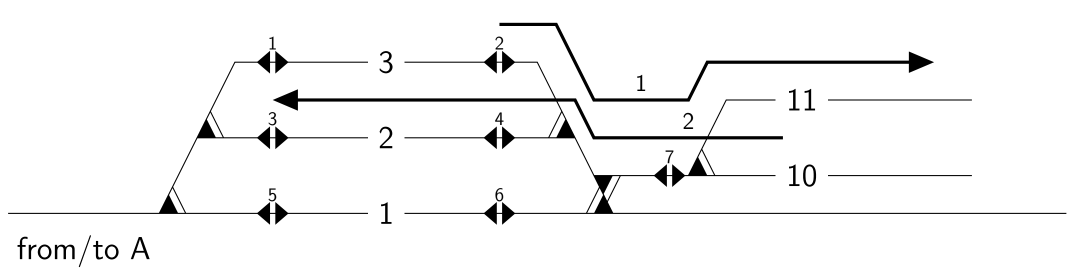


Figure 7.4: Provision movements in a station.

The benefit of these movements is the higher average speed. For provision movement into station track 2, the transition to FS is triggered in the shunting track at balise group 7 or at least in the station track at balise group 4. If the train starts the train run after a stop in the station track for passenger exchange, the train starts driving in mode FS and can accelerate up to the MA speed limit. Driving in mode SR up to the exit signal's balise group exit signal is not necessary to receive the MA and switch to FS.

A movement into the shunting track in FS is processed at a higher speed. The track section travelled on are occupied for shorter periods. That allows locking another route earlier.

Shunting Movements in Marshalling Yards

Movements in marshalling yards and small shunting areas are normally performed in mode SH. This mode limits the shunting speed, e. g. up to 40 km/h, and allows to change the direction. That is not possible in the other modes for train movements. In big marshalling yards, the track length and the distances covered by a locomotive can range from hundred metres up to several kilometres. Figure 7.5 shows a sketch of a shunting area where a train goes around track number 10, and the train needs to change the driving direction.

The train leaves track number 10 with movement 3. After the locomotive is separated from the wagons, the movement is performed in SH. After change of direction, the route for movement 4 is locked. At balise group number 4, the MA is transmitted to the train, and the locomotive enters mode FS.

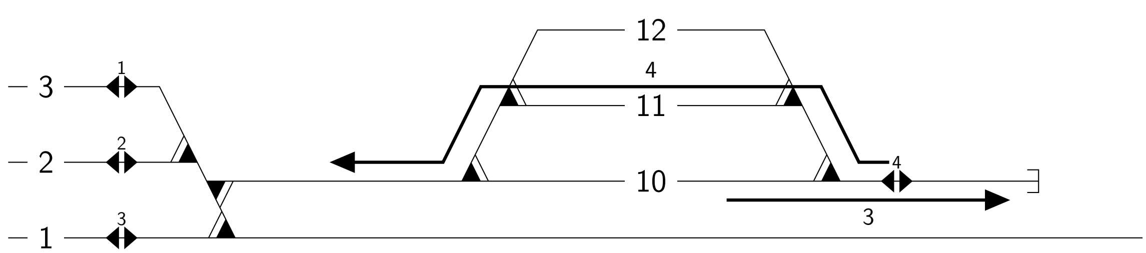


Figure 7.5: Shunting movement in a shunting area.

The new architecture allows performing such long-distance shunting movements in mode FS. Higher speeds are possible, and shunting movements are improved. A drawback is the necessary balise group which must be mounted in the shunting tracks. Furthermore, shunting in FS requires an activated braking system (air pressure). An advantage is only achieved for a single locomotive because the single locomotive enters FS quite fast. Without wagons, a locomotive enters quite fast the mode FS instead of a train with a few hundred metres.

7.2 Headway

The headway describes the temporal distance between two trains. It is defined as the distance between the blocking time stairs of a train pair. The reduction of the block length reduces the driving time in a block section.

The new architecture's advantages and features are presented in relation to the classic ETCS Level 1 setup. That affects the blocking time of a block section in several ways. Table 7.2 and the following list gives an overview of the elements of the blocking time.

- The new architecture affects the speed-depending elements. The exact speed profile of a route increases the average speed of a train. That has a impact on the speed depending elements of the blocking time. Classic speed or route signalling indicates speed restrictions in 10 km/h increments. ETCS offers a 5 km/h increment speed indication.

- The block length has an impact on the blocking time. Reducing the block length reduces the driving time for this block section. Moving block uses the same idea. It bases on infinitesimal small block sections. The new architecture allows to use reduced block length in a Level 1 system due to commanding balise groups immediately from the IL. Conventional IL systems need a well designed signalling system to achieve a reduced block length below braking distance. Classical ETCS Level 1 applications adapt to a signalling system. If the signalling system does not offer reduced block length, classic ETCS Level 1 is not able to add block sections. If the block length cannot be reduced due to the signalling system, in Germany the LZB or ETCS Level 2 is necessary. Hence, cab-signalling must be applied for signalling shorter block sections.

- The route setting and route release time depends on the IL technology. The most limiting element is the point setting time and the parallelisation of point setting. The new architecture's impact on the route locking time and route release time is not analysed in this thesis. It is assumed that there is no significant difference to common CBI. Furthermore, it is assumed that sending an ETCS telegram from IL to the balise group takes more time than sending a signal aspect to the signal. However, this time is neglectable compared to the point setting time.

The headway time increases the number of trains in an operational and technical sense. A reduced headway time allows more trains to run without conflicts. More block sections allow a higher number of train journeys. If the number of trains does not increase, the buffer time increases and improves the timetable stability.

Blocking time element	Speed depending	Operation with trackside signals	cab-signalling	Depending on locking technology
route setting time	-	x	x	x
signal watching time	-	x	-	-
approaching time	x	x	x	-
driving time	x	x	x	-
clearing time	x	x	x	-
route release time	-	x	x	x

Table 7.2: Blocking time and its parameters.

7.2.1 Reducing Blocking Time

Increasing capacity requires a reduction of the blocking time of a block section. A simple way is a reduction of the block length what means adding additional block sections. Blocking time calculation and the related blocking time stairways relies on a train run without delays.

Common block length planning rules rely on the braking distance. The main signal must be indicated by a distant signal to guarantee a train to stop in front of a stop aspect.

The new architecture bases on cab-signalling and does not need trackside signals. A minimum block length which the braking distance can derive is obsolete. Short block sections are well known in *high-performance block systems* to improve the capacity, but an ATC system like ETCS is necessary [12], [13]. Those systems must be able to provide a view over more sections than common ATP systems. It is necessary because braking takes place over more (short) block sections. The new architecture provides this information and can transmit this information in ETCS Level 1 to the train.

Now, the new architecture provides cab-signalling. Implementation of short block sections is possible. Every single track section can be used as a block section. Necessary are balise groups at the end of each dedicated track section.

In a station, the number of block sections increases if the track sections dedicated to the overlap are used as an additional block section.

Figure 7.6 shows the principle of the small block section. This procedure requires a balise group at both ends of a block section. This is an enormous effort and must be considered in the context of the operational requirements.

A short block section reduces the driving time of a block section. The headway time between two trains is reduced, and the capacity increases. Moving block is the infinitesimal reduction of a block length. This principle is not used in this architecture because it relies on trackside train detection. Moving block requires a trainborne train detection and radio

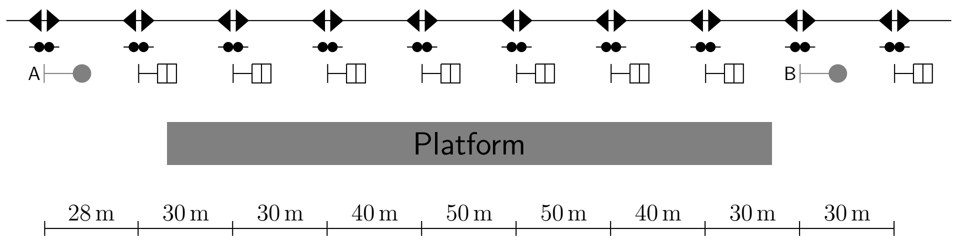


Figure 7.6: Small block sections in a station to increase capacity (according to [135]).

communication between IL and train. Even if the IL is in charge of track vacancy, the train must provide information.

On the line, it is simply possible to reduce the length of block sections and increase their number in parallel. Main lines are normally equipped with signalling equipment for both driving directions. An *opposite movement* is implemented. Block sections for both directions with the necessary train detection equipment is available. However, both block systems (for each direction) are independent of each other. The axle counters for one direction are not used for the other direction.

The new architecture allows usage of the existing axle counters for both directions. Each axle counter limits a block section which is used for both driving directions. The balise group still remain as it is dedicated to the classic setup.

Figure 7.7 shows a part of a line. The regular signals are the signals A, B, L and K. If this location is used for the opposite direction, the balise group is relevant for safety. The train driver needs information about a valid MA in the balise group if the train waits at the EoA. The block section is limited by one axle counter and another axle counter for the overlap in the nominal setup. For each driving direction, two block sections are marked. If the given field components are used dynamically, three block sections result. For the additional block sections, the overlap is set to 0 m. Two premises are that no additional axle counter are used and that the balise position is not changed. This procedure reduces the block length and the headway time.

In a modern IL, a reduction of one of both axle counter is possible. It is assumed that the train in the next block section does not stop immediately after clearing the overlap. If no track section for the overlap is available, a certain distance of the next block section in advance is defined in the MA packet as DP. That is possible if the block section is not clear. Furthermore, using a timer allows defining a certain distance time-dependent, which is used as DP for the MA.

Natural limits of block sections, like points for sidings, can use a similar principle. Normally located on the line, sidings are roughly integrated into the safety system and are operated manually. However, if such a siding is equipped with a simple train detection, a further block section can be defined. There can also be axle counters in stations necessary for train detection but do not limit a block section because the signalling distance

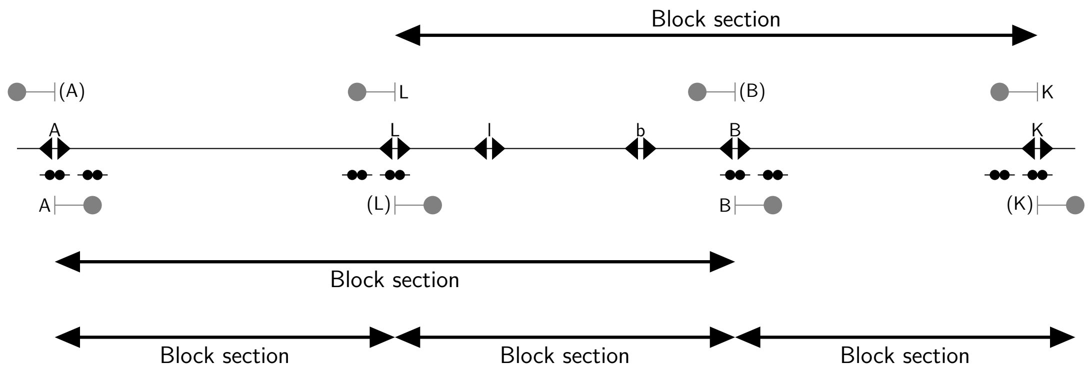


Figure 7.7: Dynamic definition of block sections on a line.

is too short. From a technical point of view, the block section is available. But, from the operational point of view, it is not usable with a trackside signalling system and the common IL.

7.2.2 Level Crossing as Block Post

As presented in chapter 6, axle counters are used to activate an LX instead of common vehicle sensors [110]. Modern bus interfaces between IL and LX allow using the IL's axle counter to activate the LX. Or vice versa: The LX axle counters are connected to the IL. The IL transmits the axle counter information to the LX or triggers the LX directly. The axle counters are always available for the IL, even if the LX is out of operation.

In general, four axle counters are used for one track of an LX – two axle counter for activation and two axle counters for deactivation for each direction. Figure 7.8 shows the setup of such an LX. For each driving direction, two block sections are implemented. Therefore, the axle counters for activation in driving direction and deactivation of the opposite direction are used for the first block section, for example, axle counter at the location of indication signal *A* and *B*. The second block section is defined with the axle counter for deactivation of the opposite moving direction and the axle counter for activation of the opposite moving direction (at indication signal *B* and signal *C*). For the opposite moving direction, the block sections are defined with the axle counters at the locations of the indication signals *F*, *G*, and *H*.

Using an LX as a block post requires special communication to the train driver. This is relevant for the block sections, which ends at the LX location. Signals are used to indicate an available MA in the balise group. If the MA ends at the LX, it is necessary to inform the train driver about the reason. The LX can be in error mode, or the next block section is not clear. This information is necessary for the train driver to decide how to behave at the EoA. If the LX is still open when the train arrives at the LX, it is impossible to

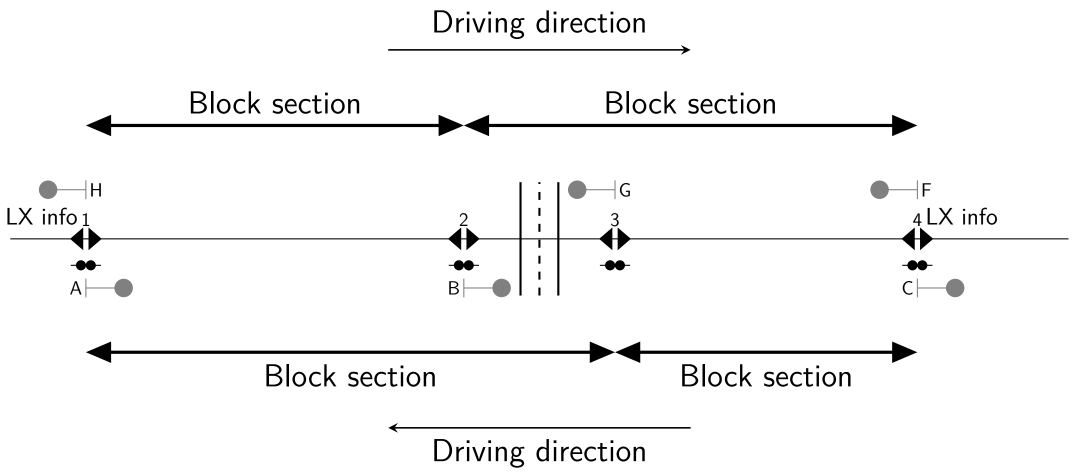


Figure 7.8: Block section due to LX axle counters.

deduct the reason for the stop without additional information. A text message sent to the train driver informs about the reason for the stop if no MA is available.

Following cases must be considered:

- Next block section is free, and LX is protected.
- Next block section is free, and LX is not protected.
- Next block section is occupied, and LX is not protected.

The case that the next block section is occupied and the LX is protected should not be a regular case because that increases the road closing time. If the next block section is not clear, the LX should not be activated. An MA cannot be defined if the block is not free.

The LX as a block post needs balise groups at the end of the block sections to transmit a new MA. These additional balise groups are put on the axle counter locations, for example. Depending on the block length, additional infill balise groups can be necessary.

7.3 Delay Propagation

Delay propagation describes the transfer of a delay from one train to another train. If a train has a delay, the following train may wait in the block section in rear of the delayed train. Depending on the number and length of block sections more, or fewer trains are affected. The delayed train must clear the block section before the following train reaches the braking curve's IP to avoid a delay propagation.

The delay propagation is not a common evaluation parameter but gives information about the stability of a timetable. A measure for robust scheduling is a minimum of delay propagation.

The delay propagation is minimised due to a shorter headway time. That is caused by additional block sections or permissive movement. The realisation of additional block section is simple by using existing track section. Permissive movements are handled in ETCS and allow a train to enter an occupied block track section. The new architecture and its route logic enable locking of a route into an occupied track section. This characteristic results from the interaction between route logic and ETCS logic. If the target track is occupied, the movement is performed in OS. How this affects safety remains to be discussed. Performing train movements with passengers into an occupied track section should no be possible by definition. But a shunting movement into an occupied track sections is a regular movement, which can be depict with ETCS mode OS.

7.3.1 Additional Block Sections

Common route logic and safety principles allow only one train in a block section or a route. If all block sections of a line are occupied with a train, no train can drive because it cannot enter an occupied track. Usually, a schedule is planned without trains waiting at stop signals due to occupied block sections. An exception is permissive train operation what allows a train to pass a signal with stop aspect [136]. Hence, additional block sections are relevant for the schedule to increase the capacity (e. g. S-Bahn Berlin or Hamburg). Also, entering an occupied block section allows reducing the delay.

In stations with classic safety equipment, a train must wait at the block or home signal of a section that is not clear or a route not locked. When a second train waits at another block signal in advance of the home signal, the train needs to drive the whole block length if the block section is cleared.

Figure 7.9 shows a sample station on a single line track. The Danger Points of the home

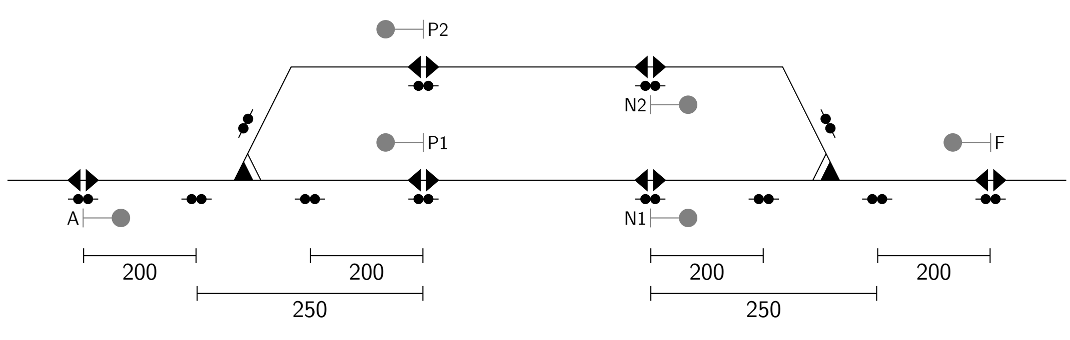


Figure 7.9: Sample station with additional track sections as a waiting position.

signals and the overlap of the exit signals have a length of 200 m. The distance between home signal and exit signal of the opposite direction is 450 m (A and Px or F and Nx).

This section is now defined as an additional block section. If the track section between N1 and P1 is occupied, the route from home signal A up to signal P1 is locked to allow a train to enter the station. The train clears the line, and the following train approaches. After the track section between N1 and P1 is cleared, the train can enter this section. For this approach, no additional components are necessary. Balises and axle counter are available.

In a further step, the overlap of the signal can be used as a block section. A length of the sections of 200 m allows a regular passenger train (length below 200 m) to remain in such a section only. In this setup, each track section is locked as a route with its corresponding MA. Additional balise group are necessary at the location of the axle counter. Hence, more components (balise groups) are used, but more block sections are defined to increase capacity.

Depending on the operating rules and system configuration, these sections are dedicated to the regular train service or degraded operation. However, in case of delays and waiting trains, these sections reduce the waiting time because more sections are available. The distance between waiting trains is reduced leading to a reduction of the travel time between the waiting locations (block sections). Using these sections in regular operation requires additional signals or rules to enter the target track if the track is empty. Otherwise, communication between dispatcher and train driver gives the signal to enter the target track.

The advantage of this procedure is a reduced delay propagation. That leads to a more robust schedule.

7.3.2 Permissive Movements

The previous section presents the usage of additional block sections for a reduction of delay propagation. A further method to reduce the delay is permissive driving [136]. In common systems, the train is allowed to enter an occupied track section if the signal is equipped with a dedicated sign (e. g. caution signal). This procedure is applied to block signals. ETCS supports that operation by using mode OS. In [137], the use of OS in Level 2 is explained. For this purpose, trackside signals are equipped with an additional signal aspect indicating permissive driving. ETCS evaluates this aspect and creates the MA in mode OS.

