

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

**ON THE TRAIL OF WEST – EAST SIGNALLING INTEROPERABILITY:
A NOVEL PROPOSAL FOR AN STM AND AN INTERFACE FOR ETCS
ONBOARD OPERATING ON CLASS B TRACKSIDE SIGNALLING SYSTEMS**



M.Sc. THESIS

Çağla Kıvılcım ÇİFTÇİOĞLU

Department of Railway System Engineering

Railway Systems Engineering Programme

FEBRUARY 2024

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(526211001)**

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Thesis Advisor: Prof. Dr. Mehmet Turan SÖYLEMEZ

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**BATI – DOĞU ARASI KARŞILIKLI İŞLETİLEBİLİRLİĞİN İZİNDE: ETCS
ARAÇ ÜSTÜ SİSTEMLERİN SINIF B HAT YANI SİNYAL SİSTEMLERİ
ÜZERİNDE ÇALIŞMASI İÇİN YENİ BİR STM VE ARAYÜZ ÖNERİSİ**

YÜKSEK LİSANS TEZİ

**Çağla Kıvılcım ÇİFTÇİOĞLU
(526211001)**

Raylı Sistemler Mühendisliği Anabilim Dalı

Raylı Sistemler Mühendisliği Programı

Tez Danışmanı: Prof. Dr. Mehmet Turan SÖYLEMEZ

ŞUBAT 2024

Çağla Kıvılcım Çiftcioğlu, a M.Sc. student of İTÜ Graduate School student ID 526211001, successfully defended the thesis/dissertation entitled “ON THE TRAIL OF WEST – EAST SIGNALLING INTEROPERABILITY: A NOVEL PROPOSAL FOR AN STM AND AN INTERFACE FOR ETCS ONBOARD OPERATING ON CLASS B TRACKSIDE SIGNALLING SYSTEMS”, which he/she prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

Thesis Advisor : **Prof. Dr. Mehmet Turan SÖYLEMEZ**
İstanbul Technical University

Jury Members : **Prof. Dr. Tankut Acarman**
Galatasaray University

Doç. Dr. İlker Üstoğlu
Istanbul Technical University

Date of Submission : 05 January 2024
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To those whose hearts lie with railways,



FOREWORD

Railway is a concept that strikes a human being at the second of stepping into the rails. It is not only an engineering miracle that takes multi-disciplinary efforts to operate but also a language and a perspective of life. Those whose hearts lie with railways can speak this language and perceive life from a specific mindset. It has been seven years since I first stepped into Rails, and since then, I have found myself reading, talking, and writing about, studying, and working for Railways. Even during holidays, I plan field trips to that country's railway lines. Today, I define myself as a woman who loves working on railways and is passionate about the vital role railways play in society. I am committed to making railways more inclusive and accessible to everyone.

I want to thank my father, Murat Koru, who was the spark of this keen interest. He has broadened my horizon towards railway engineering, specifically towards signalling systems. He still gives me presents of railway books from all over the world and most importantly, he trusts me with long, challenging railway design projects. My father and my mother, as the first engineers I have ever seen in my life, shaped my understanding in life and my ambitions. My mother, Tijen Koru, enabled me to unlock my full potential in life as a women in work life. In fact, she was the one who lead me to choose my profession that I am thankful today. I have learned from them how to be hardworking, passionate, trustworthy and kind. My brother Ali Murat Koru, who is also a passionate, hardworking engineer, supported me dearly; I am very lucky to have him by my side.

I would also like to express my gratitude to Akif Aygen, Bülent Aksoy and Emrah Adal, as their engineering mentorship enriched my perspective on life. Aladdin Bayramov, a supervisor from the Employer, later turned into a dear friend of mine, is my biggest supporter in learning more about the ALSN signalling system and shares the mutual passion for railway signalling.

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Çağla Kıvılcım ÇİFTCİOĞLU
(Electrical and Electronics
Engineer)



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ABBREVIATIONS

A	: Amper
AC	: Alternating Current
AFTC	: Audio Frequency Track Circuits
ALS	: Automatic Locomotive Signalling
ALSN	: Continuous Automatic Train Signalling
AM	: Amplitude Modulated
ANFIS	: Adaptive Network Fuzzy Interference System
ATACS	: Train Administration and Communication System
ATC	: Automatic Train Control
AuC	: Authentication Centre
BG	: Balise Group
BN	: Bayesian Networks
BSC	: Base Station Controllers
BSS	: Base Station Subsystem
BTM	: Balise Transmission Module
BTS	: Base Transceiver Stations
CAD	: Computer-aided design
CCF	: Common Caused Failures
CCS	: Command Control and Signalling
CIS	: Commonwealth of Independent States
CT	: Code transformer
CTC	: Centralised Traffic Centre
CTCS-3	: Chinese Train Control System Level 3
CTMC	: Continuous Time Markov Chains
CTT	: Code track transmitter
CW	: continuous wave
DC	: Direct Current
DMI	: Driver Machine Interface
DPLL	: digital phase-locked loop

EIR	:	Equipment Identification Register
EIRENE	:	European Integrated Railway Radio Enhanced Network
EN	:	European Norms
EoA	:	End of Authority
EOLM	:	End of Loop Marker
EOR	:	European Operating Rules
ERA	:	European Railways Agency
ERTMS	:	European Rail Traffic Management System
ETCS	:	European Train Control System
ETCS	:	European Train Control System
ETML	:	European Traffic Management Layer
EU	:	European Union
EVC	:	European Vital Computer
FFFIS	:	Form Fit Functional Interface Specification
FFFS	:	Form Fit Functional Specification
FPGA	:	Field Programmable Gate Arrays
FRS	:	Functional requirements specification
FSK	:	frequency shift keying
FSM	:	Finite State Machine
FT	:	Fault Trees
G	:	Green
GCR	:	Group Call Register
GPS	:	Global Positioning System
GSMR	:	Global System for Mobile Communications – Railway
HD-ERTMS	:	High Density ERTMS
HLR	:	Home Location Register
Hz	:	Hertz
ID	:	Identification
IF	:	immobilising failure
IRL	:	inductive-rail lines
LEU	:	Lineside Electronic Unit
LR	:	Lithuanian Railways
LRBG	:	Last Relevant Balise Group

LSS	: locomotive safety systems
LTL	: Locomotive Traffic Light
LTM	: Loop Transmission Module
MA	: Movement Authority
MDT	: Mean Down Time
MF	: minor failure
MHz	: Mega Hertz
MHz	: Mega Hertz
MSB	: most significant bit
MSC	: Mobile Switching Centre
MTBF	: Mean time between failures
MTTR	: Mean time to repair
MUT	: Mean Up Time
NEAR2	: Network of European – Asian Rail Research Capacities
NMS	: Network management Subsystem
NSS	: Network Switching Subsystem
NTC	: National Train Control System
OCC	: operational control centre
OMC	: Operation and Maintenance Center
RAM	: Reliability, Availability and Maintainability
RAMS	: Reliability, Availability, Maintainability, and Safety
RBC	: Radio Block Centre
RBD	: Reliability Block Diagrams
RFI	: Rete Ferroviaria Italiana
RL	: rail lines
RTM	: Radio Transmission Module
RY	: Red Yellow
SF	: service failure
SIM	: Subscriber Identity Module
SMS	: Short Message System
SoS	: System of Systems
SRS	: System requirements specification
STM	: Specific Transmission Module

TIU	: Train Interface Unit
TM	: Train Messages
TOA	: Time-of-Arrive
TPN	: Timed Petri Nets
TSI	: Technical Specifications for Interoperability
TTC	: Tonal Track Circuits
UIC	: The International Union of Railways
UML	: Unified Modeling Language
VLR	: Visitor's Location Register
Y	: Yellow



SYMBOLS

Ω/km	:	Ohm per kilometer
$f(x), g(x)$	:	telegram polynomials
b	:	bit
$S_0(t)$	:	Generated pulse signal
$S_1(t)$	:	Modulated ALSN Signal
F_N	:	Carrier Signal Frequency
$S'_1(t)$	:	Transmitted ALSN Signal
$S_2(t)$	:	Distorted ALSN Signal



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ON THE TRAIL OF WEST – EAST SIGNALLING INTEROPERABILITY: A NOVEL PROPOSAL FOR AN STM AND AN INTERFACE FOR ETCS ONBOARD OPERATING ON CLASS B TRACKSIDE SIGNALLING SYSTEMS

SUMMARY

ERTMS (European Rail Traffic Management System) and ALSN (Continuous Automatic Train Signalling) systems are two major signalling systems operating worldwide. ERTMS was presented to the world by Europe. ERTMS signalling system has specifications that aim to unify railway operations, resulting in interoperability between countries. Before publishing such specifications, European Rail Administrations dealt with different requirements and conditions, leading to inflexibility in management processes and inhomogeneous movement control systems. That is why they have proposed a set of specifications called ‘Technical Specifications for Interoperability’ (TSI) to enable seamless cross-border operations. The structural and functional requirements of each sub-system are provided under this directive. This dissertation will focus on TSI for “Command Control and Signalling” (CCS). The ERTMS is considered ETCS as the Class A train protection system. On the other hand, the ALSN signalling system is one of the most operational signalling systems in the world, constituting 10% of the world’s railways. TSI specifications also recognise the ALSN signalling system as one of the Class B train protection systems. Every signalling system has onboard and trackside sub-systems. ERTMS has ETCS onboard and trackside sub-systems; ALSN also has ALSN onboard and trackside sub-systems. TSI specifications define interfaces and modules to allow the operation of Class A onboard signalling systems in railway lines equipped with Class B trackside systems. This kind of module is called a ‘Specific Transmission Module’ (STM) by the TSI specifications. This dissertation proposes a novel STM and interface to allow the operation of rolling stock with ETCS onboard a railway line equipped with an ALSN trackside signalling system. The proposed STM unit is conceptualised as a system architecture, and a new standardised interface is introduced to enable signalling interoperability between ERTMS and ALSN.

A comparative literature review is performed for ERTMS and ALSN signalling systems. The study revealed that the available literature for these two systems mainly focuses on modelling, optimisation, and issues faced during implementation/operation. Additionally, ERTMS has also STM-related literature that proves the availability of efforts for integrating other signalling systems into ERTMS. There is a huge literature gap between these two systems. According to the search query performed in Scopus, the literature of ERTMS dates back to 1968, with 2,208 articles, conference papers, books, etc. ALSN signalling system was developed in the 1930s in the Soviet Union. However, the Scopus search showed that there are only 78 registered works of literature relevant to ALSN.

The major reason is that ERTMS has a set of standards and specifications that are available online to everyone around the world; however, ALSN is a closed system where no standardized approach is available with standards and specifications.

The efforts for modelling the signalling systems did not get enough attention from ALSN; however, for ERTMS, new modelling techniques with different methods are proposed by various studies. The optimisation efforts in ERTMS are more focused on bringing additional features to the already well-defined sub-systems. Some studies are related to optimising one of the most vital communications in ERTMS: communication between balise and balise transmission module. For ALSN, optimisation studies are densely focused on the immunity of ALSN code and optimisation of the system itself. ERTMS literature proposes solutions for the issues raised during the transition period from legacy signalling system to ERTMS. For ALSN, these efforts are more focused on the issues raised during the operations. As defined earlier, there is a “Specific Transmission Module” (STM) that enables ETCS onboard to receive movement authority from the legacy (national) signalling system. These signalling systems might be various, as defined by the list of Class B train protection systems. There are studies that propose new STMs.

The transition period from the legacy signalling system to the ERTMS signalling system is a challenging investment in technical and financial aspects. The investment is required to be made both in the trackside and onboard. New trains need to be acquired, or retrofitting of the existing stock needs to be initiated. Europe is still in the transition period, which is why new developments in STM technology are required, to realise the full potential of the existing railway. Another reason to adopt STM systems is to benefit from the competitiveness of the railway manufacturing market. Since this approach allows the operation of trains with ETCS onboard in other railway lines where a Class B signalling system is under operation, it automatically increases the capacity of the railway line, the internal return rate of the rolling stock investments and decreases the time spent in border crossings.

A proposition of ALSN STM is a gateway to seamless rail transportation between the “Commonwealth of Independent States” (CIS) that connects Europe to Far Asia and South Asia. To the author’s knowledge, STM for ALSN has not been proposed yet. Although Latvia, Lithuania and Estonia are part of the European Union and have the ALSN signalling system as their legacy signalling system, the attempt for an STM has not been made by those countries. Although ALSN is identified as a Class B train protection system by the interoperability technical specifications of the European Union, there is no proposed method to enable the interoperability of these two signalling systems.

To perform the requirement analysis of the newly proposed STM and interface, this dissertation analyses each signalling system’s working principle and sub-components. As the onboard components of ETCS are very crucial for this study, the identified components and their working principles are analysed. The ETCS onboard system has the following sub-components: Driver Machine Interface (DMI), European Vital Computer (EVC) Train Interface Unit (TIU), Balise Transmission Module (BTM), Loop Transmission Module (LTM), Euroradio, Odometry, Train Integrity and Specific Transmission Module (STM). To elaborate on the interface between onboard and trackside, more attention is paid to BTM. The responsibility of BTM is to send a tele-powering signal as a 27MHz Continuous wave signal to activate the balises and to receive the up-link signal generated by balises. The up-link signal received carries the

data called “telegram” in the form of a frequency shift keying (FSK) signal. The received signal demodulates in the BTM unit to be sent to EVC. As the train passes over a balise, BTM telepowers the balise, which initiates the communication between the balise and BTM. The initiated communication results in the transfer of “Uplink data”. The data processing starts in BTM, where it is demodulated to a digital telegram. BTM shares the digital telegram with European Vital Computer (EVC). In EVC, the received data is processed and displayed to train drivers on DMI.

To perform the requirement analysis, ALSN trackside sub-components are identified. The most distinctive component of ALSN trackside is the code track transmitter (CTT) that generates Green (G), Yellow (Y) and Red-Yellow (RY) ALSN codes. These codes are sent to the transmitter relay (TR), where amplitude modulation occurs with a separate AC network connection. The generated codes are given to the rails with a code transformer (CT). Whenever a train enters the block section and triggers the track vacancy detection, the ALSN codes transmission window initiates. There are three types of ALSN codes: Green (G), Yellow (Y) and Red-Yellow (RY). These codes show the signal indication of the signal light that the train is approaching. Each signal aspect has a corresponding sequence of rectangular pulses with intervals.

The required components are separately identified for ETCS onboard and ALSN trackside. For ETCS onboard, the required components are Driver Machine Interface (DMI), Train Interface Unit (TIU), Odometry, European Vital Computer (EVC) and Balise Transmission Module (BTM). For ALSN onboard, the required components are code track transmitter, transmitter relay DC & AC and code transformer. Additionally, the ETCS onboard shall be equipped with the newly proposed ALSN STM.

ALSN STM is designed to be an external type, whereas there is no direct integration to the ETCS onboard Profibus. The requirement analysis shows that ETCS onboard shall be employed as a whole, and its integrity shall not be harmed; however, the external type ALSN STM shall be designed to result in degraded situations rather than safety hazards.

As a result of the requirement analysis, the conceptual system requirements specifications of ALSN STM unit is prepared. The output of the ALSN trackside system will be the input of the ALSN STM unit. The input is AC-modulated DC impulse signals. The output of the unit is going to be the input of the ETCS trackside system. The output of ALSN STM unit will be digital telegrams that will carry the movement authority information. Since the telegram will be generated digitally by ALSN STM, the input will be directly fed into the FPGA board of the BTM unit.

The AC-modulated DC impulse signals will be picked up by the receiving coils of the ALSN STM unit. The received signals will pass through the bandpass filter to eliminate the harmonics and distortions. As ALSN employs rails as a transmission medium, ALSN signals can be attenuated. Considering that the ALSN STM has an amplifier component. For demodulation, the amplified signal will go through a digital pulse converter. At this stage, the ALSN code is transformed into a movement authority. This movement authority information is sent to the conversion unit, where it performs the act of selecting the correct telegram against the received ALSN code. The matched telegram code is generated by the telegram generator and fed into the BTM unit of the ETCS onboard.

This dissertation also proposes a novel interface as Conceptual Form Fit Functional Interface Specification (FFFIS). A novel interface, “E”, is proposed between External ALSN STM to BTM function of ETCS onboard.



BATI – DOĞU ARASI KARŞILIKLI İŞLETİLEBİLİRLİĞİN İZİNDE: ETCS ARAÇ ÜSTÜ SİSTEMLERİN SINIF B HAT YANI SİNYAL SİSTEMLERİ ÜZERİNDE ÇALIŞMASI İÇİN YENİ BİR STM VE ARAYÜZ ÖNERİSİ

ÖZET

ERTMS (Avrupa Demiryolu Trafik Yönetim Sistemi) ve ALSN (Sürekli Otomatik Tren Sinyalizasyonu) sistemleri dünya çapında işletilen başlıca sinyalizasyon sistemlerinden ikisidir. ERTMS, Avrupa tarafından dünyaya sunulan bir sistemdir. ERTMS sinyalizasyon sistemi, demiryolu operasyonlarını birleştirmeyi ve ülkeler arasında ortak işletilebilirliği sağlamayı hedefleyen spesifikasyonlara sahiptir. Bu tür spesifikasyonları yayınlamadan önce, Avrupa Demiryolu İdareleri farklı gereksinimler ve koşullar altında tren işletmeciliği yapmak durumunda kalıyordu. Bu durum ise işletme süreçlerinde esnek ve homojen olmayan hareket kontrol sistemlerinin kullanılmasına yol açıyordu. Bu nedenle, kesintisiz ülke sınırları arasında araç işletmesini mümkün kılmak için Ortak İşletilebilirlik için Teknik Özellikler' (TSI) adı verilen bir dizi spesifikasyon önerilmiştir. Her bir alt sistemin yapısal ve işlevsel gereksinimleri bu direktif kapsamında açıklanmaktadır. Bu tezin en önemli bölümü “Komuta Kontrol ve Sinyalizasyon” (CCS) için TSI'dır. Bu teknik şartname ERTMS içerisinde ETCS'i A Sınıfı tren koruma sistemi kabul eder. Öte yandan ALSN sinyalizasyon sistemi, dünya demiryollarının %10'unu oluşturan, dünyanın en işlevsel sinyalizasyon sistemlerinden biridir. TSI spesifikasyonları ALSN sinyalizasyon sistemini ise B Sınıfı tren koruma sistemlerinden biri olarak kabul etmektedir. Her sinyalizasyon sisteminin araçüstü ve hat yanı alt sistemleri vardır. ERTMS, araçüstü ETCS ve hat yanı ETCS'ten oluşur; ALSN de, araçüstü ALSN ve hat yanı ALSN alt sistemlerine sahiptir. TSI spesifikasyonları, B Sınıfı hat yanı sistemleriyle donatılmış demiryolu hatlarında A Sınıfı araçüstü sinyalizasyon sistemlerinin çalıştırılmasına olanak tanıyan arayüzleri ve modülleri de içeren tanımlar barındırmaktadır. Bu tür modüllere TSI spesifikasyonlarında 'Özel İletim Modülü' (STM) adı verilmektedir. Bu tez, ALSN hat yanı sinyalizasyon sistemi ile donatılmış bir demiryolu hattında demiryolu taşıtlarının ETCS ile çalıştırılmasına olanak tanıyan yeni bir STM ve arayüz önermektedir. Önerilen STM ünitesi bir sistem mimarisi olarak kavramsallaştırılmıştır ve ERTMS ile ALSN arasında sinyalizasyon sisteminin ortak işletilebilirliğini sağlamak için yeni bir standartlaştırılmış arayüz tanıtılmıştır.

ERTMS ve ALSN sinyalizasyon sistemleri için karşılaştırmalı literatür taraması yapılmıştır. Çalışma, bu iki sistem için mevcut literatürün temel olarak modelleme, optimizasyon ve uygulama/işletme sırasında karşılaşılan sorunlara odaklandığını ortaya çıkartmıştır. Ayrıca ERTMS'de, diğer sinyalizasyon sistemlerinin ERTMS'ye entegrasyonuna yönelik çalışmaların varlığını kanıtlayan STM ile ilgili literatür de bulunmaktadır. Ancak, bu iki sistem arasında büyük bir literatür boşluğu bulunmaktadır. Scopus'ta yapılan arama sorgusuna göre ERTMS literatürü 2.208 makale, konferans makalesi, kitap vb. ile 1968 yılından itibaren yayın yapılan bir literatürdür. ALSN sinyalizasyon sistemi 1930'larda Sovyetler Birliği'nde geliştirildi

ancak ALSN ile ilgili literatür çalışmaları Scopus araştırmasında yalnızca 78 kayıt olarak sonuç vermektedir. Bunun ana nedeni, ERTMS'nin dünya çapında herkesin çevrimiçi olarak erişebildiği bir dizi standart ve spesifikasyona sahip olmasıdır; ancak ALSN, standartlar ve spesifikasyonlarla standartlaştırılmış bir yaklaşımın mevcut olmadığı kapalı bir sistemdir.

Sinyalizasyon sistemlerinin modellenmesine yönelik çalışmalar konusunda ALSN'nin yeterince ilgi görmediği anlaşılmaktadır; ancak ERTMS için çeşitli çalışmalarla farklı yöntemlerle yeni modelleme tekniklerinin önerildiği görülmüştür. ERTMS'deki optimizasyon çalışmaları daha çok halihazırda iyi tanımlanmış alt sistemlere ek özellikler getirmeye odaklanmıştır. Bazı çalışmalar ERTMS'deki en hayati iletişimlerden biri olan baliz ve baliz iletim modülü (BTM) arasındaki iletişim optimize edilmesiyle ilgilidir. ALSN için optimizasyon çalışmaları yoğun olarak ALSN kodunun bağımsızlığına ve sistemin optimizasyonuna odaklanmaktadır. ERTMS literatürü, eski sinyalizasyon sisteminden ERTMS'ye geçiş sürecinde ortaya çıkan sorunlara çözüm önermektedir. ALSN için bu çabalar daha çok işletme sırasında ortaya çıkan konulara odaklanmaktadır. Daha önce tanımlandığı gibi, araüstü ETCS'nin eski (ulusal) sinyalizasyon sisteminden hareket yetkisi almasını sağlayan bir “Özel İletim Modülü” (STM) bulunmaktadır. Bu sinyalizasyon sistemleri, B Sınıfı tren koruma sistemleri listesinde tanımlandığı gibi birden fazla olabilir. Literatürde de yeni STM'leri öneren çalışmaların mevcut olduğu görülmüştür.

Eski sinyalizasyon sisteminden, ERTMS sinyalizasyon sistemine geçiş süreci, teknik ve mali açıdan zorlu bir yatırımdır. Yatırımın hem hat yanında hem de araüstü sistemlerde yapılması gerekmektedir. Yeni trenlerin ve demiryolu araçlarının satın alınması veya mevcut araçların bu sistemlere uyumlu olarak yenilenmesini gerektirir. Avrupa hâlâ geçiş döneminde olduğundan, mevcut demiryolunun tam potansiyelini ortaya çıkarabilmek için STM teknolojisinde yeni gelişmelere ihtiyaç duyulmaktadır. STM sistemlerini benimsemenin bir diğer nedeni de demiryolu ürün üreticilerinin rekabet gücünden yararlanmaktır. Bu yaklaşım, B sınıfı sinyalizasyon sisteminin işletildiği diğer demiryolu hatlarında da ETCS araüstüne sahip trenlerin çalıştırılmasına olanak sağladığından, demiryolu hattının kapasitesini, demiryolu araçlarına yapılan yatırımlarının geri dönüş oranını otomatik olarak artırmakta ve demiryolu hattında ülke sınır geçişlerinde harcanan zamanları azaltmaktadır.

ALSN STM önerisi, Avrupa'yı Uzak Asya ve Güney Asya'ya bağlayan “Bağımsız Devletler Topluluğu” (CIS) üyesi ülkelerden geçen ve kesintisiz demiryolu taşımacılığına açılan bir kapıdır. Yazarın bildiği kadarıyla ALSN için STM henüz önerilmemiştir. Letonya, Litvanya ve Estonya Avrupa Birliği'nin bir parçası olmasına ve eski sinyalizasyon sistemi olarak ALSN sinyalizasyon sistemine sahip olmasına rağmen, bu ülkeler tarafından bir STM girişiminde bulunulmamıştır. ALSN, Avrupa Birliği'nin ortak işletilebilirlik teknik şartnamesi tarafından B Sınıfı tren koruma sistemi olarak tanımlansa da, bu iki sinyalizasyon sisteminin ortak işletilebilirliğini sağlayacak olan önerilmiş bir yöntem bulunmamaktadır.

Yeni önerilen STM ve arayüzün gereksinim analizini gerçekleştirmek için bu tez, her bir sinyalizasyon sisteminin çalışma prensibini ve alt bileşenlerini analiz etmektedir. ETCS'nin araüstü bileşenleri bu çalışma için çok önemli olduğundan, belirlenen bileşenler ve çalışma prensipleri analiz edilmiştir. ETCS araüstü sistemi Sürücü Makine Arayüzü (DMI), Avrupa Hayati Bilgisayarı (EVC) Tren Arayüz Birimi (TIU), Baliz İletim Modülü (BTM), Döngü İletim Modülü (LTM), Euroradyo, Odometri, Tren Bütünlük ve Özel İletim Modülü (STM) adlı alt bileşenlere sahiptir. Araüstü ve

hat yanı sistemleri arasındaki arayüzü detaylandırmak için BTM'ye daha fazla dikkat edilmiş ve daha detaylı incelenmiştir. BTM'nin sorumluluğu, balizleri aktive etmek için üretilen uyandırma sinyalini 27MHz sürekli dalga sinyali olarak göndermek ve balizler tarafından üretilen cevap sinyalini almaktır. Alınan cevap sinyali, frekans kaydırmalı anahtarlama (FSK) sinyali formunda “telegram” adı verilen verileri içerir. Alınan sinyal, EVC'ye gönderilmek üzere BTM ünitesinde demodüle edilir. Tren bir balizin üzerinden geçerken, BTM balise uyandırma sinyali vererek baliz ile BTM arasındaki iletişimi başlatır. Başlatılan iletişim “cevap sinyali verilerinin” aktarılmasıyla sonuçlanır. Veri işleme, dijital bir telegramın demodüle edildiği BTM'de başlar. BTM, dijital telegramı EVC ile paylaşır. EVC'de alınan veriler işlenir ve sürücüler için DMI'da görüntülenir. BTM, alınan sinyalden coğrafi konum, rota bilgileri ve hız sınırlama bilgilerini çıkarır.

İhtiyaç analizini gerçekleştirmek için ALSN hat yanı alt bileşenleri tanımlanır. ALSN hattının en ayırt edici bileşeni, Yeşil (G), Sarı (Y) ve Kırmızı-Sarı (RY) ALSN kodlarını üreten ray kod vericisidir (CTT). Bu kodlar, genlik modülasyonunun ayrı bir AC bağlantısıyla gerçekleştiği verici rölesine (TR) gönderilir. Üretilen kodlar kod trafosu (CT) ile raylara verilir. Bir tren blok bölümüne girdiğinde ve ray boşluğu tespitini tetiklediğinde, ALSN kodları iletim penceresi başlatılır. Üç tür ALSN kodu vardır: Yeşil (G), Sarı (Y) ve Kırmızı-Sarı (RY). Bu kodlar trenin yaklaştığı sinyal ışığının sinyal göstergesini gösterir. G yeşil, Y sarıyı ve RY kırmızıyı gösterir. Ray kod vericisi, sinyal yönü bilgisini alır ve karşılık gelen kod için DC vericisi ile bir kare sinyal kombinasyonu üretir. Her sinyal göstergesine karşılık gelen kare kod dizisi mevcuttur.

Gerekli bileşenler, araçüstü ETCS ve hat yanı ALSN için ayrı ayrı tanımlanır. Araçüstü ETCS için gerekli bileşenler Sürücü Makine Arayüzü (DMI), Tren Arayüz Birimi (TIU), Odometri, Avrupa Hayati Bilgisayarı (EVC) ve Baliz İletim Modülüdür (BTM). Hat yanı ALSN için gerekli bileşenler ray kod vericisi, DC ve AC verici rölesi ve kod transformatörüdür. Ek olarak, araçüstü ETCS yeni önerilen ALSN STM'ye sahip olmalıdır.

ALSN STM harici tipte olacak şekilde tasarlanmıştır, böylece araçüstü Profibus ETCS'ye doğrudan entegrasyonu yoktur. TSI CCS, performans seviyesi ve güvenlik seviyeleri açısından ETCS hat yanı ve araçüstü için çok önemli bir gerekliliğe işaret etmektedir. Bu sistemlerin güvenlik bütünlüğü seviyesi EN50129'da tanımlandığı gibi SIL4 olacaktır. Spesifikasyon ayrıca araçüstü ETCS gerekliliğinin çok katı olduğunu belirtirken, ETCS hat yanı sisteminin daha esnek olarak tanımlandığını belirtmektedir. TSI CCS, ETCS hat yanı arızalarının güvenlik tehlikelerinden ziyade çalışma modunun bozulmasına yol açacağını belirtmektedir. ALSN hattını kullanan ALSN STM entegrasyonu performans, işlevler ve güvenlik açısından bu gereklilikleri dikkate alacak şekilde tasarlanmıştır. İhtiyaç analizi, araçüstü ETCS'nin bir bütün olarak kullanılması gerektiğini ve bütünlüğünün bozulmaması gerektiğini işaret etmektedir. Harici tip ALSN STM, güvenlik tehlikelerinden ziyade daha kötü durumlarla sonuçlanacak şekilde tasarlanmıştır ve tasarlanmalıdır.

İhtiyaç analizi sonucunda ALSN STM ünitesinin kavramsal sistem gereksinimleri spesifikasyonu hazırlanmıştır. ALSN hat yanı sisteminin çıktısı, ALSN STM ünitesinin girdisi olacaktır. Girdi, AC modülasyonlu DC kare kod sinyalleridir. Ünitenin çıktısı ise ETCS hat yanı sisteminin girdisidir. ALSN STM ünitesinin çıktısı hareket yetki bilgisini taşıyacak dijital telegramlardır. Telegram ALSN STM

tarafından dijital olarak üretileceği için girdilerin doğrudan BTM ünitesinin FPGA kartına iletilmesi planlanmıştır.

AC modülasyonlu DC kare kod sinyalleri, ALSN STM ünitesinin alıcı bobinleri tarafından alınacaktır. Alınan sinyaller, harmonikleri ve bozulmaları ortadan kaldırmak için band geçiren filtreden geçecektir. ALSN iletim ortamı olarak rayları kullandığından ALSN sinyalleri zayıflamış bir şekilde bobine ulaşabilmektedir. ALSN STM'nin amplifikatör bileşenine sahip olmasının nedenide bu zayıflamanın önüne geçmektir. Demodülasyon için güçlendirilmiş sinyal dijital kare kod dönüştürücüsünden geçecektir. Bu aşamada ALSN kodu hareket yetkisine dönüştürülür. Bu hareket yetki bilgisi dönüşüm ünitesine gönderilir ve alınan ALSN koduna göre doğru telegramın seçilmesi işlemini gerçekleştirir. Eşleşen telegram kodu, telegram oluşturucu tarafından oluşturulur ve yerleşik ETCS'nin BTM ünitesine beslenir.

Bu tez aynı zamanda Kavramsal Form Uyum Fonksiyonel Arayüz Spesifikasyonu (FFFIS) olarak yeni bir arayüz önermektedir. ERTMS sinyalizasyon sisteminin tanımlı arayüzleri “A”, “C”, “S”, “G” ve “K” arayüzleridir. K ve G arayüzleri farklı B Sınıfı hat yanı STM'ler için kullanılır. A arayüzü baliz ile anten ünitesi arasındaki hava boşluğu arayüzüdür. C arayüzü, baliz ve Hat Yanı Elektronik Birimi (LEU) arasındaki arayüzdür. S arayüzü LEU ile sistemin anlaşılanı arasındadır. Tanımlanan bu arayüzlerin hiçbiri ALSN STM entegrasyonu için geçerli değildir. Hat yanı ALSN STM ile araçüstü ETCS'nin BTM işlevi arasında yeni bir “E” arayüzü önerilmektedir.

Avrupa'yı Asya'ya bağlayan tüm uluslararası demiryolu koridorları göz önüne alındığında, ERTMS'den ALSN'ye sinyalizasyon geçişinin bir zorunluluk olduğu görülmüştür. NEAR (Avrupa – Asya Demiryolu Araştırma Kapasiteleri Ağı) adlı proje, Avrupa Birliği tarafından tüm Trans-Avrasya Demiryolu Ağlarının belirlenmesi amacıyla kurulmuştur. Tanımlanan rotaların tümü, ERTMS'den ALSN'ye veya tam tersi sinyalizasyon sistemi geçişini gerektirir. Bu analiz, ALSN STM'nin uyumsuzlukları ve eksikliği nedeniyle Avrupa – Asya Demiryolu ağlarındaki sınır ötesi operasyonlarda zorluklar, gecikmeler ve mali kayıpların yaşandığını göstermektedir. Yeni önerilen ALSN STM ile bu uluslararası demiryolu ağları boyunca demiryolu taşımacılığının rekabet gücü artırılabilir. Ülkeler arası işletme açısından tam etkileri, mali kayıplar, yolcu ve yük taşımacılığındaki potansiyel artışın başka bir araştırmanın konusu olması araştırma açısından faydalı olacaktır.