The new architecture enables more flexible use of OS and the principle of permissive driving. Common permissive movements are dedicated to block sections. Now, permissive movements are considered to enter a station track which is occupied. In means to capacity, this track is similar to a block section, even if it is in a station. This requires that the route logic allows locking a route into an occupied track section. The ETCS logic creates the MA in mode OS because otherwise, a movement is not possible. This advantage results from the interaction between route logic and ETCS logic.

The responsibility for train safety is handed to the train driver. If a train is allowed to enter an occupied track, the remaining travel distance is shortened after the train ahead has left the corresponding section.

A high benefit is achieved in station tracks with a scheduled stop for passenger exchange. The first train stays at the platform track and waits for the clearing of the exit signal. Meanwhile, the following train can enter the track section permissively. Because of a reduced speed, the following train stops behind the first train. After the first train has left the track section, the following train is allowed to move the train forward. If both trains fit into the track section, other trains can regularly occupy the previous track section. A train waiting to enter a station rides slowly into the station. The train leaves the station if the route is locked.

Figure 7.10 show an example of a track section with two trains. This procedure impacts

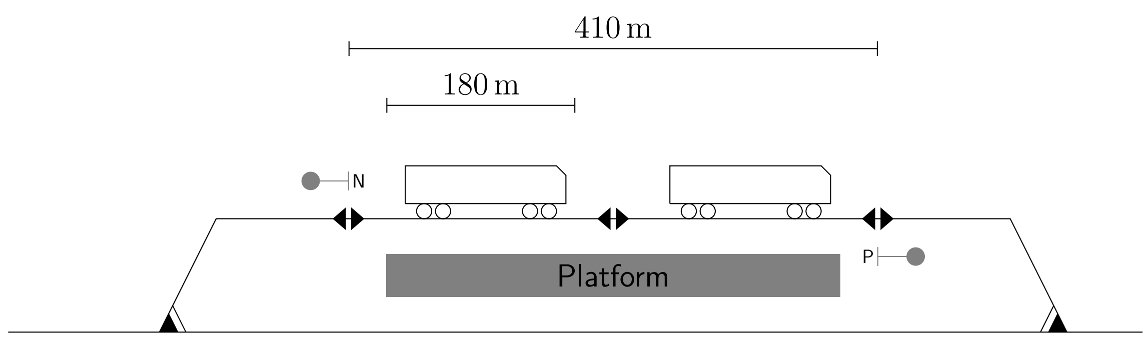


Figure 7.10: Entering a track section permissively to reduce delays.

if the previous track section is cleared and a further train uses this section to reduce a delay. Otherwise, there is no impact on operations. If a station is designed for cargo trains, the usable track length is close to 800 m. A passenger train may wait for a few hundred meters in rear of the home signal to reach the platform. OS allows reducing the distance to a minimum. A safety distance of about 50 m to 100 m should be considered, but it is still an operating rule, and not safeguarded by ETCS. The impact is the highest if both trains fit into the track section and a third train can drive up to the home signal.

If the train runs directly into the track section in mode OS, braking behind the start signal to a standstill is not necessary. Braking is delayed to a maximum to drive longer at a higher speed.

7.4 Level Crossing Closing Time

The road closing time is essential to ensure safety at an LX. The higher the road closing time, the higher the probability of trespassing the LX. This section describes some procedures to reduce the road closing time. The new architecture enables different features to activate the LX. A speed depending activation is a simple measure to adjust the activation to a running train. However, a stop in the strike-in section can be handled by a speed restriction.

7.4.1 Speed Depending Activation

Approach section design refers to the maximum speed allowed on the line. For slow trains, freight services or slow passenger trains e. g., the road closing time extends. The acceptance of railway systems may suffer from these long closing times. Activation of the LX by a time delay due to the train speed is an option. That allows adjusting the road closing time.

With classic ATP systems, it is not possible to shape speed-depending activation solidly. If the trains' speed is considered to activate an LX, a wrong estimated speed may lead to hazardous situations. Speed measuring is an option but if a speed is measured, the train is not allowed to accelerate.

To implement a speed depending activation, an axle counter for each activation speed is necessary. A further option is a delayed activation. After passing the axle counter (dedicated to nominal speed), the activation of the LX starts with a defined delay for the corresponding speed.

The speed can be measured or taken from management systems like a TMS e. g. If a reduced speed is measured and a corresponding activation point or delay is selected, no increase in speed is allowed. If the speed increases, the LX is closed too late.

ETCS allows limiting the train speed by changing the SSP or defining a TSR in the approach distance to the LX. The train driver can notice the speed limit visualised on the DMI. The new architecture allows selecting an activation point for the train. When a single activation point is used, this must be the activation point for the maximum speed. Reducing the road closing time requires a delayed activation of the LX. Figure 7.11 shows the setup to activate the LX speed-dependingly. The LX is designed for a maximum speed of 100 km/h. If a train with 80 km/h our 60 km/h approaches, a further activation point is selected, or a delay is applied for activation. Calculating a delay allows a flexible and optimal activation for the current speed.

The speed of the train can be measured or derived from the train number or other management systems. These systems are no safety systems, and the data must not be valid. Two cases are considered:

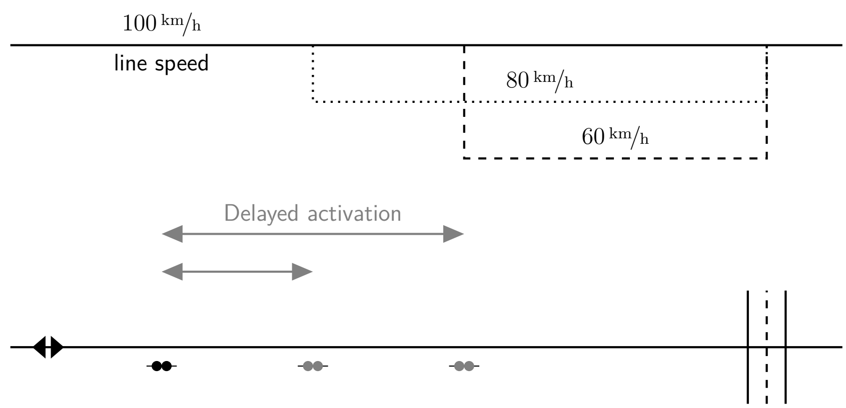


Figure 7.11: Speed depending activation of an LX

1. The given speed limit to pass the strike-in distance of the LX is **lower** than the actual or maximum train speed:
   The train slows down to the given permitted speed limit transmitted via ETCS. The road closing time is optimal for the given train speed, but the train drives with a reduced speed.

2. The given speed limit to pass the strike-in distance of the LX is **higher** than the actual or maximum train speed:
   The road closing time is estimated for a faster driving train. Hence, the road closing time is not optimal for a slower driving train because the LX closes earlier.

Both cases are not safety-critical. In each case, the maximum permitted speed is limited by ETCS. No higher speeds are possible. The single drawback is the longer road closing time. Principally, the road closing time is optimised for most cases what improves the LX operation and leads to a higher acceptance due to shorter road closing time.

The train can send its speed properties to the IL if communication from train to track is possible. If the train provides its speed properties and the information is accurate, no interfaces to non-safety systems are necessary.

7.4.2 Stop Depending Activation

In some LX applications, a stop in strike-in distance occurs, which massively extends the closing time for the road. For these particular applications, specific operational cases are defined.

If the road closing time is too long, the LX must be equipped with a full closure of the road. That case is often linked to a stop or a block signal in the approach section.

Scheduled Stop in the Strike-in Section

A scheduled stop of some trains in the strike-in distance extends the road closing time. For trains driving through with the maximum speed, the road closing time is activated suitable. However, if the train stops in the strike-in section, the time for braking, acceleration and standing/waiting (dwell time) are added to the road closing time. The acceptance of an LX is reduced if the road closing time is extended, and the road user must wait too long without seeing a train driving. To reduce the road closing time, the activation of an LX must match with the stop of a train. Therefore, a second train detector to activate a time is necessary, delaying the activation using the scheduled stop. Target is an optimised activation of the LX.

Figure 7.12 shows the setup of an LX with a stop in the strike-in section. Two speed profiles are sketched: A stop in the strike-in distance, and the case for a not protected LX. For the stop in braking distance, the existing MA is given up to the stop location. In the sketched example, this is the platform. A balise is located at the dedicated stop location. This balise group transmits a new MA to the train and, in this case, a TSR, which limits the speed. The activation point is located in advance of the stop location. Hence, the train can activate the LX after stopping. The TSR is defined for the trains' acceleration and braking properties and the remaining distance to the LX. To guarantee that the train arrives at the LX, the speed must be limited. That depends on the different local conditions.

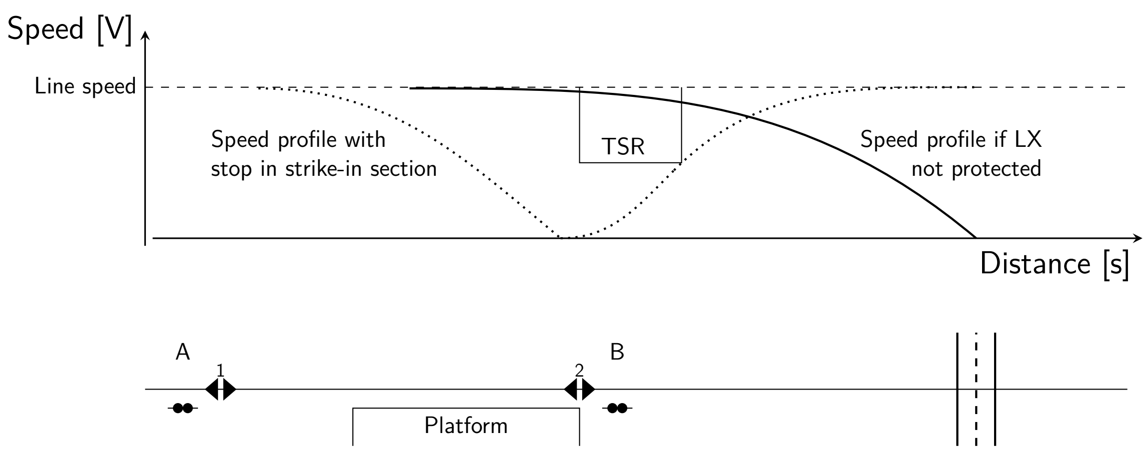


Figure 7.12: Stop in the strike-in section of a level crossing.

Block Section in the Strike-in Section

Similar to a stop in the strike-in section, there is a similar setup with border of a block section in the strike-in section. Due to an occupied block section, the MA ends in the approach section of the LX. Handling such situations requires considering different setups. Figure 7.13 shows the relevant components for the setup and the operational cases.

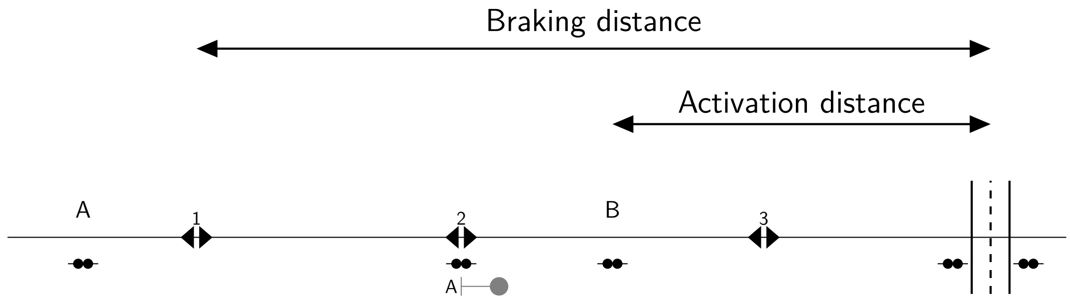


Figure 7.13: Setup of a block border in the approach section.

If signal *A* is cleared, the LX is activated at axle counter *A* or *B*. Which axle counter is selected is depending on the operational case. The LX can be operated as a route depending LX (axle counter A) or as an autonomous LX without feedback (axle counter B). For both cases, the information of the protection state is transmitted at balise group 1.

In the case that signal *A* is not cleared, the train stops in rear of the signal. The LX is not activated at axle counter *A*. Now, there are different procedures to activate the LX. It depends on the given distances. Here, it is only described qualitatively. The axle counter A in advance of the signal is used for activating the LX if the signal is cleared. If the signal shows the stop aspect, axle counter B triggers the activation of the LX. But, locking the block route can trigger the activation of the LX if there is no axle counter B. If the LX is activated by locking the route, the LX protection state is transmitted in balise group 2. If axle counter B is used for activation, balise group 3 transmits the information.

In general, ETCS can avoid such setups because the signal location can be changed quite simple. There are no restraints concerning braking distances etc. Only operational demands for an optimal block length may lead to such setups.

7.5 Fall-back Operation

Most technical systems have higher reliability than humans. That is one reason for the introduction of safety systems. Technical systems ensure a 1.000 times lower probability of failures [138]. The fewer failures occur, the less hazardous situations reveal. If a failure occurs, entering a safe state is necessary. Because the railway is a transport system, standstill is a safe condition (exeption: If a fire breaks out in a tunnel, the train must keep moving.). Thereforee, in the case of a fatal error, the trains are stopped.

Errors in railway safety systems cause delays in railway operation. The higher the traffic density, the greater the delay transmission. To operate trains in case of an error, a fall-back mode is defined, which allows a degraded operation [139].

Fall-back operation is used in different cases to operate trains (examples):

- Technical error of
  - trackside safety systems like ETCS, IL or LX
  - the trainborne ETCS equipment itself
  - further equipment not connected to the safety systems
- Operational issues like
  - a closed track or line
  - a misdirection of a train

The aim of fall-back operation is to reduce the impact on the schedule and reduce delays.

This thesis deals with cases where the train still runs with ETCS. The errors are considered from the point of view of the dispatcher. This affects operational cases as well as technical errors at the trackside safety system. It is assumed that the route logic and ETCS logic are not affected and operating properly.

The new architecture allows using the ETCS modes to safeguard train movements in a degraded mode. Routes are locked, and ETCS telegrams are created if the conditions allow an ETCS movement.

Modern safety systems can bypass the error by an action of the dispatcher [48], [140]. In this case, the controller takes responsibility for the occurred error. Locking a route is an example to illustrate the principle. The IL checks all conditions which are necessary for a route. If a point has a failure, the route is not locked. There are different states where the locking process can stop. The dispatcher checks the error, which inhibits the locking. By a particular input, the dispatcher confirms the error. This enables whole route supervision, which allows using a substitution signal or a caution signal.

These signals indicate *proceed* to the train driver. Further movements or errors require a voice order from dispatcher to the train driver. In [141], the differences between a substitution signal and a caution signal are outlined. The substitution signal bypasses the safety systems and hands over the responsibility to the dispatcher. Opposed, the caution signal hands over the responsibility to the train driver, which is in charge to supervise the path of the train.

The new ETCS architecture provides methods to perform a safe train movement in case of an error. These procedures are described in this section.

7.5.1 Auxiliary Movement in Full Supervision

The ETCS algorithm creates an ETCS message if the route is locked. That is the usual procedure. However, in fall-back mode, creating an ETCS message can be forced by the controller. This replaces the voice transmission of an order from the dispatcher to the train driver. The driveway is defined, and the MA is transmitted to the train. Like using an auxiliary or caution signal, the train should be in rear of the signal. From the IL's point of view, the track section in rear of the EoA must be occupied (with the train). The dispatcher selects the balise group, which transmits the MA for the degraded mode.

In common systems with trackside signalling, the Class B ATP system cannot be used without the signalling systems. The new architecture allows creating a valid MA if the controller checks the track conditions and bypasses the IL. Oral transmission and the bypass of the Class B ATP system is not necessary. The trainborne safeguarding systems will also work in case of an error in the route locking process.

Operating rules to reduce the speed can be applied and used in the IL. If an MA is created, the speed is reduced for the first train movement after the error occurs. Such a rule is proposed by Pachl and described in [142]. After the first train movement with reduced speed (on-site), the trains drive at normal speed.

As a general statement, trains drive in case of an error in the route logic supervised by ETCS. A bypass of the ETCS is not necessary.

7.5.2 Auxiliary Movement in On Sight

If the error requires attention from the train driver, the IL orders mode OS, and the train driver is forced to commit the change of mode. Otherwise, the emergency brakes are commanded. OS indicates an occupied track section that puts the responsibility on the train driver and requires observation of the driveway. This is similar to a caution signal aspect. The new architecture allows reducing the area for driving in OS to a minimum length. The IL identifies the issue in the dedicated route, and the ETCS logic defines the profile data and enables the switch to OS. A text message can send information about the issue in the driveway to sensitise the train driver.

Figure 7.14 shows this principle. The train is waiting in the station track in rear of signal *N2*. The route is not locked because the track section of the point is not clear. The controller bypasses the track section but cannot prove the occupancy to allow a movement FS. Therefore, the IL only permits an MA in mode OS from signal *A* to a certain element. If the train passes the element and the further route sections are locked correctly, the train switches to FS and the train drives without interruptions.

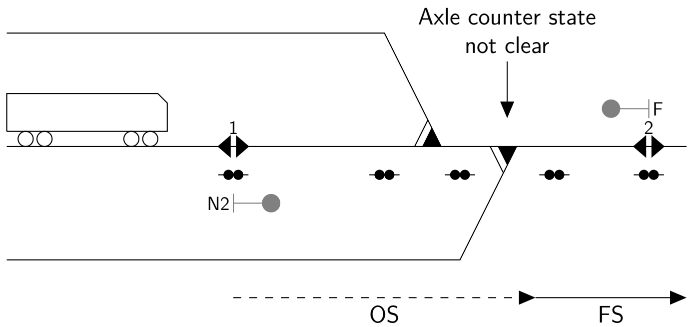


Figure 7.14: MA in fall-back mode in OS.

7.5.3 LX Chains in Error Mode

If further LX are located within an LX approach distance, these are merged to a LX chain. A single activation point is used to activate all concatenated LX. In classic applications, it is a big issue if one of these LX has a malfunction. The train driver is not able to identify the disrupted LX. A stop at each LX is necessary because no information about the disrupted LX is available. The SCI-LX interface allows identifying the disrupted LX by its assigned ID so that packet 88 can be used to inform the train driver about the relevant LX malfunction. The train driver does not need to stop at each LX of the chain but stops only at the disrupted LX. The described procedure has no impact on the regular train service. There is an impact on the operational quality only in case of a disturbance. For the road side, there is a significant impact on the road closing time.

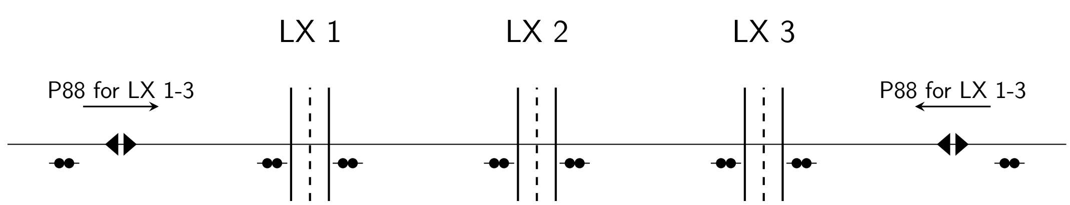


Figure 7.15: Improved handling of level crossing chains.