Bakü – Tiflis – Kars (BTK) demiryolu hattı, 3 ülkeyi (Azerbaycan, Gürcistan ve Türkiye) birbirine bağlayan TRACECA koridorunun bir parçası olarak ERTMS – ALSN geçişine güzel bir örnektir. Yapım ve rehabilitasyon çalışmaları için yaklaşık 600 Milyon Dolar yatırım bütçesi planlanmış olan bir demiryolu hattıdır. Bu ülkeler arasındaki temel sorun ortak işletilebilirlik ile ilgilidir. Türkiye demiryollarını ERTMS sinyalizasyon sistemiyle işletirken, Gürcistan ve Azerbaycan demiryolu hatlarını ALSN sinyalizasyon sistemiyle işletmektedir. Bağlantı hatlarının elektrifikasyon durumu da farklıdır. Türkiye bağlantı hattı elektriksiz (Kars – Çıldır tüneli), Gürcistan bağlantı hattı 3kV DC elektrifikasyonlu, Azerbaycan bağlantı hattı Bakü – Büyük Kesik ise 25 kV AC elektrifikasyonludur. Tüm bu farklılıkların yanı sıra Azerbaycan ve Gürcistan'ın ekartmanı 1520 mm iken Türkiye'nin ekartmanı ise 1435 mm'dir. Ülkeler bu önemli farklılıkları göz önünde bulundurarak önlem almış ve buna göre yatırım yapmıştır. Ekartmanlar arası farklılık için Gürcistan'ın Akhalkalaki istasyonunda otomatik ekartman değiştirme tesisi kurulmuştur. Azerbaycan'da elektrifikasyonlar arasındaki fark için Gürcistan sınırında AC-DC değiştirme tesisi

bulunmaktadır. Ayrıca hem AC hem de DC elektrikli hatlarda faaliyet gösterebilen araçlar Azerbaycan demiryolları tarafından temin edilmiştir. Tesislere, demiryolu araçlarına ve inşaatlara yapılan tüm bu yatırımlar, ortak işletilebilirliği artırmak için yapılmaktadır. Ancak, uygulanabilir bir çözümün mevcut olmaması nedeniyle sinyalizasyon ile ilgili ortak işletilebilirlik konusu hali hazırda eksiktir. Önerilen ALSN STM ve arayüzü, Bakü – Tiflis – Kars demiryolu hattı için de oldukça faydalı olacaktır.

Mali ve operasyonel sonuçları anlamak için benzer bir demiryolu hattına karşılaştırmalı bir yaklaşımın faydalı olacağı düşünülmüştür. München-Verona demiryolu hattı İtalya, Avusturya ve Almanya'yı birbirine bağlamaktadır. Bu demiryolu bölümü İskandinav-Akdeniz Ana Ağı ve Demiryolu Yük Koridoru 3 üzerinde yer almaktadır. Verona – Brennero 3kV DC ve Brennero – Münih 15 kV AC elektrikli olduğundan durum BTK demiryolu hattına çok benzer görülmüştür. Sinyalizasyon sistemi İtalya bölümü boyunca SCMT, Avusturya bölümü boyunca ERTMS ve Almanya tarafı boyunca PZB'dir. Bu önemli hususlar München – Verona demiryolu hattının BTK demiryolu hattı ile kıyaslanabilir nitelikte olduğunu göstermektedir. ERA (Avrupa Demiryolu Kurumu), bu bölüme ERTMS sinyalizasyonuna sahip ve 25kV & 15 kV AC elektrifikasyona sahip 55 km uzunluğunda Brenner Base Tüneli yatırımı yapmaya karar vermiştir. Bu yatırım ayrıca bir yatırımın ortak işletilebileceğini sağlayacak boyutlarını da göstermektedir. ERA'nın raporuna göre sınır ötesi operasyonda her yıl tren başına 399 dakika, tren başına ise yaklaşık 500 Euro kayıp yaşandığını göstermektedir. Yatırım kararının kendisi, birlikte çalışabilirliğin sağlanmasının milyarlarca Euro vaat ettiğini göstermektedir. Karşılaştırmalı yaklaşım, sistemler arasındaki geçiş sorunlarının yarattığı kaybı göstermiştir. Tespit edilen kayıplar 55 km uzunluğundaki Brenner Base tünelinin yatırımı ile sonuçlanmıştır. Bu, kesintisiz sınır ötesi operasyonun ve ALSN STM teklifinin önemini daha da vurgulamaktadır.



1. INTRODUCTION

1.1 Railway Signalling Systems in the World

Railway signalling systems are developed to enable safe train operation. The interlocking of signal lights and point machines was started around 1870. The primary purpose behind the efforts is to minimise human mistakes and increase safety. Train protection systems are developed to serve this purpose by supervising the driver and intervene whenever necessary. The functions of train protection systems are cab signalling, supervision and intervention. Around the World, many different signalling systems ensure train protection. The available systems can be categorised under five categories based on their function and transmission type. Group 1 is systems with intermittent transmission and without braking supervision, Group 2 is systems with intermittent transmission at low data volume and with braking supervision, Group 3 is systems with continuous transmission of signal aspects by coded track circuits, Group 4 is systems with intermittent transmission at high data volume and dynamic speed supervision and Group 5 is systems with continuous transmission at high data volume and dynamic speed supervision. From Groups 1 to 5, the signalling system is getting more advanced and complex(Theeg & Vlasenko, 2020).

Group 1 signalling systems have two functions; driver's attentiveness and automatic train stop if caution is passed. French Crocodile is considered in this group where France, Belgium and Luxembourg use it. British Automatic Warning System (AWS) is another group 1 system adopted by Britain, India and Pakistan. Additionally, there is Swiss signum as the Swiss train protection system; however, it was overhauled in 2018. Group 2 adds braking supervision to the functions offered by Group 1. The data transmission is performed with a resonant circuit with specific frequencies. The Indusi / PZB90 is considered in Group 2, whereas Germany, Austria, and the former Yugoslavia adopted it. Japanese AST-P is also a system categorised in Group 2. The Japanese system's data transmission is also realised with frequencies generated by resonant circuits. Polish KHP and Spanish ASFA are also in Group 2. Group 3

signalling system additionally provides information on the next signalling aspect of the cab. This information is generated with the coded track circuits used for track vacancy detection. ALSN signalling system is categorised under this group, constituting 10% of the world's railways. USA, Italy, Czech Republic, Slovakia and Hungary also employ signalling systems under Group 3. EVM is the signalling system of Hungary. ATB-EG also uses coded track circuits as the Netherlands 'one of the older signalling systems. The Italian BACC system is used for railway lines up to 200 km/h as a member of Group 3 signalling systems. Japanese ATC and French TVM300 are developed for high-speed railway operation in the same category. Group 4 envisages intermittent transmission with high-volume data and performs dynamic speed supervision. These systems employ different balises that allow on-spot transmission of location reference and switchable data that reflects the status of the track. Examples of this group are ERTMS Level 1 (international), Ebicab (Bulgaria), TBL(Belgium), ZUB(Switzerland, Denmark), and KVB (France). Group 5 enables continuous transmission of high-volume data with dynamic speed supervision. The continuous transmission is provided by either cable loop, radio transmission or coded track circuits. ERTMS Levels 2, 3 and CTCS 3, 4 (Chinese Train Control System) are the signalling systems that provide continuous radio communication.

This research is focused on two different signalling systems from Group 4 and Group 3 categories, respectively ERTMS and ALSN signalling. ERTMS is an international signalling system developed for continuous cross-border train operations across Europe. The ALSN signalling is one of the most operational signalling systems in the world. It is adopted in many railway lines along the international corridors connecting Europe to Asia. This study aimed to propose a method that enables seamless cross-border operation between the countries that are adopted the ERTMS and ALSN signalling. In other words, to propose an STM that allows the operation of a train with ETCS onboard on the railway line equipped with an ALSN signalling system.

This study is organised as follows. The principles of ERTMS and ALSN signalling systems are introduced in the introduction. The available research on both signalling systems is analysed and categorised in the literature review. The comparative discussion regarding the focus on the available research on both systems is also provided in this section. The methodology presents the block diagram of the ERTMS and ALSN signalling system and describes each sub-component. In that section, the

concept of signalling interoperability is described. The proposed method is presented in the following section with the requirement analysis. The proposed method section discusses the system and interface's conceptual requirements. The applicable international railway corridors are identified in the same section, and possible financial implications are envisaged. The last section delivers conclusions, a summary, and brief recommendations for future studies.

1.2 European Railway Traffic Management System (ERTMS) Principles

Achieving a certain competitiveness for railway transportation depends on factors based on the location and available alternatives. However, there are common factors that majorly increase the competitiveness of rail transport. One of them is efficient cross-border operation. Europe has more than 20 signalling systems on the existing railway network. As a common economic area, Europe has to operate the cross-border movement of goods and people. Considering this need, a Thalys train set, for example, used to be equipped with seven different onboard systems, namely; PZB/Indusi (Germany), LZB(Germany), TVM (France), KVB(France), TBL (Belgium), Crocodile (Belgium) and ATB (The Netherlands)(Baggen et al., 2008). This highly complicated the railway operation and maintenance and increased the cost of initial investments and maintenance and operation costs for the whole lifetime of the project. This situation also posed safety-critical risks for train operations. ERTMS was proposed to solve the abovementioned issues with a harmonised and standardised approach.

Within many train control systems, ERTMS unifies railway operations, resulting in interoperability between countries. Before the availability of such a specification, multiple European Rail Administrations were applying different requirements and conditions, leading to inflexibility in management processes and inhomogeneous movement control systems. The first attempt was made with Directive 96/48/EC in 1996 to increase safety, competitiveness and track utilisation (Ghazel, 2014). This directive obliges Rail Administrations to replace all new high-speed lines with ERTMS. For conventional lines, the obligation of replacement was limited to within half a year by the published “Technical Specifications for Interoperability” (Directive 2001/16/CE). In 2008, Directive 2008/57/EC was published with the entire requirement of compatibility for infrastructure and vehicles and their connection and

security levels. Based on this directive, TSI was amended with in 2009. (Młyńczak et al., 2016) The latest directive was published on 2016 with Directive (EU) 2016/797. All specifications envisage not only interoperability for newly constructed railway lines but also the compatibility of the existing lines. The primary understanding of interoperability defined with these specifications is mainly based on the compatibility of the infrastructure, power supply, train control and communication system, traffic management principles and rolling stock. This article focuses on “Command Control and Signalling” (CCS) interoperability. The ERTMS is considered the Class A train protection system. ERTMS system has two components; ETCS, the onboard trains and infrastructure installations, and GSMR, a communication system between ETCS onboard and track infrastructure. With that directive, the first version of ERTMS specification was published in 2007 with Functional Requirement Specifications (FRS) for interoperability and System Requirement Specifications (SRS) for ETCS(Ghazel, 2014). The core network corridor equipped with the ERTMS signalling system is 8,100 km. The length of ongoing railway projects that will commission the ERTMS system is twice more than the existing lines. The complete number of contracted rolling stock with the ERTMS onboard system was more than 8,250 at the end of 2020. (Agencia de Ferrocarriles de la Unión Europea., 2022a).

The original ERTMS specifications consist of “European Train Control System (ETCS)”, “Global System for Mobile Communications – Railway (GSM-R)”, and “European Traffic Management Layers (ETML)”. Although ETCS and GSMR specifications were finalised and published in 2008, ETML was abandoned due to different expectations from different Rail Administrations were raised. The main principles of ETCS are to provide all the available functions of available train control systems, to ensure the possibility of cooperation with vehicles and infrastructure and to ensure traffic management within the requirements and regulations of relevant Rail Administrations. The objectives of ETCS, on the other hand, are to provide cross-border railway operation, reduce investment and operation costs and increase market competitiveness. The ETCS component is digital signal transmission between infrastructure and rolling stock. For transmission to occur, ETCS provides multiple options such as Eurobalise, Euroloop, digital radio channel (GSMR) and specialised transmission modules (STM) that enable communication between national systems. Operational levels of ETCS are Levels 1,2, and 3, whereas there are also auxiliary

levels such as Level 0 and Level STM. Interlevel operation is only available where a train equipped with a Level 2 onboard system can operate in Level 1 equipped infrastructure. However, vice versa is not possible. (Młyńczak et al., 2016) ETCS has interfaces with GSMR radio system, trackside systems and on-board train equipment. The onboard train equipment Eurocab has transmission modules and an antenna for receiving information from trackside equipment such as Eurobalise, Euroloops or GSMR equipment. For each interface option, there are interface specifications in ETCS, namely, Functional Interface Specifications (FIS), which is for logical interoperability and Form Fit Function Interface Specification (FFFIS), which is both for logical and physical interoperability. FFFIS refers to data transmission using Eurobalise, Euroloops, interface for STM to Eurocab, interface for Juridical Recording Unit (JRU) as well as Train Interface Unit (TIU), Driver Machine Interface (DMI), the interface between Radio Block Centre to Radio Block Centre (RBC) and key management centre. The system functions for ERTMS devices include Balise/loop transmission support, train location definition, route determination and its properties, dynamic speed monitoring and other external functions. (Młyńczak et al., 2016) The primary operational function of the system is the calculation and control of braking curves as well as calculating safe speed and intervening if it is exceeded. This function requires route-related information and train data such as vehicle weight, maximum axle load, maximum allowed speed and braking system parameters. The needed route change information must be present in time and space. This information is also referred to as received authorisation which defines movement authority. This authorisation is received by the infrastructure to vehicle transmission channels. These primary objectives, interfaces and functions are transferred to operational levels and configurations as mentioned earlier by the specifications.

ERTMS has operational levels that define the operation and how interlocking communicates with infrastructure and rolling stock. The levels ETCS systems define are Level 0, Level STM(NTC), Level 1, Level 2 and Level 3. These system levels employ different combinations of trackside equipment. The ETCS onboard system has downwards compatibility, meaning the Level 2 onboard system will be operational in the Level 1 equipped railway line.

The ETCS trackside equipment includes; lineside signals, Balise (eurobalise), lineside electronic unit (LEU), radio communication centre (RBC), radio communication network (GSMR), euroloop and radio infill units. The employment of each trackside equipment per ERTMS Level is provided in Table 1.1.

Table 1.1: The employment of trackside equipment at each ERTMS operational level.

Level	0	STM (NTC)	1	2	3
Lineside Signals	✓	✓	✓	Not needed	Not needed
Balise	Another system	STM Balise	Fixed and Switchable	Fixed	Fixed
RBC	✗	✗	✗	✓	✓
GSMR	✗	✗	Partially or ✗	✓	✓
LEU	✗	✗	✓	✗	✗
Euroloop	✗	✗	✓	✗	✗
Radio Infill Units	✗	✗	✓	✗	✗

This sub-section aims to introduce the ERTMS operational level and ETCS operation modes.

1.2.1 ERTMS level 0

ERTMS Level 0 does not include any ETCS trackside equipment; it is defined as ETCS onboard system. The railway section does not have ERTMS signalling or any other legacy signalling system. The only supervision that can be performed by the ETCS onboard is to supervise the maximum speed if it were entered into the onboard system beforehand (ERA UNISIG SS26-2, 2016). The train driver is driving with the help of signal lights, and the driver can monitor the speed from DMI (Driver Machine Interface). Level 0 can also be used for the operation of lines whose commissioning of ERTMS has not been finalised (ERA UNISIG SS26-2, 2016). All the railway signalling system functions are out of the scope of ERTMS. The responsibility belongs to the train driver. Figure 1.1 shows the ERTMS level 0 operation. A track vacancy detection system can be either a track circuit or an axle counter; Figure 1.1 shows a track circuit and lineside equipment that might be used for another legacy signalling system. In ERTMS Level 0 operation, the assumption is that there is no STM

connected to the ETCS onboard to allow communication with the underlying signalling system.

ERTMS LEVEL 0

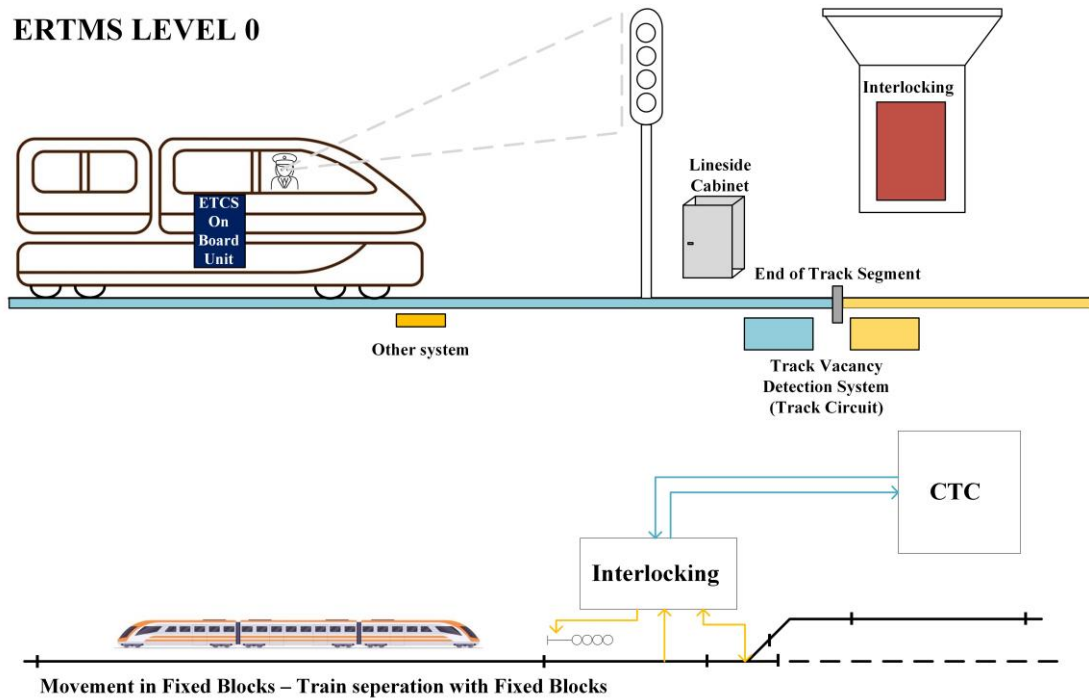


Figure 1.1: ERTMS Level 0, railway line configuration and system architecture.

The ETCS trackside components are non-existent. The ETCS onboard functions are supervision of maximum speed, reading of balises to detect ETCS Level transition and reading specific commands from that balise if available. No cab signalling is available at this level. In Level 0, the primary signalling system architecture will include bi-directional communication between CTC and interlocking and interlocking will command the other lineside components based on the track vacancy and position of movable track elements. The railway section must be divided into fixed block sections for the train to operate.

1.2.2 ERTMS level STM (NTC)

For ERTMS Level STM, there is a particular module in the onboard system called Specific Transmission Module. This module provides an interface between the legacy signalling system and ETCS onboard system. The main difference between Level 0 and Level STM is that the onboard system can reach the legacy train control system. The underlying signalling trackside would be defined in Level 0; however, with STM (Specific Transmission Module), communication between the onboard and legacy signalling system is enabled.

DMI system will provide the information received from STM, which is usually cab signalling information, speed restriction, and end of movement authority. As depicted in Figure 1.2, the ETCS onboard unit is connected to STM. The Specific Transmission Module acts like a translator at this level (ERA UNISIG SS26-2, 2016).

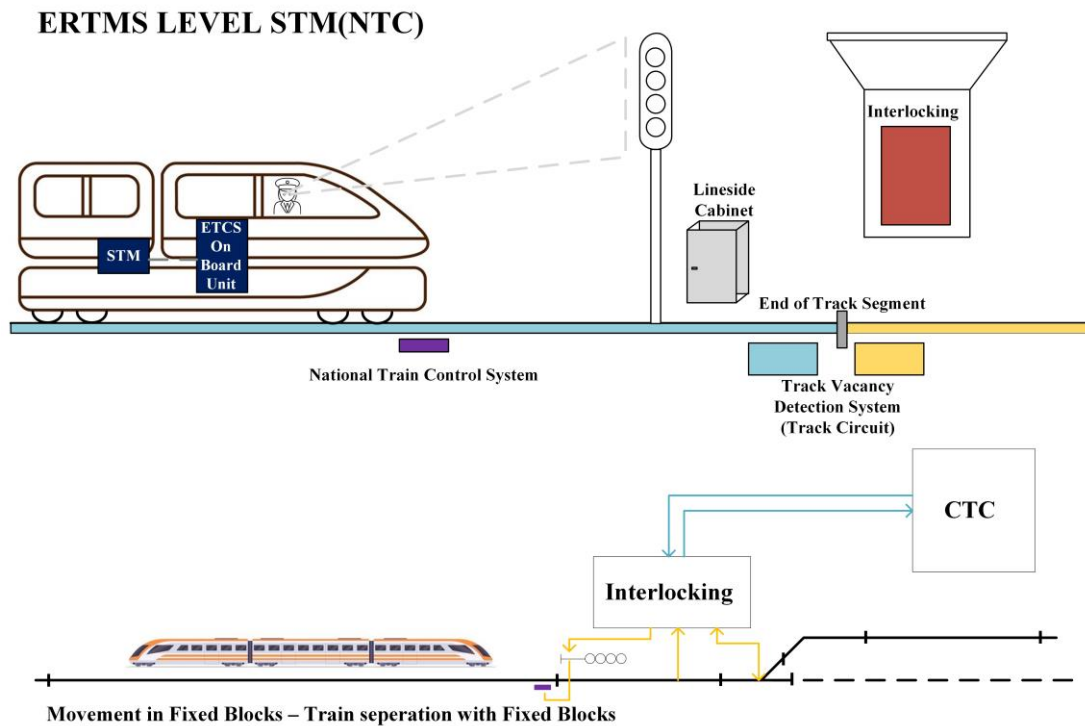


Figure 1.2: ERTMS Level STM(NTC) railway line configuration.

In Level STM, there is no ETCS trackside equipment. The ETCS onboard functions are management through STM and legacy signalling system and reading of balises to detect ETCS Level transition and, if available, reading specific commands from that balise. The cab signalling is not available. The onboard does not supervise; all supervision-related activities are left to the legacy signalling system. No cab signalling is available. The most critical issue with this level is that no specific standard defines systems supervision degree or continuous/intermittent communication. Operations safety is critically dependent on the underlying system. ETCS does not provide any train supervision. The system transition will be made by ETCS onboard system to read the switchable balise.

1.2.3 ERTMS level 1

The main target of Level 1 is to ensure rolling stock stays within the established route with allowed speed. Level 1 ETCS onboard contains European Vital Computer (EVC), in other words, onboard computer, maintenance computer, Driver Machine Interface (DMI), recorder, the route and time measuring device (odometer) and balise transmission module that all components are connected with ETCS-bus. GSMR antenna and loop transmission module are optional for Level 1 equipped locomotives. The GSMR antenna may be employed for bi-directional infrastructure–vehicle communication. Level 1 has two types of infrastructure component configuration; without and with infill functions. Fixed balises are the common elements for these two configurations as they give location-specific information. The level 1 configuration without the infill function has a spot transmission system. Switchable balises have made the transmission along the way. Train does not know the signal's information before passing through the related switchable balise. This configuration has fixed balises, switchable balises and LEUs as ETCS infrastructure components. Switchable balises are generally located around the lineside signals. Switchable balise receives the current signal aspect information from LEU and provides this data to the ETCS onboard system as a telegram. The train will receive the movement authority and end of authority from the switchable balise for the on-spot transmission system. After the train passes through that balise group, even though the next signal has turned green, it will begin braking if it does not receive the proceed command (Stanley, 2011).

However, the second configuration with the infill function has been designed to overcome that problem with the semi-continuous transmission. In this configuration, there are two options for providing semi-continuous transmission to ETCS on-board system: Euroloops or radio infill. These two options can provide information related to the current signal aspect before passing through the balise group within a certain distance; that is why it is called semi-continuous (Stanley, 2011). This eliminates the unnecessary braking caused by on-spot transmission and helps increase the railway line's availability. For this option, lineside signals are optional. In Figure 1.3, each configuration is provided.

ERTMS Level 1 is initially intended for secondary low-traffic railway lines. However, Level 1 is operational in most European countries, even on high-speed lines. Level 1 with updating additionally includes point basis or sectional basis update points either

with more Eurobalises or Euroloops. In that case, information update by the national system via STM is also possible. ETCS trackside includes fixed balises that transfer the track description, switchable balises that transmit variable information of movement authority, and LEU that reads the current signal aspect and send the related telegram to the switchable balise. Based on the interlocking functions of the underlying signalling system, the ETCS trackside system determines movement authority (MA), transmit MA and track description data to train. The euroloop or radio infill units provide semi-continuous transmission for the in-fill option.

ERTMS LEVEL 1

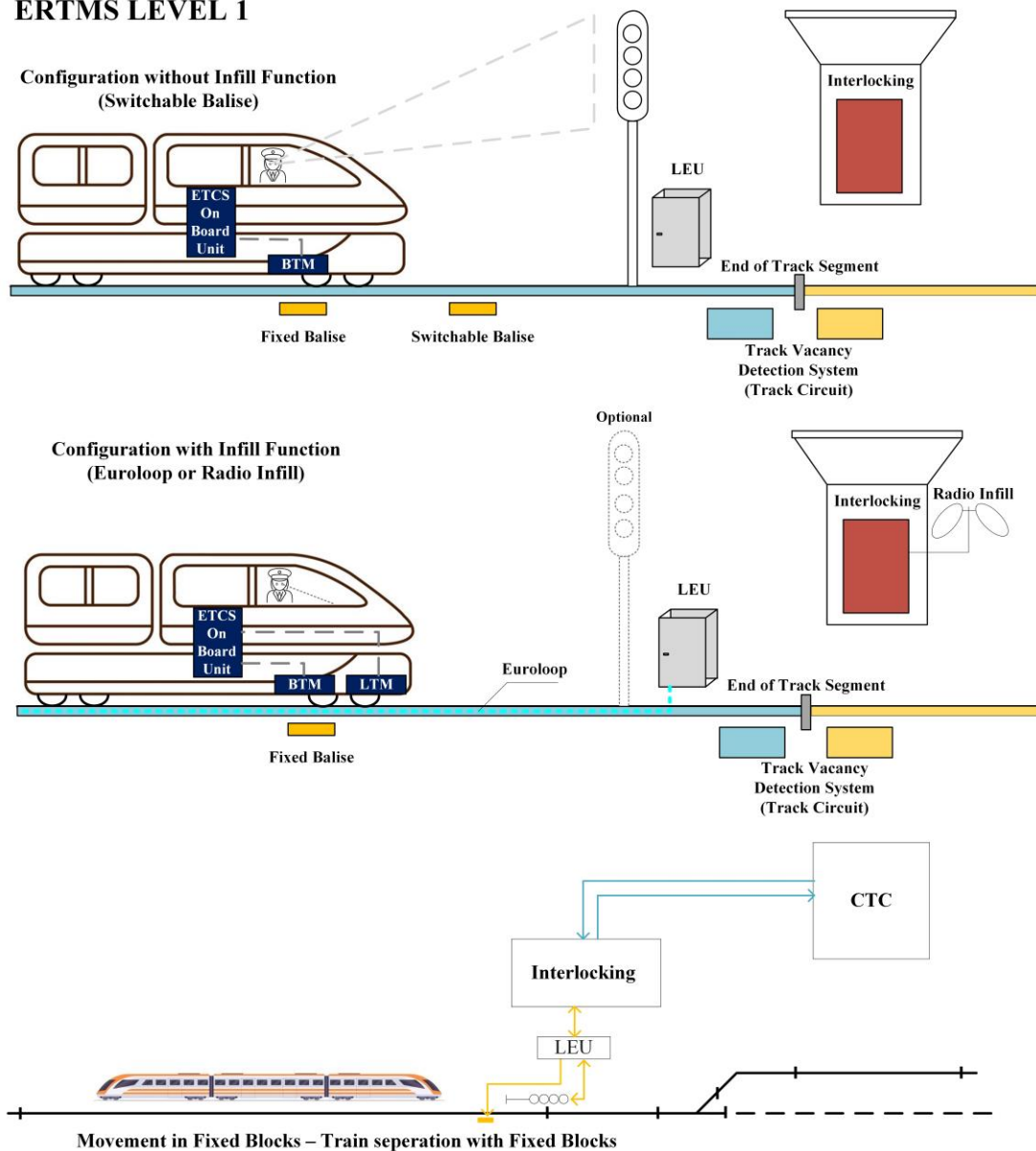


Figure 1.3: ERTMS Level 1, railway line configuration without and with infill function and system architecture.

ETCS onboard functions are receipt of track description data from fixed balise and MA from switchable balise through BTM (balise transmission module), selection of the most restrictive message among all different permitted speeds at each transmission point, calculation of dynamic speed profile according to train(running/braking) characteristics and comparing actual speed to permitted speed and command braking when necessary. The movement authority can be received from Loop Transmission Module (LTM) or Euroradio in the infill option. In ERTMS Level 1, cab signalling is available(ERA UNISIG SS26-2, 2016).

In Level 1 system architecture, the railway line is divided into fixed block sections monitored with a track vacancy system. Communication between the lineside signal and the switchable balise or euroloop is made through LEU. LEUs are connected to the interlocking system of the underlying signalling system. As can be understood from Figure 1.3, ETCS Level 1 is an overlay to the existing signalling system. Integrating any signalling system to ETCS Level 1 by interfacing each signal with LEUs and installing balises or euroloop along the railway line is possible. LEUs can also be interfaced with level crossings. Another option would be to integrate the existing signalling system through a communication network where MA is transmitted to the train via radio infill (Stanley, 2011). In either case, the railway line must be equipped with fixed balises to provide track characteristics to the onboard system.

1.2.4 ERTMS level 2

ERTMS level 2 offers a radio-based train control system. On this level, the lineside signals are deemed unnecessary since MA is transferred to the train using Euroradio. This system is advantageous over the ERTMS Level 1 system, providing continuous transmission between railway infrastructure and the onboard system and eliminating the lineside signals. ERTMS Level 2 enables continuous, digital bi-directional communication between infrastructure and vehicles via radio transmission. The GSMR antenna is obligatory in ERTMS Level 2-equipped vehicles. On the infrastructure side, additionally, RBC is obligatory installation. In this case, the need for switchable balises is omitted since the varying information of movement authority is transmitted via radio; the only requirement for balises is for location confirmation and odometer calibration. As GSMR is a requirement, the initial investment cost for Level 2 is higher (Młyńczak et al., 2016). However, the maintenance and operation

cost of the railway line is lower due to the lack of lineside signalling. The communication at this level is continuous, so traffic control throughput is intermittent, and driver intervention and knowledge of the signalling system are unnecessary. Level 2 is intended for international and high-speed railway lines.

Train vacancy detection and train integrity detection are the responsibility of the underlying signalling system. These detection systems are out of the scope of the ETCS system for this level (Stanley, 2011). Only ETCS infrastructure components are radio block centres (RBC) and fixed balises. The GSMR system enables continuous bi-directional communication between the train on-board system and RBC.

As shown in Figure 1.4, RBC has all the static data, including; static speed profiles, gradient profiles, track conditions and all the fixed balise locations as they act as milestones in the Level 2 system. RBC also has a direct connection with interlocking, enabling it to receive all dynamic data regarding the position of movable track elements and the current aspect of each signal. All this information allows RBC to calculate and provide MA or withdraw MA for each train (Stanley, 2011). With the help of a Train describer, RBC is also aware of every train ID that is on the coverage of RBC. The way MA is transmitted to the ETCS onboard unit, RBC uses the same variables for transmission as Level 1. The ETCS onboard unit is also reporting the train's location and delivering MA requests to RBC (Stanley, 2011). According to the received MA and End of Authority (EoA) from RBC via euro radio, the ETCS onboard system calculates the speed profile according to the brake characteristics of the train. It presents the results and information on the DMI. In a radio failure, the ETCS system switches to a safety reaction.