Figure 7.15 shows three LX connected to an LX chain. If LX number 3 is in error mode and a train approaches from the left, a stop at both other LX is necessary in the old architecture. With the new architecture, a stop is only necessary at the disrupted LX. Calculation of the degraded driving time for stopping at all LX within the chain determines the resulting delay. If only a stop at the disrupted LX is necessary, the delay is reduced to a minimum.

7.5.4 Opposite Track Movements

The new architecture offers an improved operation for movements on the opposite track. Signals are only acting in a dedicated direction. Hence, on common lines, separate signalling equipment is necessary. The balises have no dedicated direction, so the available balise groups are also used for movements in the opposite direction. The available axle counters of the nominal direction are also used to define block sections of the opposite direction. And vice versa, the axle counters for the opposite movement direction are used for the nominal direction.

This procedure enables different features for the opposite movement. Following benefits result:

- Reduced headway for train operation in the opposite movement direction.
- Driving trains as a bundle in the degraded mode. This is enabled by the higher number of block sections and the resulting reduced headway.
- Higher capacity for degraded operation with opposite movement.

These features arise without additional trackside components. Only available axle counters and balise groups are used. However, if the resulting capacity is not sufficient, additional components can be installed, of course.

7.6 Emergency Stop

Common operating rules state the necessity of an emergency stop function [143]. A transport system's safe state is standstill (exeption: If a fire breaks out in a tunnel, the train must keep moving.). In this case, the system has no energy, and the probability of damage is very low. Trains are stopped to avoid collisions in hazardous situations.

Today, most emergency stop calls are implemented by a voice call via train radio. The dispatcher must call a train or all trains on the line (group call) to send the emergence stop message. A train driver must stop the train immediately, even if the message was not understandable. [144]

Most common ATP systems (with punctual data transmission) do not stop a train in these situations. In general, these systems are connected to the trackside signals. Hence, it is only possible to stop a train at the signal location but not at every random location. Continuous ATC systems have a permanent communication link to the train. It is possible to send a braking command to the train. This can be a special emergency braking command or a new target speed that forces the train to stop. In the German LZB, an emergency stop is implemented. Although ETCS Level 2 can stop a train in the same way. ETCS Level 2 offers a special message to send an emergency stop to the train.

Transmitting information about an emergency stop on regional lines is performed by the dispatcher manually. A common IL does not trigger the emergency call. It is only possible with modern systems and continuous communication like ETCS Level 2 or LZB. Now, the new architecture allows to stop the train in case of an emergency at each balise group and not only at the balise group connected to the main signals. The IL sends a restrictive message if a crucial situation is detected in the route logic. That will stop the train earlier than a dispatcher, who must recognise this situation and call the involved train drivers.

Common emergency stops are transmitted without regard to transmission safety. The dispatcher is responsible for selecting the correct train or the correct line. There is no technical device that supports the dispatcher. The new architecture allows sending the emergence stop order via the safe ATP systems. The route logic or ETCS logic allows integrating supervision functions to detect hazardous situations and generate necessary messages depending on the situation. Such a detection is a common supervision of the locked route and its elements. If a track section changes its state from free to occupied, and this change is not caused by the dedicated train, a hazardous situation is assumed. Hence, the train is stopped with an emergency stop. This technical feature assists the dispatcher. The IL can send automated emergency stop messages if a hazardous situation is detected. However, the dispatcher can trigger a manual emergency message if situations occur that are not detected by the IL safety logic.

The new architecture commands every balise individually. An emergency stop order can be transmitted at every balise. In the current specification (SUBSET 26), a packet for an emergence stop order for Level 1 is not defined. Different packets that stop a train (in all relevant modes) must be transmitted to enable an emergency stop. In 6.4.2 the flank protection is described. The procedure of stopping a moving train is still the same as flank protection. A restrictive message is sent to the train in both cases, which yields to command the emergency brake.

A future version of the SRS can add a special message for an emergency stop order in Level 1. Similar to the emergency stop order for Level 2 and Level 3. Since there are other methods to stop a train, a change of the SUBSET is not necessary for the new architecture.

The balise based emergency call solves radio coverage issues on lines with missing or no sufficient radio coverage. A train will stop at each balise group and not only at the main signal where the MA is transmitted in classic ETCS Level 1 applications. Hence, the formerly as infill defined balise group allows stoping a train. An emergency stop message transmission via balise groups helps to reach the trains independently of a human reaction. However, a message via train radio should be mandatory to inform the train driver about the emergency stop. If the emergence stop is not triggered via balise, the train driver can trigger the emergency stop.

It is not the aim to make the emergence call safe with means to operational safety. Furthermore, existing technical systems should expand the classic voice transmission. The involved people are exonerated if the technical systems detect hazardous situations and generate relevant emergency messages independently. The dispatcher is still able to send an emergence stop manually. Only the additional technical way is offered as an additional feature.

7.7 Expanded Train Length

Infrastructure limits the maximum length of trains. That is due to the usable length of the station tracks and the length of passing tracks, for example [145]. These design parameters are defined by the infrastructure manager, the DB Netz AG, for example. Hence, a change of the maximum train length in an existing network is not that simple.

The benefit of a longer train length is increased efficiency. The longer the train, the more goods or passengers are transported. With SHIFT2RAIL, an essential program to shift cargo transport from road to rail is established [146]. A longer train has a lower capacity consumption than two single trains running.

The new architecture offers a method to expand the usable length of a track. The route logic allows defining the route-target individually. Figure 7.16 shows a stations's classic IL equipment with signals, axle counters, and the balise groups. The overlap and danger point distances are shown. The usable track length is the track section between both exit signal. The signals realise flank protection for routes into the other track. Track sections for the overlap and danger point cannot be used by a waiting train. Balise groups are placed at the signals, where the information is picked up.

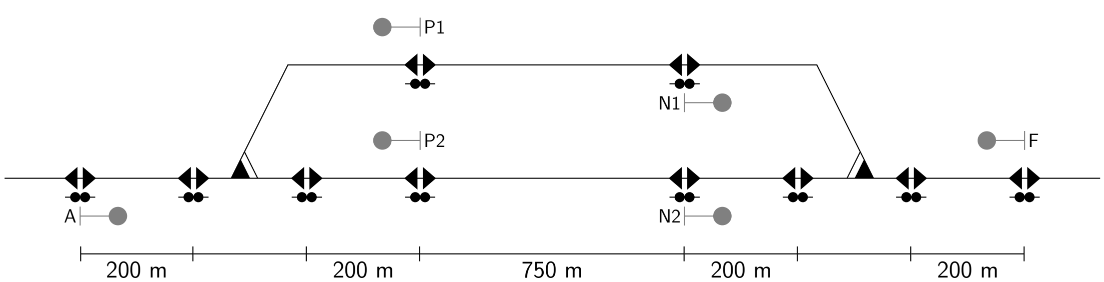


Figure 7.16: Potential to enable longer track sections.

Figure 7.17 shows the same station's setup with signal and balise group location for the new architecture. The track sections are not shown because the infrastructure's upgrading is presented and not new planning of a station. For ETCS trains, the balise group realise flank protection. If additional balise groups are placed at the end of the overlap, the overlap length can be added to the usable track length. In figure 7.17, the additional balise group are sketched. The usable length of the track sections is expanded to about 400 m (200 m overlapassumed).

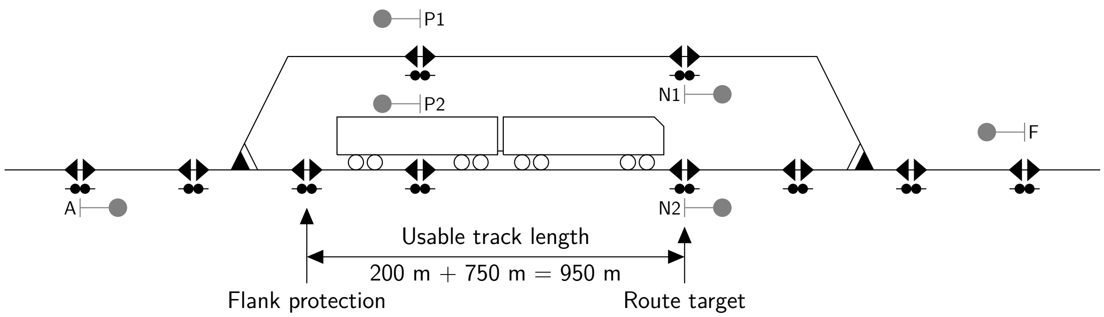


Figure 7.17: Example to run longer trains.

For the presented example, a train with a length of 950 m can use this station track. In this case, only one track section dedicated to the overlap is used. Taking the overlap of the opposite signal into account, a usable length of 1150 m results. It is possible to define an MA with a length of the overlap of 0 m.

As presented, the new architecture offers a smart method to expand the usable track length. If the MA for an entry route is locked without a DP, the speed supervision is more restrictive than an MA with a DP. Increasing the maximum train length is possible for the available overlaps and the dedicated track section. Otherwise, the location of points must be adjusted, which requires not only constructional measures. With the new architecture, the constructional measures are reduced to a minimum.

Compared to a classic IL, on a given infrastructure, only additional balise groups are necessary. Additional indication signals must be considered to inform the train driver about a locked exit route. If this procedure is not dedicated for regular operation, the dispatcher's manual information via train radio is possible. Then, the train driver gets an order to start the train movement if the train waits at an EoA without an indication signal.

Estimating the tack length requires to consider the number of balises in a balise group. Balise groups with more than one balise have a specific length between the single balises. If a minimum distance of 1.3 m is assumed, the usable track length must be reduced to this length or the balise groups' resulting length.

7.8 Integration of Sidings

Sidings are roughly integrated into the classic line topology [147]. Service movements to a siding are a special movement that is not safeguarded by a safety system. Safety is implemented rule-based without technical systems. The employees are responsible for safety. An ATP system limits the train speed but does not safeguard the track. A route is not locked, and the block systems without track vacancy detection do not work for such movements. Modern block systems with track vacancy detection allow protecting the train in the block sections. Stopping at the siding is not supervised as well as entering the siding.

A classic service movement to a siding starts in a station. The corresponding line is closed for regular train movements while the service movement is in progress. This is necessary if the classic block system is not working for this movement.

The new architecture allows a smart integration of the siding into the line topology. The siding is equipped with an IL and is an operating post like a block or a station. Trains can start and end in a siding.

From the technical point of view, only a few axle counters for the TDS of the points are necessary, one balise group, and the points. The new architecture allows the integration of the siding as a block without any additional components.

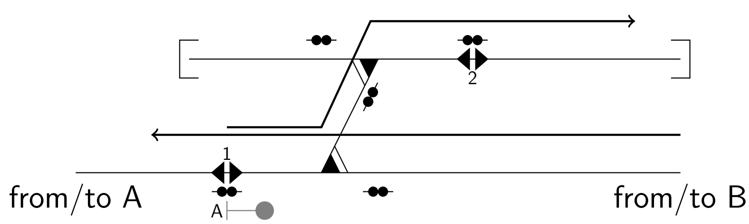


Figure 7.18: Integration of sidings with the new architecture.

Figure 7.18 shows a sketch of such an equipped siding.

Track vacancy detection is implemented for both points. For ETCS, two balise groups are used:

- Balise group 1 transmits the telegrams for entering the station.
- Balise group 2 transmits the telegrams for a movement that starts in the siding and leads to the line.

Balise group 2 is optional because balise group 1 transmits the MA for entering and leaving the siding. If both balise groups are located next to both points, only the balise group on the line is necessary. Transmitting the MA on balise group group 1 does not change operation significantly if a train leaves the siding.

Regarding figure 7.18: A train arrives from direction B to the siding. The train stops with its whole length in advance of balise group 1. The MA was defined in the corresponding station and ends at an appropriate distance in advance of balise group 1.

The train changes the direction and enters the siding in mode SR or SH. Entering mode FS is not suitable because the whole train must pass the balise group, and then, the train is already in the siding. Balise group 1 commands the train to mode SH if the points are locked.

In figure 7.19, the train approached from direction A. The MA ends at balise group 1. Entering in mode FS is possible because no change of direction is necessary. After locking the route for entering, the signal indicates the available MA in the balise group.

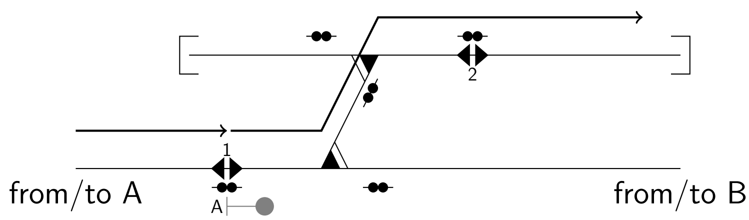


Figure 7.19: Integration of sidings with the new architecture.

Leaving of the siding is similar. Instead of installing a signal in the siding, a local operating panel or voice communication to the dispatcher is suitable for starting the train service. If the train heads to direction A, balise group number 1 transmits the MA. If direction B is the preferred target, the train moves in mode SH or SR onto the line and changes direction. Then, balise group 1 transmits the MA to the train.

The expenses for the technical equipment of such a siding are low. Signals are not necessary what reduces the number of components. However, a signal still allows adding a block section to the line. Without using additional axle counter because they are still available for the siding.

Finally, there are three reasons for technical integration of sidings:

1. The new architecture allows a smart integration of the siding into the line topology.
2. In the context of automated driving, operation without trackside signals and complete supervision is necessary.
3. Efficient integration of sidings is mandatory to increase cargo transport and a shift to rail of cargo transport.

7.9 Portion Working

Portion working describes coupling and separation of trains for a part of a route. In classic IL systems, this operational concept requires a track section to couple both trains. Hence, the operationally critical process is coupling and not separation. For coupling, both trains must enter a station track safely. Therefore, the track is distinguished at least in two track sections. The first train enters the track section normally. No other trains or occupied track sections inhibit the train movement. The second train enters the additional track section to couple with the first train. This track section is not occupied with a vehicle so that the IL can lock a route. No overlap is available because the track section is occupied with the first train. The speed is reduced to e. g. 20 km/h or 30 km/h. Figure 7.20 shows this setup. For enabling coupling, an additional axle counter is necessary and additional signals to separate the track sections.

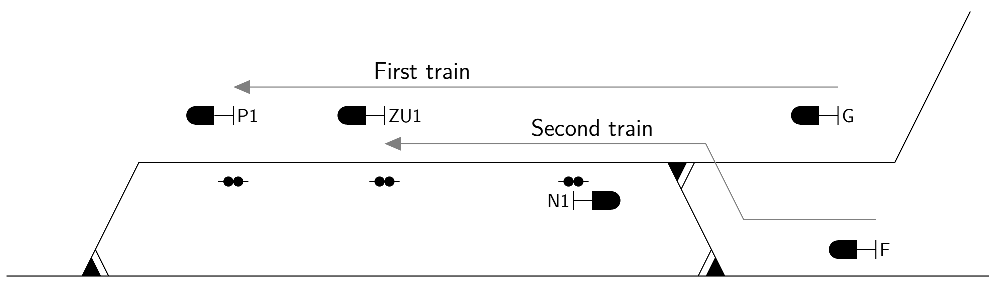


Figure 7.20: Common setup for portion working.

ETCS allows a simplified process for coupling: No additional track sections are necessary because ETCS operating modes and the MA's dynamic definition protect the trains. Figure 7.21 shows the setup. The track section is not separated. The first train enters the station track in mode FS. There is no difference compared to the classic coupling process. The second train receives an MA which ends in the middle of the track, for example. Also, the train length of the first train is considered for calculating the MA. Additional to the MA, the mode of the train run is changed to OS. The IL can lock a route into an occupied track section. Hence, mode OS is mandatory because of the occupied track section. If the OS speed limit is 40 km/h, an additional TSR can reduce the speed to 20 km/h if required by the infrastructure manager and justified in the operating rules.

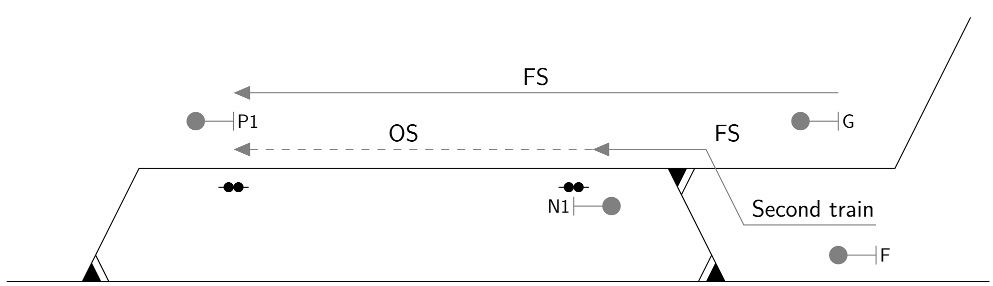


Figure 7.21: Portion working with a dynamic ETCS.

The advantage of portion working is

- the reduced number of devices,
- the simple implementation in each track if the length is suitable, and
- the software-driven implementation without additional hardware. The necessary components are available for regular service.

Chapter 8

Capacity Analysis

The capacity of a network depends on the infrastructure, interlocking, ATP system and the operating programme. The IL and ATP setup are mandatory for optimal capacity utilisation of the existing infrastructure. Finally, only constructional measures like additional points and tracks lead to an increase in capacity. Since railway infrastructure funding is limited, optimisation of ATP systems is easier and cost-efficient than constructional measures. [11]

The IL limits capacity by length and number of block sections, route locking time, signal viewing time and the available routes. The ATP protects train movements by supervising the braking curve. But the type of curve like restrictive or more risky and the functions to upgrade (infill) the movement permission have an impact on the capacity. Hence, an adjustment of the infrastructure, IL and ATP optimises capacity. But best results are achieved if all four aspects are adjusted to support one strategy. Figure 8.1 shows a diagram to depict the capacity in means of the UIC leaflet [148]. The following characteristics for capacity planning are put into context:

- Number of trains
- Stability
- Heterogeneity
- Average Speed

Figure 8.1 shows the parameters for a metro system and a mixed traffic system. The overall target is to increase all presented parameters. The capacity analysed in this thesis bases on a mixed traffic system. Hence the average speed is high, but there is still potential for a further increase. As described in the previous chapter, it is a target to increase the capacity (number of trains). But the same measures (e. g. reducing the headway time) impact the stability of a timetable.

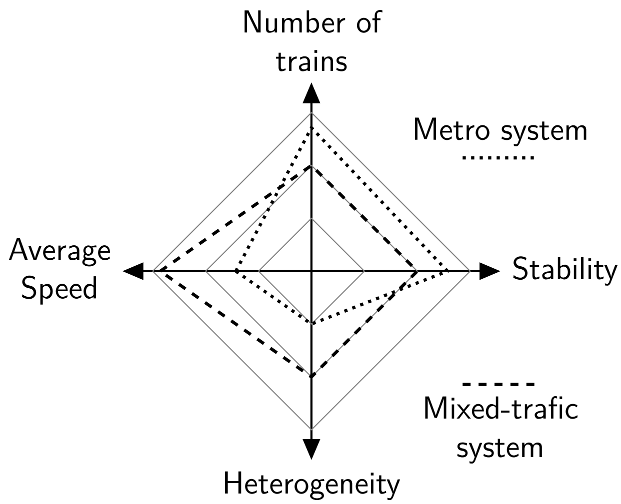


Figure 8.1: Capacity planning with means to UIC leaflet 406 [148].

Capacity analysis is processed to prove some of the described aspects and improvements of the new architecture. The focus is the new architecture's impact, which bases on ETCS Level 1. For evaluating the capacity, the new architecture compares to common ATP and classic ETCS Level 1, Level 2 and Level 3. That allows a comparison of the capacity analysis against the presented capacity analysis in chapter 3.