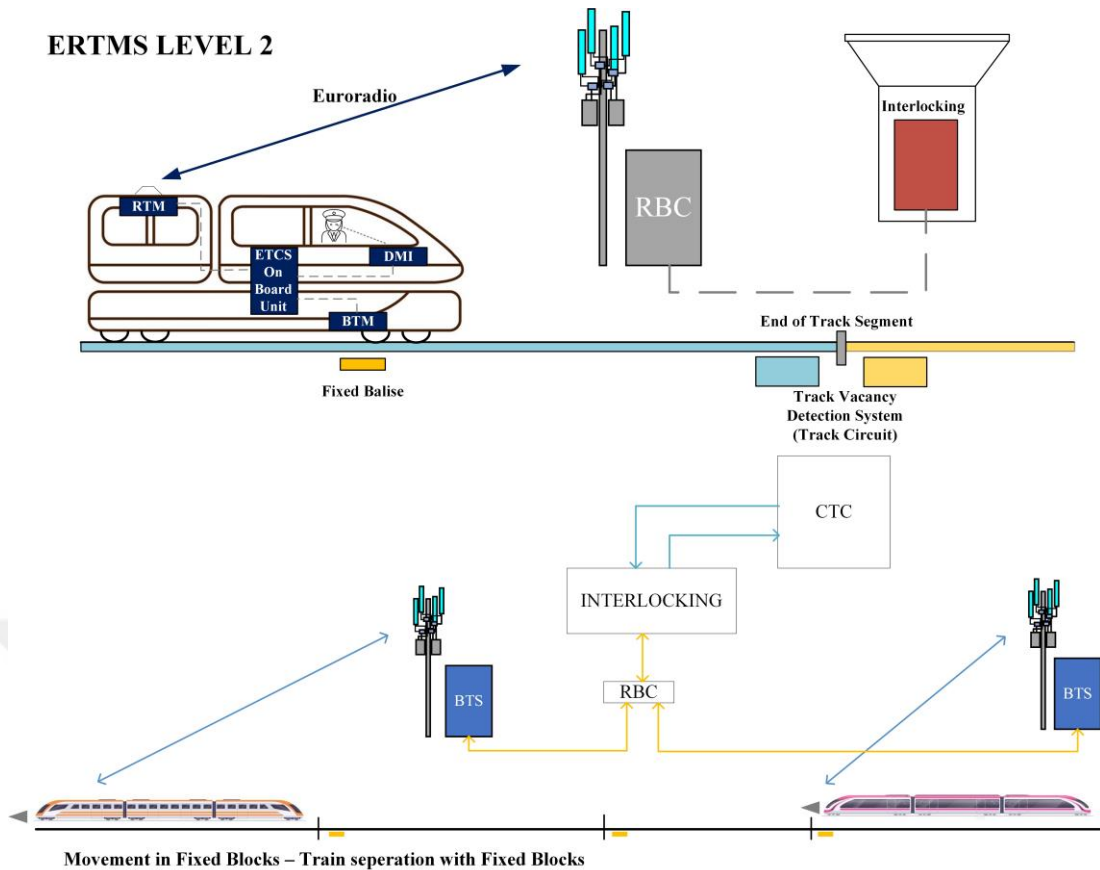


Figure 1.4: ERTMS Level 2, railway line configuration and system architecture.

In Level 2 operation, ETCS trackside components are Radio Block Centre and Euroradio, which enables bi-directional communication between onboard and trackside systems and fixed balises for location reference. RBC shall know all trains equipped with ETCS identity and shall follow the position of each train. RBC is also responsible for providing MAs according to the underlying signalling system. MAs and track descriptions shall be transferred to each train by RBC. RBC shall also be responsible for hand-overs in interface areas between RBCs to RBCs(ERA UNISIG SS26-2, 2016).

The functions of ETCS onboard include reading location reference from fixed balises and sharing to RBC, receiving MA from Euroradio, selecting the most restrictive message among all different permitted speeds at each transmission point, calculating dynamic speed profile according to train(running/braking) characteristics and sharing this information with RBC via Euroradio and comparing actual speed to permitted speed and command braking when necessary. In ERTMS Level 2, cab signalling is available (ERA UNISIG SS26-2, 2016).

The system architecture of ERTMS Level 2 leaves the function of setting and releasing route commands to the Centralised Traffic Center (CTC). It also leaves track vacancy detection and track integrity detection to the interlocking. RBC receives information from interlocking regarding the set and locked routes, types of movement on the route (shunting etc.), emergency replacement of signal to red (due to violation of flank protection, intervention of signaller etc.) ERTMS Level 2 also allows the interface to CTC. CTC can order or remove speed restrictions and unconditional emergency stops (Stanley, 2011). Some lines with ERTMS Level 2 have lineside signals and RBC. This is interpreted as the fallback system of ERTMS Level 2. If there is a radio system failure, the railway line may return to Level 1 operation instead of a degraded mode of operation. This can be a critical decision and shall be evaluated by the railway infrastructure manager. However, this fall-back system may pose problems, such as inconsistencies between the lineside signals and cab signalling (Stanley, 2011). The ERTMS Level 2 system is designed to increase the line capacity; for example, a withdrawn MA may appear on DMI and prevent unnecessary braking. However, a lineside signal with red light may prevent the driver from proceeding or even needlessly braking in a mixed operation.

1.2.5 ERTMS level 3

ERTMS Level 3 is also offering a radio-based train control system. Railway infrastructure is responsible for generating MAs, which are transferred to each train via Euroradio and GSMR network. DMI here plays a crucial role, as it does for Level 2 since no lineside signals are available along the line. ETCS onboard system itself supervises the train operation with continuous RBC communication.

The main difference between Levels 2 and 3 is the moving block principle. In ERTMS Level 3, there is no need for track segment separation by any track vacancy system. Each Level described until this section needs track segmentation by track detection means. For Level 3, this need is wholly overhauled by train integrity equipment on the train and RBC's logic of MA calculation. MA, in other words, EoA, is calculated by using the absolute braking distance of each train and adding the safety margin for each train during operation.

This calculation eliminates the fixed block principle's necessity, defined according to the rolling stock with the lowest speed. Elimination of track vacancy detection leaves a grey area in the operation. This area is covered by the train integrity equipment inside the rolling stock. On other levels, train integrity was the responsibility of either the underlying signalling system or the train driver (Stanley, 2011). This allows the maximum use of railway line capacity. The main difference in train control at each operational level is the place of data processing. In Level 1, data processing occurs onboard; meanwhile, in Levels 2 and 3, the data processing partially occurs onboard, and the rest occurs on lineside devices. (Młyńczak et al., 2016)

In Figure 1.5, ERTMS level 3 trackside configuration is provided. Only fixed balises are located on the track for location referencing and correction of an accrued error in odometry. Similar to Level 2, fixed balises are used as the location rectifying milestones for correcting the train-integrated odometer.

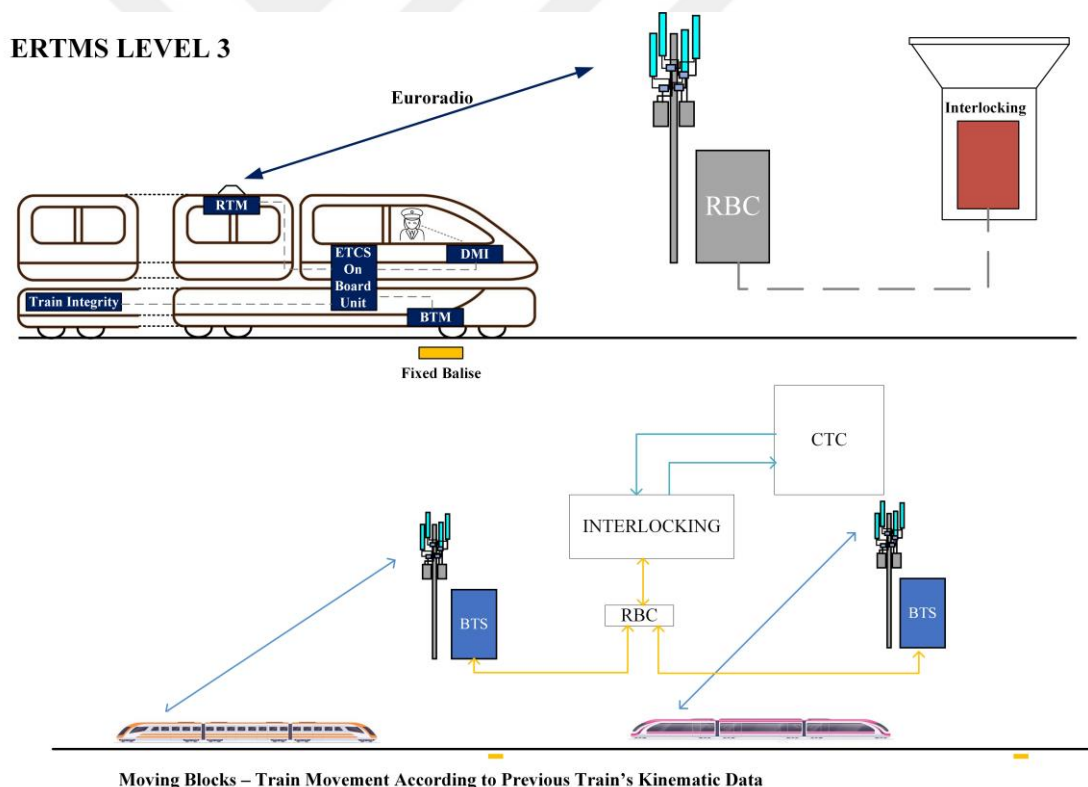


Figure 1.5: ERTMS Level 3, railway line configuration and system architecture.

It is ETCS on-board system's responsibility to report the position and integrity of the train to the RBC. The most critical issue in Level 3 operation is the operation of mixed traffic.

If the line is operated by both Level 3 and Level STM, the lineside signals and the DMI screen of the driver may indicate different MAs or messages. In this case, the infrastructure manager shall take precautions according to the possible outcome of mixed traffic and propose a unique signalling system that enables co-existing systems on the line (Stanley, 2011).

ETCS trackside system comprises Radio Block Centre, euroradio that enables bi-directional communication between the onboard system and trackside system and fixed balises for location reference. The function of the trackside system is identical to ERTMS Level 2. The function of ETCS onboard is also very similar, although the additional function is internal supervision of the train integrity.

From a system architecture point of view, it is seen that ERTMS Level 3 is no different than Level 2. There are only fewer interlocking functions in Level 3 compared to Level 2 (Stanley, 2011). There is no Level 3 line in the world that is under operation. However, the system dramatically benefits from increasing line capacity by removing the fixed block principle and calculating the train distance with each train's kinematic characteristics. The fields of usage of this level can be the lines without track vacancy systems, for rolling stock that does not trigger the existing track vacancy detection system and when the capacity increase is on demand.

1.2.6 Level transitions

For a train equipped with ETCS onboard, there are specific transition rules for entering railways with different operational ERTMS levels. This type of transition has some rules according to defined functions. The ERTMS systems generally have downward compatibility. As one of the founding principles of ERTMS, the movement without limits, one does keep in mind that level transitions should also be included in procuring train sets or locomotives for international or national railway corridors. Table 1.2 provides the permitted transitions for ERTMS Levels in grey.

Table 1.2: ERTMS Level Transitions, * describes the transition between national railway system to another and ** describes the handover between RBCs (ERA UNISIG SS26-2, 2016).

From \ To	0	STM (NTC)	1	2	3
0					
STM (NTC)		*			
1					
2				**	
3					**

1.2.7 ETCS operation modes

ETCS has operation modes to allow drivers to operate in various traffic situations. There are 17 modes available in specifications, and can be initiated by driver or infrastructure. In this article, only three modes are summarised; Full Supervision Mode (FS), Unequipped Mode (UN – it is referred to as Unfitted) and Limited Supervision Mode (LS). FS mode refers to a type of operation where every information is displayed on DMI by ETCS. In this mode, the driver is not expected to follow trackside signals. In UN mode, no ETCS equipment is on the line; the driver is expected to drive according to trackside signallers. ETCS only displays the actual speed via DMI and cannot perform train supervision as it does not receive any information from infrastructure. In LS mode, the driver follows the indications from the trackside signals; however, for the defined sections with high potential risks, the transmission between infrastructure and vehicle is performed for permanent data such as speed limit. This enables infrastructure upgrades with lower installation costs. This kind of upgrade may also be recommended for the lines equipped with traditional train protection devices and to ensure LS mode functionality. (Młyńczak et al., 2016)

1.3 Continuous Automatic Train Signalling (ALSN- Avtomaticheskaya Lokomotivnaya Signalizatsiya Nepreryvnaya) Principles

The railway with a 1520 mm rail gauge uses a particular traffic control system. This system has automatic track interlocking, dividing the railway section into interlocked blocks. All blocks are equipped with signal lights and track circuits. In this system, tracks are the conductors of the track circuit. Traffic lights are automatically changing with the help of the track occupancy information received from the track circuit. Either three-aspect or four-aspect signal lights are used. Based on which type of voltage supply is used for the track circuit, there are two categories; direct current and alternating current(coded)(Liudvinavičius & Sładkowski, 2017).

In the direct current category, the track circuit performs the duty of track vacancy detection. The DC track circuits are installed parallel among the tracks as a power source at one end of the track section and a receiver at another end. If there is no train inside the track section, the current flowing from the power source goes through the receiver's coil windings and returns to the power source. The relay is picked up, and the signal light shows a "green" light as the entrance to the track section is permissible. If a train enters the dedicated track section, the wheelset of the train short-circuits the track circuit, considering that the resistance of the wheelset is much smaller compared to the receiver's relay coil. In this case, the relay is an open circuit, meaning the signal light turns to "red" as the prohibited signal. Imagining three consecutive track sections, the first track section entrance signal is green, and the last one has a train inside the section which means the signal light is red. In this case, the track section in the middle displays a yellow signal as a caution warning (Liudvinavičius & Sładkowski, 2017).

The AC track circuits are used in electrified railways with 1520 railway gauges. AC-coded track circuits provide continuous data transmission to locomotives and perform track vacancy detection. This type of signalling is called ALSN. ALSN Signalling system is a cab signalling system that trackside information that is continuously exchanged via rails. The ALSN code combinations reflect the track status, in other words, the active aspect of the signal light. Each signal light has a specific pulse combination. Three codes are available for three-aspect signalling. The red signal is represented as red-yellow in-cab signalling, whereas the yellow signal is represented as yellow, and the green signal is represented as green. Green pulse has a three-pulse

long interval sequence, yellow has two pulses, and red has one pulse representation. These pulses are provided to the rails with a code generator device (Liudvinavičius & Sładkowski, 2017). These code combinations are also referred to as ALSN Signals. The transmitters generate ALSN Signals in the form of code amplitude-modulated current. These transmitters are located at specified distances and send ALSN signals towards the moving train (Havryliuk, 2020). Onboard antennas, which are coils, are induced with the ALSN signals. The received signal is processed by the ALSN onboard that filters, amplifies, and decodes to send to the human-machine interface (HMI). ALSN HMI is the cab display that indicates “green”, “yellow”, “red-yellow”, “red”, and “white” lights (Havryliuk, 2020).

There is various type of code generators, namely KPTŠ-5, KPTŠ-7, KPTŠ-515, KPTŠ-715 and KPTŠ-8, KPTŠ-9, KPTŠ8-15, KPTŠ-915. The code generators comprise a single-phase asynchronous motor, gearbox and three camshafts. These camshafts rotate, and based on their shapes, green, yellow and red-yellow pulses are generated. The contact time of codes depends on the motor speed, gear-box ratio etc. The structure of codes is the same for all types of code generators but the period of the code cycle changes. The period of the code is either 1.6 seconds or 1.86 seconds (Liudvinavičius & Sładkowski, 2017).

Automatic locomotive signalling, as it is referred to as ALSN, is a system that aims to provide information to the train driver about the permissible driving speeds. This system envisages transmitting information from the trackside to the onboard to control the driver's actions, limit speed, intervene and brake whenever necessary to record speed and the driver's actions. ALSN is operational in almost 100,000 km of railway in the world, which means that 10% of the world's railway employs this signalling system. This system is an overlay system to the underlying signalling system; it does not replace the central system. This system also cannot replace the signal lights; in the case of a contradiction, train drivers must obey the signal lights. The Soviet Union developed the system in the 1930s, originating from the first coded track circuits in the USA. According to new technical requirements, high-frequency track circuits are used along the stations and block sections. This type of track circuit does not generate ALSN codes if no train occupies the section. When a train is detected, an ALSN code is generated. Only the sections where train operation is non-stop along the stations are equipped with ALSN code generators.

The lack of ALSN code provides the fail-safe feature. If the track section is beyond the signal at a stop, the train will be emergency stopped. Only the drive on sight is permissible on special occasions with 20 km/h speed (Liudvinavičius & Śladkowski, 2017).

KLUB-U is an additional onboard system to ALSN onboard. KLUB-U allows the setting of actual time, train running parameters, coordinates, speed, control of maximum permissible speed, generating the corresponding automatic braking signal, control of train rolling, and electronic map data using GPS. A special bracelet checks the driver's physical condition and sends it to the driver's alertness module. The KLUB-U can be defined as a kind of ALSN onboard. This system allows the onboard system to receive and decode ALSN signals and provide the received code to the human-machine interface. It monitors the driver's vigilance and regularly controls the driver's alertness. KLUB-U indicates the train's actual speed and permissible speed, as well as the braking curve to the train driver. KLUB-U continuously monitors the brake system, and if necessary, it intervenes with automatic emergency braking. The driving events and actions are recorded in memory storage. The data of running speed, train position GPS coordinate, and locomotive light indication can be transmitted or received via GSM-R, DMR, TETRA etc. (Liudvinavičius & Śladkowski, 2017). The system checks the driver's alertness as the indication switches to a more restrictive signal. For example, when the signal returns to yellow from green, the driver is expected to confirm his alertness by pressing the alertness handle. KLUB-U performs these checks every 30 to 40 seconds; if the driver fails to press the handle, the train automatically stops (Liudvinavičius & Śladkowski, 2017).

2. LITERATURE REVIEW

The literature review for this research includes two kinds of signalling systems: European Rail Traffic Management System (ERTMS) and Continuous Automatic Train/Cab Signalling (ALSN- Avtomaticheskaya Lokomotivnaya Signalizatsiya Nepreryvnaya). The literature availability of these two systems is very different. To observe the gap between the available literature of both systems, a Scopus search query is performed for both signalling systems. The total number of available literature for ERTMS signalling system is 2,208 between 2023 – 1968. The ERTMS was published as a directive for the first time in 1996, so the increase in the works of literature can be observed after that year in Figure 2.1.

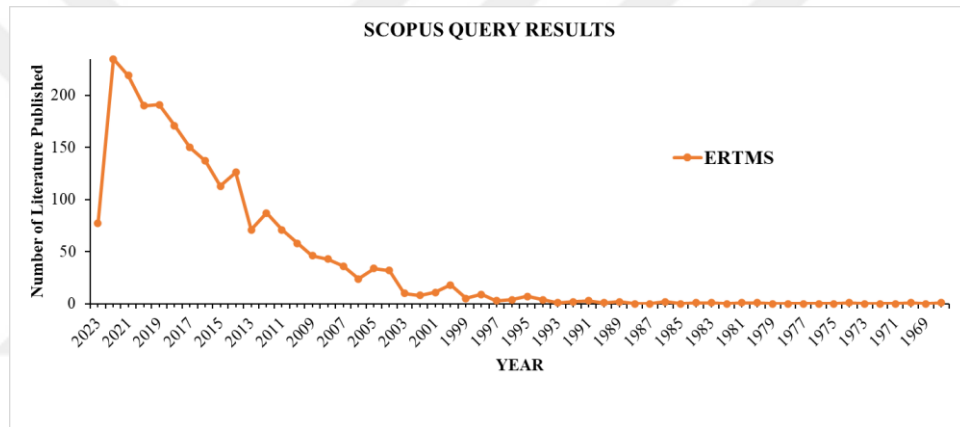


Figure 2.1: The available works of literature on ERTMS signalling systems based on years according to the Scopus query.

On the other hand, the available literature on the ALSN signalling system is comparably low. Although the ALSN signalling system was developed in the Soviet Union in the 1930s (Liudvinavičius & Śładkowski, 2017), the works of literature registered to international databases are pretty low. According to the Scopus search, only 78 registered works of literature on the ALSN signalling system exist. As can be observed in Figure 2.2, more literature has been observed to enter the database in recent years.

Comparing these two signalling systems regarding the available research shows that the ERTMS signalling system receives more attention than the ALSN signalling system. Another reason might be that the ALSN system is a closed and conservative system with a missing international representation

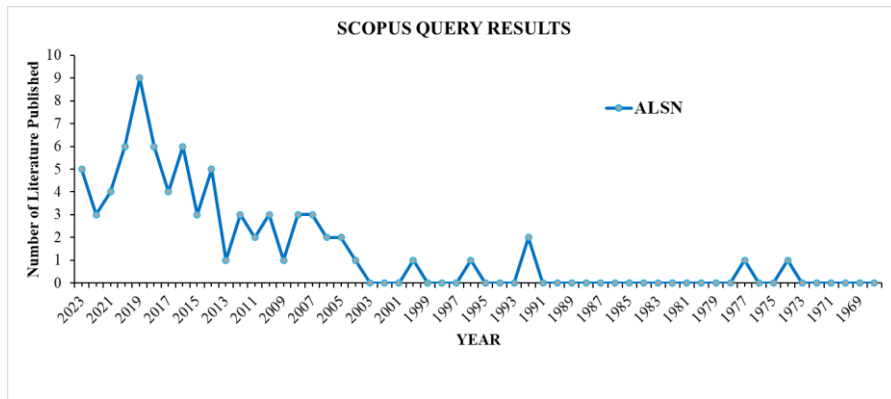


Figure 2.2: The available works of literature on ALSN signalling systems based on years according to the Scopus query.

The ERTMS signalling system has open-source specifications and standards. Figure 2.3 shows the comparison of available literature on these two systems.

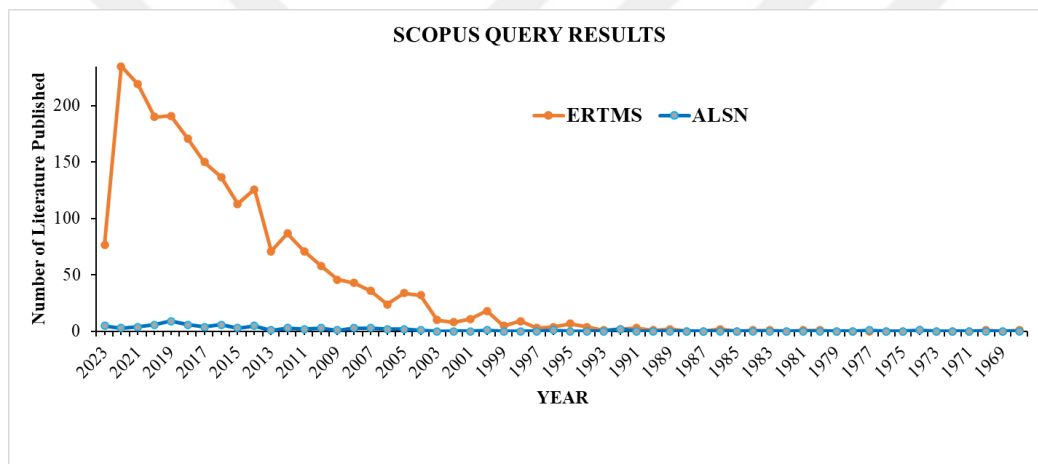


Figure 2.3: The comparison of the availability of literature in the ERTMS and the ALSN signalling system.

The document type available for each signalling system is also shown in Figure 2.4. The distribution of the document type is quite similar. The primary literature is comprised of articles and conference papers.

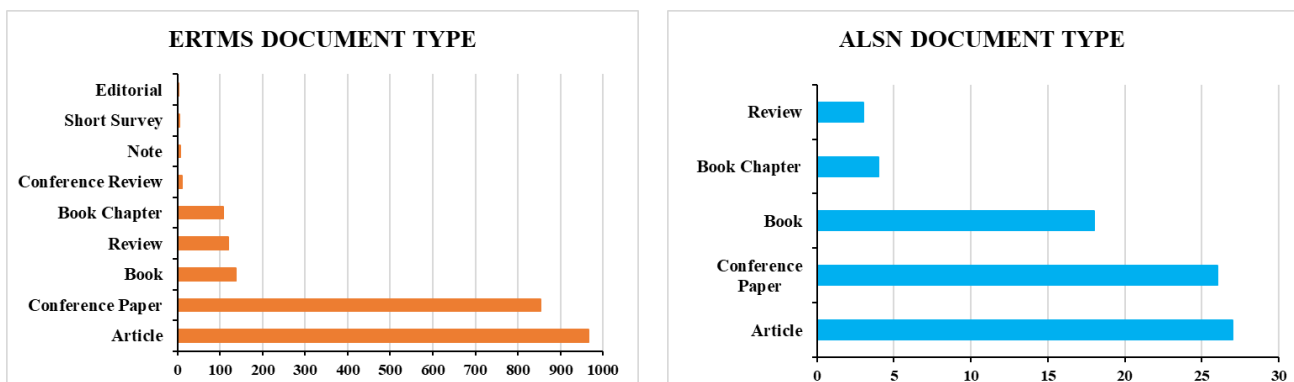


Figure 2.4: The document type categorisation of the available literature.

This section of the research will review the literature for both signalling systems. The performed literature review will be analysed separately for the ERTMS and ALSN signalling systems. This study showed that the researchers mainly focus on three topics: modelling, optimisation and issues faced during the implementation or operation.

2.1 Literature Review in ERTMS

The literature review for the ERTMS signalling system mainly focused on modelling ERTMS using different methods, proposing optimisation to increase reliability and safety or increasing capacity and issues faced during the implementation of ERTMS. There are also works of literature that envisage the integration of the legacy signalling system into the ERTMS system with an STM. Therefore, the reviewed literature will be analysed under the sub-headings of modelling, optimisation, issues and problems faced during the implementation and proposition of STM technology.

2.1.1 Modelling

The modelling ERTMS signalling system is one of the primary focuses of the available literature. Different tools are proposed to model ERTMS, such as UML Class Diagrams, State Charts, System of Systems (SoS), Fault trees, Bayesian Networks and Petri Nets. The aim of the modelling proposition includes overcoming the complexity of ERTMS specifications (Ghazel, 2014), avoiding ambiguities of the ERTMS specifications (Piccolo et al., 2015), evaluating dependability parameters and identifying failure and repair rates (Qiu et al., 2014), analysing and designing system reliability (Soares & Zio, 2006) exploring the impact of degraded operation (Dhahbi et al., 2011), validating the assumptions used for safety proofs and scenarios (Ferlin et al., 2016) and monitoring of train movement for Level 3 operation (Durmuş et al., 2012).

A study undertaken regarding subset formalisation for ERTMS/ETCS specification verification is analysed. (Ghazel, 2014) The article emphasises the importance of ERTMS/ETCS specifications in achieving interoperability, rail companies' economies of scale, and railway safety required for dense traffic and high-speed railway operations. After the first publishment of ERTMS specification in 2007, the European Commission made more and more amendments in the following years. The primary

concern regarding the requirement specification for such a safety-critical system is ambiguities in the specifications. While targeting interoperability, the inconsistencies and inaccuracies that lead to bugs or errors made during the system development stage have caused severe results. This study proposes a translation for the SRS subset of modes and transitions into a formal model/ conditional transition system to prevent such deviations.

ERTMS/ETCS specifications define three application levels as Level 1, 2 and 3. The main aim of these levels is to determine the interaction between the train and infrastructure. In ETCS Level 1, the communication between train and infrastructure is made through Eurobalise within certain intervals in the form of static and variable data. Eurocab decides the maximum speed and braking points based on the received movement authority. In ETCS Level 2, communication is made through the GSMR link between the train and signalling infrastructure directly from the Radio Block Centre. Eurobalises are only installed to rectify the information generated by the odometer. According to the author, maximum benefit would be achieved with level 2 operation. (Ghazel, 2014) ETCS Level 3 differs from Level 2 with the moving block principle. Train rear location and train integrity gain importance in that type of operation. It is noted that railway needs and the existing situation of the railway line are essential variables to consider while deciding which ETCS Level to proceed. Also, upgrading from one level to another level is possible.

The ERTMS subsets also define the transition between application levels. However, it is not the only criterion to determine the operation. ETCS operation modes also define the system's behaviour based on its environment. Operation mode is a combination of multiple definitions: these are ETCS application levels, active functions of onboard, the responsibility of the onboard system and the driver and a set of transitions between modes. These modes are defined in "Subset 026 ERTMS/ETCS System Requirement Specification Chapter 4 Modes and Transitions" as 17 different ETCS operation modes such as No Power, Full Supervision, etc. Ghazel (2014) proposes a static model to avoid errors and inconsistency while developing the system. To achieve this, a UML class diagram is extracted from the specification to determine all the necessary variables and the scope of the process and to extract all the relations between variables. First, modes are enumerated as a variable and two strings were defined for onboard and driver responsibility. Later, "priority" was defined as an integer for the transition

between source and target modes. Priority is assigned to prevent conflict arising from activating more than one ETCS mode. The constraints caused by object constraint language were also added to the class diagram. “Cadence SMV” is used for verifying properties. To enable transitions, several guards are defined in the developed class diagram. Guards are conditions that need to be satisfied for a transition to happen. The interdependencies of guards are highlighted as a sensitive issue that requires a high level of expertise in ERTMS/ETCS specifications. This issue was handled with the classification of elementary conditions. Transition priorities are depicted using a “Finite State Machine” (FSM) that prioritises the highest number assigned in a nested way (Ghazel, 2014). The proposed framework for formally verifying ETCS modes and transition is tested on the generated SMV. The results showed that the framework holds the necessary safety requirements.

Piccolo et al. (2015) employed a state chart to model the ERTMS/ETCS trackside subsystem according to the requirement specifications. The Italian national company that manages the railway infrastructure is called RFI (Rete Ferroviaria Italiana). In 2005, RFI initiated a project to use formal methods for ERTMS Level 2 operational high-speed and high-capacity railway lines. Using formal language is essential because it enables verification of inconsistencies, if any, helps to solve conflicting logic, and checks accessibility based on the requirements. The State Chart is easy to follow, considering it can be visually expressed and supports formal specifications and verification. The verification is carried out by an additional tool called “Certifier” and an Independent Safety Assessor.

The model development process started with functional scenarios based on UNISIG Specifications “Subset 026 Chapter 5 Procedures”. All the messages are extracted based on the functional scenarios, and new scenarios are developed. This step enabled the developers to realise message sequence and correlation. Following that, the variables and their relationships are defined, as well as their default values. After completing the mode, the national ETCS specification by RFI is also rearranged and prepared. The comparisons and analyses are made. The main aim of the model development is to produce a model that can be used. Considering that train-centric representation has been developed to ensure realistic results.

Natural language specification and rail layouts of Milano-Bologna and Bologna-Firenze High-Speed railway lines are analysed in detail (Piccolo et al., 2015). The developed system is checked to see if it fully complies with the ETCS Italian system. Another benefit of the model is that it shows all the logic of the signalling system.

The ERTMS trackside subsystem state chart model consists of logical states and logical state transitions. Every ETCS trackside requirement is represented either as a state or transition. The transitions are tied to a group of conditions. As a transition activates, the system moves from one state to another. The model is verified with the “Statement Certifier” tool. This tool enables the developers to find non-determinism and to verify that all states are reachable, range violations, state sequence, and expected and unexpected conditions.(Piccolo et al., 2015)

Although ERTMS specifications are publicly reachable and many rail authority has implemented the system before, understanding every aspect of the ERTMS signalling system is not easy. The above articles proposed modelling techniques to simplify and clarify the ERTMS specifications to avoid complexity, ambiguities and mistakes.

Qiu et al. (2014) proposed a model of ERTMS Level 2 as a System of Systems (SoS) using state charts. SoS concept is mainly used for complex high-level systems that require hierarchy. This study recognised that ERTMS Level 2 has not been considered an SoS that also acknowledges the unavailability of the system caused by network failures and human errors. The article proposed an SoS of ERTMS Level 2 that includes three independent, heterogeneous, autonomous, and geographically distributed systems. These systems are the onboard, trackside, and radio transmission systems.

Reliability, Availability, Maintainability, and Safety (RAMS) allocation can be set to individual systems to meet specific RAMS goals in SoS systems, or the RAMS measures of SoS systems can be apportioned so that individual systems can be designed to meet specific RAMS goals. This study highlights that quantifiable goals such as performance and cost are easy to decompose. However, railway availability is not easy to apportion. According to specifications, the operational availability of ERTMS/ETCS shall not be less than 0.99973.

The concept of operational availability is not the same for each system, so the authors recognise this property as emergent. The concept of emergence can have two effects on RAMS assessment; it can generate unidentified system-level failures, or the generated system-level failures can violate SoS RAMS goal (Qiu et al., 2014).

ERTMS has been modelled with StoCharts as the extension of Unified Modeling Language (UML) statecharts. However, there was no tool to support this model. Later, this model was adopted as Modelling, Description Language for Stochastic and Timed Systems. There are several attempts available to upgrade the ERTMS modelling. European Railway Agency has initiated a “European Railway Formalization and Validation Project”, which proposes formalisation and validation tools. This article presents a model of ERTMS Level 2 using state charts. The designed SoS of ERTMS Level 2 has three systems: onboard, trackside, and GSM-R. For the onboard system, five modules are identified: Radio Transmission Module, Balise Transmission Module, Train Interface Unit (TIU), Driver Machine Interface (DMI) and European Vital Computer (EVC). The Radio Transmission Module (RTM) enables bi-directional communication between onboard and trackside. The Balise Transmission Module (BTM) reads telegrams received from balises and provides power to balises. The Train Interface Unit (TIU) enables bidirectional communication with train equipment. The Driver Machine Interface (DMI) provides bidirectional communication with the train driver. The European Vital Computer (EVC) controls the train speed and generates the braking curve according to the received telegrams from balises. In the onboard context, if the driver fails to take the necessary action, the onboard system operates via the TIU system. The trackside system generates the train routing by receiving track vacancy status and train positions and shares the speed profiles with the trains. There are two modules of the trackside system: interlocking and separation. Interlocking is primarily responsible for train routing based on the received information of track vacancy. Separation has two sub-modules, Eurobalises and RBCs. Eurobalises generate telegrams that carry location-specific information. RBC, on the other hand, is linked with interlocking, and it generates movement authorities. GSM-R, as another system, provides bidirectional communication. If the frequency of the messages is between 876 – 880 MHz, it means that the direction is from train to track; if the frequency of the message is between 921 – 925 MHz, the direction is from track to train (Qiu et al., 2014).

The article also discusses state charts as the most suitable method to model SoSs since they enable modularity and design of a hierarchical structure. On the other hand, the Markov chain method does not support hierarchical representation, and it restricts the transitions to the same level. The comparison showed that SoSs can be represented with a much smaller number of states and transitions since it is modelled with state charts. This comparison is valid since all the subsystems of ERTMS defined above are independent (Qiu et al., 2014). The emergent property of ERTMS Level 2 is modelled considering taking over from the train driver, other automatic procedures and the occurrence of failure in the SoS level. The model considers the unavailability of SoS as an emergent property. The human factors are calculated by analysing 107 railway accidents in the United States between 2007 – 2011. The error rate is calculated for the simulation purposes. Network failures are also calculated as network failure rates based on the realistic data acquired from the Federal Railroad Administration between the same years. The simulation is developed using Stateflow, which is a toolbox of Simulink. The transition rates, the communication probabilities, etc., are inserted into the simulation. The failure dependency focused on by this article is Common Caused Failures (CCFs). ERTMS Level 2 CCFs have critical importance since RAMS requirements state that CCF analysis shall be performed for redundant safety-related functions to prevent single failures. As a result of 100 simulations over two years, five parameters of RAMS are analysed: Mean Up Time (MUT), Mean Down Time (MDT), Mean Time To Failure (MTTF), Mean Time Between Failures (MTBF) and instant unavailability. The study showed that the unavailability is caused by the components' reliability and depends on the component's position in the system.

Another research (Soares & Zio, 2006) is focused on creating an ERTMS Level 2 model to analyse the reliability aspects. The researchers preferred using Fault Trees (FT) and Bayesian Networks (BN) for proper expressive power and solution efficiency. Other methods, such as Reliability Block Diagrams (RBD), Continuous Time Markov Chains (CTMC) and Stochastic Petri Nets, are referred to as having limited expressive power and not compatible with large and complex systems. BN's advantages are also highlighted as the available support for multi-state events, noisy gates, common mode failures and detection of reliability bottlenecks. The authors used SHARPE software to solve FT and Netica by Norsys to solve BN (Soares & Zio, 2006).

ERTMS Level 2 architecture is analysed, and three systems are identified: On-board, Trackside and Lineside. The onboard system is responsible for controlling train movement, following the speed profile that is based on the data transmitted via the GSM-R network. The onboard system is equipped with RTM, BTM, TIU, DMI and EVC, as explained in detail in the previous sections. EVC is a safety-critical system, so it is designed according to 2 out of 3 architecture (Triple Modular Redundant architecture). EVC also has an interface with the odometer located on the train. The trackside system is responsible for transmitting movement authority, static speed profile emergency data, etc., with RBCs. There are two communication interfaces for RBC: GSM-R and wide area network that connects interlocking with RBC and also connects neighbouring RBCs. The lineside system is acknowledged as balise groups. The balise groups (BG) are responsible for transmitting data telegrams consisting of geographical positioning information.

According to ERTMS/ETCS RAM requirements (safety is out of the scope of this study), there are three types of system failure modes. First, immobilising failure (IF) is caused by two or more trains switched to on-sight mode (not under full supervision). Second, service failure (SF) is caused by only one train that is switched to on-sight mode. Last, minor failure (MF) leads to unscheduled maintenance and all the failures that are not causing IF or SF. The lineside model structure is developed according to reliability parameters such as MTBF, MTTR and redundancy. The redundancy of balises can vary between 2 to 8 balises. The specification required UBAL to be smaller than 10^{-7} . The failure of adjacent balises causes IF. The proposed structure of the balise group (BG) contains two balises. Although specifications allow eight balises, the analysis shows that installing eight balises can be only meaningful when low reliable balises are used. Instead, using balises with moderate reliability will prevent frequent track maintenance. Even in the worst case, where a balise is unavailable ($UBAL = 10^{-5}$), the other balise would be much higher ($UBAL = 10^{-7}$). So, it is possible to neglect the lineside system for reliability analysis (Soares & Zio, 2006).

The on-board model structure is undertaken with only two states available or unavailable. It is also realistically assumed that there is no repair technician available onboard. All the sub-systems are added to the analysis. For EVC, 3 CPUs for dedicated memory, 1 FPGA-based voter, power supply and BUS interconnecting are considered. The reliability of these components is extracted from datasheets. Other sub-systems of

onboard systems, such as BTM, RTM, etc., are followed according to standards. If the onboard system is unavailable for one train, it means service failure; however, if it is unavailable for one or two trains, it will lead to immobilising failure. The system analysis discusses that the RAM requirement values are hard to meet even with a completely redundant system with highly reliable components. Despite that, the article suggests a balanced choice of MTBF for onboard components. The trackside mode structure has a similar model to EVC, where there are additional components called GSMR and WAN. There is also another difference in that a dedicated technician is always available in the field. Trackside system failure causes immobilising failure since each RBC will manage at least two trains. For GSMR and WAN values, the information available in the datasheet has been used. The components are assumed to be easily accessible, and there are hot-replaceable spare parts (Soares & Zio, 2006). Further analysis of the trackside model shows that the MTTR is taken as 15 minutes, which is a more realistic approach to reaction time.

The completed FTs are combined with BN formalism as a global model structure. ERTMS failure is designed to have three state variables: IF, SF, MF and no failure. A common source of failure is also possible since if all the RBCs are located in the same building, then UPS failure becomes a common source of failure. The global model analysis showed that if there is IF, the probability of failure probability is 80% for Trackside and 16% for the onboard. For SF to occur, the responsibility is 100% for the onboard.

Modelling ERTMS is beneficial to analyse the system's reliability, availability, maintainability and safety. With the help of modelling, component and subcomponent-based failure rates, common cause failures and the relationship between availability and reliability can be identified and analysed.

Dhahbi et al. (2011) model ERTMS Level 2 with coloured Petri Nets based on train movement and localisation of railway track equipment. The authors classified two systems under ERTMS, ETCS and GSM-R, and selected ERTMS Level 2, considering that it benefits fully from the features of GSM-R. GSM-R transmits the movement authority information to the Radio Transmission Module (RTM) located in onboard. Level 2 operation includes Eurobalises to transmit location-specific information, called position markers, to the onboard system. The data transmitted by Eurobalises are only available when the train passes over it. The location information received by

the Balise Transmission Module (BTM) located in onboard is used to reset the odometer. The information received by RTM and BTM is processed in onboard and is shown to the driver through the Driver Machine Interface (DMI). If the train cannot detect Eurobalise or balise group, it leads to degraded operation. The presented model focuses on the interaction between onboard and Eurobalises and certain cases of Eurobalise degradation.

Eurobalises are a very important part of ERTMS interoperability. It enables communication between onboard and lineside equipment via magnetic transponder technology. Eurobalises are usually used on the track in groups, varying from 2 to 8. The balise group has its own group identity and coordinate system. Each group has also an internal numbering from 1 to 8. The odometer sets the location of a train; however, the odometer defines the position according to the position reference received from the Last Relevant Balise Group (LRBG). The role of Eurobalise is safety-critical, and any degradation will cause severe dysfunctions. (Dhahbi et al., 2011) According to ERTMS specifications, if two consecutive balise groups are not detected and the second balise group location has passed, ETCS onboard shall command service brake.

The coloured petri net is selected to model such degradation in this context since Petri nets can be used to analyse continuous variables such as position and speed. CPN tool is used as a simulation tool. The presented model simulated the communication between the odometer and Eurobalise through European Vital Computer (EVC). The EVC supervises the target distance and speed curve in the model. The case malfunction is also integrated into the system as “Eurobalise dysfunction”, “BTM antenna dysfunction”, and “non-detection of Eurobalise”. The Petri net model includes a model for Balise malfunction as “Balise out of order” and BTM antenna malfunction as “Detector out of order”. One of these malfunctions or both leads to warning messages to show in DMI via EVC “Missing balise”. The model also included the odometer error caused by sliding or skating of wheels. The driver is informed through DMI whether or not the error has accumulated on the odometer. As a result of the simulation, the errors related to the eurobalise detection and position-related errors are analysed. The error of “non-detection of a positioning balise group” leads to errors in odometer calculation, dysfunction of the balise detection system and the positioning of the balise group. The “non-detection of the consecutive positioning balise group” error has more

serious consequences. The error accumulated on the odometer is doubled, and dysfunction in balise detection and second positioning balise group is continued.(Dhahbi et al., 2011) The error of serious accumulation of errors is severe; however, it is not likely to happen. Error in the second positioning balise group means the railway line maintenance is critically flawed. The error in BTM leads to a bad estimation of train location. All of the analyses made through proposed coloured Petri nets showed that any malfunction in the balise requires a train brake.

Another modelling proposition for scenario testing is proposed by (Ferlin et al., 2016). Hierarchical Coloured Petri Net is the most preferable railways modelling language. The advantages of using Petri Nets in modelling railway interlocking systems are numerous. Petri Net's mathematic semantics are compatible with the railway specifications. The use of coloured tokens facilitates the modelling of large-scale systems. Follow-up is easy since it is a graphic language. Ferlin et al. (2016) employed the Petri Net model to model ERTMS. They propose an interlocking structure with three components: track, signal system and trains. The track includes turnouts, traffic lights, automatic signal elements and track circuits. The track has elements that automatically operate. The signal system includes operational rules and control processes that are either automatically calculated or operator-verified. Trains require a route, and this component includes conditions about the route run and railway condition state. In the proposed framework, trains are modelled with tokens so that they are systematically updated. The other components, track and signal system, are modelled with Petri Nets. The developed model has three levels. The component level determines the sub-systems and interfaces between these sub-systems. The scenario level models the procedures between the train and track equipment. The detailed function level is the lowest level model that can be used for different scenarios(Ferlin et al., 2016).

Whether it is a degraded operation scenario or a safety-proof case, ERTMS modelling is important to realise the outcomes of the implemented or planned system. The system planning level works requires the development of such models to validate and verify the outcome. Modelling is also handy for developing and testing new concepts, such as the moving block principle.

As detailed in the above sections, ERTMS Level 1 and Level 2 are based on the fixed block principle, whereas ERTMS Level 3 is based on the moving block principle. For semi-formal modelling of ERTMS, EN50128 recommends using automata and timed Petri nets (TPNs). Durmuş et al. (2012) have proposed a modelling technique for ERTMS Level 3 that switches, signals are modelled with discrete Petri nets (DPNs) and train movements are modelled with continuous Petri nets (CPNs).

The train control characteristics are modelled using controllable batches with four features: length, acceleration, head position and driving speed. This modelling aims to keep a safe stopping distance between trains. According to ERTMS Level 3, the safe stopping distance is calculated as the sum of safe braking distance and safety margin. The safety margin is equal to the length of a train. This study's case study focused on high-speed lines with 300 km/h and 320 m long trains. The safe stopping distance is calculated as 7500 m. The simulation area includes Station A and Station B, with two platforms on each station and a 200 km long single-line connection between these two stations. Balises detect the station entry and exit, and these balises are modelled as discrete places. The switches are modelled using continuous places, considering that more than one train is expected to enter. 200 km long single line has been modelled using batch place(Durmuş et al., 2012). Twenty-six high-speed trains with 320 m length are simulated along a 200 km long batch place. The rear train needs to control its speed and acceleration value according to the speed and acceleration of the preceding train. In the batch place, the location of the rear and preceding train is compared, and a reference speed and acceleration value are produced. The produced values are compared with the actual values of the rear train to produce a jerk value(Durmuş et al., 2012). MATLAB Simulink is used to perform simulation.

2.1.2 Optimisation

There is available research on the optimisation of the ERTMS signalling system. The proposed methods aim to optimise block section lengths with a minimum amount of signalling equipment(Vignali et al., 2020), to optimise the capacity of the railway network (Cuppi et al., 2021), to optimise the availability of the current system with additional communication link (Song et al., 2019). Among the propositions of system optimisation, there are methods to optimise the communication between the balise and balise transmission module (BTM), considering that it is one of the most critical and

vital communication links for the ERTMS signalling system. The proposed optimisations include the FPGA module of BTM (Park & Cho, 2022), the time synchronisation of BTM (Kurz et al., 2007), the measures against the vulnerabilities of balises (Wu et al., 2017) and the model of balise BTM communication to identify interfaces (Rodriguez et al., 2016).

Vignali et al. (2020) focus on the computation of the block section lengths based on the headway provided by the Employer for ETCS Level 2 operation. As ETCS/ERTMS provides uninterrupted train operation between countries, many European countries upgraded their railway lines to an ETCS signalling system. It also offers cost-effective solutions while increasing the line capacity. ERTMS design has many critical elements; this article focuses on identifying the signal positions and block section lengths that satisfy the specifications and requirements. If the main focus of this effort is to maximise the network capacity and thus minimise the headway, the investment cost increases. The authors offer a different methodology for designing the railway signalling layout, mainly based on the Blocking Time Model of ETCS Level 2 and the contractual headway requirement. This methodology also considers layout, typology and train characteristics and employs a Simulation tool that allows the backward calculation to verify the results.

The existing research for developing the optimal signalling system is analysed in this study. The first attempt of using a software-based design tool was used to minimise headway in metro lines. Later on, other studies divided and categorised the line as “constraint”, “stretchable”, and “critical” to address each category with different headway criteria to optimise the overall layout. Another study considered the effect of a gradient, minimum headway and average train speed and used an algorithm to define the positions of signalling blocks. In the available research, the concept of optimisation for signalling systems is often linked with the minimisation of energy consumption (Vignali et al., 2020). A study proposed a combinatorial optimisation model that reduces the computational time while minimising both headway and energy consumption. Another study presented a discrete time network model that minimised energy consumption and aimed to maximise the objective function of railway line capacity. A stochastic queueing theory is also proposed for the estimation of delay propagation for capacity analysis. There is also an available study that focuses on the same target under ERTMS specifications. However, all of the available studies

consider a single train without considering the presence of other trains, and they generally disregarded the installation cost as it inevitably increases as the headway decreases (Vignali et al., 2020). The available literature that recognises the disturbed conditions, such as operational trains with separate characteristics that also comply with ETCS/ERTMS specifications, is also reviewed. It is noted that the best improvement is observed under ETCS level 2 operation. The authors highlighted one available study that considers both capacity maximisation as well as installation and operation cost, which uses a stochastic multi-train simulation model integrated with a black-box optimisation loop.

The proposed methodology's main target is to achieve the contractual headway with the optimal block section lengths and minimum amount of signalling equipment. The starting point of the methodology is the "Blocking Time Model" of ETCS Level 2, which is the addition of route setting time, indication time, section length occupation, overlap occupation, train length occupation and free track detection. The sum of all parameters gives the headway duration (Vignali et al., 2020). For the backward calculation to be performed, the required inputs are train characteristics, the operational plan, the railway line gradient profile, the speed profile and contractual headway, and the required block section length by the railway operator. These variables are used as the input of the headway assessment software tool. The output of the software is the list of track vacancy detection equipment and marker boards' kilometric locations. Three main scenarios were used in the simulation: Case A, "continuous headway requirement with same train graph," where the train characteristics are considered identical; Case B, "continuous headway requirement with different train graph," where a stopping train follows a non-stopping train and Case C "headway at splitting point" where two different trains (freight and passenger) converge and diverge to a splitting point. For each case, the overlapping headway requirement is defined. This methodology is applied to a railway line located in Denmark, where the existing signalling system is renewed as ERTMS Level 2. The results showed that contractual headway is ensured using the proposed method and software. (Vignali et al., 2020)

ERTMS is operational not only in Europe but in many other countries outside of Europe as well. For example, ETCS Level 1 is operational in Finland, the United Kingdom, Spain, Belgium, Luxembourg, Thailand, Australia, New Zealand and Saudi

Arabia. ETCS Level 2 has a higher initial investment cost compared to Level 2, and technically, it is much more complex. Italy has preferred Level 2 on every high-speed and high-capacity railway line. As described in the earlier sections, Level 3 is still under development. As was the case in Level 2, Onboard continuously communicates with RBCs. However, ETCS Level 3 does not require a track vacancy detection system. Train integrity control is employed. This concept is referred to as the moving block principle. Cuppi et al. (2021) presented a study that aims to increase the capacity of Italy's high-speed and high-capacity railway lines. The proposed method is called High-Density ERTMS (HD-ERTMS), which is a sub-category of ERTMS Level 3, which is a fixed virtual block with trackside train detection. The reason behind this consideration is that HD-ERTMS will be overlaid with the legacy signalling system of Italy. The main motivation of this research is to overcome the limits posed by the Level 2 operation. There is an operational headway limit of 24 trains per hour and a constraint of capacity for GSM-R communication (Cuppi et al., 2021).

In HD-ERTMS, all HD-ERTMS trains are managed by Nodal RBCs. The occupation state of virtual sections is managed by interlocking based on the information received from train integrity. This process would result in the best performance with the HD Operational plan and all operational trains to be equipped with ERTMS. However, one of the important features of HD-ERTMS is to have both trains with ERTMS onboard and national signalling onboard. The main idea is to keep traditional block sections physically and to divide these block sections into virtual sections further. The traditional block section length is 900 m to 1350 m. Virtual block sections proposed by the authors are ranging between 450 m to 300 m. The operational scenarios developed include sending two consecutive ERTMS trains to one traditional block section. Since the traditional signalling is valid, the block signal would turn red; however, when the ERTMS train leaves the 2/3 virtual block section, the other train is accepted by the block section. However, this is not valid if a traditional train is sent following the ERTMS train. In this case, the entry signal to the block stays red as the ERTMS train empties the block section. With these scenarios, simulations were carried out using the OpenTrack tool. The results showed that HD ERTMS is increasing the line capacity by 56% for each station (Cuppi et al., 2021).

Song et al. (2019) aim to propose an overlay to ERTMS Level 2 operation that can support the system when it cannot ensure fail-safe operation. They aim to increase safety through a new train protection solution that works in parallel to the ERTMS system. It is also argued that redundant train-distance measurement strategies can be adopted to make it more affordable. As MA+ employs the moving block principle, it does not interrupt the ETCS-2 system yet can protect safety when ETCS level 2 fails. This is valid for the Train Administration and Communication System (ATACS) in Japan and the Chinese Train Control System Level 3 (CTCS-3) in China. MA+ is proposed to increase system availability via the Time-of-Arrive (TOA) distance estimation method.

Movement authority (MA) in Level 2 operation is carried by radio message, specifically message 3, Packet 15 from track to train. MA has several sections from the current train location to the end of authority. The MA is based on two important factors: the data and the communication. In terms of data aspect, the possible failures can be balise failure, block section occupancy, control centre being out of service and failure in onboard equipment. In terms of the communication aspect, the failure could be related to the transmission module. This research claims that additional data resources and independent communication links are needed to improve the current system. The MA carries the following information: scalar magnitude (train movement), vector direction and information about other objects such as trains and switches. However, it does not carry information about the switch position and status. Also, it does not give the location of the preceding train. MA+ proposed in this article enables train-to-train communication as well as train-to-switch communication. If any unsafe situation occurs where the intertrain distance is short, MA+ will interfere with safely executing the brake (Song et al., 2019).

The MA+ system requires a new train-centric communication unit within every train, and a switch announcement unit broadcasts the location and status of the switches. This also means that the transceiver unit is in charge of exchanging the location between the train (and their communication units) and receiving the data broadcasted from switch announcement units. The Algorithm, on the other hand, receives information from all the equipment, including the ATP and outputs a result accordingly. In addition, for trains to switch communication, it is also possible to link between trains, which share information with the other trains on speed, position,

direction, ID, and length through the onboard equipment and transfer to others. For the acquisition of train distance data, this article proposes two strategies. The normal strategy proposes using “Train Messages (TM)” and digital maps to perform correct distance estimation. The backup strategy is considered to be used when the onboard equipment or RBC is malfunctioning, and then TOA distance estimation undertakes and defines headway distance. (Song et al., 2019)

To perform the above-mentioned estimations and duties, each train needs to be equipped with a “train-centric communication unit,” and the switches need to be equipped with a “switch announcement unit”. The train-centric communication unit is responsible for exchanging train location data with other trains and receiving information from the switch announcement unit. The directional antenna detects the preceding train and, with the ID number MA+, recognises the train-specific features as well. The algorithm enables the calculation of distance with the received information from trains and other automatic train protection equipment. The digital map contains railway line-specific information such as stations, tracks, curves, etc. The simulation was carried out for the proposed MA+ system overlayed into ETCS Level 2 and Level 3. MA+ results with the minimum train headway distance compared to ETCS Level 2 and Level 3. The gap between ETCS and MA+ increased as the train speed reached 300 km/h. (Song et al., 2019)

Some studies propose various innovations for Eurobalise and BTM. Park & Cho (2022) focuses on increasing the processing efficiency of the balise transmission module (BTM). BTM has two components: an antenna and a module. Wu et al. (2017) analysed the vulnerabilities of Eurobalise and BTM communication and presented solutions to take measures against malicious interferences. Kurz et al. (2007) researched the time synchronisation of BTM subsystems. Rodriguez et al. (2016) modelled Eurobalise and BTM and performed tests to assess interferences.

2.1.3 Issues and problems faced during the implementation

ERTMS signalling system is a well-established system with a full set of specifications and standards. However, it requires a transition while promising interoperability in cross-country operations. During this transition period, the countries are facing some issues. Adaptation requirements have many facets that need to be implemented by the adopting countries. The literature about the issues faced in the implementation of

ERTMS focuses on the transition from legacy signalling system to ERTMS (Smith et al., 2012), the cross-border implementation of ERTMS (Rajabalinejad & Schuitemaker, 2017), technological issues and issues faced by the train drivers (Rosberg et al., 2021).

The idea of interoperability is based on the study carried out by the European Commission in 1989 regarding signalling issues. The major coverage of the study was about the incompatibility of many legacy signalling systems in Europe and the necessity to develop a signalling methodology that enables safe railway operation. The interoperability problems have multiple facets: signalling, energy, infrastructure and rolling stock. The focus of this article is interoperability for signalling (ERTMS system) and implementation problems faced during the transition from legacy signalling system to ERTMS (Smith et al., 2012).

The ERTMS system's main aim is to increase rail transport's competitiveness. This aim is achieved by facilitating cross-border operations, standardised safety in operations and creating a single market for railway manufacturers. The high-speed railway lines have the priority of the ERTMS transition; conventional lines are the second. Interoperability comprises technical requirements, which are the use of the same interfaces between the equipment and operational requirements, which are the use of the same interfaces between the machine and driver. ERTMS system is the implementable system for obeying signalling interoperability. ERTMS consists of four layers. These layers are European Operating Rules (EOR), European Traffic Management Layer (ETML), Euro-radio (GSM-R) and European Train Control System (ETC). This research is focused on the technical layer, ETCS and GSMR (Smith et al., 2012).

Spain is the first European country to implement ERTMS. During the deployment, Spain faced many problems. These problems are mostly related to the unavailability of fully developed specifications and the integration problems with available onboard and trackside equipment suppliers. For the implementation of level 2, GSMR specifications were not completed, so the works were delayed during the testing of reliability. Spain has overcome these problems with laboratory testing, reviewing the Juridical Recorder Unit and analysing RBC logs. Another issue faced during the transition period was related to the driver's behaviour. ERTMS requires serious attention on DMI, whereas the legacy signalling systems mainly require the driver to

pay attention outside the train. The problems faced by Britain were related to the DMI. It has been depicted that the DMI screen was not visible due to sun glare and similarities between icons. These types of errors can lead to human errors in human-driven operations. The Netherlands also experienced delays and problems due to unclear specifications that were solved by laboratory testing and applying EN 50128 and EN 50129. France has experienced GSMR-related issues where GSM-R calls were dropped. This unexpected termination of the call posed safety problems. During the implementation of ERTMS, the problems faced were requirements, specifications and testing, operational procedures and human factors (Smith et al., 2012).

According to the International Union of Railways, ERTMS aims to enhance cross-border interoperability and interoperability in suppliers and manufacturers, which will eventually improve the competitiveness of rail transport. There is also another well-known aim of ERTMS, which is making rail transport safer. The improvement in safety results from continuous supervision of train speed (in ETCS Levels 2 and 3), reduced human-related errors and decreased amount of “signals past at danger”. Rajabalinejad & Schuitemaker (2017) argued that ERTMS is an overlay to the existing signalling system and does not necessarily result in safer rail transport. The assumption that ERTMS is replacing the existing signalling system is not correct. Additionally, the implementation of ERTMS does not automatically contribute to safety. The implementation and planning are quite important.

Interoperability brought by ERTMS has two facets: cross-border operation and railway supplier market. The competition has increased because of this incentive; however, many other manufacturers implement the specifications as they understood or processed. According to this study, Dutch national safety goals are based on ALARP (As low as reasonably practicable principle) and the standstill principle. This led to a selection of risk-reducing measures with the perspective of cost-benefit. Several accidents are considered to have happened due to this approach (Rajabalinejad & Schuitemaker, 2017).

The research is based on findings from ERTMS implementation available on national data and semi-structured interviews with key Dutch stakeholders. It has been argued by some articles that ERTMS specifications are incomplete, unstable and language is too formal. The available documentation is perceived as insufficient by the railway stakeholders. The implementation methods are dependent on the railway line and the

country. For example, France made no changes to migrate ETCS Level 2. However, Germany and The Netherlands invested a lot and experienced difficulties that led to discontinuation. This further shows that ERTMS applications have unique sides even though the standards and specifications are the same. Also, different operational levels require different amounts of initial investment. ETCS Level 1 requires more infrastructure investment than Level 2; meanwhile, in Level 2, more investment is moved to ETCS trains. As there are different kinds of levels implemented inside and outside of the European countries, more transitions are required to be made. The findings showed that ETCS is a complex system with many transitions where train drivers and signallers cannot process the failure easily because of the technological complexity and lack of knowledge (Rajabalinejad & Schuitemaker, 2017).

There are also sociotechnical safety issues. The unstable and incomplete specifications are claimed to be misinterpreted, and many more variations are produced by suppliers and stakeholders that compile tendering documents. For cross-border railway lines, stakeholders that do not understand their language and culture pose more risk of compromising safety issues. It is added that no one wants to assume the risk of interfacing two different countries' railway sections; a central designer is missing. Even in the planning phase, it has been depicted that safety issues are stalled due to the system's complexity (Rajabalinejad & Schuitemaker, 2017).

In another case, Sweden started to deploy ERTMS in existing railway lines in 2011 and 2012. Rosberg et al., (2021) analysed the reason behind the reported implementation problems. This analysis reveals if the experienced problems can be overcome during the network planning phase. The drivability analysis is recommended during the planning stage to prevent the potential implementation problem experienced after deployment. In Sweden, drivability analysis has become important for the planning of retrofitting projects from Automatic Train Control (ATC) to ETCS.

A systematic literature review has been performed in Scopus and Spark Rail. Also, specific reports about ERTMS implementation experience and other available data were analysed as provided by the Swedish Transport Administration. The guidelines employed in this study focus on three viewpoints for this analysis: the population (the train drivers), the intervention (ERTMS signalling) and the outcome (driveability). The results are analysed under technological issues and train drivers (Rosberg et al., 2021).

The technological issue can be handled and considered at the network planning stage. This aspect has three categories: speed, braking curves and DMI. As explained above, Sweden mostly performed retrofitting projects to transition the existing railway lines from ATC to ETCS. The changing speed is a problem in this implementation. The topographic characteristics of these lines stayed the same. Due to their line characteristics, these lines impose varying speed restrictions compared to newly built railway lines. ETCS onboard intervenes whenever the target speed exceeds 5km/h. However, ATC's limit to intervene is broader, which is 10 km/h. It means that the number of interventions will be higher and very close to each other. The driver needs to follow up quickly since the driver avoids intervention. The different approach to the braking curve is also an issue compared to ATC and ERTMS. ETCS imposes additional braking times and indicates speed changes 450 m earlier than ATC(Rosberg et al., 2021). DMI indications are higher compared to ATC. The driver must follow the indications where speed changes are constantly varying intensively, which can increase the cognitive workload. An experiment showed that the train driver's attention is outside 75.3% of the driving duration when the driver is guided by lineside signalling. In the case of ERTMS, the driver can only pay attention outside 39.3 % of the driving duration. However, watching outside to realise ETCS markings and damaged overhead contact lines is critical for train drivers.

The train driver issue represents the human part of drivability. Driving style is affecting train operation. It is seen that the drivers tend to lower the speed to eliminate the risk of ERTMS intervention compared to lineside signalling. A driver's braking behaviour is mainly related to passenger comfort and adjusting the speed for a smooth ride; however, slow driving eventually decreases the train capacity. The workload is another issue. There are conflicting results in the literature review on this matter. Some research indicated that workload is increased in reported cases because of the complex speed profile and badly planned transitions between operational levels and legacy signalling systems. Other research claimed that due to automation and clear indications from DMI, errors of the driver are corrected by ERTMS. As a result, technological issues that cause implementation problems during network planning shall be defined with drivability analysis, and the design needs to be corrected. However, train driver-related issues such as driving behaviour cannot be corrected at the planning stage(Rosberg et al., 2021).

2.1.4 STM technology proposition

As explained in the preceding section, transitioning from the legacy signalling system to the ERTMS signalling system is challenging in terms of technical and financial aspects. The financial investment is not only required on the trackside but also on acquiring new trains or retrofitting the existing rolling stock. The transition period in Europe is still in progress, and during this period, a new development in STM technology is required to utilise the full potential of the railway network. In addition to the transition in Europe, due to the success of the ERTMS, there are also propositions to adapt and adopt STM-like systems. The competitiveness of the railway manufacturing market draws attention from all over the world.

According to (Mikulčić et al., 2020), ERTMS is not only developed to disable the incompatibilities in signalling systems or safety requirements, but it is also developed for setting a standard in rolling stock characteristics. The legal framework for railway packages by the European Commission and TSI directives aims to increase rail transport competitiveness and technical harmonisation. However, the European Railway Agency (ERA)'s report on interoperability showed that ERTMS trackside deployment in Europe is only 14% for core network corridors, and for GSMR deployment, the percentage is 60% by 2019 (Agencia de Ferrocarriles de la Unión Europea., 2022b). This indicates that Europe itself is also under a transition process towards ERTMS. During this transition period, the STM device gained a lot of importance. STM devices can receive trackside data from the national train protection system and transform the received data into an understandable format for the ETCS onboard system (Mikulčić et al., 2019).

This study focuses on this transition process and proposes the argument that the use of a specific transmission module is the solution to provide compatibility between legacy signalling systems and ERTMS. The proposed system is named “AP STM”, and it enables connection between PZB 90/ Indusi and ETCS (Mikulčić et al., 2020). PZB 90 and Indusi are widely used in the national networks of Austria, Bosnia and Herzegovina, Croatia, Germany, Macedonia, Montenegro, Israel, Slovenia, Serbia and many other countries. All of these countries, except Israel, share cross-border railway connections. Train operation between countries is only possible if the train onboard is equipped with a PZB90/Indusi train protection system.

PZB 90/ Indusi system has three different trackside balises along the right side of the line that use inductive transmission to send the information onboard (Mikulčić et al., 2019). These balises are located at a braking distance apart from their related signal. Onboard's two locomotive balises receive the transmission. The received data contains information on their related signals aspect. Locomotive balises provide the input to the central unit, which indicates speed restriction, driver's response, or braking interventions (Mikulčić et al., 2020).

The railway lines equipped with PZB 90/ Indusi are analysed by this study regarding ERTMS transition status. The results show that the percentage of ERTMS deployment in comparison with the total length of the railway network is Israel 8%, Slovenia 28%, Romania 15%, Macedonia 4%, Croatia 7%, Germany 4% and Austria 22%(Mikulčić et al., 2020). Trackside deployment is not the single criterion of evaluation. The availability of ETCS onboard locomotives is also an important issue to consider for fully operational ERTMS. Among the mentioned countries, Croatia and Macedonia do not have any locomotives with ETCS onboard; Romania only has seven, and Slovenia only has 3. The main reason for the low number of locomotives with ETCS onboard is the high cost required for retrofitting and new acquisition. The average cost of retrofitting is 482,500 EURO per locomotive, and for new locomotives, the cost of an onboard unit is 300,000 EURO(Mikulčić et al., 2020). The latest status of both the trackside and the availability of an onboard system indicates that full deployment of ERTMS still requires many years. The transition with STM seemed a wise option for the whole duration.