8.1 Network Modelling and Calculation Principles

8.1.1 LUKS

The software package LUKS is provided and developed by the VIA Consulting & Development GmbH [149]. It is used for numerous railway management and operations issues. It enables the input and management of infrastructure and train data, timetable construction, analytical and simulative performance calculation, and timetable robustness tests on a central database. Different algorithms and principles are implemented in LUKS. The basis of all calculations in LUKS is the minimum headway times and blocking time stairs of the trains according to the acknowledged blocking time model. [150], [151]

8.1.2 Analytic Capacity Calculation

In the analytic capacity calculation, a distinction is made between node and line analysis. A railway node is divided into route nodes and station tracks. When a train enters a station, the train rides through the route node and arrives at a station track. The route node is a connecting element between line and station track. The route node is divided into smaller serial route nodes. Capacity measure for a route node or serial route node is the **waiting time or the occupancy time of a route node**.

The line is separated into one block section at least. For each section, the blocking time is calculated. Putting together the blocking time of each block creates the stairway of a line section. If two trains run on a line, there are two stairways on the line section. Pushing both stairways together until they touch in one block defines the headway of this train pair on the line.

The result of an analytic capacity is a theoretical capacity on the line.

Method

The calculation of the capacity in this chapter bases on the blocking time and the STRELE formula [152]. The STRELE formula calculates the expected knock-on delays on a railway line. Input parameters for the STRELE formula are the minimum headway times, the number of trains and the entry delays. The train type is necessary for considering the ranking.

As introduced in chapter 3, the blocking time describes the temporal occupancy of a block or track section for a train. The sequence of several block sections of a line form the blocking time stairways. Putting together two blocking time stairways lead to the temporal distance of two following trains. This temporal distance is called *minimum headway time*. The resulting minimum headway time is mandatory for the analytical capacity calculation performed in this chapter. [133]

Capacity is calculated as the *number of trains* in a given time slot and a defined quality level. Even if a schedule is used to calculate the minimum headway times, the capacity calculation itself is schedule independent. That means the headway times for each theoretical train pair are calculated and considered in relation to the probability of occurrence. Only the number of trains in the time slot is relevant for the calculation. The number of trains is calculated for each driving direction. In this thesis, the number of trains of both directions is merged and referenced to the zero case. That gives the relative increase of capacity. This calculated capacity is a pragmatical value and not a theoretical one.

Selection of a Network

Mandatory for the capacity analysis is a railway network. Capacity analysis can use a generic network or an existing network. In the context of this thesis, mainline, regional lines and high-speed lines are analysed.

Most **regional lines** are single-track lines. Crossing loops are placed in regular intervals to allow trains to pass if they run in different directions. Single lines are less-used railway lines where the passenger's traffic density and the train service do not justify a second track. There are scheduled stops between the crossing stations. Electrification is rarely available, but this depends on the infrastructure manager who operates and may own the line. It impacts the used rolling stock and the acceleration of the trains. Regularly, there is no heavy cargo traffic. Exceptions may be light cargo traffic if there are sidings where companies connect to the railway network. Regional lines are connected to a railway node (central station) where the transition to other transport services is possible. The speed on regional lines depends on the selected braking distance. In Germany, speeds up to 120 km/h are used. Usually, a lot of LX are available on regional lines.

Mainlines build the comprehensive railway network. It consists of double-track lines, connects cities, and large stations like marshalling yards, e. g., the speed is up to 160 km/h. Traffic density is high, and the track is maintained to a higher standard than regional lines. Normally, there are few LX on the main lines.

The **high-speed** lines require special construction. Definition of high-speed is different around the world. Most countries define high-speed as a speed above 200 km/h. Special requirements to the train and the track are stated for a safe operation. High-speed trains connect big cities and serve only stations where the catchment area offers a relevant number of passengers.

Network Modelling

Modelling of the network and the corresponding safety systems is essential for an adequate capacity analysis. LUKS is a tool for railway operation and not for safety systems. Only capacity relevant aspects of the safety systems are modelled. Hence, only the relevant axle counters for route release or the signal stop event are modelled. Signals and balise groups have an effective direction. The following conditions are considered:

- A signal limits a block section. It covers the functionality of a balise group which acts in the same directions. Such a signal is mirrored with a signal for the opposite direction at the same location. Hence, a block section for the opposite direction is implemented. This principle is shown in figure 8.2. Two balise groups are placed at the signal for providing also infill functionality of this location. A train termination location is placed 1 m in rear of the signal to use the location as a route target of the opposite direction. Hence, the given axle counter is used.

- Each infill balise group is modelled with a second balise group for the opposite direction. This is the procedure to model a balise group, which transmits infill information for both driving directions.

- The route release location for the nominal direction remains at the regular location. For the added opposite direction, a default length of 1 m is used. It is not intended to add additional axle counters for an overlap for the opposite movements.

- If an LX is modelled as block post, using a signal at the LX location defines the block section. Two balise groups are used, one at the signal location and the other as an infill balise group in braking distance. If a regular balise group is in this surrounding area, no additional balise groups are used.

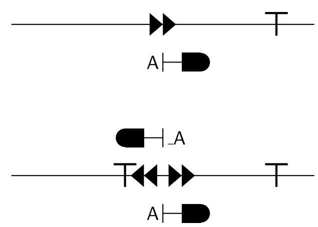


Figure 8.2: Modelling of the new architecture with LUKS (above: classic setup, below: new setup).

8.2 Network Description

The scope of the analysed network is the railway node Aachen and the surrounding lines. These are:

- Mainline from Rheydt to Aachen (line no. 2550)
- Mainline from Cologne to Aachen (line no. 2600)
- Regional line from Herzogenrath to Stolberg (single-track line, line no. 2570)

This network covers all general types of lines like regional line, mainline and a high-speed line. There is a large node Aachen-Central and the station Düren. This network is used to perform capacity analysis. It is an existing network with realistic block sections. Figure 8.3 shows a sketch of the network of the new architecture.

Aachen is located in the border triangle with the Netherlands and Belgium. Hence, there are international lines from

- Aachen Central via Aachen Süd to Belgium,
- Aachen West to Belgium (cargo trains)
- Herzogenrath to Netherlands and from
- Stolberg to Belgium.

These international lines are not regarded in this thesis. However, they show the need for an international European ATP and ATC system.

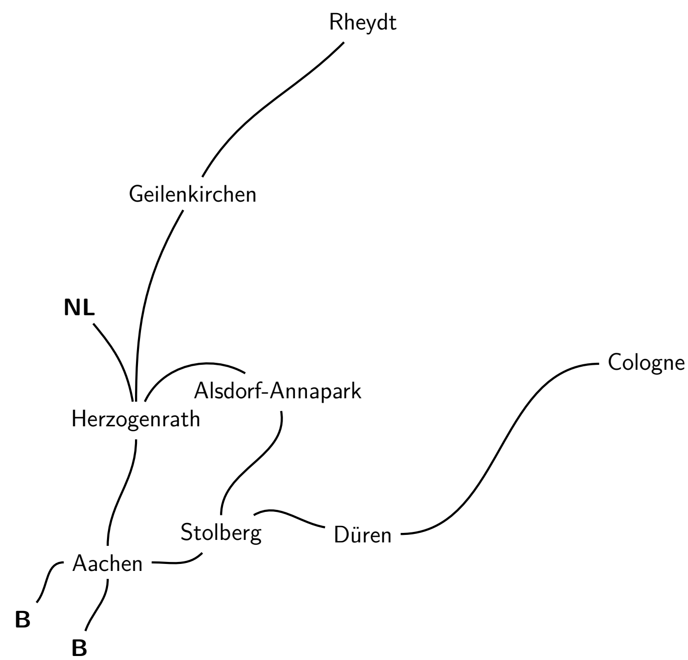


Figure 8.3: Overview of the selected network.

A given infrastructure is used, but it is not stated that the modelled infrastructure is 100 % exact. The given data are not up to date and do not correspond with the current state of affairs. Constructional measures in the last years have not been considered in detail. Hence, there may be some minor deviations from the real network. That does not matter, as the capacity analysis is not aimed at evaluating the capacity of the line. Furthermore, the aim is to evaluate the differences between the different ETCS levels and the impact of the new architecture.

A basis for the capacity calculation is a simplified schedule. This schedule aligns with the real one. Following simplifications are applied:

- Each line uses the same tracks the whole day.
- Freight trains run hourly. They run during the day and not at night. That is not the usual procedure, but allows to consider a heterogeneous train mix on a line and the impact of accelerated cargo trains due to ETCS. The number of freight trains is assumed and smaller than the passenger trains.
- High-speed trains like the ICE and Thalys are modelled as the same type in the same cycle. Hence, there is no difference between ICE and Thalys. This simplification leads to an 1 hour cycle for high-speed trains.
- The dwell time of the trains is 0.5 min for the regional trains and 2 min to 4 min for the high-speed trains.

Table 8.1 shows the modelled schedule for the capacity calculation.

Line	Path	Interval	Operating Hours [h]
ICE	Cologne – Aachen – Brussels (B)	1 h	7 - 20
RE 1	Aachen – Cologne	1 h	5 – 22
RE 4	Aachen – Rheydt	1 h	6 – 21
RE 9	Aachen – Cologne	1 h	5 – 22
RE 18	Aachen – Herzogenrath – Maastricht (NL)	1 h	5 – 23
RB 20	Alsdorf-Annapark – Herzogenrath – Langerwehe	1 h	5 – 23
RB 20	Stolberg – Herzogenrath – Stolberg-Altstadt	1 h	5 – 23
RE 33	Aachen – Rheydt	1 h	6 – 24
Cargo 1	Aachen-West – Rheydt	1 h	8 – 15
Cargo 2	Aachen-West – Cologne-Ehrenfeld	1 h	8 – 18
Both RB 20 form a 0.5 h interval between Alsdorf-Annapark and Stolberg.			

Table 8.1: Scheduled trains for capacity calculation.

8.3 Use Cases

Different use cases are modelled to estimate the capacities of the new architecture. For the capacity-evaluation, a PZB/LZB setup is chosen as the reference case. The focus is on several Level 1 setups. A capacity calculation is also processed for a Level 2 setup and a Level 3 setup. That allows a comparison to the presented capacity values in chapter 3.

For all ETCS use cases, SBD is active.

Zero Case (PZB/LZB)

The network's common (and given) setup is equipped with PZB and LZB (high-speed line) and is used as the comparative case. This represents the current operation and the signalling.

ETCS Level 1

This setup describes the application of the classic ETCS Level 1 FS. All track sections and signal locations remain. The route logic is not changed, and ETCS connects to the signals only. Infill balise groups are located 300 m, 1000 m, and 1300 m in rear of the main signal. The following distances are used on the single-track line: 120 m, 400 m, and 520 m. High-speed trains are running with ETCS Level 1 FS.

This setup compares the capacity between PZB/LZB and the classic ETCS Level 1 FS setup.

ETCS Level 1 Dynamic

The dynamic setup uses the given track sections, but the MA is dynamic. Now, all signal locations are effective for both driving directions. The balise groups transmit telegrams for both directions, not limited to the (formerly) main signal's effective direction. Only available field components as in the classic ETCS Level 1 are used. Distant signals are not necessary.

ETCS Level 1 Improved

Increasing capacity requires constructional and operational measures. The boundary condition for optimisation is to add a minimum of additional field components to the infrastructure. Existing devices are used for a smart improvement of operation. In the optimised Level 1 setup, additional block sections are added:

- In Aachen West, due to the rail topology.
- In track number 2 in Herzogenrath where no exit route is planned.
- Four LX between Geilenkirchen and Herzogenrath are implemented as a block post (only one additional section per LX) and for the driving direction Geilenkirchen–Herzogenrath.
- An additional block section is implemented between Lindern and Hückelhoven–Baal in rear of the platform. The platform is located in rear of the home signal. Due to the additional block section, a stopping train clears the new block section what allows the following train to approach.

ETCS in mode FS allows higher speed for cargo trains and a higher line speed on regional lines. There is no need for a reduced line speed if cab-signalling is used and trackside signalling is simplified or not applied.

- The line speed of the single-track line between Stolberg and Hezogenrath increases about 40 km/h (80 km/h up to 120 km/h).
- The cargo trains' maximum speed increases about 20 km/h (100 km/h up to 120 km/h).

Reducing the headway time requires more or well-located infill locations [37]. Detailed optimisation of the balise group location is not performed. While estimating the capacity, balise groups are added for reducing the approach time. Balise groups are added at the following locations:

- An additional infill balise group between home signal G and exit signal N4 in Horrem.
- Additional infill balise groups in Aachen Rothe Erde (direction Stolberg to Aachen).

ETCS Level 2

The improved setup is used for the capacity analysis of the ETCS Level 2setup.

Each train runs in ETCS Level 2. The speed of the trains is not changed compared to the improved Level 1 setup. There are no additional block sections compared to the improved Level 1 setup.

ETCS Level 3

This setup is identical to the previous Level 2 setup. Now, the trains are running in ETCS Level 3 with moving block.

8.4 Results and Evaluation

In this section, the results of the capacity calculation are presented. The main interest is increasing capacity between the zero case and the ETCS Level 1 improved setup. But also, the differences between the three Level 1 setups and the Level 2 setup are essential. Between Level 1 classic, Level 1 dynamic, and Level 1 improved, the additional block sections' and the speed increase are included. These parameters are more important than the ETCS itself. Therefore, also the number and the average length of the block sections is presented. For the capacity, not the average length of the block sections is relevant. It is only the relevant block section. ETCS only enables the additional block sections.

The results are presented for each line, according to the capacity analysis presented in chapter 3.

Aachen – Cologne

The mainline Aachen – Cologne has a high-speed part. The capacity for the described use cases is presented in figure 8.4. On the high-speed part between Düren and Cologne, the high-speed trains (ICE and Thalys) drive 250 km/h. With classic ETCS Level 1, the capacity decreases. Adding block sections with a dynamic ETCS, and harmonising the speed of the trains leads to an increased capacity.

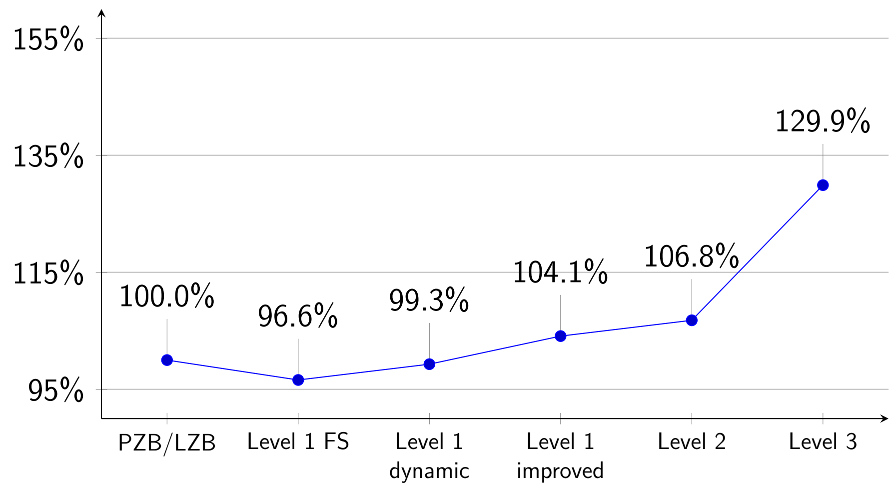


Figure 8.4: Capacity (both directions merged) of ETCS on line Aachen – Cologne.

The block length is presented in table 8.2. The average block length of the zero case setup is about 1400 m. Due to the improvement of the setup due to the new architecture, the block length is reduced to 1140 m. The signals of the opposite direction establish additional block sections. This is a reduction of 20 %. The number of block sections increases from 45/46 (from AC/to AC) in the zero case up to 61/51 block sections in the improved setup. The interesting difference for both directions depends on the signalling equipment for the opposite movement direction.

Line	AC – Cologne		Cologne – AC		Average
	#	length	#	length	length
Zero case	46	1.404 m	45	1.407 m	1.406 m
Improved	61	1.060 m	51	1.231 m	1.146 m

Table 8.2: Number of block sections and their length on line Aachen – Cologne.

Figure 8.4 presents the capacity for the different setups. The capacity for the classic ETCS Level 1 decreases compared to the zero case. The dynamic setup is similar to the zero case due to additional block sections. But the improved setup with additional infill or block sections increases the capacity of 4 % compared to the zero case. Level 2 has a slightly higher capacity. The locations of the balise groups are not optimised according to the train types. Due to the different train types and train speeds, the IP is different for each dedicated EoA. For such a case, Level 2 has an advantage against Level 1. The different speeds and braking curves limit the capacity increase. Level 3 reduces these drawbacks of different speeds due to the advantages of moving block. Capacity increases by approx. 29 % compared to the zero case.

Aachen – Rheydt

The railway line Aachen – Rheydt represents a common mainline. The line is only equipped with PZB because the speed is limited to 160 km/h.

Table 8.3 presents the block length and the number of block sections for this line. For the zero case setup, the average block length is 2180 m. The improved setup reduces this length to 1230 m. This is a reduction of 45 %. The number of block sections increases from 25/26 (from AC/to AC) up to 45/44. Hence, the signalling equipment is similar for both directions.

Line	AC – Rheydt		Rheydt – AC		Average
	#	length	#	length	length
Zero case	25	2.216 m	26	2.151 m	2.184 m
Improved	45	1.209 m	44	1.250 m	1.230 m

Table 8.3: Number of block sections and their length on the line Aachen – Rheydt.

Figure 8.5 presents the capacity for the different setup for the line Rheydt – Aachen. The capacity increase is higher compared to the line Aachen – Cologne. That depends on the one hand on the speed of the train, which is not that divergent. On the other hand, the block length is more reduced compared to the line AC – Cologne. Due to the higher reduction of the block length, the capacity increase is higher than on the line AC – Cologne. A further aspect is the increased speed of the cargo trains. This leads to a harmonisation of the speeds, which allows an increase of capacity. Two interesting aspects are:

- The capacity with ETCS Level 1 classic does not decrease.
- The capacity increase of the Level 1 improved setup and Level 2 setup is nearly similar.

With the optimised ETCS Level 1 setup, the capacity increases by approx. 12 % compared to the zero case. Level 3 will increase capacity by up to 45 % with moving block. The main driver for the capacity increase in Level 1 is the harmonisation of speeds, the additional block sections, and the additional infill locations.

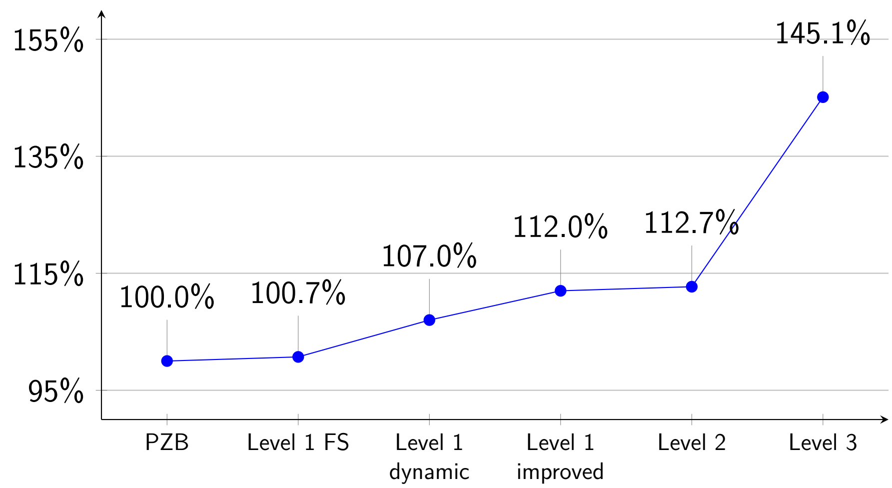


Figure 8.5: Capacity (both directions merged) of ETCS on the line Aachen – Rheydt.