There are two alternatives to the STM application. One alternative requires an external connection of STM to the ETCS onboard with a standard interface such as Profibus. The other alternative is to integrate STM to ETCS onboard internally. The comparison between these two alternatives depends on the type of locomotive, whether it is new or old. The proposed "AP STM" is categorised as the first alternative where it provides an external STM technology. In the railway market, external STM technology is very limited. Other external Indusi STM solutions are available, such as Siemens "Trainguard" and Bombardier Transportation "EBI Cab". Both of these systems can be converted to ETCS onboard subsystems, and all of the three solutions are reliable with 2oo2 (two out of two) architecture. However, the proposed "AP STM" receives the data from Indusi trackside balises and converts the received data into a format that

can be processed by the ETCS on-board system(Mikulčić et al., 2020). Integrating AP STM to DMI to display Indusi-specific information is also possible. Data entry is also shared with ETCS. The architecture of the connection of AP STM to ETCS onboard's European Vital Computer (EVC) is with Profibus DP protocol so that the communication is provided with a single bus. The connection to DMI is made with hardwire (Mikulčić et al., 2019).

This new STM device is developed as a result of a 14-month-long initial research phase, which includes potential market research, formulation of the technological concept, experiments for technical feasibility and prototype validation in the laboratory. During the development stage, ETCS standards, specifications, and FFFIS requirements are followed (Subset 056, 057, 058, Profibus EN50170). For software design, EN50128 is applied. For hardware, EN 50129 is applied, and DIL4 conformance is targeted. The chosen system typology for AS STM is a distributed system, considering that separated modules will be easy to implement, and update and simpler integration will be possible. Also, the system modularity is considered. The advantage of modularity is that the failure of individual modules does not affect the other modules (Mikulčić et al., 2019).

Interoperability of ERTMS is based on two key interfaces: air-gap interface and human-machine interface. Air-gap interface refers to the interface between trackside equipment and onboard equipment. There are two types of airgap interfaces in ERTMS. One of the airgap interfaces is between Eurobalises and the Balise Transmission Module (BTM). This interface is used during spot transmission of fixed and controllable balises. On-spot transmission is the only air-gap interface ETCS Level 1 operation. The other airgap interface is between GSM-R and Euroradio. This interface provides continuous transmission of movement authority. In ETCS Level 2 operation, controllable balises are no longer needed due to continuous communication between onboard and GSM-R. However, spot transmission for location reference is required with fixed Eurobalises. ETCS Level 2 operation requires both airgap interfaces to be operational. Human-machine interface is performed by Driver Machine Interface (DMI). This interface is available in all levels of ETCS operations since it is onboard-dependent equipment (Fanea, 2017).

The ERTMS functional language is well defined in specification SUBSET-026 for variables, packets, messages and telegrams. The definitions are separated both for Eurobalise telegrams and GSMR messages. Since this research mainly focuses on the interoperability of ETCS Level 1 operation, more focus is provided on the Eurobalise airgap interface. The minimum set of requirements is defined in FFFIS specifications for Eurobalise and BTM and testing specifications. For the DMI interface, interoperability is ensured with the harmonisation of touch screen, soft key displays and, most importantly, the availability of a library of symbols and sounds. The specifications of DMI ensure the train driver's operation in cross-border networks(Fanea, 2017).

The success of ERTMS in interoperability is not only cross-border operation. ERTMS specifications are open to the public and reachable to everyone. The development and testing methods are also standardised for almost every sub-component and equipment. This enabled the railway manufacturing market to become a multi-vendor competitive market and interchangeability of suppliers. The specification in both technical and functional aspects enriched the railway operators, railway experts and manufacturers and all of them have access to high-end, off-the-shelf signalling systems (Fanea, 2017). The increasing success of ERTMS draws international attention. In 2014, 57% of ERTMS trackside investment was made in Asia, Africa and the Middle East. However, 41% of the investment was made in Europe. The non-European countries that have adopted ERTMS include China, Australia, India, South Korea, and Saudi Arabia.

Fanea (2017) discusses the similarities between ERTMS and Positive Train Control (PTC) (USA's automatic train protection system), that both systems are deployed as an overlay to the existing signalling systems. The main aim of both systems is to ensure safety and interoperability. The proposed convergence of ERTMS and PTC covers the migration of Euroradio safety layers to 220 MHz or 160 MHz to comply with PTC. This convergence enables the communication of PTC with the ERTMS onboard subsystem. The author also highlights that such attempts are available as Kazakhstan deployed ERTMS with Tetra radio (Fanea, 2017).

2.2 Literature Review in ALSN

ALSN signalling system has been under operation since 1930s, the system has been implemented and maintained for a long period. Considering that the available literature on ALSN is more focused on optimising the existing system. The modelling propositions are comparably low in number. Studies also focus on the issues and problems faced during the operation.

2.2.1 Modelling

ALSN signals are amplitude-modulated signal representations of the signal light aspect currently available on the related track section. ALSN signalling system depends on transmitting these signals through rails without suffering serious distortion. The distortions may cause misinterpretation of the signals in the decoder of ALSN onboard. The regular failures in the ALSN signalling system are caused by the influence of traction current, harmonics, changes in the magnetic field, power transmission lines that are crossing the railways, height differences in the receiver coils, etc. (Prisukhina et al., 2019). Considering the ALSN system is actively used in a 67,000 km long railway network, scientific research on resolving the failures mentioned above is relevant and needed to increase safety on railways. ALSN signalling system employs continuous data transmission through rails to ensure traffic safety in railway operations. The transmitted data carries information about the signal indication of the upcoming section. Data is in the format of coded signals (ALSN signals or ALSN codes): Green (G), Yellow (Y) and Red-Yellow (RY). Safety critical failures in the ALSN system are either caused by the distortions in coded signals' time parameters or the distortions induced by the destabilising factors. These factors can be a lack of preventive maintenance, violations of standards and regulations, design or installations. To prevent these failures, precautions such as staff training and storing necessary spare parts need to be taken. While designing the ALSN signalling system, certain parameters require consideration, such as selecting the correct technical parameters for the code transmitter. External disturbances are another issue that requires the attention of the designer and the operator, such as temperature changes, humidity, traction current, any high voltage transmission line crossing, etc.

The modelling propositions for the ALSN signalling system aim to identify the cause of failures (Onischenko & Chernykh, 2019), the causes of distortions in the received data (Tetiana et al., 2019), and to generate a set of ALSN codes for data training purposes (Prisukhina et al., 2019).

Onischenko & Chernykh (2019) developed a mathematical model of the ALSN signalling system with a 25 Hz code transmitter. In this model, the external and other types of disturbances can be modelled and easily tested to take necessary precautions. Low noise immunity is the main issue for the Russian railway that operates with the ALSN signalling system. The major academic work focuses on eliminating disturbances and signal distortions. Usually, the cause of the distortion is not singular, which makes it more complex to apportion the reasons. The diagnosis requires special measurement and recording equipment of track and locomotive and a team of experienced experts that will debug the collected information. Instead, this article proposes to model ALSN that allows testing and debugging with an automated monitoring system (Onischenko & Chernykh, 2019). A model is developed using the Matlab Simulink program.

Ukrainian Railways also operates six major railway networks. These railway networks are in varying lengths, from 3207 km to 4668 km. These networks are either non-electrified, DC or AC-electrified; however, all of them are equipped with the ALSN signalling system. ALSN system, namely the automatic locomotive signalling system, has multiple carrier frequency options. 50 Hz is used for railways with DC electrification, and 25 Hz & 75 Hz are used for railways with AC electrification. The ALSN codes are generated with tonal track circuits such as TTC 3 at 420, 480, 580, 720, and 780 Hz with 8 and 12 Hz modulation. Rails are used as the transmission medium; however, in AC-electrified railways, return current also returns to the substation through rails. Tetiana et al., (2019) focus on this issue and develop an algorithm to classify the measurement performed along the track to identify the problematic operation of ALSN TTCs (Tonal Track Circuits).

The existing situation of the operational TCCs can be checked using a car laboratory. This method allows the operators to determine the parameters by recording the received data by the locomotive. The operator usually performs this measurement twice a year. The computer attached to the locomotive registers every ALSN signal received by the receiver coil of ALSN onboard. The developed methodology starts

with the pre-measurement study. The initial data that must be prepared beforehand includes the name of the railway section, stations, type of track circuits, length of the railway line, the sampling frequency and setting of the quantisation step of the analogue-to-digital converter. The attached system records all the measurements and forms the data. The proposed algorithm decodes the received data and determines if there are any distortions, the cause of distortion, or if the received data fits any predefined green, yellow, or red-yellow (Tetiana et al., 2019). For example, the algorithm imposes a threshold to amplitude and duration to decide whether it is an impulse or an interval.

Prisukhina I V et al., (2019) propose to generate a certain set of signals using a classification algorithm to minimise the failures caused by such distortions. The classification algorithm will be located in ALSN onboard. So that the receiver will distinguish the original code even though the received signal is distorted. This generic algorithm requires training with certain signals that are known in advance. The correctly modulated and distorted signals need to be generated. These signals can be created either by the recording method with an oscilloscope from the rails or by a simulation model of signals. This article develops a simulation module for the generation of ALSN signals.

2.2.2 Optimisation

Optimisation is the major concern of researchers. The literature on optimization of ALSN signalling system can be further categorized as the optimisation of the ALSN code immunity towards distortions and the system level optimizations. The optimisation regarding the disturbances immunity includes proposing an automated system for detecting ALSN code disturbances (Havryliuk, 2019, 2020), developing a method to select the optimum ALSN code carrier frequency (Leushin et al., 2020), the optimum voltage supply for track circuit (Aripov et al., 2016), the optimum track section length (Aliev & Aliev, 2022) and proposing an optimised analogue-to-digital converter (Baranov et al., 2019). The system level optimisations cover the ALS-EN system for high-speed operation (Alexandrovich, 2017; Nikitin et al., 2017), ALS upgrade with GPS and GSM-R (Liudvinavičius & Śladkowski, 2017) and proposing the adoption of automated drawings (Sedykh et al., 2018).

Track circuits are playing a major role in automatic train control systems. The main functionality is track vacancy detection. For the ALSN signalling system, audio frequency track circuits, in other words, tonal track circuits, are used. AFTCs (Audio Frequency Track Circuits) generate amplitude shift keying signals that have low noise immunity. This leads to vulnerability to wide-band frequency interference. Havryliuk, (2019) proposes a method that employs digital wavelet packet transform, Shannon entropy and artificial neural network to automatically detect possible disturbances in ALSN signals. The railway operators usually perform periodic maintenance for keeping the parameters as requested. However, imagining that AFTCs are distributed systems that span tens of kilometres. Keeping track of the parameters and periodic maintenance is technically and financially challenging. Wavelet Transform has recently been used for simultaneously analysing the signal time and frequency domains.

AFTC comprises an audio frequency generator, filter, and cable that connects it to the receiver in the control room. In this setting, the receiver performs the safety critical evaluation, which is the track vacancy detection. The AFTC receiver checks the received signals' carrier frequency and modulation frequency according to the defined thresholds to make a decision. The disturbances in the signals are usually observed in four results. The first result is the loss of some pulses or the loss of amplitude to a level. This result is observed when there is a short-term interference on the rails. The second result is the excess pulses that lead to spikes during pause intervals. The third result is the continuous interference observed. These interferences can be either caused by the asymmetry in two rails, traction current harmonics or the harmonic caused by the source voltage of AFTC. The last result is the sharp impulse observation. The proposed methodology uses the wavelet packet energy Shannon entropy to reveal the ALSN signal sections/segments with interference. Later on, these segments are analysed using discrete wavelet packet transform to determine the type and parameters of the distortions(Havryliuk, 2019).

As ALSN signals travel through rails, the amplitude and duration of signals can be distorted by other devices along the rails, traction current, rail magnetisation and electromagnetic interferences, as well as deterioration of the transmitter itself. Havryliuk (2020) focuses on the defining distortions of ALSN signals with periodic controls during maintenance and search methods to identify and categorise the source

of problems for preventive maintenance. The existing literature proposes a fast and short Fourier transform. However, this methodology proved to be ineffective due to the non-stationary disturbances. The wavelet transform is proposed for the analysis of distortion. For the categorisation of distortions, the literature proposed an artificial neural network. This article proposes adopting an Adaptive Network Fuzzy Interference System (ANFIS).

ALSN Signal codes have 1,2, or 3 pulses that amplitude-modulated code. Based on the type of message transmitted, “red-yellow”, “yellow”, and “green” are available. The signal period varies between 1.6 seconds to 1.86 seconds to distinguish the neighbouring track circuits. Based on the conditions of the railway line, the carrier frequency can be chosen as 25 Hz, 50 Hz and 75 Hz. The ALSN signals current distribution differs at the relay or along the railway line. The signal current mean value for AC track circuits is 4.8 A, whereas for DC track circuit 6A. For the train decoder, ALSN antenna, to detect the correct number of pulses and pauses, the received combination shall be compatible with the normative values. When the normative values are received within a minimum duration of the pulse of 250 ms by the ALSN antenna, decoding is completed within 45 ms to 70 ms (Havryliuk, 2020).

With the measurements, the signal distortion measured between the track transmitter and the rail at the relay end is compared. The Green pulse is an example; the track transmitter generates 0.35 s first pulse, 0.12 s first pause and 0.22 s second and third pause. At the relay end, the measurement showed that 0.20 s is the first pulse, 0.11 is the first pause, and 0.07 s is the second and third pause. Typical distortions of ALSN signals are depicted as the signal with a changed duration of the first pulse and pause, the signal with decreased amplitude, the signals with amplified pulses, the signal with one or more divided pauses, the signal with complete decay in one or more pulse and the signal with continuous long term interference. The common cause of divided pauses, appearance and disappearance of pulses is usually the train movement from one track circuit to another. This article uses wavelet analysis using discrete wavelet packet transform. As a result of calculated WPESE values, it has been seen that the major distortion is “continuous long-term interference”.

The main cause is the electrical asymmetry in rails and loss of attenuation coefficient in the input filter of the ALSN antenna. The results are also analysed with ANFIS. The results showed that the WPESE method is more sensitive and successful for the preliminary detection of problem segments. However, ANFIS allows the quantification and categorisation of signal distortions (Havryliuk, 2020).

According to Leushin et al. (2020), there are three types of interferences: rail lines (RL) and inductive lines inductive-rail lines (IRLs). The interferences cause malfunctions in the system and lead to a capacity decrease in railway lines. Leushin et al. (2020) propose a method to select the optimum carrier frequency for ALSN. The main target is to keep IRL attenuation minimum and maximum noise immunity.

The major issue of interferences in ALSN is that carried data loses the speed of data transfer and its volume. To minimise the effects, the proposed methodology has three steps. The first step is calculating the ALSN signal's attenuation in RL, IL and IRL on the carrier frequency. The second step is to determine the noise immunity of the locomotive receiver on the carrier frequency. Lastly, select the optimum carrier frequency based on the analysis result. The operating ranges of ALSN transmitters have an average frequency to eliminate the influences of harmonics, that is, the multiples of 50 Hz. The calculated attenuations and test results showed that the attenuation of ALSN signals in the RL increases as its carrier frequency increases. Meanwhile, attenuation in IL decreases. The attenuation in IRL is at a minimum between 250 – 400 Hz. The tests were carried out for noise immunity using the KLUB-U onboard system. The minimum IRL attenuation and the maximum noise immunity are achieved with the optimum ALSN signal channel, the AM signal, with carrier frequency between 325 Hz and 375 Hz (Leushin et al., 2020).

The Republic of Uzbekistan is modernising its railway. The top priority is to increase the passenger train speed. Tashkent – Samarkand railway has already been upgraded to 150 – 250 km/h for passenger trains. Modernisation includes strengthening the railway tracks, adjusting turnouts to higher speeds and enlarging technical buildings. One of the other major works is to upgrade the legacy signalling system. Aripov et al. (2016) reviewed the modernisation works carried on in Uzbekistan and the motivation behind these works. Upgrading to a high-speed railway requires considering a solution that will provide protective measures against possible natural phenomena, fault tolerance, a limited response time, high equipment performance and availability of

monitoring devices for tonal track circuits. It has been decided that an ALSN signalling system will be used to meet these requirements, and an axle counter device will be used to track the vacancy detection system. After the selection of the main system components, the track circuit is modelled mathematically by the authors, and it is recommended to use the proposed calculations to find the optimal voltage supply and track section length (Aripov et al., 2016).

Aliev & Aliev (2022) proposed an algorithm to define the optimum length of the track section for ALSN code transmission to be successful. The track section refers to the track within the track code transmitter and the receiver. As external disturbances are the major problem, the optimum track section length shall consider the possible distortions on the ALSN signal. The track section, code track transmitter, receiver and rail, and the locomotive are mathematically modelled. The created model is transferred to a software algorithm. This software algorithm is developed to calculate the optimum length of the track section. The input required by the software is the planned length of the track section, ballast resistance, ALSN current and voltage under the receiving coil of ALSN onboard. The output results in the output voltage and current of the frequency converter. One can ensure the optimal track section length by checking the planned track sections. According to a trial, for 10 Ω/km ballast resistance, the length that ALSN signals can reach is up to 5,500 m without needing any repeater (Aliev & Aliev, 2022).

In the ALSN signalling system context, track circuits perform three main duties. These duties are track vacancy detection, continuous data transmission to the onboard system and rail monitoring. The continuous transmission occurs when the onboard's receiving coils pick up the ALSN signals generated by the track circuit. The rails are used as the transmission medium. In the case of electrified railways, the rails are used to transmit both ALSN signals and return traction current. Baranov et al. (2019) argue that the reliability of the ALSN signalling system depends on the design of the types of modulation, single encoding, signal-receiving operation and computation circuit according to the noise characteristics generated by the electromagnetic interference. It is claimed that electromagnetic interferences need to be studied, and based on the results, the rest of the encoding, modulation, onboard filtering and decoding systems need to be designed or considered.

The safety and reliability of ALSN operation are related to types of noises such as fluctuations, pulsed, harmonics and their numerical representation (Baranov et al., 2019). The noise models and their characteristics are needed at a certain accuracy to acquire a full model of the available noises along the railway section.

There is equipment called “Noise measuring equipment (NME)” to measure the noise. This equipment has connection to both trackside and onboard connection. During the measurements, it is important to register both the driving regime, such as acceleration, braking, etc. and the noise, as well as the time and place of the recording. NME consists of oscillograph data, stored pulses, harmonics and fluctuation noises. NME’s algorithm provides the results of minimum and maximum amplitudes of measurements and the amplitude and durations of the pulses. The algorithm also results in a set of data that allows the user to perform statistical processing. Baranov et al. (2019) propose an analogue-to-digital conversion method to convert the measured analogue noise data to processable digital data within the requested accuracy.

Automatic Locomotive Signalling (ALS) is the ancestral signalling system of the ALSN signalling system. With the continuous data transmission through rails, ALS has been transformed into ALSN. This system enables the train’s speed control and provides information about the next section’s status with the next signal aspect, thus increasing the safety of railways. However, there are also disadvantages to the ALSN signalling system. The ALSN codes are very limited (green, yellow, red-green), which is unsuitable for high-speed train operation. The amplitude modulation is highly susceptible to external noises and interferences. There are also other kinds of operational limitations, such as using electromagnetic relays, dependability of stability of the source voltage, and receiving signals from adjacent tracks (Alexandrovich, 2017). Despite these known disadvantages, ALSN is widely used. Russian Federation, Belarus, Estonia, Latvia, Lithuania and Ukraine use the ALSN signalling system (Cheptsov et al., 2013). The upgraded version of ALSN is also available, and it is called ALS-EN. This signalling type is only operational in high-speed railway lines of the Russian Federation. Considering that ALS-EN is only employed in a single country, it would not be the central focus of this research. However, the working principle and transitions will be explained.

ALS-EN enables the transmission of more data to the locomotive. These data include the number of free blocks ahead, the aspect of the signal light, speed restrictions, the length of the section ahead, the information of diversion, transition to double or single track, and the number of station sidings that the train is approaching (Alexandrovich, 2017). ALS-EN is developed for high-speed lines up to 200 km/h. This system uses two sub-channels and phase modulation with a carrier frequency of 174.38 Hz. To increase noise immunity, the codes are generated with modified Bauer code. ALS-EN has two evaluators onboard to increase the system's reliability. However, there are three trackside evaluators (Nikitin et al., 2017). The code track transmitter has the 2 out of 3 architecture.

ALS-EN trackside has a network transformer, signal conditioner power supply, code track transmitter (CTT), and power amplifier. CTT generates phase-shift keyed signals with the carrier frequency. In the case of failure, the code track transmitter has two degraded outputs: partial failure and complete failure. The onboard of ALS-EN is composed of receiver coils, filter, amplifier, locomotive circuit switching unit, electronic unit, and locomotive indication unit. Receiver coils pick up the signal that is processed in the onboard system. The indication unit can give the train driver information such as the number of free block sections, the type of block section, the signal aspect, diversion(if any), etc. The transition between ALSN and ALS-EN is automatically triggered as the receiving coil for ALS starts to pick data, whereas the other receiving coil receives no signal.

The number of code combinations that ALS-EN supports is 16 messages with 8 bits and two sub-channels, in total 256 unique commands. Certain research in the literature argues the amount of combinations is not enough for high-speed train operation. Two research studies are proposing the use of "sum module weight code WSM(5,3)", 5 data bits, and three control bits (Nikitin et al., 2017), (Alexandrovich, 2017). If WSM(5,3) were to be employed, the total number of unique commands is 1024. Another advantage of the proposed model is the high noise immunity. According to the comparative analysis of Bauer code and WSM (m,k) code, it has been seen that the failure rate detection is better in WSM (m,k). The calculated failure is $8,25 \times 10^{-16}$ (Alexandrovich, 2017).

JSC Lithuanian Railways (LR) has started to renovate and renew its locomotives and rolling stock. Lithuania has both ETCS signalling and ALSN signalling systems. The existing locomotives have locomotive safety systems (LSS) compatible with the ALSN trackside system. LR is considering an LSS that would not reduce the interoperability of ETCS equipment and national legacy signalling system ALSN equipment (Liudvinavičius & Śladkowski, 2017). However, the requirements of the ALSN onboard system and ETCS onboard are quite different. The permissible speeds and the objects along the route are embedded in the memory of LSS; however, this information is transferred to ETCS on board with balises. The position of a train is known by GPS coordinates and track circuits. When proposing a new LSS, LR has focused on GSM-R. Lithuania was one of the first Post Soviet countries to install a GSM-R communication network. There is an interface between the GSM-R network and the LSS onboard. This interface enables data transmission and control to the operational control centre (OCC). The data of received trackside signal, train's speed, driver attentiveness, etc., is transferred to OCC, and any command from OCC, such as emergency or forced braking, can be sent to LSS via GSM-R. For the ALSN signalling system, some systems perform train control using a GPS. With the help of GPS, LSS receives track-specific information such as the profile and longitudinal plan of the route. The received information can be evaluated, and the speed and fuel consumption of the locomotive can be automatically adjusted. This will result in an innovation for the existing LSS system, where the drivers can only manually control the train. This new proposition of LSS integration with GPS enables the deduction of the accumulated energy consumed. Additionally, the GSM-R interface of LSS enables data transmission via the GSM-R network. The data of ALS signals, speed limits or employees working on maintenance can be transmitted to the LSS from OCC. The train integrity is also proposed to be controlled by the speed and route of the last wagon and changes in the pressure of the last wagon (Liudvinavičius & Śladkowski, 2017).

90% of the railway network of Russia is using relay-based interlocking. According to Sedykh et al. (2018), design engineers in Russia perform railway signalling system designs manually. The human-dependent design process is time-consuming and open to mistakes. The signalling design is a rather complex issue that requires more attention and automation. Sedykh et al. (2018), propose a method for designing automated drawings according to "the JSC Russian Railways" specifics.

The signalling system adopted by the Russian Federation is the ALSN system as automatic train protection. However, there is also an underlying signalling system that is comprised of interlocking and block sections. Along the stations, the interlocking system arranges the manoeuvres and passenger and cargo loading actions with the help of the operator in charge. The operator needs to initiate the automation sets arranged within the interlocking. The interlocking commands trackside equipment, including signal lights, point machines, impedance bonds, and track circuits. All trackside equipment is interconnected with the local control room via cabling. On the other hand, block sections only include the signal light as trackside equipment and the control is automatically performed. For designing trackside equipment, the required documentation includes station signalling layout for single track, interlocking table, station signalling layout for double track, track insulation plan and cabling plan. At the beginning of the 21st century, Russian Railways formed an electronic archive and established a documentation flow with a CAD system with certain supervision functions (Sedykh et al., 2018). The required components for such a system are chosen as follows: the format of data presentation, the graphical format of drawings, the data exchange format and the data exchange format for other related systems. The authority has given an integrated decision. Having an integrated solution is very important to avoid serious labour contribution, waste of time, data loss and augmentation of errors. The approved design procedure has elaborated CAD features and an integration core complying with the industry. The new procedure includes a display of the station signalling layout interactively with the automation facilities. The program also plots the interlocking table. The program generates the double-track signalling layout automatically after entering the single-track signalling layout. Based on the electrification, an insulation plan is generated automatically. For the cable plan, the program allows us to connect trackside equipment(Sedykh et al., 2018).

2.2.3 Issues and problems during operation

In the ALSN signalling system, traction current asymmetry is the major cause of the interference on the track circuits. Although there are some measures against this interference, such as the use of electric filters, they do not provide the desired degree of attenuation. Such interferences are claimed to cause 30 failures in the ALSN signalling system per hour (Shamanov, 2014). The referred asymmetry takes place either in rail lines under the receiving coils of the ALSN onboard or the rail connection of the track circuit receivers. The system limits are 4% for AC traction current and 6% for DC traction current. For example, if the maximum value of AC traction current is 300 A, the maximum current asymmetry should not be more than 12 A. However, this information is not valid for today's conditions. The magnitude of the current and the harmonics are highly dependent on the model of the electric locomotive, their driving modes, the condition of the current-carrying conductors and longitudinal and lateral track resistance (Shamanov, 2021). There are also operational problems when DC and AC railway lines are running parallel in certain sections; a new set of interferences needs to be considered (Havryliuk et al., 2022).

The carrier frequency of ALSN equipment needs to be chosen differently from the frequency of AC traction current. This does not ensure immunity since the traction current can be twofold higher than the ALSN signal current. These types of harmonics cannot be eliminated simply with electric filters. The separation of each track section, ALSN signals, and impedance bonds are used along the railway lines. Impedance bonds allow the flow of traction current to the next section, but it does not allow the flow of the ALSN signal, thus merging with the data of the next section. However, in the case of traction current asymmetry, the interference from the traction current to the original ALSN signal occurs (Shamanov, 2014).

Shamanov (2015) indicates that to control the interferences caused by traction current, the traction current needs to be standardised, and techniques must be developed to protect the ALSN signal. The main reason for traction current asymmetry is the asymmetry in the rail resistances. The rail resistance asymmetry is caused by many factors. One of the factors is the degradation of sleepers' insulation. This might also be observed when the earth connection of the railways is getting loose (Shamanov, 2014). The electrical resistance of the rails is also highly dependent on the temperature changes. For example, the rail type R65, with the temperature change of -40 to $+40$,

has its rail resistivity increased from $0.29 \Omega/\text{km}$ to $0.83 \Omega/\text{km}$. The electrical resistance of rails depends on the rail-cover plates at the connecting sections. The corrosion, dust, snow, etc., causes cover plates to lose contact. Other materials block the loose points. In that case, on these rail sections, the rail's electrical resistance increases, generating resistance asymmetry. A similar issue is valid for grounding sockets. The contact corruptions on copper wires, cuffs or clamps result in loss of electrical contacts. The increased traction current running along the rails is also the major cause of electromagnetic corrosion. The effect of mutual inductance generated by the contact wires also causes interference(Shamanov, 2015).

The usual studies focus on the data measured directly from the rails. However, after receiving coils pick up the ALSN signal, the input of the receiving coil and the output of the locomotive filter and amplifier are different. The difference between AC 50 Hz harmonics amplitude and ALSN 25 Hz signal amplitude is massive; therefore, the degree of immunity should not be only considered with the signal-to-noise ratio. Shamanov (2021) recommends using the ratio of signal power to total noise power at the receiving relay.

If a harmonic that is high enough to create a pulse in the receiving coil is generated during the interval, the ALSN onboard LTL gives a “white lamp”. This means that there is no relevant ALSN code received. This kind of failure has the highest rate. To trigger a pulse in the locomotive receiving coil, the current needs to be 12 mA. The filters defined by the specifications are insufficient to eliminate the real attenuations. The sensitivity of the ALSN signals to the traction current asymmetry can be lowered by using pulsed relay elements with large return coefficients or by increasing the efficiency of noise-filtering techniques(Shamanov, 2021).

The conventional electrified railway lines where the signalling system is ALSN usually is DC electrified. Along these lines, the carrier frequency of the ALSN signals is 50 Hz. Havryliuk et al. (2022) recognise the problem of parallel railway lines, where one is DC electrified and the other is AC electrified. The problem here is posed by the interference posed by the AC traction network to failure in the ALSN signalling system. To make sure that the railway line has electromagnetic compatibility (EMC), a simple model of distribution of interference is needed and a method for monitoring electromagnetic interference (EMI) in rails is needed. Simulation of EMC is a widely used concept for testing electric rolling stock or determining the causes of failure in

ALSN. The available methods are, namely, “The simplified International Telegraph and Telephone Consultative Committee (CCITT) method”, “Calculating the EMI impact for each conductor,” and “Multiconductor Transmission Line (MTL). A model to be beneficial needs to represent the feeder zones, location of traction substations, longitudinal track’s heterogeneous structure and impedance of rolling stock. It has been identified that available models did not model the longitudinal inhomogeneity of the rails, and a method for monitoring interference has not been proposed(Havryliuk et al., 2022).

The model includes two parallel tracks, one being AC electrified and the other being DC electrified. The traction power substations and overhead contact lines are represented in the model. The track inhomogeneity is represented by serially connected sections that are internally assumed to be homogeneous. For the sake of simplicity, all the currents in conductors are calculated with the assumption that there is no track circuit. The effect of the track circuit is insignificant in terms of conductor current calculations. Later on, the current interference caused in the railway line with DC traction is specified. In this model, the victim is the ALSN codes transmission through the DC railway line since its carrier frequency is the same as the AC traction current. The model is mathematically built, and the realistic parameters are entered into the system. The proposed model showed that the induced current in DC electrified decreases as the track spacing increases. The same also applies as rail-to-ground conductance decreases. This research also proposes a method for monitoring EMI. For the investigation, the red signals are measured at the inputs and outputs of 10-track circuits. A random noise interference with 50 Hz, varying amplitude of 0.1 to 0.5 of the existing signal amplitude is given. After that, the values of the signal-to-noise ratio are calculated. A correlation coefficient has resulted from this study to evaluate the distortions at ALSN signals(Havryliuk et al., 2022).

2.3 Comparative Discussion

The literature review of both signalling systems showed that modelling, optimisation and issues faced during implementation and operation are of common interest. For ERTMS signalling system more modelling works are performed with the state-of-art modelling tools and methods. The modelling works did not receive enough attention on the ALSN signalling side. The optimization efforts in those two signalling systems

are available. However, in ERTMS signalling, the optimizations proposed at the system level include increasing availability and the railway network's capacity. However, the sole focus for the ALSN signalling system is to upgrade the communication between the code track transmission equipment and the locomotive's coil receiver or filter. In the ERTMS signalling system, there are also a specific interest in the communication between balise and balise transmission module (BTM). The issues and problems faced for the ERTMS are mostly experienced during the transition period from the legacy signalling system to the ERTMS system. As ERTMS envisages cross-border operations, the projects covering more than one country also pose serious issues for rail administrators. The transition period requires financial, social and technical investment. The ALSN signalling system has been stationary since it was in operation since the 1930s. The problems faced are discussed throughout operation and maintenance. Table 2.1 shows the reviewed literature for the ERTMS and the ALSN signalling systems.

Both ERTMS and ALSN signalling systems can be considered the overlay to the underlying interlocking system, trackside system and central traffic control (CTC). ERTMS has two major components, trackside and onboard, that communicate through GSM-R or air-gap interfaces. ALSN signalling system also has two components: the trackside and the onboard system. The communication between these two components is made through the rails. The communication medium is different for both of the systems. But their functional role is identical: to ensure the safe operation of railway, to control trains in the case of emergency by intervening, and to perform the commands received by the interlocking system.

The main idea behind the ERTMS signalling system is interoperability. The interoperability terminology has many facets; it is not simply the cross-border operation of rail networks. In the context of signalling, this terminology also refers to increasing safety in railway operations with the standardised onboard systems and trackside systems, creating a single human-machine interface, standardising the expected level of reliability and availability of the equipment, enabling multi-vendor competitive rail manufacturers market and interchangeability in devices. Thus, ERTMS is a system that enhances the competitiveness of rail transportation.