Herzogenrath – Stolberg

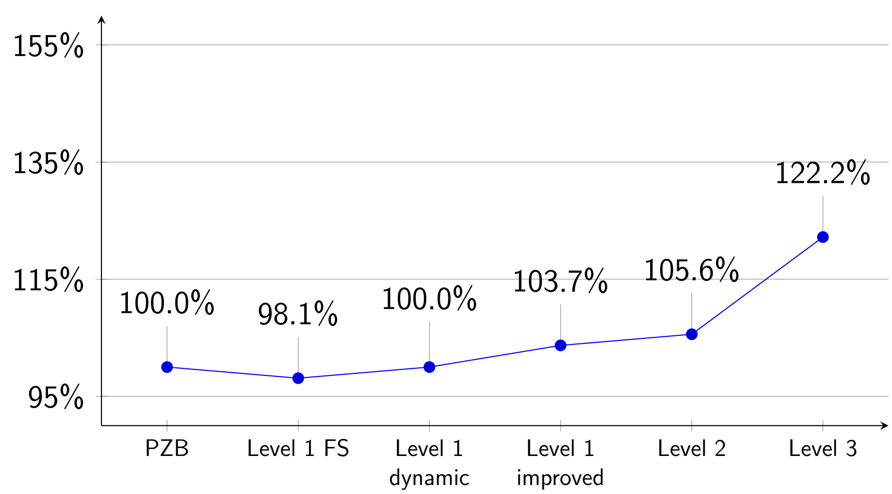


Figure 8.6: Capacity (both directions merged) of ETCS on single-track line Herzogenrath – Stolberg.

The new architecture and ETCS generally have no significant impact on the capacity on single-track lines. That depends on the big issue of the ability of crossing stations on single-track lines. Only the method of capacity calculation (timetable-independent) leads to the increase of capacity. This depends on train headway times and train pairs of the same direction, which are not realistic due to the timetable. Hence, a theoretical capacity is calculated which does not depict the practical operation.

The common setup for ETCS Level 1 and Level 2 has no block sections on the line. Hence, a train enters a line only if the preceding train leaves and clears the line (arrives in the next station). Level 3 with moving block allows entering the line if the distance to the first train is long enough. But moving block has no impact on the opposite movement, which is the common operational case on single-track lines.

	Herzogenrath – Stolberg	
	#	length
Zero case	9	2.003 m
Improved	18	1.080 m

Table 8.4: Number of block sections and their length on single-track line Herzogenrath – Stolberg.

Table 8.5 shows the headway time on the single-track line for the following movements and opposite movements to outline this fact. The headway time does not change significantly for opposite movements. The change for the following movements is minimal except for Level 3. Performance increase for single-track lines with several branches if several branches are served, and two trains have the same route on a common line section. Hence, the increase of capacity is relevant if such a line's schedule provides following train runs.

Train Pair	**Zero Case**	**ETCS**				
Headway time	PZB	Level 1			Level 2	Level 3
in [mm:ss]		classic	dynamic	improved		
Opposite	10:12	10:17	10:16	09:54	09:53	09:40
Following	08:33	09:12	08:13	07:57	07:52	01:57

Table 8.5: Headway time single-track line Herzogenrath – Stolberg.

Resume

The presented capacity analysis in chapter 3 deviates from the processed capacity analysis in this chapter. That simply depends on the different boundary conditions. In chapter 3, generic lines are regarded. Here a given network is analysed and improved. The application of ETCS Level 1 is different compared to the classic ETCS setup in chapter 3.

Principally, the capacity increases with the number of block sections. Puting more block sections in a same distance reduces the average length of the block sections.

A further reason for an increased capacity is the location of infill balise groups. An optimised location of infill balise groups reduces the approach time and blocking time for a track or block section.

Harmonising the train speeds also increases capacity. If the train's average speed is similar, the same distance is driven at the same time. Hence, a passenger train with several stops must drive faster than a freight train without stops.

Chapter 9

Further Impact

The new architecture does not only affect railway operations. Also, safety, economic efficiency, project planning, security and power consumption (energy) are improved. This chapter gives a brief impact of the new architecture on these aspects.

In the context of this thesis, these aspects are not evaluated in detail. For a detailed analysis of these topics, further thesis' can be written. Hence, only some items concerning this thesis a picked out.

9.1 Safety

This section describes the new architecture's impact on safety. It is outlined, how the new architecture improves safety specially in fall-back mode compared to common IL and ATP systems.

Safety is the main purpose of IL and ATP systems. Safety is defined as a certain (low) level of risk. The CENELEC norm defines several safety levels, especially the EN 50126 [153]. Risk analysis considers all relevant hazardous situations and defines the total probability of entering a hazardous situation in relation to the severety of the resulting harm (damage of property or health of people). Special processes and methods have been developed for this purpose [20]. In this thesis, hazard analysis is not performed.

Safety is evaluated in comparison to existing systems (CBI) and operational situations. The regarded operational cases are:

- Train movement
- Shunting movement
- Fall-back movement
- Movements in OS

For each situation, safety is estimated for two different cases:

1. Class B (here: PZB) compared to classic ETCS Level 1 FS.
2. Classic ETCS Level 1 FS compared to dynamic ETCS Level 1 FS.

Hence, ETCS and its application is the focus of the considerations in this thesis.

[82] gives a comparison between the different Class B systems in Europe. The countries which migrated to ETCS first had old safety systems as well as safety issues. Most of the existing Class B safety systems have no full supervision, and only the braking curve is supervised. ETCS enables an improved safety level due to FS. But the enabling technology respective the process is cab-signalling and not ETCS itself. There are different similar systems available, which use cab-signalling and have a high safety level like LZB, e.g. These systems are used for high-speed trains and mostly not in the conventional railway network.

The new architecture has a safety impact on train, shunting, and service movements. These are performed without relevant technical support in common safety systems.

Train Movements

Safety of train movements increases due to FS. Improved safety between Class B and classic ETCS is achieved due to FS and restrictive braking curves [154]. Braking curves are more restrictive compared to Class B system's braking curves basing on trackside signalling. These systems supervise speed reduction but no individual braking curves of the train. The IP depends on the individual train properties. Compared to Class B system, ETCS has a movement permission up to the EoA. In contrast, most Class B reduce the movement permission if a signal and the corresponding distant signal indicates stop.

There is no difference in safety between classic ETCS Level 1 FS and the dynamic ETCS Level 1 FS because the train movement is performed in FS. Classic ETCS FS setup does not link every balise group due to operational issues like repositioning and infill. Both are ETCS in mode FS. A slight improvement is achieved if all balise groups are linked. A missing balise group leads to a restrictive reaction, which stops the train. This restrictive reaction must be defined.

Shunting Movements

Shunting movements are not handled in common ATP systems. Safety for shunting movements is a rule-based process without technical support. Trains operate at low speed, and the train driver drives on sight. Most ATP systems do not safeguard the train speed for a shunting movement. Shunting movements must be regarded for flank protection for train movements. Therefore, shunting signals are used which are equipped with a PZB magnet, for example.

ETCS provides different procedures to safeguard shunting movements in SH:

1. SH only supervises a ceiling speed.
2. The shunting area is limited by a list of balise groups that are allowed to pass or a list of balise groups that are not allowed to pass.

As outlined in section 7.1.4, provisioning movements are processed in mode FS or OS. Both modes supervise a shunting movement against profile data, whereas SH only supervises a ceiling speed. Performing a shunting movement in FS is identical to a train movement. For that case, there is no difference between shunting and train movement. A shunting movement in OS has a reduced safety level (compared to FS) because the train driver is responsible for stoping the train in front of an obstacle. Instead of SH a full MA is available on the train in mode OS. The impact on safety is great compared to common shunting movements without any technical supervision. Movements between normal station tracks and the shunting tracks are mostly performed in FS or OS.

The described safety impact on shunting movements results due to the new architecture. This is a result of the dynamic transmission of telegrams to the balise. The generic algorithm of the route logic and the ETCS logic creates the telegrams because the classic shunting signals do not provide information about the locked shunting route. In classic ETCS Level 1 application, there is

- no way to select a shunting route relevant message by evaluating lamp currents of the shunting signal, and there is
- an enormous effort to predefine telegrams for every possible movement.

Compared to train movements, there is an improvement in safety between Class B systems and classic ETCS. Transition to SH is triggered by the train driver or by the infrastructure. However, in classic ETCS, only the ceiling speed is supervised. A limitation of the shunting area is not possible.

The dynamic ETCS allows limiting the shunting area. Shunting movements in FS or OS are possible. The new architecture leads to a significant improvement in safety for shunting movements.

Fall-back Movements

The safety of fall-back movements increases. With common ETCS Level 1 applications, an MA cannot be transmitted at a shunting signal location to the train if the signal indicates proceed. The route cannot be derived from the shunting signal aspect. Also, substitution and caution signal do not indicate the driveway, and necessary profile data is not defined. The new architecture creates the corresponding profile data for an MA independently of any signal indication and enables the train movement's supervision in fall-back mode. The IL knows the driveway and locks the route elements. In degraded mode, the dispatcher is responsible for safeguarding the infrastructure. The telegrams for a train movement are created in a special process, not triggered by the route logic but by the dispatcher.

This procedure is the digitisation of formerly handwritten commands. These commands are replaced by the MA or other movement permissions of the IL. With a written order, the train driver must pay attention, there is no technical device that supervises the train driver. In [20] and [143], the probability of a human error vs. an error of a techical system is outlined. This depicts the advantage and increased safety of the new architecture respective a technical system in general.

Today, such operational situations are part of the curriculum to remove uncertainty and gain routine [155], [156]. The new architecture fills this gap with the support of the dispatcher. Depending on the situation, the train driver does not recognise a degraded mode because it is handled only by the dispatcher without interaction with the train driver.

Evaluating fall-back movement's safety must consider the responsibilities of the dispatcher and train driver. In classical use cases with Class B systems, both parties are involved in fall-back mode. The dispatcher secures the driveway if the route is not locked completely. The train driver passes the signal without an active ATP system if a signal indicates the degraded mode.

The new architecture allows using ETCS in fall-back mode. If the dispatcher can define an MA, the train receives an MA as if it is no degraded mode. From the train‘s point of view, there is no difference to regular train service. If there are disruptions, which require train driver's contribution, train service in mode OS or SR is defined. Mandatory is a locked route and active route supervision.

Movements in On Sight

In different sections of this thesis, the mode OS is used in a certain situation. OS is a suitable mode for fall-back mode and hands over the responsibility to the train driver. OS helps to ensure a decent safety level for degraded operation. The increase in safety by using OS for a train movement is depending on the use case.

The impact on safety must be regarded from different points of view:

- Train service in OS improves safety compared to Class B ATP systems which do not cover such operational situations.
- Train service in OS would reduce safety if the train service was previously carried out in FS.
- Using OS for shunting service improves safety because such a shunting service is safeguarded compared to Class B, classic ETCS and the use of SH.
- Using OS for fall-back mode increases safety because this service is not safeguarded with Class B systems and classic ETCS.

Further situations for using OS is portion working and entering an occupied track section in regular mode. Today, portion working is a procedure which is operated on sight. Hence, OS is the best mode to map portion working. Entering an occupied track section in OS can be discussed. But, due to common safety rules a regular train movement into an occupied track will not be possible.

Resume

The general impact of dynamic ETCS Level 1 on safety is presented. Table 9.1 gives an overview of the presented aspects. A vast improvement is achieved for shunting and fall-back mode. There are situations of fall-back mode that are now safeguarded with the new architecture. For these cases, the new architecture allows technical support, which is not possible in classic setups with Class B ATP systems (e. g. PZB). The safety of train service does not increase as much.

	Class B	Classic ETCS	New Architecture
Train service	0		
FS	- - -	++	++
OS	- - -	+	+
Shunting service	0		
FS	- - -	- - -	++
OS	- - -	- - -	+
SH	- - -	+	+
Service movements	0	+	++
Fall-back operation	0	- - -	++

Description

++	high improvement
+	improvement
0	no improvement
- - -	no statement possible

Table 9.1: Impact on Safety.

9.2 Economic

An economic improvement of the new architecture is expected. This section presents a comparison of the number of balise groups, as well as additional components (e. g. network components), necessary for a common ETCS Level 1 system, or an IL in general, compared with the new architecture. A brief evaluation of current activities regarding standardisation of interfaces, e. g. EUlynx or NeuPro.

Economic efficiency is a parameter to evaluate an infrastructure safety system. Each component costs money and requires a communication interface for data exchange. [157] describes the financial effort for cabling an IL. Cabling takes 10 % to 20 % of investment cost for an IL [107]. Field components take about 30 % of the costs for an IL.

The new architecture reduces that effort by using modern bus interfaces. In chapter 5, the project ERTMS Regional is presented, which connects all field components via radio communication to the Train Control Centre. The benefit is a minimum of cabling, but a power supply is still necessary. Also, devices for radio communication are required as well as ensuring security.

A reduction of components is achieved by merging components or substituting functions. An example is train detection via trackside sensors or a trainborne train detection by odometer and GNSS. Providing the flexibility of trackside train detection and trainborne train detection needs components at the track and on the train. It is expensive double equipment. The number of necessary components trackside or trainborne must be compared to the number of trains equipped with the relevant components. The financial effort for axle counters and for the GNSS equipment can be compared. But also the reliability and dependency to other organisations must be considered, e. g. for GNSS.

Next to the number of components, the architecture also has an impact on subcomponents. That impacts the efficiency of a system. This means that not only the main components like axle counters, signals, etc., are necessary. Also, components for communication are required. The innovation program DSD defines an IL architecture that is entirely network-ready [8], [158], [50]. The world wide web grants access to every component which allows to control these components, e. g. This requires a communication device for every field component with means for communication security. Each component needs redundant network access and redundant power supply. That is mandatory because each component must be safe on its own. Whereas common bus communication between the field components and IL does not need a special communication device with security overhead. This is an integrated architecture but is still provided by one supplier. Exchange of components of different suppliers is not possible. A communication chip that provides bus access is necessary and simply integrated into the supplier's system architecture. Hence, the described architecture in this thesis is smart and minimises the number of network components.

Required Number of Balise Groups

In this thesis, the number of balise groups of the different setups is compared. The balise is the central component for ETCS Level 1. The location and transmitted data at a balise group impact the capacity and is of enormous importance. The main feature of the new architecture is the dynamic usage of the balise groups and a detaching of the dedicated direction as in classic ETCS applications. In chapter 8, the capacity of a network equipped with the new architecture is estimated. In the classic architecture, some balise groups are close to each other. These balise groups are substituted by one balise group. This balise group transmits the telegram for both driving directions. That saves field components and the corresponding network infrastructure like LEU/BCU and cabling.

Table 9.2, 9.3 and 9.4 show the number of balise groups for the classic ETCS, the dynamic ETCS and the improved Level 1 setup. The three tables give the number of balise groups for the line sections and the stations. If a station's balise group is substituted with a line section's balise group, the balise group is counted to the station. Balise groups in a station track (infill for the exit signal) are merged with the opposite direction's corresponding infill balise group. In short tracks, the infill balise group is merged with the balise group at the exit signal's location in the opposite direction. On the line, the balise groups are merged if they are in a range of 100 m.

On the high-speed line, the saving is 22 % for the line Aachen to Cologne. That means the capacity is increased while reducing the number of balise groups. Adding two balise groups for the improved setup increases the capacity. Since the number of balise groups is

#	Station / Line	no. BG Classic	Dynamic	Improved
1	Rheydt to Baal	51	48	48
2	Baal	32	28	28
3	Baal to Lindern	8	4	5
4	Lindern	34	29	29
5	Lindern to Geilenkirchen	8	7	7
6	Geilenkirchen	28	25	25
7	Geilenkirchen to Herzogenrath	16	15	21
8	Herzogenrath	34	27	28
9	Herzogenrath to Kohlscheid	8	6	3
10	Kohlscheid	30	27	27
11	Richterich	16	8	8
12	Aachen West	33	21	25
13	Aachen West to Aachen Central	2	2	2
	Sum:	303	247 -19 %	259 -15 %

Table 9.2: Overview balise groups Aachen to Rheydt.

around 420, the two additional balise groups do not change the relative amount of balise groups.

On the main line, the number of balise groups is reduced about 19 % from the zero case to the dynamic setup (303 to 247). Twelve balise groups are used to increase the capacity leading to a reduction of balise groups by about 15 % compared to the zero case. The saving relies on the expanded range of features of the balise group. Two aspects must be regarded and cannot be separated:

- Expanding the component's range of features improve operation.
- But not every component location allows substitution of a component.

There are locations that require an additional balise group at a certain location to improve the system's performance. These are still locations where no balise groups are merged due to a dependency on the direction and the precise location. For example, if there is a long distance between two infill balise groups, the approach distance depends on the balise group in rear of the IP.

On the single-track line between Herzogenrath and Stolberg, the number of balise groups is reduced by about 25 %. For the improved setup, there is no difference. The single-track line does not allow to increase capacity without changing the track layout. Therefore, the number of balise groups does not change between the dynamic and improved setup.

#	Station / Line	no. BG		
		Classic	Dynamic	Improved
1	Aachen Central	77	39	39
2	Aachen–Rothe Erde	34	22	23
3	Aachen–Rothe Erde to Stolberg	24	20	20
4	Stolberg	39	32	32
5	Eschweiler	20	14	14
6	Eschweiler to Langerwehe	18	16	16
7	Langerwehe	33	29	29
8	Langerwehe to Düren	36	33	33
9	Düren	80	59	59
10	Düren to Dorsfeld	30	27	27
11	Dorsfeld to Horrem	22	19	19
12	Horrem	40	35	36
13	Horrem to Lövenich	22	21	21
14	Lövenich	22	19	19
	Sum:	527	410 -22 %	412 -22 %

Table 9.3: Overview balise groups Aachen to Cologne.

#	Station / Line	no. BG		
		Classic	Dynamic	Improved
1	Alsdorf - August Schmidt Platz	20	16	16
2	August Schmidt Platz – Annapark	6	5	5
3	Alsdorf - Annapark	24	14	14
4	St. Jöris	24	22	22
	Sum:	74	57 -25 %	57 -25 %

Table 9.4: Overview balise groups single-track line Herzogenrath to Stolberg.

The reduction of about 20 % to 25 % is only a small part of the whole project cost of a railway infrastructure project [107]. An interesting comparison of the number of balise group is given in chapter 10.

Further Network Components

The new architecture bases on a simple bus communication without overarching networks between IL and field components. The interfaces to field elements are proprietary and not standardised. No special security devices for communication are necessary because there is no open network. Only a simple bus interface is used [159]. As proposed in NeuPro or EUlynx, an open architecture requires network access for each field component. A dual communication channel achieves availability. Figure 9.1 presents both architectures, a network-based architecture and a bus communication. Therefore, two modems are required. The Rail Safe Transport Application (RASTA) protocol is necessary for security aspects concerning the packet transmission via IP-based Ethernet.

The power supply is special for a standardised architecture. There is no central power supply in the IL providing the power for the corresponding field elements. Each standardised field element needs its own power supply, which should be doubled in the case of a failure. This setup is necessary for each field element of the NeuPro architecture. Additional costs for these communication devices have to be considered by evaluating an architecture and the expected benefits of standardised components and network communication.