Table 2.1: The result of the literature review for the ERTMS and the ALSN signalling system

No	ERTMS LITERATURE REVIEW		CATEGORY	ALSN LITERATURE REVIEW	
	Author & Publication Date	Contributions		Author & Publication Date	Contributions
1	Ghazel, 2014	Formalising the subset 026 Chapter 4 ERTMS specifications using UML Class diagram	MODELLING	Onischenko & Chernykh, 2019	Modelling ALSN Signalling System with Matlab Simulink to develop an automated monitoring system
2	Piccolo et al., 2015	Proposing the use of state charts to represent ERTMS specifications to avoid ambiguities.		Tetiana et al., 2019	Developing an algorithm for the car laboratory data analysis to identify any kind of disturbances.
3	Qiu et al., 2014	Proposing a model of ERTMS as a System of System (SoS)		Prisukhina I V et al., 2019	Generating ALSN signals using simulation tools to generate a set of signals for training a classification algorithm
4	Soares & Zio, 2006	Proposing a model of ERTMS using Fault trees and Bayesian Networks to analyse the reliability aspects.		Havryliuk, 2019	Developing an algorithm to determine the type and parameters of the distortions that appeared in ALSN signals.
5	Dhahbi et al., 2011	Proposing a model of ERTMS using coloured Petri Nets		Havryliuk, 2020	The ALSN signal distortions and the use of ANFIS in the categorisation of signal distortions

Table 2.1: The result of the literature review for the ERTMS and the ALSN signalling system (continued)

No	ERTMS LITERATURE REVIEW		CATEGORY	ALSN LITERATURE REVIEW	
	Author & Publication Date	Contributions		Author & Publication Date	Contributions
6	Durmuş et al., 2012	ERTMS Level 3, moving block principle is modelled using Discrete Petri Nets (DPNs) and Continuous Petri Nets (CPNs)		Leushin et al., 2020	Proposition a methodology of finding the optimal carrier frequency to minimise ALSN signal attenuation and to maximise noise immunity
7	Ferlin et al., 2016	Modelling of ERTMS with coloured Petri Nets		Aripov et al., 2016	Proposing the mathematical modelling of the track circuit to find the optimal voltage supply and track section length.
8	Vignali et al., 2020	Proposing a methodology to determine the block sections according to ERTMS Level 2 operation		Aliev & Aliev, 2022	Proposing an algorithm to define the optimal track section length without ALSN signal distortions.
9	Cuppi et al., 2021	Working principles of newly proposed HD-ERTMS. This system is proposed to overcome the capacity limitations for Level 2 operation.	OPTIMISATION	Baranov et al., 2019	Proposing a method for an analogue-to-digital conversion that is used for the noise measuring equipment used to increase the reliability and safety of the ALSN system
10	Song et al., 2019	Proposing a new system called MA+ to ensure the fail-safe operation of ERTMS Level 2		Nikitin et al., 2017	Working Principle of ALS-EN Signalling system, Proposing

Table 2.1: The result of the literature review for the ERTMS and the ALSN signalling system (continued)

No	ERTMS LITERATURE REVIEW		CATEGORY		ALSN LITERATURE REVIEW	
	Author & Publication Date	Contributions			Author & Publication Date	Contributions
11	Park & Cho, 2022	Proposing a new method to increase the efficiency of the Balise Transmission Module	ISSUES AND PROBLEMS		Alexandrovich, 2017	WSM(m,k) code instead of Bauer code.
12	Wu et al., 2017	Proposing countermeasures towards the Balise transmission vulnerabilities.			Liudvinavičius & Sładkowski, 2017	Introduction of a new locomotive safety system that includes ALSN onboard, GPS and GSMR interface.
13	Kurz et al., 2007	Proposing adding a new time synchronising component to the Balise Transmission module to decrease the delay and jitter.			Sedykh et al., 2018	Proposing of an integrated and automated method of signalling design for Russian Railways.
14	Rodriguez et al., 2016	Proposing a model of Eurobalise and Balise Transmission module to assess interferences.		ISSUES AND PROBLEMS	Shamanov, 2021	Methods for lowering the sensitivity of ALSN signals towards the interferences caused by the AC traction current and harmonics
15	Smith et al., 2012	The problems faced during ERTMS implementation are analysed.	ISSUES AND PROBLEMS		Shamanov, 2015	Analysis of the sources of the interference caused by the traction current. The proposed method is to figure out the main sources of traction asymmetry.

Table 2.1: The result of the literature review for the ERTMS and the ALSN signalling system (continued)

No	ERTMS LITERATURE REVIEW		CATEGORY		ALSN LITERATURE REVIEW	
	Author & Publication Date	Contributions			Author & Publication Date	Contributions
16	Rajabalinejad & Schuitemaker, 2017	The challenges and problems faced during ERTMS implementation are analysed.			Shamanov, 2014	Analysis of the sources of the interference caused by the traction current. The proposed method is to figure out the main sources of traction asymmetry.
17	Rosberg et al., 2021	The effect of drivability analysis is carried out in the network planning stage. ERTMS implementation problems can be overcome. This article compares ERTMS with legacy signalling systems since the problems appeared after switching to ERTMS.			Havryliuk et al., 2022	Method for evaluating the EMI effects on ALSN codes of AC electrified railway lines to DC electrified railways laid in parallel.
18	Mikulčić et al., 2020	Proposing a new STM technology for Indusi system	STM			
19	Mikulčić et al., 2019	Proposing a new STM technology for Indusi system				
20	Fanea, 2017	Interoperability features of ERTMS and the possibility to converge ERTMS and PTC (Positive Train Control).				

Regarding interoperability specifications, ERTMS is referred to as a Class A train protection system, whereas ALSN is considered a Class B train protection system. The ALSN signalling was the main system of the Soviet Union until it fell apart. Considering that the Soviet Union was composed of 15 different republics, it is understood that the system was designed to enable interoperability. Today, these countries are called the “Common Wealth of Independent Countries” (CIS). These countries still operate most of their railway line with the ALSN signalling system.

The ERTMS has a set of specifications and standards for system and performance requirements and testing methods. These standards define the trackside and the onboard systems in detail. There are also interoperability specifications for “command-control and signalling”. These specifications are publicly available, and most of the standards are adopted by the countries that employ the ERTMS signalling system. The publicly available specifications of the system, performance, functionality and testing are reachable by the railway authorities, experts, engineers and manufacturers. The open-access information leads to the development of the system. For the ALSN signalling system, the situation is reversed. The ALSN signalling system is operated, rehabilitated and maintained in accordance with the Rail Administrator’s requirements. The newly planned or built railway lines in those countries are also performed using the specific requirements prepared by the Rail Administrator or the Government. The ALSN system is not competitive in terms of manufacturers as only few “Common Wealth of Independent Countries” (CIS) can produce railway products. The unavailability of internationally accepted specifications and standards is one of the major disadvantages of the ALSN system.

Safe operation is the major aim of a railway signalling system. Reliability, availability, maintainability and safety (RAMS) are well defined in the European Standards. The manufacturers, engineers and Rail Administrators are aware of the numerical outcomes for the expected RAMS values. The ERTMS modelling research focuses on apportionment to evaluate reliability and availability assessments. To prevent inconsistencies, the methods of modelling, testing, verification and validation are described in the European Standards.

The safety, reliability and availability are also major concerns for the ALSN signalling system. However, there is no structured method of calculation or approach is available. The approach to modelling the ALSN signalling system is subjective, and there is no structure to validate and verify. This fact increases the vulnerability of the ALSN system.

The safety-critical failures lead to a degraded mode of operation in the ERTMS system. The specifications define the failures and their identified degraded mode. On the other hand, for the ALSN system, the safety-critical failures only result in “white code” for Locomotive Traffic Light (LTL) and emergency braking intervention. This leads to inefficient train operation, whereas ALSN’s most common safety critical failure is ALSN signal distortion, a common problem.

Based on the literature and the specifications, the ERTMS signalling system has operation levels according to the operational speed of up to 350 km/h and capacity. Increasing the operational speed is not a research issue; the required system for such speed is available as an off-the-shelf solution. However, for the ALSN system, speeds higher than 160 km/h require additional precautions. The limiting factor of ALSN codes is the variety: green, yellow, and yellow-red. The high-speed train operation requires complex data transfer between the trackside and the onboard, such as speed restrictions. ALS-EN system was developed by Russia, which allows the sharing of 256 unique commands. The research on this issue proposes increasing the data size to 1024 unique commands. But ALS-EN system is employed in Russia, and other user countries did not adopt this approach.

Although operational speed is not an issue for the ERTMS signalling system, the increasing capacity is a topic for research. The existing railway lines in Europe are almost saturated, and there are certain limits in capacity to the defined operational levels. Recent research is focusing on train-to-train communication to minimise the headway. For the ALSN signalling system, capacity was not a major concern yet. The competitiveness of the rail sector needs to be enhanced as a priority.

There is a disadvantage to the ERTMS signalling system. It requires a transition period for the trackside renewal investment, procurement or retrofitting of rolling stock, and training of new operators, maintenance personnel and drivers. The transition period requires time and a financial budget. Since the publishment of specifications in 2007,

the European Union Agency for Railways has been working to improve the railway networks in Europe and aims to increase interoperability within EU borders. The interoperability efforts have resulted in improvements; however, the progress is still slow. The specifications, rules and procedures have reached a level of maturity, but the improvements in infrastructure and rolling stock are slow. According to the Railway Safety and Interoperability Report 2022, most of the non-application of fixed installation related to Technical Specification of Interoperability (TSI) is Control Command and Signalling (CCS). By the end of 2021, the non-applications of CCS are more than 70. The EU's target is to deploy the ERTMS signalling system to the core trans-European transport network by 2030 and the whole European network by 2050. The target length by the end of 2023 is 15,700 km. However, the total length of the core network corridors with ERTMS is 8,100 km by the end of September 2021. (Agencia de Ferrocarriles de la Unión Europea., 2022a). This further proves that the transition period of the ERTMS system for Europe requires more time than envisaged. The core network corridor lines percentage of ETCS and GSM-R deployment are provided in Figure 2.5.

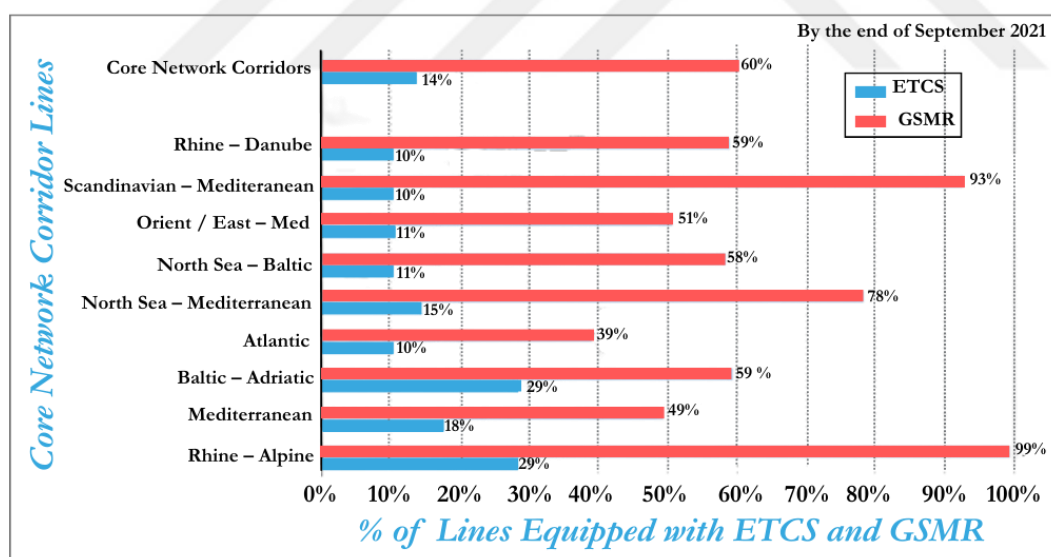


Figure 2.5: The percentage in ETCS and GSM-R deployment in the core network corridor lines. This graphic was taken from (Agencia de Ferrocarriles de la Unión Europea., 2022a)

The total number of non-application requests is 139 for rolling stock TSI. According to a survey carried out by the National Safety Authority, 17% of the vehicles are only equipped with ERTMS onboard.

Figure 2.6 shows the total number of new and retrofitted vehicles available per country at the end of 2020. It shows the uneven distribution of ERTMS onboard systems among EU countries. The non-existing countries have no eligible rolling stock or no data available (Agencia de Ferrocarriles de la Unión Europea., 2022a).

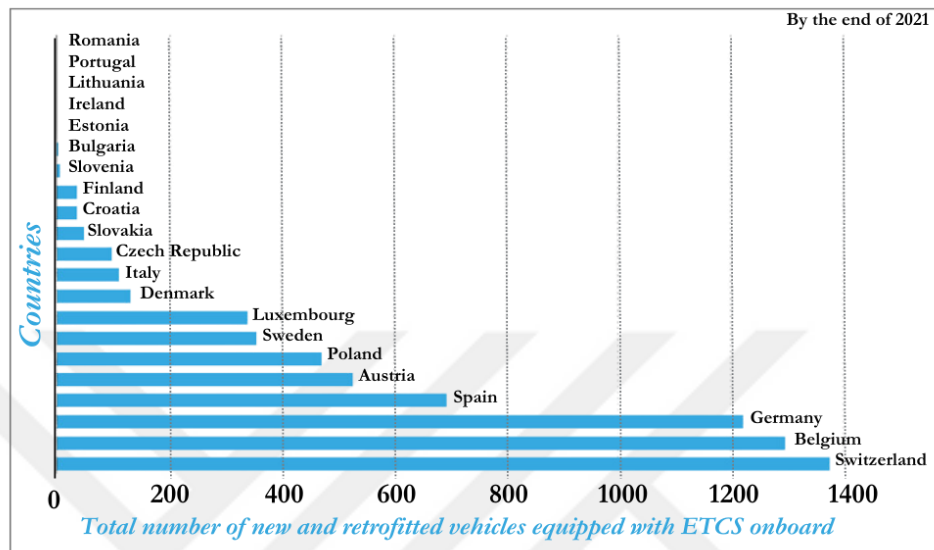


Figure 2.6: Total number of new and retrofitted vehicles equipped with ERTMS onboard per country. This graphic was taken from (Agencia de Ferrocarriles de la Unión Europea., 2022a)

Considering the required time, two additional needs of Rail Administrators appeared during this transition period. Firstly, Rail Administrators would like to operate the existing rolling stock (especially for freight operation) along the railway lines with ERTMS trackside. During this period, many countries that adopted ERTMS preferred to use their legacy signalling system as a fall-back system. This helps their railway system to be redundant and enables their older train sets and locomotives to be operational in the railway section with ERTMS. Secondly, the Rail administrators would like to operate newly acquired train sets, locomotives and retrofitted rolling stock in the railway lines that have not been upgraded to ERTMS trackside yet. As mentioned above, interoperability recognises Class B train protection systems and ERTMS specifications cover Specific Transmission Module with “K” and “G” interfaces. These concepts enable integrating Class B/ legacy signalling systems to communicate with the ERTMS onboard system. The newly procured train sets and retrofitted locomotives with ERTMS onboard need STM module integration. This enables an ERTMS train to operate on railway lines without the ERTMS trackside. The STM technology can be either implemented as an internal or external device that

allows Rail Administrators to establish the most efficient way of the transition period in operation and maintenance. The efforts on STM technology are the result of this transition period. However, STM needs to be perceived as a way to accomplish worldwide interoperability and increase rail transport's worldwide competitiveness.

ALSN signalling system is operational in 10% of the whole railway network of the World. A proposition of ALSN STM is a gateway to seamless rail transportation between the “Commonwealth of Independent States” (CIS) that connects Europe to Far Asia and South Asia. To the author’s knowledge, STM for ALSN has not been proposed yet. Although Latvia, Lithuania and Estonia are part of the European Union and have the ALSN signalling system as their legacy signalling system, the attempt for an STM has not been made by those countries. ALSN STM that allows the operation of ERTMS onboard in the ALSN trackside system would enable trains with ETCS onboard to operate across Europe and Central Asia. The interoperability of ERTMS depends on the air-gap interface and the human-machine interface. The proposed STM is an external STM that substitutes the air-gap interface by translating the data received from the rails for the use of BTM. The human-machine interface will stay the same in conformance with the specifications. The novelty proposed by this research is to enable seamless operation between countries operating ERTMS and countries operating ALSN with the proposed model of ALSN STM.

The advantages of the ERTMS system over the ALSN system are discussed. Considering that the ALSN system’s major decision-making mechanism is at the onboard section, the trackside equipment is simply coded track circuits. ALSN STM technology that enables ETCS to be employed onboard for the railways with ALSN trackside system would unlock the full potential of ETCS onboard for the countries that operate with ALSN. This research identifies the required interface envisaged with ETCS onboard and STM and the communication structure between ALSN trackside and onboard to propose an external STM that allows ETCS trains to operate on the railways with the ALSN signalling system. The proposed system will increase the safety and availability of railway operations and enhance the rail operator’s reach to the multi-vendor railway market for rolling stock. Two major outcomes of this research are to increase interoperability between European and CIS countries and to increase competitiveness in railway networks of CIS countries that employ the ALSN signalling system.

3. METHODOLOGY

This study proposes an STM for ALSN signalling system trackside to enable the operation of the ERTMS signalling system onboard. To develop an architecture of the proposed innovation, the basic definitions of both systems will be explained, and a block diagram of both systems will be presented in this section.

The proposed novelty enables the rolling stock equipped with the ETCS onboard system to operate the railway lines equipped with the ALSN trackside system. A block diagram of each system will be presented to develop an understanding of both signalling systems, and the signalling interoperability will be described in the context of European Union Directives.

3.1 Block Diagram of ERTMS System

ERTMS has two components: ETCS and GSM-R. ETCS has two main sub-components: trackside systems and onboard systems. As discussed in earlier sections, the primary responsibility of trackside systems is to enable communication between the train and the operational control centre/ the interlocking. The primary responsibility of the onboard system is to evaluate the received information from the trackside system and the train characteristics, to provide the results in DMI and to interfere whenever necessary. GSM-R system is located in the lineside; however, it is defined as a separate component of ERTMS. It allows voice and data transmission through radio communication.

The block diagram of the ERTMS system is provided in Figure 3.1. This diagram shows ETCS trackside components with tones of red and ETCS onboard components with tones of blue. GSM-R is shown as violet. As not all the components are operational at all levels, this block diagram identifies the level operations with a colour-coded legend. Blue represents the communication of components for Level 1 operation, and red represents Level 2—the colour red and yellow show the relationship between components during Level 3 operation. The green colour shows the connection between the underlying signalling system and the STM module for Level STM operation.

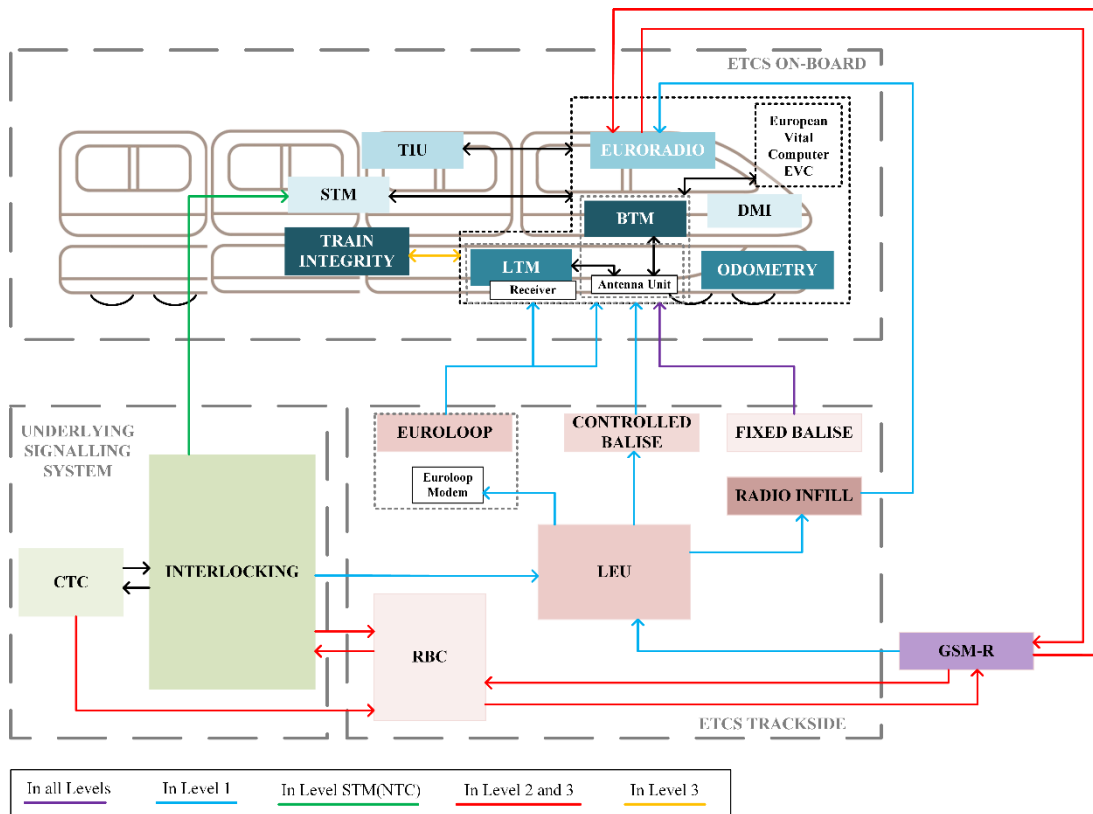


Figure 3.1: The Block Diagram of ERTMS.

3.1.1 GSM-R

GSMR operates within the 900 MHz band that enables voice data transmission, group calls, priority definition, and functional addressing. The system architecture includes the Network Switching Subsystem (NSS), Network management Subsystem (NMS), Base Station Subsystem (BSS), Base Station Controllers (BSC) and Base Transceiver Stations (BTS). As explained in ERTMS operation levels 2 and 3, GSMR transmits movement authority from RBC. The legal framework of ERTMS envisages GSMR as a way to ensure calling connectivity for train radio, shunting, rescue and area connections (Młyńczak et al., 2016). It is seen as an integral part of European Rail integration; the specifications define GSMR developed at UIC as the “European Integrated Railway Radio Enhanced Network” (EIRENE). There are available functional (FRS) and system requirements (SRS) of GSMR. Distinctive features of GSMR are its ability to transmit data between a central unit and the terminal, allowing mobility of the terminal and separation of information about the user and the equipment (Młyńczak et al., 2016). Essential elements of GSMR are summarised as Subscriber stations that is the transceiver or SIM card, Base Transceiver Stations (BTS) that allows mobile stations communication, Base Station Controller (BSC) that

controls BTSs and provides a connection with the radio station, Mobile Switching Centre (MSC) that performs connectivity between subscribers, Home Location Register (HLR) that is a database with information of subscribers and their locations, Visitor's Location Register (VLR) that is a database of subscribers travelling in MSC area, Authentication Centre (AuC) that contains the IDs of the subscribers, Equipment Identification Register (EIR) that allows follow up of stolen and damaged transceivers, Group Call Register (GCR) that is a database of generated subscriber groups, Operation and Maintenance Center (OMC) and Short Message System (SMS). The connectivity is continuously formed between the subscriber and the base station where only direct connection is allowed in special cases, e.g., when there is no GSMR connection. The connection between BTSs and BSC has multiple alternatives, such as digital, landline or radio links. BSC and MSC communication, on the other hand, is provided with a transmission network, usually with a fibre optical network. GSMR has many advantages over analogue communication systems. These advantages are the identification of subscribers' authenticity, encoding of the information sent and using temporary mobile subscriber identity. GSMR system operational frequency range is 876 – 880 MHz for mobile to base stations and 921-925 MHz for reverse communication. The channel distance is 200 kHz, and the top to down duplex system is 45 MHz, with 19 channels with different frequencies. The priority feature allows for forming a multi-level hierarchy, where specifications define the priorities of specific calls to elaborate on which calls need to be served first. As explained above, data transmission is one of the most important reasons to employ GSMR in ERTMS specifications. GSMR enables ETCS data transmission for infrastructure to the vehicle, connectivity between the national signalling system and Radio Block Center, shipment tracking, the transmission of rolling stock data and connectivity between dispatchers and field transcribers. (Młyńczak et al., 2016)

3.1.2 ETCS trackside

ETCS Trackside includes the devices and equipment installed along the railway line. These devices vary based on the level of operation; however, to clarify the system components, balise, euroloop, radio infill unit and lineside electronic unit (LEU) will be described in this section.

Balise enables railway infrastructure to communicate with the on-board system. Balises can be installed on the line either in a group form or a single balise. A group of balise can have between 2 to 8 balises. Each Balise has its own coordinate system and contains a minimum of the below information (ERA UNISIG SS26-2, 2016);

- The internal number of balise in the group
- The total number of balise in the group
- The balise group identity

Balise is a passive device powered by an induced couple remote signal provided by the antenna unit of BTM of the ETCS onboard system. This activating signal is called a tele-powering signal in the form of either a 27 MHz Continuous Wave signal or a 27 MHz signal with a toggling 50 kHz modulation. Balise shall create a response to these two tele-powering signals to enable interoperability. Receiving this signal, Balise generates an inductively coupled up-link signal as a response. The generated response is in the form of a 4.2MHz shift keyed up-link signal with 3,9 MHz keyed as “0” and 4.5 MHz keyed as “1”, as provided in Figure 3.2.

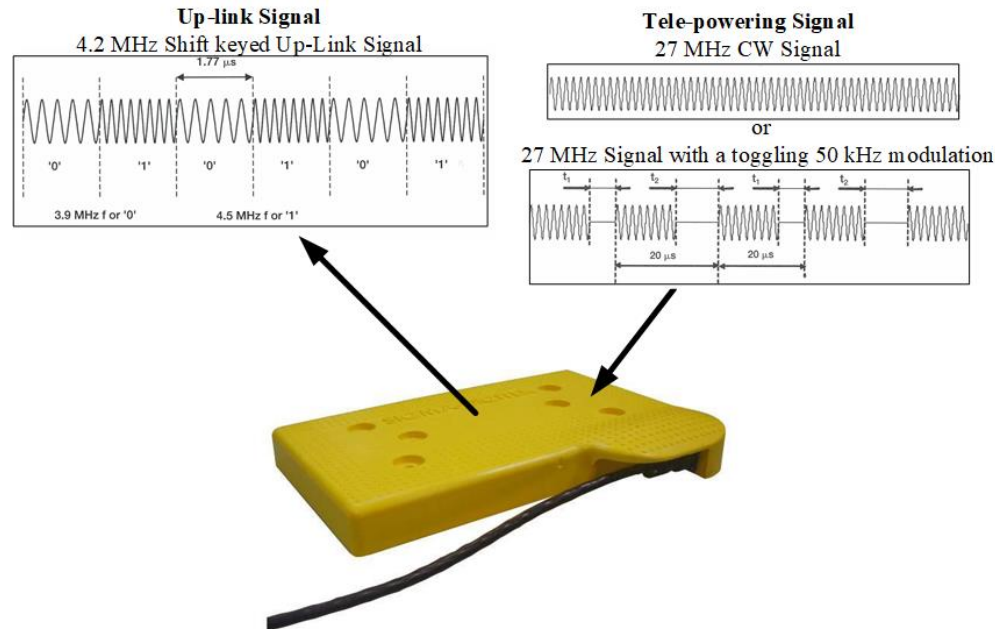


Figure 3.2: Balise tele-powering signal and response up-link signal.

As identified in the ERTMS level operation, there are two types of balises: fixed and switchable balises. Fixed balises are employed to provide location references. For the fixed balises, the response is the fixed programmed information stored in the balise. For the switchable balises however, the response is controllable with the connection

to LEU and LEU's connection to the interlocking. The switchable balise transmits movement authority information. Balise provides one of the most vital systems in ETCS trackside: on-spot transmission. The balise transmission module (BTM) picks up either variable messages from the switchable balise or fixed messages from the fixed balise while passing through on the balises or while standing over the balises. This data transmission is safety-critical. One of the downsides is that this transmission is made through an air gap, and there is no handshaking, which means no acknowledgement of data transfer. According to the specifications, Balise can provide transmission to moving trains with up to 500 km/h speed. Balises shall be installed in the middle of the track, with the exact distances to each rail. Balises can be installed on the 93 mm to 210 mm range of the top of the rail. There are two types of balises: standard size and reduced size, depending on the telegram length to be transferred by LEU or the embedded data. It is allowed to combine these two types on the same railway line. The connection between LEUs and balises on the track can be up to 500 m (Stanley, 2011).

Balise transmission enables on-spot transmission; there are also devices in ETCS trackside that provide semi-continuous transmission. These devices are also called components with infill function. The main concern for on-spot transmission by Balise is the changes that arise in the MA after the train passes the last relevant group of Balise (LRGB). When MA changes after the train passes through the balise, the driver may observe the signal light with a different MA than the one received from LRGB, which may lead to discrepancies. While the train driver slows down after receiving a stop command from LRGB, the service brake, dependent on the train's braking characteristics, will overtake when operating with release speed. The train can only stop at a certain distance; this situation limits the release speed if the overlap area is short. Components with infill functions optimise the track use by providing semi-continuous transmission to ETCS on-board. In both cases, the euroloop and the radio infill system receive MA from controlled balises (Stanley, 2011).

Euroloop is one of the semi-continuous transmission providers for Level 1 with infill function. Euroloop is a leaky cable that can be installed on either side of the track. Euroloop transmits the same telegram code as Balise; however, due to its physical characteristics, it transmits with a lower data rate (Stanley, 2011). The general configuration of the euroloop is provided in Figure 3.3. This example shows the use

of the euroloop between the main and distant signal for line optimisation. Euroloop is a single coaxial cable laid between a specific section (maximum 1000 m). Communication between LEU and Euroloop is made by a loop modem on the lineside. The entrance of a euroloop section is announced by a balise group called End of Loop Marker (EOLM). This balise group transmits the loop identity and spread spectrum key to correct the spreading sequence of the loop.

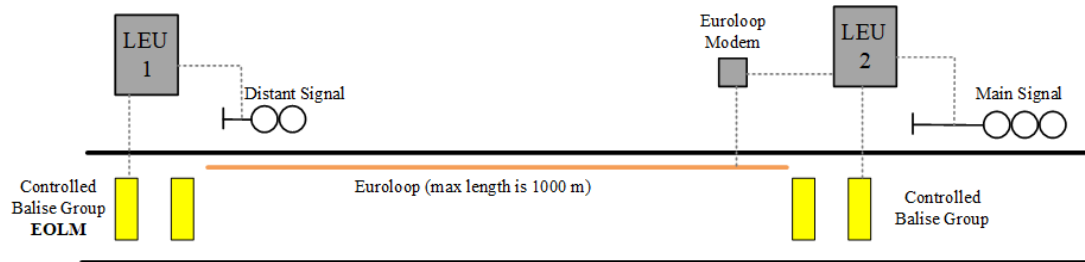


Figure 3.3: Euroloop site configuration between main and distant signal.

When there is no train present, euroloop stays inactive. With a balise interrogation signal, euroloop becomes active. Euroloop transfers the same message it receives from the other end of the balise group as an up-link signal in the 9MHz to 18MHz band (Mendizabal et al., 2016). This way, the ETCS on board will arrange the release speed and be aware of changing MAs. Euroloop is a solution generally where overlap areas are shorter.

Radio infill is another way of providing a semi-continuous transmission method for Level 1 with infill function. Radio infill requires a GSM-R system since it cannot be resolved with location-based LEUs. The LEU shall be centralised to command the controlled balise along the line, as shown in Figure 3.4. Radio infill uses the GSM-R radio communication to transfer messages to controlled balises through a centralised LEU (Stanley, 2011).

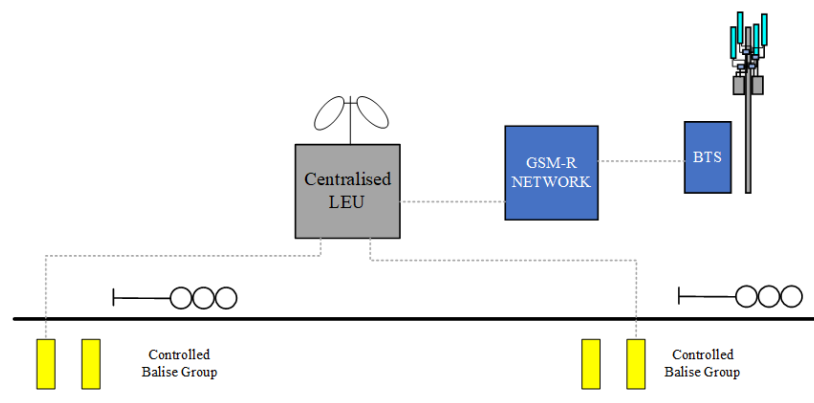


Figure 3.4: Radio infill site configuration.

In this case, the main difference between Level 2 and Level 1 with radio infill function is that GSM-R is not used for communication with the ETCS on-board system; rather, communication with ETCS on-board is achieved by controlled balises. GSM-R might serve the train operation by other means, such as communication between railway operation staff, drivers, shunting areas, etc.

Lineside electronic unit (LEU) is majorly employed for ETCS Level 1 infrastructure. The main function of LEU is to receive the information from lineside signals and interlocking, then to send this information to controlled balises. Before sending information received from lineside signals and interlocking, LEU selects the telegrams and messages to send the switchable balises. These balises can be either in a group or single. Based on the selected telegrams and messages, LEU groups the messages with a header and application-dependent information in the form of packets (ERA UNISIG SS26-7, 2016). These packets are transmitted to each balises. This process can be a direct connection to balises via cable or GSM-R or a direct connection to a euroloop modem connection.