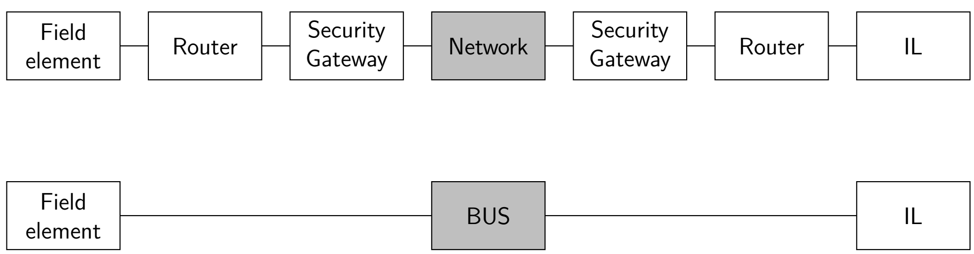


Figure 9.1: Necessary components for (open) network and bus communication.

Additional components for network-based communication do not change the features of the field component and IL itself. They are additional components which leads to additional security issues. Hence, there is no way to reduce the cost of standardised interfaces between IL and field components.

9.3 Project Planning

The impact on project planning is tough to describe. It is different from supplier to supplier. Hence, in this section, a few ideas are presented, resulting from the new architecture. Major topics are creating project data and the corresponding approval process.

A slight impact on constructive engineering is achieved due to a reduction of signals and simplifying the signalling system. Each signal is identical from a technical point of view. Full equipped signals with matrix indicators are not necessary, for example. As described in other chapters, the number of required balises is reduced due to the new architecture. This has also an impact on the necessary time for mounting balises in the track. Because of the telegram's dynamic and generic creation, no predefined telegrams in the LEU are necessary and the correct allocation to a signal is omitted.

A suppliers task is the transformation from planning part 1 (PT 1) to planning part 2 (PT 2). This includes the IL hardware planning, the corresponding field components, and the route logic implementation. In classic applications, the routes are defined and given in the PT 1.

As described in chapter 6, the IL's classic project data is replaced by a three-layer model containing the project data (supplier-specific parametrisation of the hardware and software), the route model with the track topology and the ETCS model for the ETCS relevant data. [129]

For the ETCS logic, a generic algorithm creates the telegrams at runtime, but certain processes require a definition in the data model. Switching the level or the mode must be considered at project time, and the model must contain the necessary data.

In the new architecture, routes are not planned and defined at project time. Only the necessary model is defined. The same applies to the ETCS model. The generic algorithm allows the creation of the routes and telegrams at runtime [160].

The common approval process of a CBI, its safety logic and routes is an expensive process to check the generic features and project data. In the new architecture, there are no predefined routes or ETCS telegrams. It is not necessary to approve the routes and functions. A generic safety case is necessary to ensure that project data and function are independent. These can be defined to check all features which can occur in an IL.

The new architecture impacts on IL planning and allows to simplify the general line and station planning rules. A famous example is the impact on the overlap or the ETCS pendant, the SvL. In ETCS, the SvL can be defined dynamically. This allows changing the usable length of track sections. However, defining block sections on the line requires new handling. A block section is now regarded for both driving directions.

Optimal utilisation of the infrastructure requires a well-designed balise group location. They should be located in rear of the IP for the driving train types. Changing the rolling stock over the years may lead to adjusting the balise group to achieve the best possible use of the infrastructure.

9.4 Security

In modern communication systems, security aspects are new and essential because of telegram based communication. The several IL generations up to the early CBI are a kind of analogue system because they have no communication interfaces to other systems. Their features and the implemented safety is circuit driven. The demand for network based systems leads to discussions about security. A network based systems must be designed with respect to security. An aspect in this context is *resilience*. Resilience describes the system's robustness against disruptions. In the context of security, it describes the return to regular operation after an attack or disruption. In principle, the fewer points of attack are offered, the fewer the probability of an attack. For the railway safety system, safety is the highest good. Operational quality and availability are secondary.

There are different aspects to consider for evaluation: The network & communication type and the attack type.

Network & Communication Types

The use of COTS products and telegram based communication requires considering system security. Norm **EN 50159** defines the requirements for safe communication [161]. This distinguishes between three different communication systems:

1. Communication systems, which are static during the whole life cycle. No unauthorised access is considered.
2. Communication systems, which have participants that are not known at the moment of design. These participants must be approved to get access permission. No unauthorised access is considered.
3. Communication systems that are open and participants are not known and not approved. Unauthorised access is considered for security aspects.

The norm EN 50159 gives no precise definition for the three types of networks. Hence, the definition of class 1 and class 3 network types is clear. A class 2 network is a network type in between class 1 and class 3. Security is not necessary because the participants are authorised and approved. However, they are still not known at the design time or project time of the system. For a small and lucid network, the effort for coordinating the access and participants is manageable. With increasing network size, that aspect disappears.

These network types are closely connected to the communication type. Security is depending on the used communication medium. For example, every radio network is open, and access cannot be denied, especially eavesdropping. This depends on the electromagnetic waves which are received everywhere in the surrounding area. For evaluating security, two aspects are considered.

- Wired vs radio communication
- Open vs closed network

Radio communication is simple to access and disrupt. A simple jammer can disrupt communication without direct access to communication devices. Wired communication requires access to the cables, and a plug is necessary to connect a device to the network.

Destroying a cable is easy to interrupt communication, but this requires direct access to the cable. However, this is more complicated than using a jammer and disrupt radio communication.

An open network has no limited access. Every user gets access to the network. Even if user authentication is necessary to participate, hacking would be possible and disrupt the system. Eavesdropping is still possible, and communication can be analysed. Vulnerabilities may be detected, and an attack of the system is possible. Communication via an open network requires the standardisation of the communication protocol.

A closed network does not provide access to additional users. The network participants are known, and if the protocol is not open, no one can get access. Analysing communication is very complicated if the protocol and encryption are not known.

Figure 9.2 shows the three-tier model of the IL architecture with the relevant interfaces and their properties. As mentioned in chapter 6, proprietary interfaces connect the IL with the field components directly. No standardised interfaces and open networks are used. Communication interfaces between the single safety systems (IL, LX and RBC) are standardised. The communication interface to the control desk (Command & Control (CC)) and management systems like a TMS is standardised. The local distance between these systems requires a communication network. Bus communication is not that suitable.

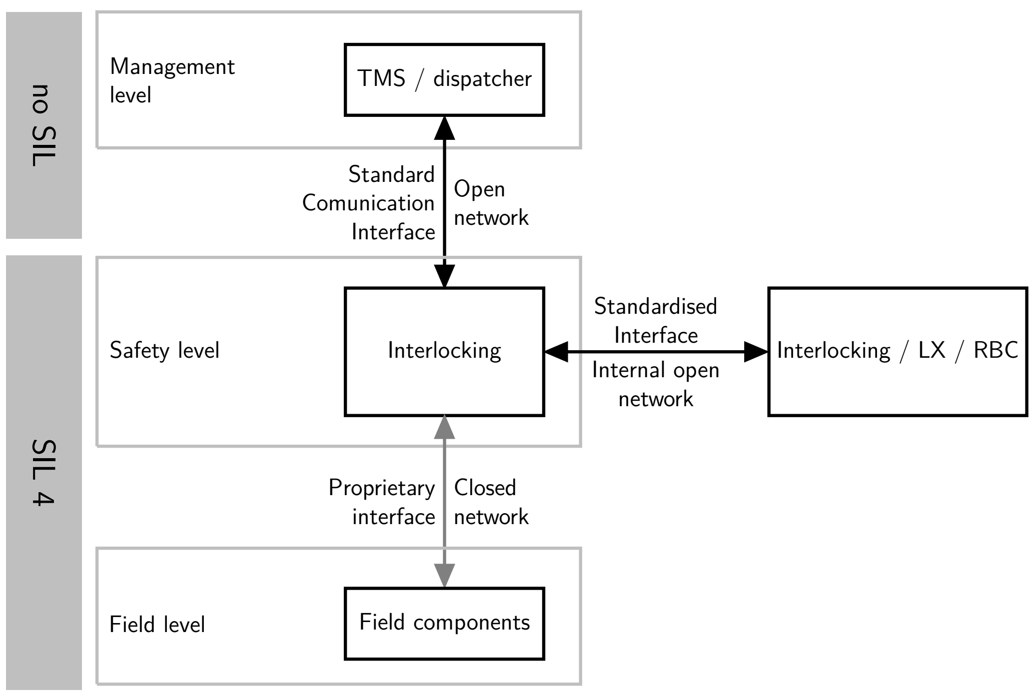


Figure 9.2: Basic security-relevant interfaces - no SIL.

In common IL, block communication is realised as point-to-point connection: Information is exchanged only between two adjacent IL. This information exchange is not changed. Only the connection is realised with a network instead of a point-to-point connection.

The presented architecture has a minimum number of open interfaces. Each IL is an encapsulated system itself safeguarding the controlled track area. Field components are not connected via open networks to the IL. If the communication between the controller desk or further management systems is attacked, the IL remains safe. Even if the communication to connected IL systems is disrupted, the IL is reduced in operational quality but still safe. Communication between IL and related field components relies on local bus communication and not on open networks. Secure data communication is not processed in an open network. The communication to further IL systems can be established in open networks, then security is necessary. A private (local area) network would be a smart solution to achieve a minimum of security issues. Access to a local bus communication is only possible through physical contact to the wire and knowledge of the protocol.

An advantage of a closed communication network between field and the IL logic is security. If the communication is disrupted, safety is not given. A standardised communication interface offers access more simple than non-standardised communication in a closed network. The best system design is an architecture, which does not allow security attacks.

The described interfaces only belong to the IL, but ETCS interfaces have the same importance. With ETCS, the importance of the interfaces to the train is increasing. ETCS offers two communication channels. There is a near field communication via balises and radio communication via GSM-R. Depending on the communication distance attacking balise communication is more complicated than attacking GSM-R communication. Jamming is possible for both communication channels – a jammer with the relevant frequencies is necessary.

Attack Types

Different Class B ATP systems are basing on near field radio communication via balises. For example, these are the PZB magnets that transmit information about the signal aspect to the train. In this case, it is not telegram based communication. However, other Class B ATP systems transmit a telegram via balise or track circuits.

There are two general attack types:

1. Impairment of communication and, thus, disruption of the IL safety functionality.
2. Attacking a security system and disrupting operational safety.

Both types harm railway operations. The first attack type is simple to realise, independent of the network type. However, this does not interfere with the safety of the system. After an attack or any other disruption, the system must be in a safe state. The second attack type is critical. If a system is hacked and access is gained, operational security is endangered. Getting access can lead to a command that could be valid but leads to a hazardous situation. In railway, activating the substitution signal may lead to a hazardous situation because the IL is bypassed.

Resume

The new architecture fulfils all reasons for safe and resilient systems.

- Standardised communication interfaces are reduced to a minimum for suitable operation and flexibility.
- Closed communication connections do not require intensive security activities.

9.5 Energy

Energy is necessary for operating trains and the rail infrastructure (safety systems, e. g.). It is not the first topic if improvements are discussed. However, it is an important topic that impacts efficiency and life cycle costs.

Kunze describes in [162] the energy systems of railway safety systems. In the past, light signals cause high energy consumption. Approaches to reduce energy consumption of IL and the signalling systems were developed.

Now, the architecture of the IL changes due to digitisation. Proposed in NeuPro or EUlynx, the focus is placed on decentral network architecture. In this context, the infrastructure manager should consider not only the operational, maintenance or economic advantages or drawbacks. Energy is regarded as well. It is necessary to consider the different ways of communication made necessary by the architecture. Defining an architecture has a significant impact on communication, as outlined in 6.

Currently, digital and communication systems' energy consumption accounts for increasing total electricity consumption. This power consumption depends on the establishing of cloud systems and the rising data transmission. Digitisation as a megatrend is said to solve many problems. Hence, the optimisation of power consumption is proposed. Same aspects should be considered in the system design for railways. Of course, energy consumption of the safety system is a minor issue compared to the energy consumption of the train itself. But considering all components of all IL there is a hugh potential to reduce energy consumtion.

Providing a so-called Software as a Service (SaaS) as centralised systems needs higher energy consumption because of the necessary communication [163]. Transmitted data rates are rising, and network's operation and transmitting data needs energy, especially wireless communication. Energy consumption of data centres increases continuously. The energy savings are exceeded by the increasing demand for cloud and network solutions [164].

A report [165] considers two aspects of energy consumption:

- Energy for production of a system or device.
- Energy for operation of a system or device in operation.

Energy for production is neglected in this thesis. In the railway industry, the long life cycles are compared to the short life cycles of modern communication devices. Due to the long life cycles, production costs are neglected. Energy consumption for a system in operation distinguishes between power demand for the system and external systems like communication systems.

The power consumption is depending on the communication channel and the transport medium.

- The resistance of fibre optic cable is very low. Network nodes require energy for processing the information in the nodes.
- Copper is a common conductor for cables with low resistance. Network connections are more and more ported to fibre optics to achieve higher bandwidth and reduce the data transport resistance.
- Radio communication is a wireless transport of information. It is well known as a fundamental technology for today's mobile communication. The required energy of this information transport is not in focus if the technology is used. Compared to fibre optic cables and copper cables, air as a transport medium has a very high resistance compared to cable-bound communication.

It is a linear relationship: The more information is transmitted, the higher the energy consumption.

Energy for the transmission of the information is only one side. The other point is the energy consumption of the network devices enabling and building up the communication network. The more devices are involved for communication, the higher the energy consumption.

There are examples of power consumption, depending on the amount of data [165]. However, this example shows the energy consumption for transmission and viewing a film via streaming. This example cannot be transferred directly to the IL. The amount of data is very different, but it outlines the energy increase if the data volume increases.

The presented IL architecture transmits vital data via local area bus communication. There are short distances between field elements and the safety logic respective the IL. Telegrams are sent to the train via balises over a short distance (near field communication). Even in balise communication, there are approaches to save energy [166].

The proposed new architecture has a decentralised approach to limit communication. The new architecture bases on a simple interface to the field components which avoids a communication overhead. A decentral architecture with wired communication reduces the energy consumption regarding components and communication to a minimum.

Chapter 10

Evaluation

The previous chapters present several aspects of a new and integrated ETCS Level 1 architecture and the impact on relevant topics. The presented aspects are interesting, and the architecture itself is very innovative. An evaluation of the described architecture and the impact is necessary to describe the value and potential of the new architecture. Two topics are used to evaluate the benefits of the new architecture:

1. Impact on the presented issues in chapters 4 and 5.
2. Benefits and drawbacks of the new architecture on the major stakeholders.

Finally, a statement about the new architecture and the presented features is given.

10.1 Impact on Presented Issues

First, the influence on radio communication is considered. The new architecture impacts all issues due to Level 1 and wired bus communication.

- Open network and security
  The new architecture is intended for wired bus communication in a safety environment. No open networks in the safety environment of the IL are used, neither between train and track. Hence, for the new architecture, security must roughly considered due to closed networks.
- Limitation of capacity and number of communication channels (trains)
  The new architecture communicates via balises with the trains. Since there is no radio network with a limited number of channels, there are no capacity constraints due to the radio communication network.

- 5G and higher frequencies
  Switching from the default GSM-R to a future system like LTE or 5G requires fundamental network structure and hardware changes. Due to high frequencies, the range of radio masts decreases. A higher number of masts is necessary, and the effort of operating a radio network decreases. Using lower frequencies similar to GSM-R is possible. However, the capacity decreases with lower frequencies. The new architecture bypasses this issue because of the focus on Level 1.

A significant topic of railway is operation. Some selected projects (see chapter 5) present drawbacks and issues of current ETCS applications.

Since most projects focus on Level 2, the new architecture introduces interesting topics to improve operation with Level 1.

- VDE 8
  The example of VDE 8 looks at the evaluation of the balises used on a line. On VDE 8, balises are used only as fixed data balise and not as transparent data balise connected to a signal or IL.

  Table 10.1 shows the average number of balise per km for the VDE 8.1 & 8.2 compared to the line Rheydt – Aachen – Cologne. That allows a comparison of the necessity of balises for ETCS Level 1 and Level 2. Also, the number of balises for the single-track line Herzogenrath – Stolberg is given to show the necessary balises for a single-track line.

  However, that is only a rough estimation because the planning principles on the VDE 8 are not known in detail. Also, the number of stations on VDE 8 must be taken into account. Furthermore, VDE 8 is a high-speed line, and in this thesis, a mainline (with a high-speed part) and a regional line (single-track line) are regarded. But this aspect is very interesting, because the number of balise groups is very similar for all types of lines.

#	**Project**	**Level**	**Balises**	**Length** [km]	**Relative** [1/km]
1	VDE 8.1 and VDE 8.2	L2	3.000	313	9 – 10
2	Rheydt – AC – Cologne	L1	1.288	125	10 – 11
3	Rheydt – Aachen Central	L1	500	55	9 – 10
4	Cologne – Aachen Central	L1	788	70	11 – 12
5	Stolberg – Herzogenrath	L1	114	20	5 – 6

Table 10.1: Comparison of the number of balises on VDE 8 and the lines analysed in this thesis

.

But the intention is that even in Level 2 (and maybe Level 3) several balises are necessary for the position adjustment. A similar number of balise allows almost the same quality of operation in Level 1 with the new architecture, but an RBC and the GSM-R radio communication infrastructure is not necessary. For the VDE 8.1 and VDE 8.2 lines, even 5 RBC are necessary.

A cost comparison is not performed because the necessary prices are not available. The fact that no security in an open network is necessary helps to reduce the cost of equipping a line.

- High-speed Spain
  The new architecture is dedicated to regional and secondary lines. High-speed lines are not in the focus of the new architecture. But as seen in Spain, ETCS Level 1 FS is well working for high-speed lines.

  The different concepts for data management allow a multi-section signalling or MA definition. This will be necessary for high-speed lines due to long braking distances.

  Using ETCS Level 1 for high-speed traffic needs appropriate legal boundary conditions.

- Basel Badischer Bahnhof
  The mentioned problems with the available GSM-R radio channels are obsolete in the new architecture. Communication is processed via balises which is not limited due to available channels.

  The aspect of a radio dial-in for shunting movements is switched off. A level transition, mode transition or dial-in is commanded for a certain route. No fixed data balise group is necessary for dial-in due to the dynamic ETCS Level 1 solution.

- Capacity decrease with Level 2
  The new architecture does not touch the ETCS specification and adjusts them. Capacity-limiting factors are the braking curves and the infill locations. These parameters which define the braking curve are not changed. The national values allow easy adjustment of the braking curve.

  As shown in chapter 8, the increase in capacity results due to additional and shorter block sections. The new architecture allows a smart integration of additional block sections. This principle can also be applied to ETCS Level 2. If the block sections are well optimised in ETCS Level 1, there is almost no further increase in capacity if the same line is equipped with ETCS Level 2. The drawback of Level 2 is the complex and elaborate radio communication and the RBC. Algorithms and project data must be adjusted to exploit the effort.

  If the block sections are optimised, there is no significant benefit by using Level 2. Only an upgrade to Level 3 increases the capacity due to the moving block.

- Shunting with ETCS Level 1
  The new architecture allows innovative processing of shunting movements. Shunting routes are locked, and the train receives either an MA (using mode FS or OS) or the balise groups, which are allowed or not allowed to pass for shunting in mode SH. Shunting service in SH allows a simple change of direction but limits the speed. Shunting service in FS theoretically allows higher speeds.

- ERTMS Regional (Sweden) and ERTMS Level 3 Regional (Italy)
  Both projects yield an ETCS architecture dedicated to regional lines. The approaches are different in detail.