3.1.3 ETCS onboard

ETCS onboard system is crucial for this research. This study assumes that a train with a fully equipped ETCS onboard system is moving along the railway line. The onboard system's subcomponents are Driver Machine Interface (DMI), Train Interface Unit (TIU), Balise Transmission Module (BTM), Loop Transmission Module (LTM), Euroradio, Odometry, Train Integrity and Specific Transmission Module (STM). STM will be separately discussed in this section.

DMI is ETCS onboard equipment that provides a Man-Machine Interface. In fact, the DMI system is connected to the European Vital Computer (EVC), which is the main decision maker in ETCS on-board. DMI interprets the received inputs as meaningful data, diagrams or audible information to the driver, collects the driver's commands and transforms these commands into EVC commands (Bondavalli et al., 2009). DMI is a joint device for both ETCS and GSMR. Its interface is explained with colour categorisation. The white indication means that there is no need for driver intervention in a normal situation. The yellow indication still conforms to the normal situation but requires the driver's response. The orange indication translates as an exceptional situation requiring the urgent attention of the driver. If the DMI indication is red, it is

identified that the system has undertaken the driver since the driver did not act in accordance with warnings. The specifications also define areas as A, B, C, D, E, and F. A is braking data, B is speedometer, C speed values provided by ETCS, D shows route information, E shows vehicle device operation, and F is driver's keyboard. (Młyńczak et al., 2016)

The specifications of ETCS do not declare a standard form of communication between EVC and DMI. There are two main ways of configuring DMI and EVC. One of them is that DMI is installed as a terminal of EVC, which means that EVC decides what, when and how to indicate the information. The other way is to configure DMI as a standalone unit, where DMI is the decision maker on how to interpret the received input from EVC. Certain communication protocols are used in the market, such as RS485, Profibus, Ethernet or MVB (Stanley, 2011).

The Train Interface Unit provides boundary communication between the train or locomotive and EVC. TIU distributes the necessary commands generated by EVC, such as braking and closing the circuit breaker of the pantograph, to the train's related components. There are several implementations of TIU, which include MVB (multiple vehicle bus), Profibus or interface via wire. The retrofitting of existing rolling stock is usually made with a wire connection; newly manufactured rolling stock with ETCS onboard uses other interface methods. ETCS specifications standardise data type and possible values for all input and output information. Possible information exchange between EVC and TIU are braking control (i.e. emergency braking), cab status information (i.e. direction controller), radio functions and locomotive or train control (i.e. change in traction power, closing and opening of pantograph) (Stanley, 2011).

According to ERTMS specifications, certain requirements need to be fulfilled by Eurobalises. The balise activation volume is important for defining the air gap between BTM. The specifications define X (-1300; +1300 mm), Y (-1400; +1400 mm) and Z (+220;+460 mm). The transmission rate shall be 564.48 kbits/s, and the frequency shall be 3.951 – 4.516 MHz. Eurobalise comprises three components: a telegram generator, a radio transmitter and an antenna (Rodriguez et al., 2016). The telegram generator monitors the approaching trains within the activation volume; if any train is detected, it generates telegrams with the defined length, structure and format. Eurobalises operate with passive transponder technology (Kurz et al., 2007).

The main responsibility of BTM is to send a tele-powering signal as either a 27 MHz Continuous Wave signal or a 27 MHz signal with a toggling 50 kHz modulation to activate the balises and receive the up-link signal generated by balises. BTM is also responsible for demodulating the received telegrams from Balise to EVC. In addition to these main functions, BTM determines the existence of a balise on the track so that the system does not miss balises during operation. The communication between Eurobalise and BTM is initiated as the train passes over a balise. BTM telepowers the balise. Balise sends the stored data as it is called “Uplink data”. The processing of uplink data starts in BTM, which receives the signal and demodulates it to a digital signal. The demodulated signal is sent to BTM. BTM sent the data to European Vital Computer (EVC). In EVC, the received data is processed and displayed to train drivers on DMI. BTM extracts the information on geographical position, route-related information and, if available, speed restriction information. BTM module also can calculate the moving direction (Wu et al., 2017).

BTM includes an antenna that is mounted on the bottom of the rolling stock in a metal frame structure. The placement of the antenna is critical to balise transmission since this transmission uses an air gap. By standard, the antenna shall be mounted at a distance of 15.5 to 25 cm from the top of the rail (Mendizabal et al., 2016). BTM consist of 3 components: BTM Control Unit, FPGA Board and Analogue Unit (Kurz et al., 2007). BTM is connected to EVC via an ethernet link. The connections between internal components are shown in Figure 3.5. Analogue modules are a BTM antenna, transmission unit, combination filter and receiver unit.

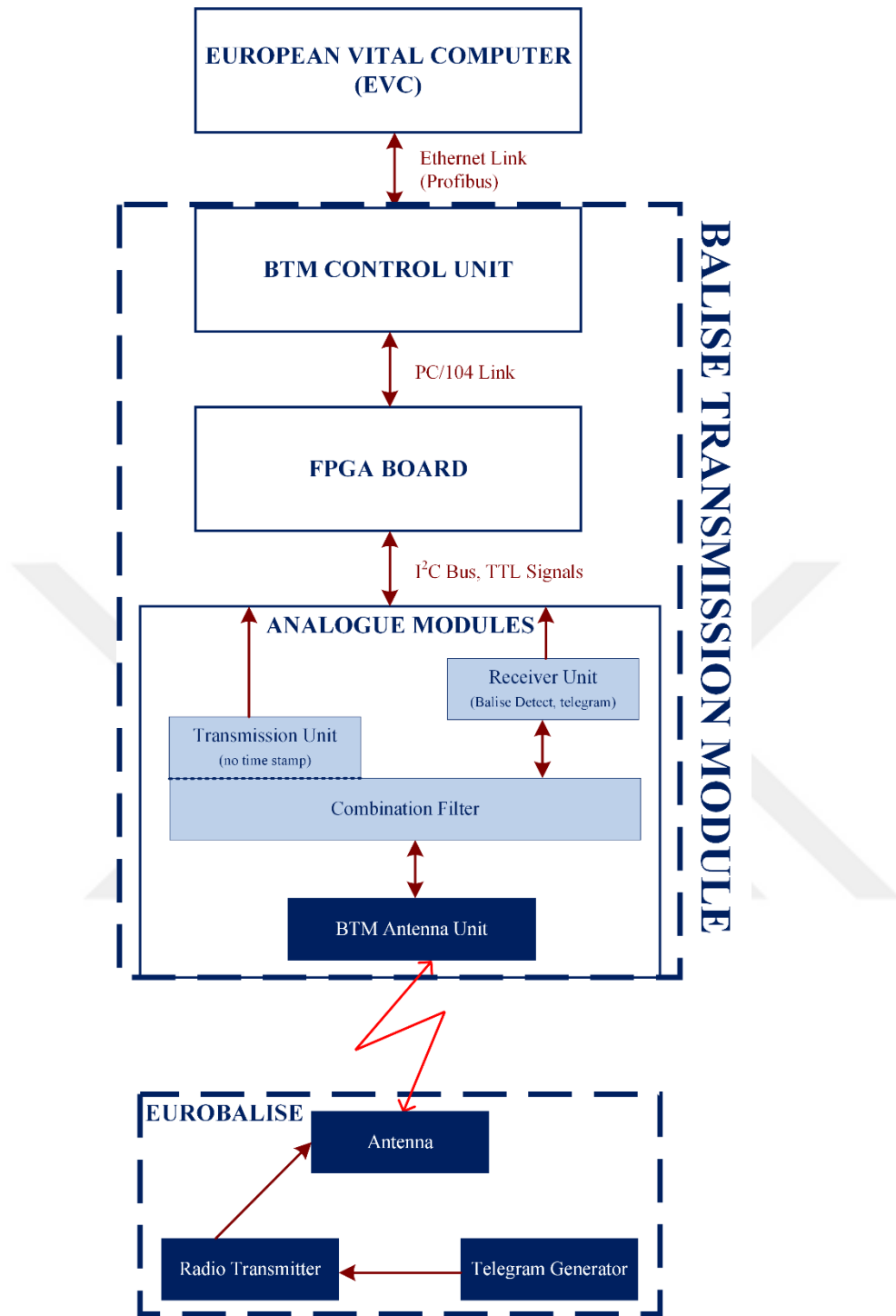


Figure 3.5: Balise Transmission Module internal components and connection types.

Eurobalise, as a passive transponder, will be supplied with energy by the Transmission Unit. There is a required tele-powering field strength for Eurobalise to transmit the telegram. This level is indicated as the 2nd level in Figure 3.6. The Transmission Unit is responsible for generating a 27.095 MHz tele-powering signal, which is transmitted by BTM Antenna Unit. The average power consumed is 20 W, and with this power, Eurobalise, which is located 60 cm away from the antenna, can be activated. The

Combination filter is used to combine signals that are incoming and outgoing. After activating the Eurobalise, the BTM Antenna unit receives the FSK data signal. As a result of this transmission, there are two important outputs: the extracted telegram data and 2 Balise Detect signals. These two signals are generated by the Receiver Unit to indicate the start and end of transmission. When the telegram transmission starts, it needs to reach the 2nd level, as indicated in Figure 3.6, to trigger the Balise Detect signal in BTM(Kurz et al., 2007). The location references of Eurobalise are determined with Balise Detect signals.

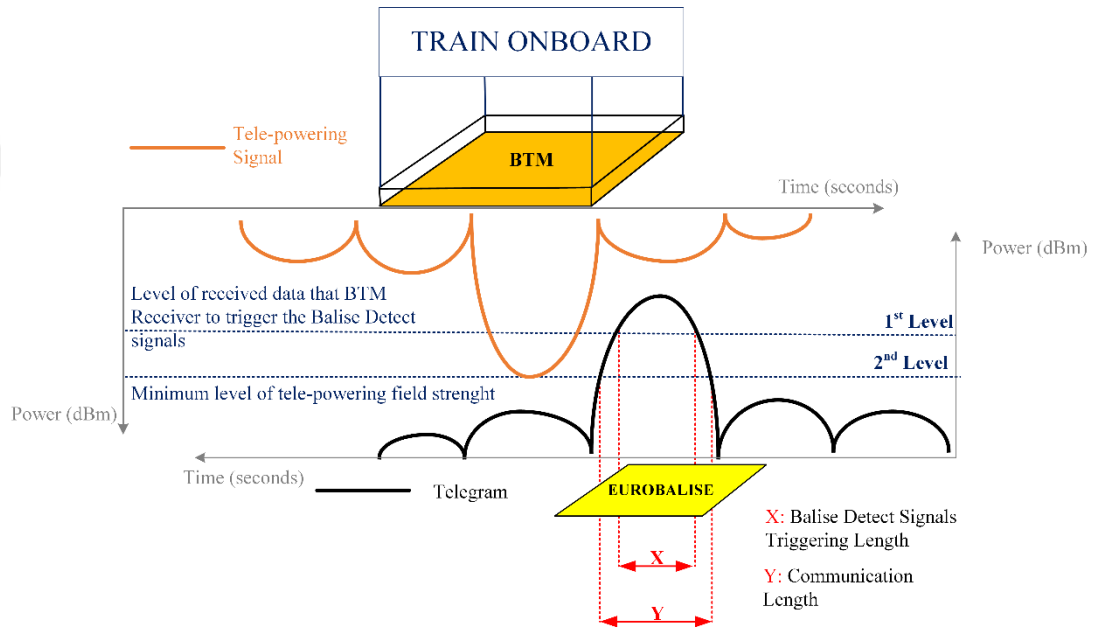


Figure 3.6: BTM and Eurobalise transmission schematic (this drawing is adapted from (Kurz et al., 2007).

The receiver unit usually receives the telegram data input at -50dB. The Receiver Unit performs the analogue signal processing, which is the conversion of the FSK signal to a digital signal. The digitalised signal is sent to the FPGA Board to be processed (Kurz et al., 2007). FPGA Board employs frequency shift keying (FSK) demodulation. The analogue-to-digital conversion is corrected with a digital phase-locked loop (DPLL) since the width of the signal is not accurate. (Park & Cho, 2022)

There are two receivers for each type of telegram. The demodulation of a balise telegram follows the below steps; assume that $f(x)$ and $g(x)$ are polynomials;

- Step 1: “ $n+r$ ” consecutive bits are received. The leftmost bits represent the oldest data, and the rightmost bits are the newest data. With the “First in, First out” buffer type, as the new bit is received, the old bit is discarded.

- Step 2: The parity check is made with the first “n” bits. If the first “n” bits can be divided with $g(x)$, it means that the parity check is successful. If the parity check fails, the window must be shifted, and the first step shall be reconsidered.
- Step 3: This is the repeatability check step. The extra “r” bits are checked whether they coincide with the first “r” bits. If they coincide, the repeatability check is successful. If not, the first step shall be reconsidered.
- Step 4: This step is performed to find the most significant bit (MSB). The first “n” bits are divided by $f(x)$, and the 10-bit remainder is checked if it is a specific value. If it is, then the first bit is MSB. If it is not or the remainder is an “impossible” value, the first step shall be reconsidered.
- Step 5: This is a word-valid check. Every 11-bit word is checked according to the 11 to 10 conversion table. If the 11-bit words are not available in the table, the first step shall be reconsidered.
- Step 6: Telegram is considered safe.
- Step 7: The inversion bit is needed to be checked in this step. If b109 is 1, all the bits in the telegram need to be inverted; if not, they stay as it is.
- Step 8: The control bits b108 and b107 is needed to be checked. If these bits are as follows: b108 = 1 or b107 = 0, the demodulation shall be aborted, and the DMI shall display “unknown telegram format.”
- Step 9: At this step, 11 to 10-bit transportation is inverted.
- Step 10: Encrypted signals are interpreted as plain text between b106 – b95. This step is called “de-scramble.”
- Step 11: This step gives the output and the inversion bit (b109).

The first nine steps are called the telegram valid check step. The last step before providing output is “10”; this is called the “de-scramble” step (Park & Cho, 2022). The polynomials used for the telegram demodulation are provided below;

$$f_s(x) = x^{10} + x^8 + x^7 + x^5 + x^3 + x^1 + 1 \quad (1)$$

$$\begin{aligned}
g_s(x) = & x^{75} + x^{72} + x^{71} + x^{70} + x^{69} + x^{68} + x^{66} + x^{65} + x^{64} \\
& + x^{63} + x^{60} + x^{55} + x^{54} + x^{49} + x^{47} + x^{46} \\
& + x^{45} + x^{44} + x^{43} + x^{42} + x^{41} + x^{39} + x^{38} \\
& + x^{37} + x^{36} + x^{34} + x^{33} + x^{32} + x^{31} + x^{30} \\
& + x^{27} + x^{25} + x^{22} + x^{19} + x^{17} + x^{13} + x^{12} \\
& + x^{11} + x^{10} + x^6 + x^3 + x^1 + 1
\end{aligned} \tag{2}$$

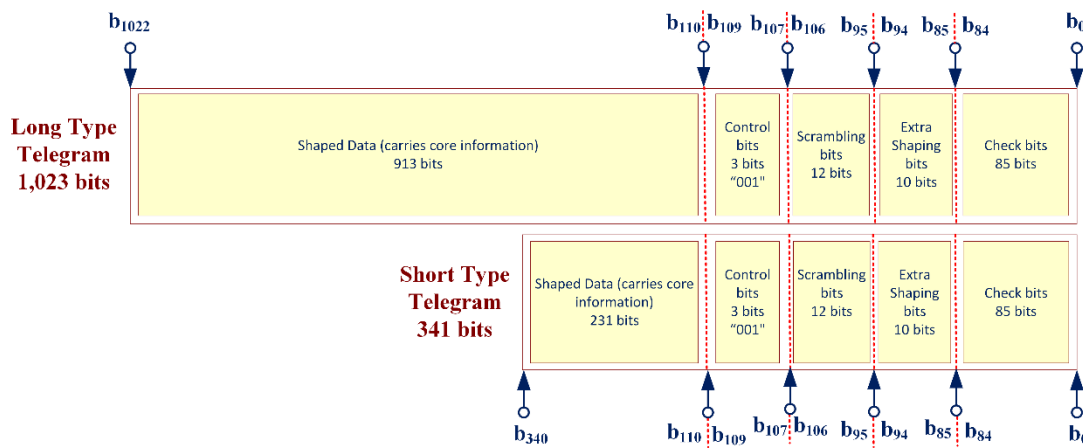
For long type telegram demodulation;

$$f_L(x) = x^{10} + x^9 + x^7 + x^6 + x^4 + x^3 + x^2 + x^1 + 1 \tag{3}$$

$$\begin{aligned}
g_L(x) = & x^{75} + x^{73} + x^{72} + x^{71} + x^{67} + x^{62} + x^{61} + x^{60} + x^{57} \\
& + x^{56} + x^{55} + x^{52} + x^{51} + x^{49} + x^{46} + x^{45} \\
& + x^{44} + x^{43} + x^{41} + x^{37} + x^{35} + x^{34} + x^{33} \\
& + x^{31} + x^{30} + x^{28} + x^{26} + x^{24} + x^{21} + x^{17} \\
& + x^{16} + x^{15} + x^{13} + x^{12} + x^{11} + x^{10} + x^9 + x^4 \\
& + x^4 + 1
\end{aligned} \tag{4}$$

These polynomials are used to identify the starting point of the telegram and check its parity (Park & Cho, 2022). After the completion of the above steps, the FPGA board puts a time stamp on the valid telegram. FPGA board stored the data extracted from telegram until the BTM Control Unit reads the data and sends it to EVC. The delay allowed between receiving the telegram to share it with EVC is 7.2 ms (Kurz et al., 2007). This communication is specifically defined with ETCS SUBSET-036 to enable interoperability between ETCS-deployed railway lines (UNISIG SUBSET-036, 2015). The specifics include the transmitted telegram's data structure and the core information's packet type. There are two types of telegram: long-type telegram with 1023 bits and short-type telegram with 341 bits. Both of the telegram types have the same data structure. The first 109 bits of both types of the telegram have “3” control bits (b109 – b107), “12” scrambling bits (b106 – b95), “10” extra shaping bits (b94 – b85), “85” check bits (b84 – b0). The control bits are constant strings of 001. The scrambling bits are the initial state of the scrambler. Extra shaping bits are used to enforce constraints on check bits. The 85-bit check bits consist of 75 parity bits for error correction and 10 bits for synchronising purposes (Wu et al., 2017). Based on the type of telegram, the rest of the bits, either “913” or “231” bits, are provided as shaped data. This data is scrambled to avoid any transmission errors. It carries real information. The packet type defines the core information carried by the telegrams. The specifications define the packet types for fixed and controllable Eurobalises to enable interoperability. Figure 3.7 shows the data structure and packet types for telegram data/ uplink data.

Telegram Data/ Uplink Data Structure:



Telegram Data/ Uplink Data Packet Type:

FIXED BALISE

- Position and geographical location information
- Permanent Speed Restriction
- Linking data for neighboring balises
- Gradient of railway
- Other information

CONTROLLABLE BALISE

- Movement Authority
- Temporary Speed Restriction
- Linking data for neighboring balises
- Other information

Figure 3.7: To achieve interoperability, telegram data/uplink data structure and packet type for fixed and controllable Balise.

LTM is responsible for providing ETCS on-board communication with ETCS infrastructure by receiving telegrams sent via euroloops. Like BTM, LTM gives a Tele-powering signal as either a continuous or toggling form to activate the euroloops. LTM receives the response up-link signal generated by euroloop, then it modulates the transmitted signal and sends it to EVC. LTM and BTM use the same antenna for transmission (Mendizabal et al., 2016).

Euroradio is the component of ETCS on-board for interfacing the GSM-R radio network with EVC. Since radio data is a non-safe data type, the primary function of euroradio is to protect safety in data transmission via GSM-R radio. Euroradio is a protocol stack that ensures safe data transmission. With this protocol stack, euroradio enables ETCS on-board to initiate a connection to RBC with the application layer. Other layers in the protocol are safety, transport, network and data link layers. The physical layer of the euroradio protocol is interpreted as GSM-R (Stanley, 2011).

Odometry is an ETCS onboard component that allows measurement of distance moved. Distance moved by the train is an important input for ETCS on-board to know where the train is along the railway infrastructure. Odometry performs this measurement by recording the wheel revolutions. That is why its measurements'

validity depends on wheel geometry and unevenness of tracks. Odometry is sensitive equipment. Its measurements contain two types of error that must be carefully considered: inherent error and accrued error. As the name suggests, odometry's properties cause inherent errors. Accrued error, on the other hand, increases as the travelled distance increases. Accrued error is rectified using fixed position markers fixed balises at certain intervals along the railway line. However, it is known that inherent errors cannot be rectified with fixed balises (Stanley, 2011). In order to keep these errors at acceptable levels, the ETCS specification defines the confidence interval for error distribution. For every ETCS Level operation, keeping odometry error distribution inside the confidence interval shall be considered during the placement of fixed balises along the railway line.

Train integrity equipment is not defined as a component of the ETCS onboard system. However, it is important for ETCS on-board in Level 3 operation. For Levels 0, 1, 2 and STM (NTC), it is possible to leave train integrity supervision to the driver or underlying signalling system (e.g. track vacancy detection). Train integrity equipment on rolling stock enables trains to check train integrity in motion. There are multiple applications based on different types of rolling stocks. If rolling stock consists of only one vehicle, it can be located in the vehicle itself. When there are multiple units with multiple engines in another vehicle, the train integrity status is based on the information that the train line is not broken; no unit is separated from the set. Where there are freight wagons, the train integrity equipment can be based on additional equipment mounted on the last train wagon (Stanley, 2011).

3.2 Block Diagram of ALSN System

The continuous automatic cab signalling (ALSN) signalling system has two major components: trackside and onboard. In the ALSN trackside, the movement authority is carried to the driver with ALSN codes. ALSN codes carry the information through rails. In other words, the transmission medium is the rails.

For this research, the ALSN trackside system is crucial. The block diagram for the ALSN signalling system is provided in Figure 3.8. The ALSN trackside components are shown as shades of red, and the ALSN onboard components are shown as shades of blue. In ALSN, no specific system is defined to provide voice and data communication, as is the case for GSM-R.

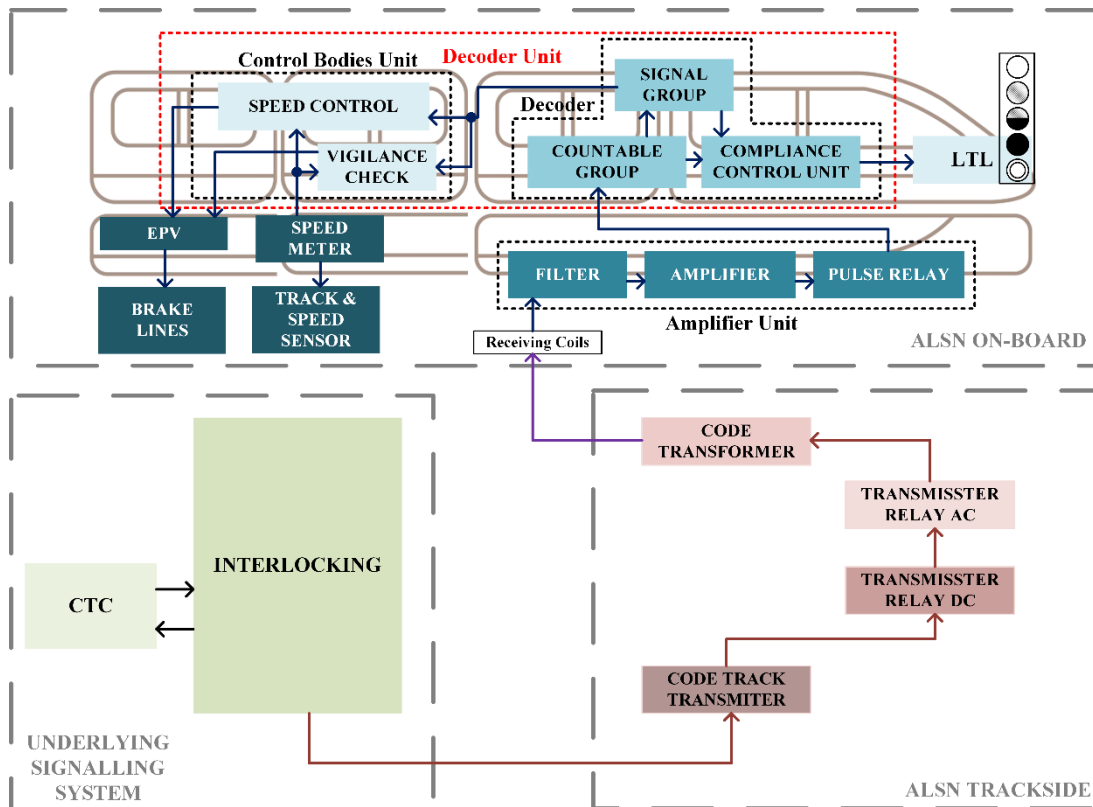


Figure 3.8: The Block diagram of the ALSN signalling system.

3.2.1 ALSN trackside

The most distinctive component of ALSN trackside is the code track transmitter (CTT) that generates Green (G), Yellow (Y) and Red-Yellow (RY) ALSN codes. These codes are sent to the transmitter relay (TR), where amplitude modulation occurs with a separate AC network connection. ALSN uses rails as the data transmission medium. The generated codes are given to the rails with a code transformer (CT). Whenever a train enters the block section and triggers the track vacancy detection, the ALSN codes transmission window initiates.

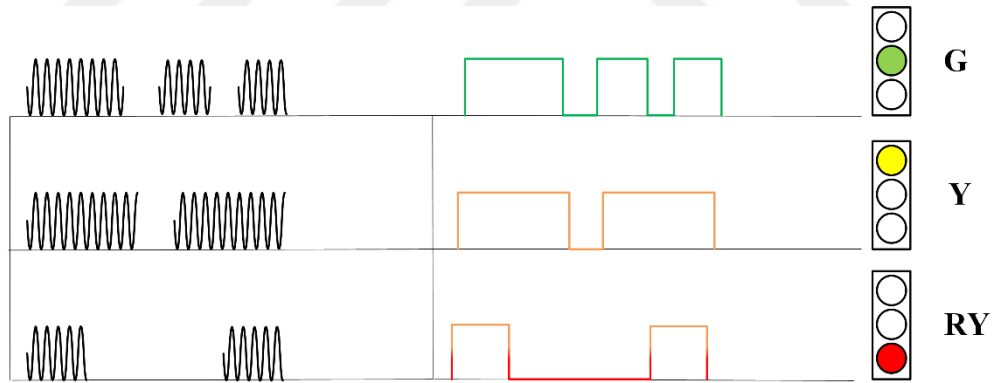
There are three types of ALSN codes: Green (G), Yellow (Y) and Red-Yellow (RY). These codes reflect the signal indication of the signal light that the train is approaching. G indicates green aspect indication, Y is yellow, and RY is red. The code track transmitter receives the signal aspect information and generates a pulse signal with the DC transmitter. Each signal aspect has a specific sequence of rectangular pulses with intervals. The code track transmitter (CTT) type determines the cycle time of these pulse signals. If the CTT type is 5, 515, 8 or 815, then the code cycle is 1.6 seconds. The nominal durations of the ALSN codes are provided in Table 3.1.

Table 3.1: Nominal Durations of ALSN Codes.

ALSN Code	1st Impulse ms	1 st Interval ms	2 nd Impulse ms	2 nd Interval ms	3 rd Impulse ms	3 rd Interval ms
Green “G”	350	120	220	120	220	570
Yellow “Y”	380	120	380	720	-	-
Red Yellow “RY”	230	570	230	570	-	-

The generated pulse signal undergoes amplitude modulation with an AC transmitter. This signal is called $S_0(t)$. Figure 3.9 shows the DC pulse signals and AC amplitude-modulated signals for green, yellow and red-yellow ALSN signals. The generator outputs the signal $S_1(t)$ propagating along the rails. Equation 4 shows the relation between $S_0(t)$ and $S_1(t)$. F_N is the carrier signal frequency of 25 Hz, 50 Hz or 75 Hz.

$$S_1(t) = S_0(t) \cdot \sin(2\pi F_N t) \quad (4)$$

**Figure 3.9:** Pulse signal and AC amplitude modulated ALSN codes of green, yellow and red yellow.

The rail transmission converts the signal into $S'_1(t)$. The rail transmission changes the original signal because of track resistance, inductance, rail insulation resistance and track capacitance. Under normal weather conditions, track resistance is negligible; track capacitance is also very low for signals up to 100 Hz. So, the track section that ALSN codes transmission acts like a low-pass filter with track inductance in series and rail insulation resistance between two rails in parallel—the low-pass filter with a certain cut-off frequency. So, during transmission, signal $S_1(t)$ transforms to $S'_1(t)$.

As the transmission medium, rails are susceptible to interferences. The interferences distort the $S'_1(t)$ signal to $S_2(t)$ when it has reached the onboard's receiving coil. If the external distortions are represented with $D(t)$, the equation of $S_2(t)$ (Equation 5) is provided below;

$$S_2(t) = S'_1(t) + D(t) \quad (5)$$

3.2.2 ALSN onboard

ALSN onboard has the receiving coils (RCs) connected in series. Received coils send the received codes to the amplifier unit of ALSN onboard. The amplifier unit includes a filter, an amplifier and a pulse relay. These sub-components are responsible for bandpass filtering to the operating frequency range, increasing the signal's amplitude and demodulating the signal as DC pulses. Next, the processed code enters the major component of ALSN onboard, the Decoder unit. Decoder has sub-components: countable group (CG), signal group (SG) and compliance control unit (CCU). The countable group counts the DC pulses; later on, the Signal group decodes the received signal. Compliance control compares three cycles of pulse to ensure that the received signal is correct and continues. If the received signal is safe, it is displayed in the locomotive traffic light (LTL), the human-machine interface of the ALSN system. LTL shows the approaching signalling aspect; however, if code is lost after receiving green or yellow, it will give white code, and if code is lost after red-yellow, LTL indicates a red signal (Onischenko & Chernykh, 2019).

The other sub-components of the decoder unit ensure train safety. Control bodies unit (CB) and automatic braking devices (EPV) are used for train driver attentiveness checks and automatic train stopping. Control bodies unit includes speed control (SC) and vigilance driver check (V). They both check the train speed based on the indication of LTL and the actual train speed. The train speed is measured with a Sensor of Track and Speed (STS) and Speed Meter (SM). If the actual train speed is higher than expected, then EPV activates the automatic emergency brake (Onischenko & Chernykh, 2019).

The received signal $S_2(t)$ goes through the filter of the locomotive, where it becomes $S_3(t)$. The onboard filter is a bandpass filter. For example, for a 25 Hz carrier signal, the lower limit is 18 Hz and the upper limit is 32 Hz. As a result, shape distortions might be observed in the filtered signal $S_3(t)$ during this period. (Prisukhina et al., 2019). The ALSN signal transmission process is provided in Figure 3.10.

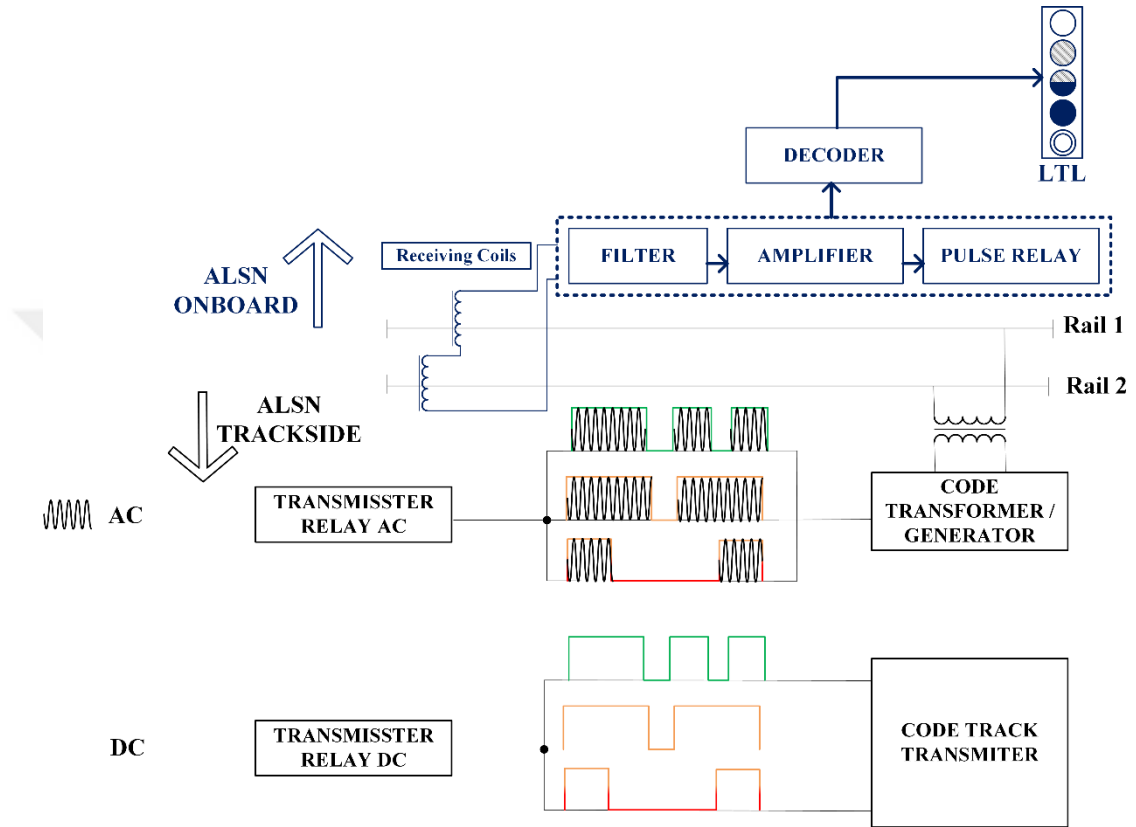


Figure 3.10: ALSN signals generation, transmission and display process.