  ERTMS Regional in Sweden focuses on the complete reduction of wired connections. Field elements are commanded via radio communication. Of course, there is a potential in saving cost for constructional measures. However, on the other side, a radio network like GSM-R must be available and operated. This is an issue on regional lines in rural areas. Comprehensive radio coverage cannot be assumed in the next decades. Radio communication is not only necessary for the train but also for safeguarding the infrastructure. Furthermore, energy consumption increases if radio communication is introduced.

  Similar reasons are the issue for the ERTMS Level 3 Regional project. Next to the radio communication infrastructure, a GNSS infrastructure and corresponding trainborne equipment are necessary. The overhead increases even if the cost for cabling are reduced, and field elements are reduced. The effort for operation increases. Hence, for operation in ERTMS Level 3 Regional several independent infrastructure systems are necessary. These are the signalling system, a radio communication infrastructure and a GNSS infrastructure. If one of both non-rail infrastructure systems fails, regular train service is not possible.

  A reduction of field elements like axle counters and implementing a trainborne train detection is hard to handle. If a train is switched off and no power supply for subsystems like ETCS is available, there is no chance to detect the train, and the IL must handle this situation.

10.2 Stakeholder Evaluation

Projects are one side of the coin. Several stakeholders are on the other side. It is not target-oriented to design an exciting and innovative architecture without looking at different stakeholders and their demands. If all stakeholders a benefit from a new system, it is the simplest way to implement it because all stakeholders are interested in supporting the new system. It is like a win-win situation for each stakeholder. In this section only a few major stakeholders are considered to give a brief overview.

Passenger

The new architecture directly impacts the passenger with reduced driving time and improved delay propagation. For the passenger, faster transport is achieved. If issues occur during a train run, an improved delay propagation reduces the overall delay faster than a classic infrastructure.

Operational Aspects
An indirect impact yields to portion working and to a reduced headway time. The new architecture initiates both. No special setup in the track is necessary for portion working.

The reduced average driving time and shorter block sections reduce the headway time. However, the capacity of the line rises. That leads to a better service to the passenger because more train can run on the line or more different relations are operated.

Further Aspects
Further improvements for the passenger are a slightly higher safety. This is not a big issue because the rail is still the carrier with the lowest probability of accidents.

A more important aspect to the passenger is an improved economic efficiency which reduces the fare. Also, the ecological aspects due to energy savings increase the image of the transport system.

Freight

The new architecture also impacts freight trains. As for the passenger, the transport time is reduced due to higher average speed. The reduced transport time increases the attractiveness of cargo logistics. More traffic switches from road to rail.

Another aspect is the integration of siding. The new architecture allows a smart integration without a high effort for technical installation like signalling. Only a point machine, the balise groups and a control system (the IL) are necessary for the efficient operation.

Infrastructure Manager

The new architecture has the greatest impact on the infrastructure manager. Following benefits result:

- A shorter headway leads to an increased capacity and more trains running. More train-path fees are earned.
- A reduced road closing time leads to an increased acceptance of LX and a (hopefully) decreasing number of accidents.

- An improved operation in fall-back mode. Safety in fall-back mode increases. There is a higher potential for safeguarding movements in a degraded mode.
- From an operational point of view, there are more aspects:
  - Longer trains are simply implemented in the existing network without expensive change.
  - Sidings are simply integrated into the IL architecture without great effort.
  - Portion working to improve train operation does not use a special setup of a station track; every track with the required length is suitable for portion working.

Further aspects which have a benefit for the infrastructure manager are safety, economic, security and energy efficiency.

The investment and maintenance cost in relation to the operational quality are better compared to common systems. Also, no intensive security measures are necessary due to a closed network within the safety level. An optimal number of components and no need for radio communication leads to a reduced energy consumption.

Railway Undertaking

The railway undertaking achieves different benefits from the new architecture. A faster driving time leads to a greater attractiveness for the passenger. Goods are transported faster, which increases the competitiveness of road cargo transport. For a degraded mode, the safety rises and operation is improved.

An expanded train length allows transporting more goods. One train substitutes even more trucks and truck driver. Transport energy is saved, and the ecological aspect increases.

Longer passenger trains are limited by the platform's length and not by the length of the track sections.

Safety leads to a reduced number of accidents and damages of rolling stock. Efforts for such incidents and the further costs like sales losses due to the accident are minimised.

The new architecture with dynamic telegrams and FS allows automated driving.

Society

Society has some benefits from an improved railway system. Some aspects are directly depending on the described architecture.

First, the road closing time is reduced for some LX. A reduced closing time increases the acceptance of an LX. This reduces accidents because the road traffic user does not try to bypass a closed LX. [58]

The improved economy of the new architecture allows the society (the government) a faster and more cost-efficient modernisation of the rail network. However, not only the cost is reduced, but also the operational quality increases. Closed to this efficiency is the energy consumption. As presented, the architecture influences the energy consumption that can be measured immediately and converted to CO_2 saving.

Chapter 11

Summary and Outlook

11.1 Summary

The main topic of this thesis is the development of the new architecture. Therefore, the first part of this thesis describes the necessary fundamentals. The excursus to radio communication outlines the complexity of the technology and the challenges for a use in railway systems. The most important chapters describe the impact of the new architecture on operation, safety, security, planning, energy and economics. Also, a capacity calculation is processed to compare the new architecture to Level 2 and Level 3.

Essential features and advantages of the new architecture are:

- Commanding balises directly from the IL.
- Using standardised communication interfaces between safety systems like IL, LX, RBC, and command & control systems.
- Defining signal locations and block sections without dependency to classic signalling principles.
- Detachment from radio communication and GSM-R leads to a smart architecture without dependency on other complex infrastructure systems.
- Shunting movements are simple to handle in the new architecture and ETCS Level 1.
- Operation in fall-back mode with an improved safety level.
- Energy-efficient and secure operation without security effort.
- Cab-signalling allows simplifying the signalling system. That enables a high-performance block system without particular ATC systems.

So to say, ETCS Level 1 is a regular ETCS level and not only dedicated to migration. The application of ETCS Level 1 increases the capacity and is close to the capacity of Level 2. In addition, the drawback of radio communication is eliminated.

11.2 Outlook

This thesis gives a rough overview of the new architecture. Many topics are mentioned or briefly discussed to outline the advantages of the new architecture. All of the topics need detailed consideration and development to launch such a system.

- The new architecture bases on the creation of the ETCS telegrams at runtime. Therefore, an algorithm is necessary which performs this calculation. But also, a reliable model for the ETCS data is essential.
- The interaction between IL and LX and the impact on the road closing time is briefly discussed. This impact should be analysed in detail on different existing LX. Standard LX but also extraordinary LX should be in focus of such an investigation to evaluate the impact.
- The capacity analysis is a rough evaluation of the impact of the new architecture. A detailed capacity analysis should be performed. Therefore, simulation can be used to estimate the delay propagation. This allows evaluating the robustness of a timetable. An increased network size, optimised balise group locations, and synthetic networks are not regarded in this thesis.
- The latency of radio communication is not regarded in this thesis and of the communication system in general. This is decisive for the definition of the architecture but also has a significant impact on capacity.

Some topics have not been discussed in this thesis.

- The control panel of the dispatcher must be adopted if no trackside signals are available.
- Using ETCS in fall-back mode needs a change of the operational rules. Also, the handling of ETCS and its integration into the control panel must be discussed.
- A bidirectional communication via balise between train and track was defined in the first specifications of ETCS but was removed since it was not used. Compared to the former safety systems, the new digital architecture allows such communication. The benefits of such communication should be discussed. A reintroduction should only be considered if it leads to a significant improvement of operation.

- Railway operation with automated trains is not considered in this thesis. Generally, FS is a fundament for automated driving. Further interfaces and the feedback from the train to the dispatcher or TMS must be outlined.

There is a lot of potential for further considerations. Not all demands can be covered with a single architecture. A significant increase of capacity is achieved with ETCS Level 3. But the migration to a comprehensive moving block will take decades. The limiting factor for the migration to Level 3 is the long-term life cycle of railway infrastructure and rolling stock. The infrastructure needs an ETCS equipment as well as rolling stock. ETCS Level 3 is only a benefit if the capacity is sufficient. Otherwise, a new construction of lines is necessary to improve capacity significantly and sustainably. With increasing traffic, the capacity for degraded operation should be considered. This does not mean errors in safety systems but the closing of a line in the case of accidents, maintenance of the track or constructional activities.

List of Figures

List of Tables

References

[1] Thorsten Dellmann. Megatrends und deren Herausforderungen an die Bahn. *Eisenbahntechnische Rundschau*, (12):2, December 2008.

[2] Deutsche Bahn AG – Investor Relations. Integrierter Bericht 2019. Technical report, Deutsche Bahn AG, Berlin, March 2020.

[3] Geschäftsstelle des Beauftragten der Bundesregierung für den Schienenverkehr. Masterplan Schienenverkehr. Technical report, Bundesministerium für Verkehr und digitale Infrastruktur, Berlin, June 2020.

[4] Martin Henke. Auf der Agenda: Reaktivierung von Eisenbahnstrecken. Technical report, Verband Deutscher Verkehrsunternehmen e.V. (VDV), April 2020.

[5] Deutsch Bahn AG. Digitale Schiene Deutschland. www.digitale-schiene-deutschland.de. Accessed: 2020-11-12.

[6] smart rail 4.0. http://www.smartrail40.ch. Accessed: 2020-11-08.

[7] NetworkRail. The Digital Railway Programme. https://www.networkrail.co.uk/wp-content/uploads/2018/05/Digital-Railway-Programme.pdf. Accessed: 2020-11-12.

[8] Michael Leining and Bernd Elsweiler. Signaltechnik 4.0 - Industrialisierung der Signaltechnik. *Deine Bahn*, (1):6–11, 2014.

[9] Marin Guss. Der Bedeutungswandel des Stellwerks. *Deine Bahn*, (8):30–33, 2018.

[10] Verband der Bahnindustrie in Deutschland e.V. Die Zukunft der Schiene soll rasch beginnen, November 2019. Industriebeitrag für industrielles Rollout DSTW/ETCS.

[11] Jochen Trinckauf. Digitalisierung im Bahnsystems. *Deine Bahn*, (11):7–9, 2019.

[12] Martin Beyer, Steffen Jurtz, Michael Langhof, Peter Reinhart, and Thomas Vogel. ETCS as a carrier system for improved performance at S-Bahn Stuttgart. *Signal & Draht*, 111(6):6–16, 2019.

[13] Stefano Baglivo, Vincent Blateau, and Fabio Senesi. Innovative ETCS-Funktionen für stark beanspruchte Bahnknoten. *Der Eisenbahningenieur*, pages 50–54, June 2020.

[14] Lionel Arend, Laurel Pott, Nico Hoffmann, and Ronny Schanck. ETCS level 2 without GSM-R. *Signal & Draht*, 110(10):18–28, 2018.

[15] Klaus Finken, Thomas Hamblock, and Georg Klöters. The ZSB 2000 on the way to ETCS. *Signal & Draht*, 107(10):32–37, 2019.

[16] Verband der Bahnindustrie in Deutschland (VDB). *Jahrbuch des Bahnwesens 2010: 175 Jahre Eisenbahnen in Deutschland*. DVV Media Group GmbH - Eurailpress, 2010.

[17] Hans G. Wägli. *Hebel, Riegel und Signale*. Diplory-Verlag, 2018.

[18] Ulrich Maschek. *Sicherung des Schienenverkehrs - Grundlagen und Planung der Leit- und Sicherungstechnik*. Springer Vieweg, 4th edition, 2018.

[19] Jörn Pachl. *Railway Signalling Principles*. May 2020.

[20] Birgit Milius. *Konstruktion eines semi-qualitativen Risikographen für das Eisenbahnwesen*. PhD thesis, Technische Universität Carolo-Wilhelmina zu Braunschweig, Braunschweig, 2009.

[21] Albrecht Hinzen. *Der Einfluss des menschlichen Fehlers auf die Sicherheit der Eisenbahn*. PhD thesis, Rheinisch-Westphälisch Technische Hochschule Aachen, Aachen, 1993.

[22] Bundesministerium für Verkehr der Bundesrepublik Deutschland. *Eisenbahn Bau- und Betriebsordnung*. 2018.

[23] Jörn Pachl. *Systemtechnik des Schienenverkehrs - Bahnbetrieb planen, steuern und sichern*. Springer Vieweg, 9th edition, 2018.

[24] Hans Leister. ETCS in Germany - The Chance for More Traffic on Rail?! From Perspective of a Railway Operator. *ZEVrail*, (143):10–13, January-February 2019.

[25] Gregor Theeg and Sergej Vlasenko. *Railway Signalling & Interlocking*. Eurailpress, 1th edition, 209.

[26] Peter Winter, Jens Braband, Paolo de Cicco, Patrick Deutsch, Poul Frosig, Klaus Konrad, Libor Lochmann, Dan Mandoc, Harald Reisinger, Bernhard Stamm, Jaime Tamarit, and Ekkehard Wendler. *Compendium on ERTMS: European Rail Traffic Management System*. UIC - International Union of Railways, 1st edition, 2009.

[27] UNISIG. System Requirement Specification – Subset 026. Technical report, European Railway Agency (ERA), Brussels, 2016.

[28] UNISIG. ERTMS/ETCS – Functional System Requirement Specification. Technical report, European Railway Agency, Brussels, 2007.

[29] UNISIG. Form Fit Functional Interface Specification (FFFIS) – Subset 036. Technical report, European Railway Agency (ERA), Brussels, 2015.

[30] Hans Bierlein. TSI Control/Command für das konventionelle Bahnsystem. *Signal & Draht*, 95(5):6–9, 2003.

[31] Michael Leining. Die betriebliche Interoperabilität des Systems ETCS in Deutschland. *Signal & Draht*, 107(7+8):6–9, 2015.

[32] Jens Eisen and Egbert Voigt. XML-basierte Prüfung der RBC-Streckenprojektierung. *Signal & Draht*, 95(5):18–22, 2003.

[33] Mathias Hering, Rasmus Krevet, and Marco Liesch. Availability of the Worlds first ERTMS/ETCS Level 2-Line. *Signal & Draht*, 95(9):46–47, 2003.

[34] Josef Löwe and Wolfgang Opp. Das Radio Block Center Trainguard 200 RBC. *Signal & Draht*, 104(3):29–31, 2012.

[35] Thorsten Büker and Alexander Kuckelberg. ETCS approximation by legacy ATP/ATC systems under railway operation research methods. *Signal & Draht*, 105(10):38–50, 2013.

[36] Thorsten Schaer. Der Einfluss von Betriebsführungskonzepten in großen Bahnnetzen. *Signal & Draht*, 95(9):6–12, 2003.

[37] André Feltz, Nils Nießen, Tobias Walke, and Jürgen Jacobs. Analysis and optimisation of ETCS parameters in the Luxembourg railway network. *Signal & Draht*, 109(3):6–17, 2017.

[38] Lars Fehlauer and Richard Kahl. Einfluss der ETCS-Bremskurven auf die Infrastrukturplanung. *Der Eisenbahningenieur*, pages 34–37, August 2019.

[39] Ekkehard Wendler. Einfluss von Zugbeeinflussungskomponenten mit Infill-Funktionalität auf das Leistungsverhalten von Bahnanlagen. Technical report, Gutachten International Union of Railways (UIC), 2006. Expert report on behalt of the UIC.

[40] Ina Bleicher. Die Herausforderungen des neuen integrierten Bediensystems bei der DB Netz AG. *Signal & Draht*, 106(4):30–33, 2014.

[41] Ralf Knapp and Steffen Henning. Bedienung und Anzeige im Stellwerk ZSB 2000. *Signal & Draht*, 97(10):30–34, 2005.

[42] aba/pbz. Elektronisches Stellwerk: Killer der Zukunft Bahn? *PRO BAHN Zeitung*, (3):37–41, 2001.

[43] Georg Klöters and Steffen Henning. LED-Signalgeber - zehn Jahre Erfahrung im Eisenbahnbetrieb. *Signal & Draht*, 105(4):18–27, 2013.

[44] ETCS in Germany - The Chance for More Traffic on Rail?! From Perspective of the DB AG. *ZEVrail*, (143):4–6, January-February 2019.

[45] Frans Heijnen. EULYNX - The next signalling strategy for Europe. In *Signalling seminar IRSE ITC - JR East*, April 2016.

[46] Nicholas Spies, Michael Klein, Jörg Schurig, and Thomas Schuhknecht. Pre-production Digital Signalling technology project planning at Deutsche Bahn. *Signal & Draht*, 111(9):28–33, 2019.

[47] Heinz Laumen. Operating Railways in conflict between digitization and safety. Keynote speech at the International Railway Symposium Aachen (IRSA) 2019, November 2019.

[48] Ralf Knapp and Thomas Hamblock. Erweiterung des Leit- und Bediensystems und des Stellwerks ZSB 2000. *Signal & Draht*, 103(11):8–12, 2011.

[49] Walter Heydt. Stellwerksfernsteuerung mittels Verfahrenssicherung am Fdl-Arbeitsplatz. *Signal & Draht*, 100(6):24–27, 2008.

[50] Michael Kant and Andreas Priebe. Security for Safety. *Signal & Draht*, 110(5):37–44, 2018.

[51] Lothar Fendrich and Wolfgang Fengler. *Handbuch Eisenbahninfrastruktur*. Springer Vieweg, 2014.

[52] Georg Klöters and Andreas Priebe. Long-term experience with LED signals in a digital context. *Signal & Draht*, 110(12):6–11, 2018.

[53] Verband Deutscher Verkehrsunternehmen (VDV). *Vorschrift für die Sicherung der Bahnübergänge nichtbundeseigener Eisenbahnen (BÜV NE)*. 2001.

[54] DB Netz AG. *Richtlinie 815 - Bahnübergänge Planen und Instandhalten*. 2018.

[55] Henk B. Scholten. Level Crossing in The Netherlands - Past, Present and Future. *Signal & Draht*, 95(7+8):36–40, 2003.

[56] Henri Werdel and Patrick Melchior. Bahnübergangssicherung in Luxemburg mit BUES 2000. *Signal & Draht*, 95(10):25–30, 2003.

[57] Office of Rail Regulation. Level Crossing: A guide for managers, designers and operators. Railway Safety Publication 7, December 2011.

[58] Eric Schöne. Bahnübergänge: Zwischen Restrisiko und Sicherheitslücke. *Eisenbahntechnische Rundschau*, (3):12–17, March 2016.

[59] ETCS System Requirement Specification 03.01. Technical report, European Rail Research Institut, Brussels, 1996.

[60] Pia Habel. 5G für Deutschland. https://www.telekom.com/de/medien/medieninformationen/de fuer-deutschland-598876, April 2020. Accessed: 2020-11-16.

[61] Deutsche Telekom AG. 5G frequency auction by the Federal Network Agency – 5 questions and answers about the auction. https://www.telekom.com/en/company/details/5-questions-and-answers-about-the-5g-frequency-auction-550970, February 2018. Accessed: 2020-11-14.

[62] Jochen Schiller. *Mobile Communications*. Pearson Education, 2nd edition, 2003.

[63] Ismet Aktas, Alexander Bentkus, Florian Bonanati, Armin Dekorsy, Christian Dombrowski Michael Doubrava, Ali Golestani, Frank Hofmann, Mike Heidrich, Stefan Hiensch, Rüdiger Kays, Michael Meyer, Andreas Müller, Stephan ten Brink, Neda Petreska, Milan Popovic, Lutz Rauchhaupt, Ahmad Saad, Hans Schotten, Christoph Wöste, and Ingo Wolff. Funktechnologien fur Industrie 4.0. Technical report, Informationstechnische Gesellschaft im VDE (ITG), Frankfurt am Main, June 2017.

[64] Xichun Li, Abudulla Gani, Rosli Salleh, and Omar Zakaria. The Future of Mobile Wireless Communication Networks. 2009.

[65] Sanjaz Kumar, Gagan Gupta, and Kunwar Rajat Singh. 5G: Revolution of Future Communication Technology, October 2015.

[66] Julia Moßner, Linda Bergmann, and Sebastian Human. Internet of Things – Definition, Technologie und Anwendung. https://www.industry-of-things.de/internet-of-things-definition-technologie-und-anwendung-a-878883/, November 2019. Accessed: 2020-11-16.

[67] K. Chopra, K. Gupta, and A. Lambora. Future Internet: The Internet of Things-A Literature Review. In *2019 International Conference on Machine Learning, Big Data, Cloud and Parallel Computing (COMITCon)*, pages 135–139, 2019.

[68] Dr. Silvio Döring, Wolfgang Gemeinhardt, and Frieder Bautz. Opportunities and Challenges of 5G Technology for Smart Mobility and Smart Rail. *ZEV Rail*, (142):4–9, 2018.

[69] Claude E. Shannon. A mathematical theory of communication. *The Bell System Technical Journal*, 27(3):379–423, 1948.

[70] Harry Nyquist. Certain topics in telegraph transmission theory. *Proceedings of the IEEE*, 90(2):280–305, 2002.

[71] Electronic Communications Committee. ECC Report 294 - Assessment of the spectrum needs for future railway communicatoins. Technical report, European Conference of Postal and Telecommunications Administrations (CEPT), 2019.

[72] Alex Brand and Christian Nänni. Railway and passenger communication: the transition from 2G/GSM-R to 5G/FRMCS as viewed by SBB. *Signal & Draht*, 111(7+8):6–15, 2019.

[73] Ian Fogg. Quantifying the global 5G experience across ten operators. https://www.opensignal.com/2020/05/20/quantifying-the-global-5g-experience-across-ten-operators, May 2020. Accessed: 2020-11-10.

[74] Nokia. A new platform for rail communications – adopting 5G for railways. *White Paper*, 2019.

[75] Heinz Laumen and Steffen Henning. Obsoleszenz im Bereich LST. *Signal & Draht*, 104(4):6–12, 2012.

[76] Georg Klöters and Ulrich Herten. The use of LST interfaces to avert the negative effects of obsolescence. *Signal & Draht*, 109(11):26–33, 2017.

[77] Marcel Schneider and Bastian Kogel. Wie sich das Verkehrsverhalten prognostizieren lässt. *Der Nahverkehr*, 53(7+8):57–60, August 2017.

[78] Wichtiges Bekenntnis der Politik – Schienengipfel bringt wertvolle Klarstellungen / Jetzt kommt es auf die Umsetzung an. https://www.allianz-pro-schiene.de/presse/pressemitteilungen/wichtiges-bekenntnis-der-politik/. Accessed: 2020-11-08.

[79] Lars Schnieder. Cybersecurity management in railway application development. *Signal & Draht*, 111(4):17–22, 2019.

[80] Hans Leister. ETcs und digitale Technologie für Stellwerke. *Eisenbahn-Revue International*, (8-9):417–422, 2017.

[81] Commission Implementing Regulation (EU) 2017/6. Technical report, The European Commission, Brussels, 2017.

[82] Rositsa Ahmakov, Salem Blum, Thorsten Büker, Nicolaas de Vries, Jürgen Jacobs, Urs Kramer, Jost Lüking, Daniel Meurer, and Katharina Lechner. Grundlagenerarbeitung für die nationale ERTMS/ETCS Migrationsstrategie – Schlussbericht. Technical report, Im Auftrag des Bundesministerium für Verkehr und digitale Infrastruktur (BMVI), Bonn, 2018.

[83] I.J. Iglesias, A. Berrios, A. Arranz, M. Cambronero, J.A. Jimenez, C. Arias, I. Ribera, D. Molina, J. Tamarit, and J. Bueno. Rail Interoperability in Spain. ERTMS real deployment, 2005.

[84] Juan Hernández. Positive ETCS deployment progress for the Spanish network. https://www.globalrailwayreview.com/article/5566/positive-etcs-deployment-progress-for-the-spanish-network/. Accessed: 2020-15-01.

[85] Reiner Behnsch, Jörg Peter Osburg, and Detlef Schwarz. Gemischtes ETCS-Ausrüstungskonzept für den Knoten Basel. *Signal & Draht*, 103(12):12–18, 2011.

[86] Herbert Widner. The GSM-R Fixed Terminal System - possibilities, migration and safety. *Signal & Draht*, 97(9):43–47, 2005.

[87] Henri Werdel, Jean-Jaques Kolb, André Feltz, and Hans Kast. Provision of Complete Luxembourg Railway Network with ETCS Level 1. *Signal & Draht*, 95(9):50–54, 2003.

[88] Jörg Bormet and Rainer Eschlbeck. ERTMS Regional - Ein ETCS Level 3 Projekt für regionale Strecken. *Eisenbahntechnische Rundschau*, (11):14–17, November 2013.

[89] Wim Coenraad. Level 3: From High Speed Vision To Rural implementation.

[90] Piero Petruccioli. Italy: Trials begin for ERTMS Level 3 Regional System – a new way of developing railway operations beyond the digitalisation of signalling. *UIC electronic newsletter "UIC eNews" Nr 573*, (573), November 2017.

[91] Maximilian Wirth and Andreas Schöbel. Headways in ETCS Levels 2 and 3 on the main urban railway line in Vienna. *Signal & Draht*, 112(4):21–26, 2020.

[92] Matthias Busse. *Der optimierte Einsatz von ETCS-Bremskurven*. PhD thesis, Technische Universität Dresden, Dresden, 2021.

[93] Elisabeth Kretschmer and Michael Dieter Kunze. Ausrüstungsvarianten bei ETCS Level 3. *Deine Bahn*, (11):26–32, 2019.

[94] sbb/an. Migration zu ETCS in der Sackgasse? *Eisenbahn-Revue*, (6):282, 2017.

[95] Claudia Krahl. ETCS und Leittechnik. *Der Eisenbahningenieur*, pages 28–33, January 2016.

[96] UNISIG. Form Fit Functional Interface Specification (FFIS) - Subset 036. Technical report, European Union Agency for Railways, Brussels, 2007.

[97] Maarten Bartholomeus. No barriers for level crossings with ERTMS. In *Aspect2019*. Institut für Bahnsysteme und Bahntechnik, April 2019.

[98] Daria Menzel, Martin Sommer, and Jochen Trinckauf. New secondary railway – innovative safeguarding vehicle movements. *Signal & Draht*, 112(11):6–11, 2020.

[99] Colin Williams. The next ETCS Level? pages 75–79, August 2016.

[100] Christoph Gralla. *Zur Gestaltung einer ETCS-Migration eines Eisenbahnverkehrsunternehmens*. PhD thesis, Technische Universität Carolo-Wilhelmina zu Braunschweig, Braunschweig, 2009.

[101] Christoph Lackhove. *Methode zur Optimierung der Migration von ETCS*. PhD thesis, Technische Universität Carolo-Wilhelmina zu Braunschweig, Braunschweig, 2013.

[102] Miroslav Obrenovic. *Methodik für die Migration von Systemen der Eisenbahnleit und -sicherungstechnik am Beispiel der Einführung von ETCS*. PhD thesis, Technische Universität Carolo-Wilhelmina zu Braunschweig, Braunschweig, 2009.

[103] Simon Frederik Rüsche. *Untersuchungen zu Effizienzsteigerungen des European Railway Traffic Management Systems ERTMS durch die Einführung von paketvermittelten drahtlosen Uebertragungsverfahren*. PhD thesis, Gottfried Wilhelm Leibnitz Universität Hannover, Hannover, 2010.

[104] Benedikt Wenzel. *Entwicklung eines neuartigen rechnergestützten Validierungsverfahrens für telegrammbasierte Zugsicherungssysteme am Beispiel von ETCS*. PhD thesis, Technische Universität Dresden, Dresden, 2013.

[105] LTEmobil. LTE-Netzabdeckung in Deutschland. https://ltemobile.de/lte-verfuegbarkeit/lte-netzabdeckung/. Accessed: 2020-11-16.

[106] Bundesnetzagentur. Website Breitband-Monitor. www.breitband-monitor.de. Accessed: 2020-11-16.

[107] Christian Sevestre. Reduction in Cost of Signalling. *Signal & Draht*, 99(5):30–35, 2007. ITC of IRSE.

[108] Markus Burhard. Vom Signalisierten Zugleitbetrieb zum ESTW-R am Beispiel des ZSB 2000. *Signal & Draht*, 102(6):16–22, 2010.

[109] Thomas Koch. Adapter solutions for level crossings and older interlocking systems within the ZSB 2000 system. *Signal & Draht*, 108(10):34–41, 2016.

[110] Holger Wiegmann and Leo Gossen. BUES 2000 mit Achszählern und Fernüberwachung für Polen. *Signal & Draht*, 105(10):28–31, 2013.

[111] Michael Fußy. ETCS Level 2 ohne Signale – Erstmals in Deutschland im Projekt VDE 8. *Signal & Draht*, 102(6):16–22, 2010.

[112] Manuel Hoeft and Werner Oberländer. Bediensysteme für Stellwerke auf Strecken mit geringer Verkehrsdichte. *Signal & Draht*, 99(4):22–28, 2007.

[113] Joern Pachl. Die Bedeutung betrieblicher Regelwerke für die Leit- und Sicherungstechnik. *Der Eisenbahningenieur*, 100(12):32–38, 2008.

[114] Frank-Bernhard Ptok and Friederike Salbert. Einsparung von Signalen bei ETCS. *Eisenbahntechnische Rundschau*, (11):682–688, November 2007.

[115] Steffen Schmidt and David Grabowski. The "ETCS Interlocking. *Signal & Draht*, 110(10):29–39, 2018.

[116] Daria Menzel. A generic concept for safeguarding vehicle movements. *Signal & Draht*, 111(10):6–15, 2019.

[117] Frederik Düpmeier, Miroslav Pejic, and Bila Üyüumez. Smarte Sicherungslogik für das Stellwerk der nächsten Generation. *Deine Bahn*, (11):33–37, January-February 2019.

[118] Frederik Düpmeier. Entwurf einer neuen, regelbasierten Sicherungslogik unter Annahme der vollstaendigen Ortung aller Schienenfahrzeuge. In *Scientific Railway Signalling Symposium 2017*. Institut für Bahnsysteme und Bahntechnik, April 2017.

[119] Hannes Kaltheis. Intelligent sensor technology for efficient track vacancy detection. *Signal & Draht*, 110(9):83–91, 2018.

[120] Juliette Marais and Salvatore Sabina. Signalling: Verifying train position by satellite. *Railway Gazette International*, July 2020.

[121] A. Mirabadi, N. Mort, and Felix Schmid. Application of sensor fusion to railway systems. *IEEE International Conference on Multisensor Fusion and Integration for Intelligent Systems*, pages 185 – 192, 01 1997.

[122] Henri Werdel, Wilhelm Viehbeck, and Robert Hastert. Dynamische Fhargastinformation in Luxemburg. *Signal & Draht*, 97(6):29–33, 2005.

[123] Dietrich Müller and Matthias Schütze. Die dynamische Fahrgastinformation bei der U-Bahn München. *Signal & Draht*, 100(1+2):26–32, 2008.

[124] Bernd Krüger and Ralf Knapp. Zugnummernmeldung im Stellwerk ZSB 2000. *Signal & Draht*, 98(7+8):19–22, 2006.

[125] Stephan Breu, Gerald Thiemt, and Michael Kant. LeiDis-N Network Dispatching at the Network Management Centre of DB AG at Frankfurt. *Signal & Draht*, 95(6):32–36, 2003.

[126] Rolf Seiffert. Train Integrity, making ETCS L3 happen. *Signal & Draht*, 102(9):49–50, 2010. ICT of IRSE.

[127] Makrus Brunner, Raphael Wietlisbach, Sara Durot, and Daniel Müller. Switching modes as a new and efficient solution for flank protection. *Signal & Draht*, 108(10):26–33, 2016.

[128] Susanne Wunsch and Birgit Jaekel. Modellprinzipien des RailTopoModel. *Der Eisenbahningenieur*, pages 18–23, March 2017.

[129] Ulrich Maschek. *Datenmodell zur Planung von Stellwerken*. Dissertation, Technische Universität Carolo-Wilhelmina zu Braunschweig, 2002.

[130] Jörg Pferdenges and Torsten Steinhöfel. Relaisblockanpassung ZSB 2000. *Signal & Draht*, 105(7+8):21–23, 2013.

[131] Michael Lübbers and Wolfgang Gallisch. DB AG: Weg zu einer funktionalen und standardisierten Blockschnittstelle. *Signal & Draht*, 103(10):6–11, 2011.

[132] Thorsten Schaer. Der Weg zu leistungsfähigen Netzknoten eine Analyse unter Einbeziehung von ETCS. *Eisenbahntechnische Rundschau*, 53(4):219–224, 2004.

[133] Wiebke Lenze and Nils Nießen. Optimization of Speed Changes and its Effects on Running Time Capacity. In *Proceedings of the 16th International Conference on Railway Engineering, Design and Operation*, Lissabon, Portugal, July 2018. COMPRAIL2018.

[134] Alfred Veider, Hans Boyer, Dietrich Rhein, and August Zierl. Betrieblich optimierter Eisatz von ETCS-Level 1. *Signal & Draht*, 94(7+8):13–18, 2002.

[135] Peter Reinhart. Bahnbetrieb und Bahnverkehr in Großprojekt Stuttgart-Ulm. Presentation at TU Berlin, December 2017.

[136] Jörn Pachl. Betriebliche Rückfallebenen auf Strecken mit selbsttätigem Streckenblock. *Signal & Draht*, 92(7+8):5–9, 2000.

[137] Markus Stang. Realisierung des ERTMS-Piloten auf dem Korridor IV in Rumänien. *Signal & Draht*, 105(7+8):37–41, 2013.

[138] Jens Braband, Bernd-E. Brehmke, Stephan Griebel, Harald Peters, and Karl-Heinz Suwe. *The CENELEC-Standards regarding Functional Safety*. PMC Media House GmbH, 1st edition, 2006.

[139] Tobias Lindner. Entwicklung einer Methode zur Bewertung unterschiedlicher Rückfallebenen. *Signal & Draht*, 104(5):37–39, 2012.

[140] Roland Sölch, Peter Alker, Manuel Hoeft, and Werner Oberländer. Fahrstraßen-Prüfung und -Überwachung (FPÜ) im ESTW L90 am Beispiel Erfurt. *Signal & Draht*, 94(11):16–18, 2002.

[141] Jörn Pachl. Sicherheitsempfehlungen der BEU nach dem Unfall von Bad Aibling. *Deine Bahn*, (3):6–13, 2019.

[142] Jörn Pachl. *Ersatzsignal*. January 2020. Vortrag im Eisenbahnwesen-Seminar an der TU Berlin.

[143] Untersuchungsbericht Bad Aibling–Kolbermoor. Technical report, Bundesstelle für Eisenbahnunfalluntersuchung, Bonn, 2018. Aktenzeichen: 60uu2016-02/005-3323.

[144] Frank Hebel. Konzernrichtlinie 481.0202 – Telekommunikationsanlagen bedienen. Technical report, DB Netz AG, Frankfurt, 2014.

[145] Überblick: Wie der Güterzug länger werden kann. https://www.allianz-pro-schiene.de/themen/aktuell/740-meter-gueterzug/. Accessed: 2020-11-09.

[146] Shift2Rail website. https://shift2rail.org/. Accessed: 2020-11-09.

[147] Roland Sölch, Peter Alker, Manuel Hoeft, and Werner Oberländer. Signalisierter Zugleitbetrieb. *Signal & Draht*, 96(5):16–22, 2004.

[148] Union Internationale des Chemins de fer. UIC Code 406, June 2013.

[149] Company Website. VIA Consulting & Development GmbH. www.via-con.de. Accessed: 2020-11-11.

[150] VIA Consulting & Development GmbH. LUKS – Analysis of lines and junctions. www.via-con.de/development/luks/. Accessed: 2020-11-11.

[151] David Janecek and Frederic Weymann. LUKS – Analysis of lines and junctions. In *Proceedings of the 12th World Conference on Transport Research (WCTR)*, Lissabon, July 2010.

[152] Wulf Schwannhäuser. *Die Bemessung von Pufferzeiten im Fahrplangefüge der Eisenbahn*. PhD thesis, Rheinisch-Westphälische Technische Hoschschule Aachen, Aachen, 1974.

[153] Jens Braband, Bernd-E. Brehmke, Stephan Griebel, Harald Peters, and Karl-Heinz Suwe. *Die CENELEC-Normen zur Funktionalen Sicherheit*. Eurailpress Tetzlaff-Hestra GmbH & Co. KG, 2006.

[154] Maarten Bartholomeus, Bruno van Touw, and Ello Weits. Capacity effects of ERTMS Level 2 from a Dutch perspective. *Signal & Draht*, 103(10):34–40, 2011.

[155] Tobias Lindner, Birgit Milius, Daniel Schwencke, Marcus Arenius, Oliver Sträter, and Karsten Lemmer. Ansätze zur Ableitung der menschlichen Zuverlässigkeit im Eisenbahnwesen. *Signal & Draht*, 104(6):6–11, 2012.

[156] Andreas Steinweg, Jörg Demitz, Thomas Herbst, and Attila Dobrosi. The BEST PRESIM Project: The modernisation of the training system for train controllers at Deutsche Bahn (DB). *Signal & Draht*, 109(11):17–25, 2017.

[157] Peter Hefti and Reto Wagner. Die neue dezentrale Stellwerksarchitektur Sinet im kommerziellen Betrieb der SBB. *Signal & Draht*, 110(5):36–40, 2018.

[158] Andreas Kaldenbach and Alireza Jafari. Digitale Stellwerke bei der DB Netz AG: Auf dem Weg zur Serienreife. *Deine Bahn*, (11):16–20, 2019.

[159] Ralf Laukien. NeuPro at Bombardier – Status and Experience. *IRSE Meeting in Braunschweig*, November 2015.

[160] Michael Meyer zu Hörste. Europäische Vereinheitlichung der Zugbeeinflussung. *Deine Bahn*, (3):29–32, 2008.

[161] Railway applications - Communication, signalling and processingsystems. Technical report, European Committee for Electrotechnical Standardization, Brussels, 2010.

[162] Michael Kunze. *Ein Beitrag zur Systematisierung und Weiterentwicklung der Stellwerks-Energieversorgung*. PhD thesis, Technische Universität Dresden, Dresden, 2015.

[163] Nakku Kima, Jungwook Chob, and Euiseong Seob. Energy-credit scheduler: An energy-aware virtual machine scheduler for cloud systems. *Future Generation Computer Systems*, 32:128–137, March 2014.

[164] Ralph Hintermann. Wachstumsschub durch Cloud Computing – Effizienzgewinne reichen nicht aus: Energiebedarf der Rechenzentren steigt weiter deutlich an. Technical report, Borderstep institut, Berlin, 2020.

[165] Hugues Ferreboeuf, Maxime Efoui-Hess, and Zeynep Kahraman. Lean ICT – Towards Digital Sobriety. Technical report, The Shift Project, Paris, March 2019.

[166] Vincent Blateau, Cécile Lauriac, and André Radomiak. Innovative integration for the deployment of ETCS Level 1 LS. *Signal & Draht*, 108(9):14–21, 2016.