The distortions of the ALSN signals and their causes are various. Deviations of the above given time parameters are observed when CTT's rotating part needs maintenance, any fluctuations in its supply voltage, etc. The fluctuations in supply voltage lead to harmonics in a carrier signal that leads to non-sinusoidal signals. This leads to misinterpretation of the actual code sent. Another cause is the instability of the track resistance. The ALSN signalling system uses rails as a transmission medium, so track resistance is important. The track resistance is highly dependent on the weather conditions.

3.3 Signalling Interoperability

The Technical Specification for Interoperability is defined with EU Commission Regulation Directive 2016/797. This directive provides definitions for each of the structural and functional requirements of the subsystems. The available TSI specifications are available for the following subsystems and subjects: Energy, Rolling Stock – Locomotives and Passengers, Rolling Stock Freight Wagons, Command Control Signalling, Operation and Traffic Management, Infrastructure, Noise, Safety in Railway Tunnels, Persons with Disabilities and with Reduced Mobility, Telematics Applications for Freight Service and Telematics Applications for Passenger Service. The relevant TSI specification for this research is “Command Control Signalling TSI” (CCS TSI). This section will review and analyse the requirements of TSI specifications for the signalling subsystem, considering ETCS Level 1 Trackside and ETCS onboard unit. The envisaged rules and requirements for STM or the underlying national signalling system will also be summarised. This specification focuses on Class A Train Protection systems and defines how they can be implemented on the trackside and onboard. The interfaces between these components are also one of the main subjects. The specification also identifies Class B systems and how to interface and integrate such a system with Class A systems. For this research, understanding the terms of interoperability for ERTMS systems as Class A and understanding of the integration ways of the ALSN system as Class B is very important(EU 2016/919, 2016).

The geographical scope of CCS TSI refers to the high-speed railway lines for speeds equal to or greater than 200 km/h and 250km/h and conventional railway lines for passenger and freight services and mixed traffic. It is also noted that the scope of these specifications also applies to 1435 mm and 1520 mm track gauges. This is an important factor to consider since, contrary to the generic approach; track gauge is neither the only criterion that defines interoperability nor a single criterion that prevents interoperability.

CCS TSI refers to two main sub-systems: trackside and on-board. Each sub-system is defined within three features: functions (crucial for the safety of railway traffic), interfaces and level of performance (needed to meet the essential requirements). The parts defined under sub-systems are train protection, voice radio and data radio communication and train detection. The specification refers to the ETCS train

protection system and GSMR radio system as Class A and refers to other train protection and voice radio systems as Class B. Class B systems are defined in another documentation named “List of CCS Class B Systems ERA/TD/2011-11”(ERA, 2019). As one of the main topics of this study, ALSN is covered in this extensive list as it is in use in Latvia, Lithuania and Estonia, as well as dozens of other train protection systems that co-exist in European Union territories. CCS TSI specification refers to the requirements for Class A train protection, radio network and interface with train detection systems. The requirements for the Class B system are generally assumed to be the responsibility of the relevant Member State. Additionally, STM defines “K” and “G” interfaces between Class A and Class B systems.

The essential requirements are categorised under safety, reliability and availability, health, environmental protection, technical compatibility and accessibility. The requirements and referred articles for the essential requirements are summarised in Table 3.2 (EU 2016/919, 2016).

CCS TSI’s 4th Chapter specifies “the characterisation of the subsystems”. In this chapter, basic parameters for safety characteristics, ETCS on-board and trackside functionality, GSMR functions, onboard and trackside interfaces, key management, ETCS -ID management and train detection system, EMC between trackside and train, ETCS & GSM-R DMI, data recording interface, visibility of trackside objects, construction of equipment and compatibility of ETCS & Radio. This study mainly focuses on the trackside system and its interface with onboard, key management, ETCS-ID management, DMI, data recording, construction of equipment and compatibility of ETCS & Radio will not be reviewed and summarised. This chapter also indicates that Class B systems and STMs that enables Class A on-board system to operate in Class B infrastructure are the responsibility of the railway network owner (EU 2016/919, 2016).

For TSI compatibility to be fully achieved, there are two major goals. The system shall have standardised functions, interfaces, and performances to ensure that every train will react in the same way according to the data sent by trackside equipment. The other major goal is to standardise train-to-track and track-to-train communication(EU 2016/919, 2016).

For safety, as discussed in the previous paragraph, the hazard of excessive speed and distance limit shall be on the tolerable rate of 10^{-9} h⁻¹ for random failures valid for both trackside and onboard. This is defined as Safety Integrity Level 4 in EN 50129. The specification is strict for ETCS onboard to fully comply with these standards.



Table 3.2: CCS TSI Specifications for The Essential Requirements of CCS Sub-Systems.

Specific Aspects of the CCS Sub-Systems Chapter 3		Basic Parameters Chapter 4	
		Functional and Technical Specifications of the Subsystems (Chapter 4.2.)	Corresponding Mandatory Specifications
Safety	This requirement is the measure for limiting the level of risk for the occurrence of an incident within the scope of services. This requirement is apportioned between trackside and on-board. Changes made in the system by the operator must be evaluated and managed according to the risk management process referred to in Regulation No 402/2013.3.	The Tolerable Hazard Rate is 10^{-9} h⁻¹ for random failures valid for both trackside and on-board. This is defined as Safety Integrity Level 4 in EN 50129. Safety requirement is apportioned between trackside and on-board.	-SUBSET-091 Safety Requirements for the Technical Interoperability of ETCS in Levels 1 and 2 - Safety requirements for ETCS DMI function
Reliability and Availability	This requirement is apportioned between trackside and on-board. The requirements of maintenance are referred to here, considering the effect of wear and age.	The occurrence of failure modes is preferred. The expected system response in the case of a safety hazard is the creation of degraded situations rather than decreasing the safety of the system.	N/A

Table 3.2: CCS TSI Specifications for The Essential Requirements of CCS Sub-Systems. (continued)

Specific Aspects of the CCS Sub-Systems Chapter 3		Basic Parameters Chapter 4	
		Functional and Technical Specifications of the Subsystems (Chapter 4.2.)	Corresponding Mandatory Specifications
Health	This specification refers to the prevention of any health hazards caused to persons using the system or having access to the system.	N/A	N/A
Environmental Protection	This specification is for CCS equipment to prevent any potential environmental hazard. The referred hazards include the emission of heat or fire in the case of fire, abnormal contamination, noise pollution and level of vibration that may endanger the system integrity.	N/A	N/A
Technical Compatibility	This specification includes functions, interface and performances of sub-systems. It has three categories: electromagnetic compatibility (EMC) within railway boundaries, basic parameters about how to apply subsystems and what functions subsystems must perform and the rules of operation for sub-systems. (Details are provided in Chapter 4 for each subsystem). The engineering compatibility is	For EMC, the requirement is the specification for the interface between rolling stock and trackside. 4.2.11 4.2.16 For environmental conditions, all requirements shall be respected. Materials regulation No1302/2014	- For EMC, ERA/ERTMS/033281, Interfaces between CCS trackside and other subsystems - All available regulations are listed in Table A.2 of the

Table 3.2: CCS TSI Specifications for The Essential Requirements of CCS Sub-Systems. (continued)

Specific Aspects of the CCS Sub-Systems Chapter 3		Basic Parameters Chapter 4	
		Functional and Technical Specifications of the Subsystems (Chapter 4.2.)	Corresponding Mandatory Specifications
	referred to as EMC and compatibility to physical environmental conditions.	(LOC&PAS TSI) shall be respected.	specifications regarding environmental conditions.
Accessibility	There is no mandatory requirement for accessibility	N/A	N/A

However, for ETCS trackside it is less strict. Trackside ETCS shall be more flexible if it fully complies with the CCS TSI. Any failure shall not lead to safety hazards; instead, the system shall lead to degraded situations. In degraded situations, the overall safety of the system may decrease. The specification defines failure as the termination of an item's ability, and the failure mode is the effect caused by the failure generated. To ensure that all the management procedures for degraded situations are followed, the railway operators shall prepare an "EC declaration of verification" for ETCS trackside or onboard, which contains availability/reliability values related to each failure mode.

The ETCS on-board has the following primary functions:

- Acknowledging the train characteristics such as maximum train speed and its braking performances;
- Selecting the correct supervision mode based on the information received from the trackside; odometry calculation;
- Recognising the location of the train based on the information received from balises;
- Estimating and supervising the dynamic speed profile based on the information received from the trackside and within the limit of train characteristics;
- Performing the intervention function whenever necessary.

The functionality and performance requirements are referred to in TSI as provided in Table 3.3. ETCS onboard communication shall be made through balise, euroloop, air-gap data transmission and for radio infill and GSM-R, it shall be made through radio data transmission. The communication with STM, in other words, Class B infrastructure function, includes management of the STM output, providing input data for STM and management of STM transitions. STM communication is an integral part of this research.

The ETCS trackside functionality's main goal is to provide a safe route or path for a certain rolling stock. To meet the goal, certain functions need to be performed by ETCS trackside. These functions are;

- Determining the location of the train with the help of Balise (this is featured in Level 2 and 3 operations),

- Translating the information received from trackside equipment into a standardised format for ETCS on-board and delivering movement authority and track-related descriptions to the train.

As explained in the ETCS on-board section, additional specifications between on-board and trackside are also valid for trackside, such as balise and euroloop data transmission. Trackside is also responsible for giving information and orders to the ETCS onboard, such as opening the circuit breaker of the pantograph when passing through the neutral zone. This responsibility is referred to as optional and tied to national rules and results of risk assessments. ETCS trackside shall also handle the management of transition between RBC supervision areas, which is relevant for Level 2 and 3 operations (EU 2016/919, 2016).

GSM-R is used for mobile communication and data transmission. TSI requires GSM-R application at every operation Level. Basic communication function-related specifications are summarised in Table 3.3. Basic communication requires additional standardisation on ASCI (Advanced Speech Call Items) features, SIM cards and location-dependent addressing. The application of basic communication shall provide voice and operational communication to railway operators. Further, TSI specifies the standards for high-priority call confirmation, functional addressing, functional number presentation and user-to-user addressing as provided in Table 3.3. These defined functions of GSM-R are required for ETCS operation Levels 1,2 and 3. However, the data communication feature of GSM-R is only mandatory for Levels 2, 3 and radio in-fill applications of Level 1. TSI requires ETCS onboard to perform at least two simultaneous communication sessions with ETCS trackside. The specifications for data communications are provided in Table 3.3.

The interfaces are an integral part of interoperability. This is also the core focus of this research. CCS TSI has identified three types of interfaces in ERTMS: air gap interfaces, onboard interfaces and trackside interfaces. Air gap interfaces refer to on-board and trackside interfaces as well as GSM-R. The basic parameters relevant to air gap interfaces shall respect the physical, electrical and electromagnetic values, the communication protocol and the communication channel's availability.

Table 3.3: CCS TSI Specifications for Basic Parameters of CCS Sub-Systems.

Chapter 4 Basic Parameters for CCS sub-systems	Implementation Specifications	Performance Specifications
ETCS On-board Functionality	-ERA/ERTMS/003204, ERTMS/ETCS Functional requirement specification -SUBSET-026, System Requirements Specification -SUBSET-040, Dimensioning and Engineering rules -SUBSET-108, Interoperability-related consolidation on TSI Annex A documents	- SUBSET-041, Performance Requirements for Interoperability
ETCS Trackside Functionality	-ERA/ERTMS/003204, ERTMS/ETCS Functional requirement specification -SUBSET-026, System Requirements Specification -SUBSET-040, Dimensioning and Engineering rules -SUBSET-108, Interoperability-related consolidation on TSI Annex A documents	- SUBSET-041, Performance Requirements for Interoperability

Table 3.3: CCS TSI Specifications for Basic Parameters of CCS Sub-Systems. (continued)

Chapter 4 Basic Parameters for CCS sub-systems	Implementation Specifications	Performance Specifications
	General Requirements	
GSM-R Functionality <u>Basic Communication</u> <u>Voice and Operational Communication Application</u>	- EN 301 515, Global System for Mobile Communication (GSM); Requirements for GSM operation on railways - TS 102 281, Detailed requirements for GSM operation on railways - For ASCI Features: TS 103 169, ASCI Options for Interoperability - For SIM Card: (MORANE) P 38 T 9001, FFFIS for GSM-R SIM Cards - For Location Dependent Addressing: (MORANE) F 10 T 6001, FFFS for Location Dependent Addressing // (MORANE) F 12 T 6001, FIS for Location Dependent Addressing - EIRENE FRS, GSM-R Functional requirements specification - EIRENE SRS, GSM-R System requirements specification - For High Call Priorities: (MORANE) F 10 T 6002, FFFS for Confirmation of High Priority Calls // (MORANE) F 12 T 6002, FIS for Confirmation of High Priority Calls - For Functional Addressing: (MORANE) E 10 T 6001, FFFS for Functional Addressing // (MORANE) E 12 T 6001, FIS for Functional Addressing - For Presentation of Functional Numbers: (MORANE) F 10 T 6003, FFFS for Presentation of Functional Numbers to Called and Calling Parties // (MORANE) F 12 T 6003, FIS for Presentation of Functional Numbers to Called and Calling Parties -For User-to-User Signalling: ETSI TS 102 610, Railway Telecommunication; GSM; Usage of the UUIE for GSM operation on railways	

Table 3.3: CCS TSI Specifications for Basic Parameters of CCS Sub-Systems. (continued)

Chapter 4 Basic Parameters for CCS sub-systems	Implementation Specifications	Performance Specifications
<u>Data</u> <u>Communication</u> <u>Applications</u>	- EIRENE FRS, GSM-R Functional requirements specification - EIRENE SRS, GSM-R System requirements specification	

An air-gap interface exists for balise, euroloop and radio communication with the train. The specification provides standards to obey for balise and euroloop air interface as provided in Table 3.4. Data communication has sub-requirements such as operational frequency band, protection against interference, data communication protocols and requirements for radio in-fill applications.

The standardised ETCS onboard interfaces are the interface between GSM-R data communication and ETCS onboard, odometry and the interface between ETCS onboard and Class B on-board. The interface between GSM-R radio and ETCS onboard is relevant for Class A on-board (ETCS) and Class A radio (GSMR). Whenever radio in-fill is available, the interface requirements are also valid, as provided under Table 3.4. The standards for the odometry interface are also provided under the same table. The last interface is crucial for this study, which is for an on-board system that includes ETCS and Class B train protection features. CCS TSI also defines further specifications for this kind of interface.

The interface between Class B balises and ETCS on-board BTM (Balise Transmission Module) is categorised as “K Interface,” which allows STM to receive information through the ETCS onboard antenna and “G Interface,” which defines an air-gap between ETCS on-board antenna and Class B balises. The schematic provided in Figure 3.11 has been extracted from both SUBSET 026-2 and CCS TSI that describes “K” and “G” interfaces and the management of transitions. These interfaces are not mandatory for achieving interoperability; however, if STMs are aimed to be used conjointly, they shall comply with these interface standards. The management of the transition between ETCS onboard and Class B onboard is recommended to be handled with the provided standards as given in Table 3.4; however, if the system cannot meet these standards, then the railway operator needs to review whether the system requires additional measures in the trackside system.

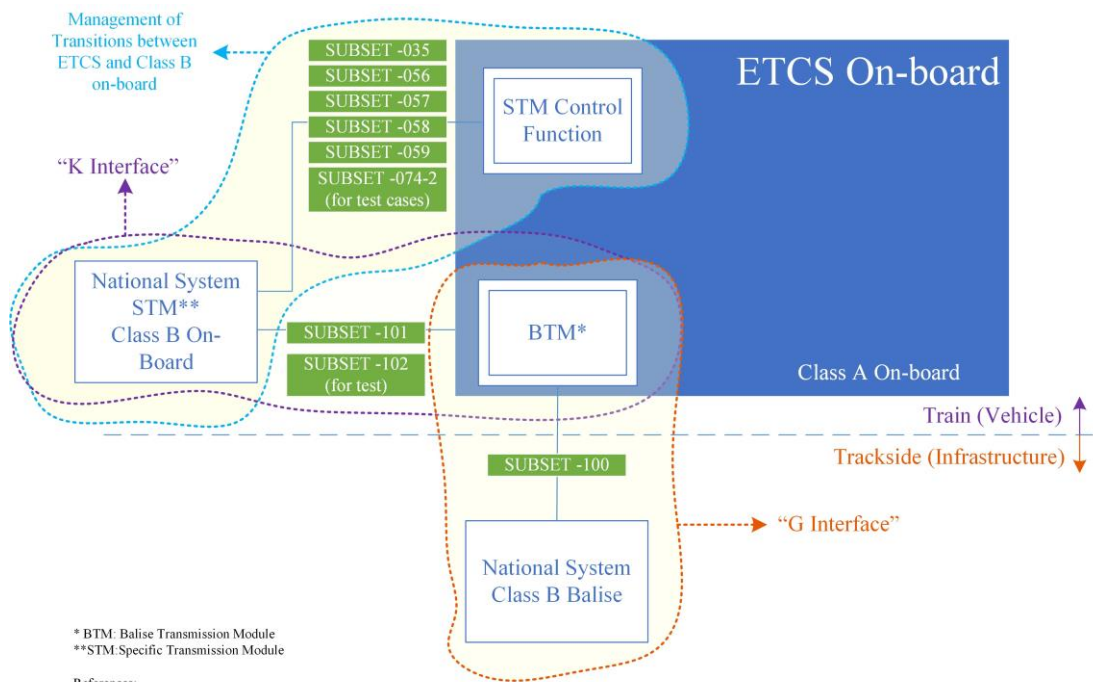


Figure 3.11: Schematics showing the specifications for K & G Interface and management of transitions between ETCS and Class B on-board

The ETCS trackside interfaces have five important components: the interface between GSM-R and ETCS trackside, the interface between Eurobalise and LEU (Lineside Electronic Unit), the interface between Euroloop and LEU, the data exchange interface between RBCs and the technical interface between two RBCs. The interface between ETCS trackside and GSM-R (Class A radio system) has its standards, as provided in Table 3.4. There are also standards and specifications for interfaces between Eurobalise and LEU and Euroloop and LEU. These specifications are only to be considered where they exist in the specific system under consideration. Two functions for the RBC data exchange interface are defined: “Handing over” and “Accepting” for neighbouring RBCs. Additionally, technical interface specifications for two RBCs have further specifications as indicated in Table 3.4. The specifications are shown in the schematics shown in Figure 3.12.

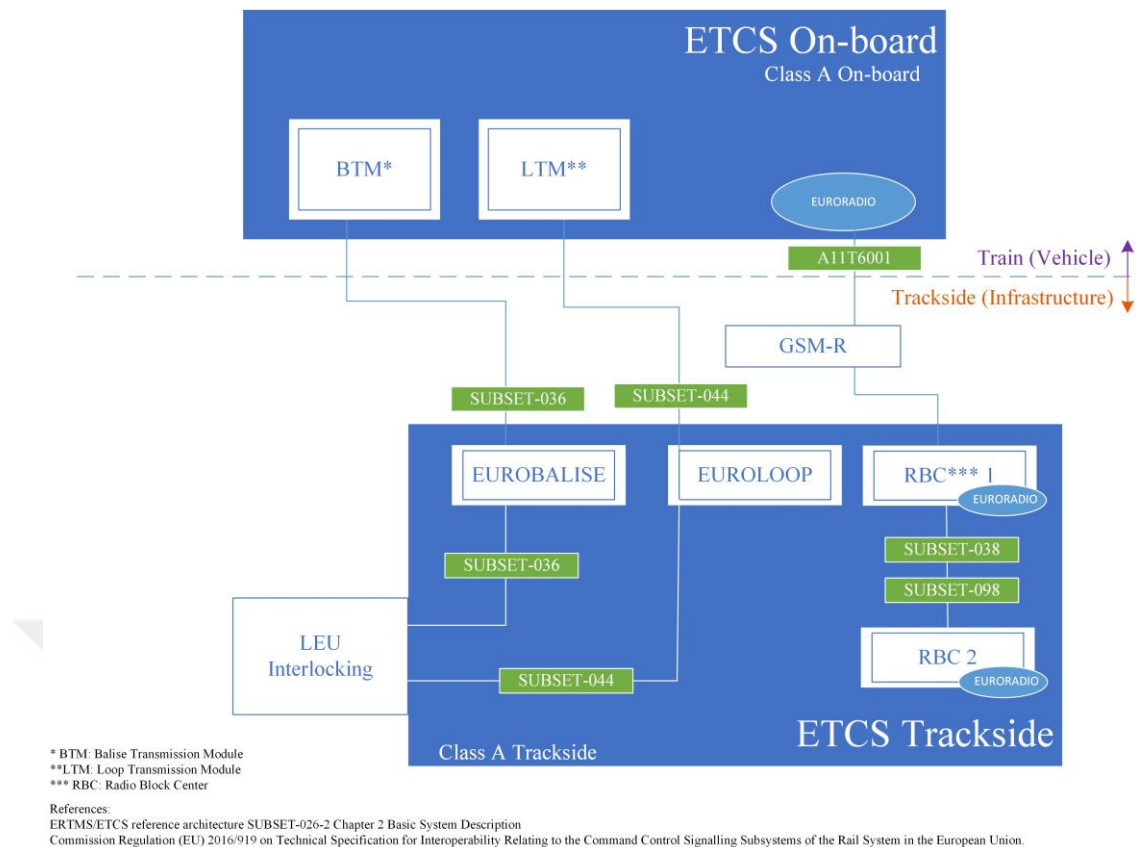


Figure 3.12: Schematics showing ETCS Trackside Interfaces.

The train detection system is not a system that CCS TSI standardises. However, the interface between the train and track detection system is defined in the specification. Electromagnetic compatibility is an interface requirement for train and trackside. CCS TSI specifies EMC interface requirements for train detection systems as well.

All interfaces defined under CCS TSI are summarised under Table 3.4, as shown below.

Table 3.4: CCS TSI Specifications for Defined Interfaces.

Chapter 4 Basic Parameters for Interfaces	General Requirements
<u>Eurobalise Communication with Train</u>	- SUBSET-036, FFFIS for Eurobalise - SUBSET 085, Test specification for Eurobalise FFFIS
<u>Euroloop Communication with Train</u>	- SUBSET-044, FFFIS for Euroloop - SUBSET-103, Test specification for Euroloop
ETCS and GSM-R Air Gap Interfaces <u>Radio Communication with Train</u>	- For operational frequency band: EN 301 515, Global System for Mobile Communication (GSM); Requirements for GSM operation on railways // TS 102 281, Detailed requirements for GSM operation on railways // EIRENE FRS, GSM-R Functional requirements specification // EIRENE SRS, GSM-R System requirements specification - For interference protection: EIRENE FRS, GSM-R Functional requirements specification // EIRENE SRS, GSM-R System requirements specification - For data communication protocols: SUBSET-037, EuroRadio FIS // SUBSET-092-1, ERTMS EuroRadio Conformance Requirements - For Radio In-fill Requirements: SUBSET-047, Trackside-Trainborne FIS for Radio infill // SUBSET-048, Trainborne FFFIS for Radio infill

Table 3.4: CCS TSI Specifications for Defined Interfaces.(continued)

Chapter 4 Basic Parameters for Interfaces		General Requirements
ETCS On-Board Interfaces	<u>GSM-R Data Communication</u>	- For Class A Radio (GSM-R) and ETCS On-board interface: A11T6001, (MORANE) Radio Transmission FFFIS for EuroRadio
	<u>Odometry</u>	- For Radio Infill interface: SUBSET-048, Trainborne FFFIS for Radio infill
	<u>Interface Between ETCS and Class B Train Protection (On-board)</u>	- SUBSET-046, Radio infill FFFS - SUBSET-048, Trainborne FFFIS for Radio infill
	<u>Interface Between ETCS Trackside and GSM-R</u>	- For the management of transitions between ETCS and Class B on-board: SUBSET-035, Specific Transmission Module FFFIS // SUBSET-056, STM FFFIS Safe time layer // SUBSET-057, STM FFFIS Safe link layer // SUBSET-074-2, FFFIS STM Test cases document // SUBSET-059 Performance requirements for STM // SUBSET-058, FFFIS STM Application layer
ETCS Trackside Interfaces	<u>Interface Between Eurobalise and LEU</u>	- For K Interface: SUBSET-102, Test specification for interface 'K' // SUBSET-101, Interface 'K' Specification - For G Interface: SUBSET-100, Interface 'G' Specification
		- A11T6001, (MORANE) Radio Transmission FFFIS for EuroRadio
		- SUBSET-036, FFFIS for Eurobalise

Table 3.4: CCS TSI Specifications for Defined Interfaces.(continued)

Chapter 4 Basic Parameters for Interfaces	General Requirements
<u>Interface Between Euroloop and LEU</u>	- SUBSET-044, FFFIS for Euroloop
<u>Functional Interface between RBCs</u>	- SUBSET-039, FIS for the RBC/RBC handover
<u>Technical Interface between RBCs</u>	- RBC-RBC Test specification for safe communication interface -SUBSET-098, RBC-RBC Safe Communication Interface
Trackside Train Detection System	<u>Interface Between Train and Trackside Train Detection (including EMC requirement)</u> - ERA/ERTMS/033281, Interfaces between CCS trackside and other subsystems

“K” and “G” interfaces are developed for KVB, Ebicab and RSDD (KER) balises. KVB is the French ATP system, Ebicab is Bombardier Transportation’s ATP system, and RSDD is the Italian ATP system. Interface “G” supports five different types of balises: A (parallel/grey balise in Sweden and Norway), B (serial balise in Sweden), C (mini balise in Norway), D (Parallel balise in French) and E (serial balise in France). The requirement defines the signal, physical, coding, and data layers of the interface between these types of balise and BTM. The “G” interface has two-way communication, G4 represents the tele-powering, and G1 represents the up-link data transmission from Balise (UNISIG SUBSET - 100, 2012). The “K” interface envisages a method to read KER balises with a small antenna and BTM function adaptations. By making this modification, the antenna unit reads KER balises, and the BTM function decodes the message and transfers it to KER STM. From here, KER STM is connected to EVC with a Profibus connection. The main aim of the “K” interface is to enable the existing transmission system to perform the same actions of STM when using onboard BTM. This approach eliminates the requirement for an additional antenna to read KER balises. The “K” interface is not mandatory; installing a KER STM is also possible by installing the dedicated antenna(Lundberg & Sjöbergh, 2005).

The ERTMS specifications support KER STM; the interfaces and possible interferences are well-defined for enabling interoperability in those systems. To prevent confusion in transmission, the BTM antenna has two modes of tele-powering signal: 27MHz non-toggling continuous wave (CW) signal or 27MHz signal modulated by toggling 50 kHz signal. The toggling signal is used where KER STM will operate the onboard system. When the onboard system does not require information from the KER system, the ETCS onboard turns off the toggling signal and turns on the CW signal. In this case, KER balises are not wakened up by the CW signal and do not create confusion(UNISIG SUBSET-036, 2015).

As this research aims to develop an STM for ALSN, “K” and “G” interfaces provide insights into approaching this problem; however, they do not propose a solution. The ALSN system uses coded track circuits that are continuously active as the train enters a track section; they do not require a tele-powering signal to be awakened. Additionally, BTM does not have the necessary components to decode ALSN codes. Considering these fundamental differences, a new solution and a new interface are required for ALSN STM.



4. PROPOSED METHOD

4.1 Problem Definition

ERTMS signalling system is defined and analysed in three sub-components: ETCS onboard, ETCS trackside and GSMR. ALSN signalling system is defined and analysed in two sub-components: ALSN trackside and ALSN onboard. Until this date, no transition, STM or interface was defined for train operation between these two signalling systems. Trains equipped with ETCS onboard cannot proceed to the railway lines equipped with ALSN trackside. Although ALSN is identified as a Class B train protection system by the interoperability technical specifications of the European Union and ALSN STM has an identified unique code in ETCS language as “NID_STM / NID_NTC: No. 39”(ERA_ERTMS_040001, 2023), there is no proposed method to enable the interoperability of these two signalling systems.

As highlighted in the former sections, interoperability is an important factor for the competitiveness of rail transport. As the competitiveness of rail transport increases, passenger and freight attraction is possible from other modes of transport. Currently, no signalling system enables interoperability between ERTMS and ALSN signalling systems. This causes huge delays at border crossings due to the need to change locomotive or train sets. Interrupted transportation puts rail transport between countries with these signalling systems in a disadvantageous position. The limited freight and passenger volume results in low income for Rail operators. The lower income critically affects the investment made in railway infrastructure and vehicles, which leads to more degradation in railway competitiveness as a mode of transport. Interoperability in signalling is one of the key steps towards seamless cross-border operation.

The proposed method is an ALSN STM that allows the operation of trains equipped with ETCS onboard in the railway lines equipped with ALSN trackside. The train movement from the countries that adopted ERTMS to the countries that adopted ALSN would be possible with the proposed STM, interface and transition. The proposed STM will be external type. The system's inputs are ALSN codes, and the system's outputs are telegrams. This system aims to translate ALSN codes to digital telegram packets for ETCS onboard to demodulate and process the received information. The layout of this section will be as follows. First, there will be a requirement analysis to analyse the

necessities to realise such STM. Afterwards, the block diagram and interface for the ALSN STM will be proposed. The applicable cross-border operations will be summarised, and the financial implications will be discussed.

4.2 Requirement Analysis

ALSN STM is proposed as a novelty in this research. The differences between the ERTMS and ALSN signalling systems are explained, and the conditions for interoperability of the signalling system are presented. According to TSI, compatibility can be achieved if two major goals can be achieved. First, the functions, interfaces and performances shall be standardised. Secondly, train-to-track and track-to-train communication shall be standardized. The proposed ALSN STM shall have a standardised set of specifications and interfaces to be compatible with TSI. Additionally, TSI is very strict on the safety of the ETCS onboard system, whereas the tolerable hazard rate shall be 10^{-9} h⁻¹. However, for ETCS trackside, the requirements are not so strict. The failures that occurred on the ETCS trackside system shall not lead to safety hazards; rather, they shall result in degraded situations. The proposed ALSN STM employs the ETCS on-board and the ALSN trackside. The ETCS on-board will be utilised as the main decision maker for train supervision and protection to enable compatibility with TSI. The functions and performances of ETCS onboard will be valid for this setting. Also, in the literature, the interoperability of signalling systems is defined with two types of interface: air-gap and human-machine interface. The proposed STM does not change the human-machine interface, which is DMI; DMI will be available with the standardised indications. The air-gap interface will differ from the Balise operation; however, the information will be provided as a digital telegram. However, the interface needs to be redesigned, considering that the defined interfaces for STM “K” and “G” are unsuitable for the proposed method. The ALSN trackside functions are defined as explained in the former section; however, the performances of ALSN trackside are not clearly standardised. As foreseen in ETCS specification, the proposed STM need to inform ETCS onboard for a degraded mode of operation in the case of any hazard in ALSN trackside. Additionally, train-to-track and track-to-train communication requires definition. The inputs of the ALSN STM will be track-to-train communication for Level STM operation. This will be a novel definition of track-to-train communication. Another track-to-train communication will

be provided by fixed balises as defined in the specifications. However, train-to-track communication is only envisaged with the use of fixed balises. Since the ALSN trackside does not require a tele-powering signal. This study will provide conceptual functions, interface and performance of ALSN STM operation, and it will define train-to-track and track-to-train communication.

As defined in the methodology section, the interoperability of similar STMs is defined for other signalling systems. TSI envisages the requirements of STMs as system requirement specification (SRS) and form fit functional interface specification (FFFIS). This study aims to identify the conceptual architecture of such a system and the conceptual requirements and definition of a new interface for further enhancements. The conceptual SRS of the proposed system will identify the required components from ETCS onboard and ALSN trackside, input data for STM, management of STM data processing, output data for STM and management of STM transition. The conceptual FFFIS will identify a new interface between STM and ETCS onboard. To enable the TSI compatibility, the functions, interfaces and performances will be conceptualised under SRS of ALSN STM, and the train-to-track and track-to-train communication will be conceptualised under FFFIS.

The operation of ALSN STM is envisaged to be performed under Level STM. As defined in the introduction, Level STM requires an additional module on the ETCS onboard to enable track-to-train communication. An additional module needs to be defined. Different types of STMs are available on the market, either external or internal. The standardised KER STMs have a direct interface to European Vital Computer (EVC), identified as internal STMs. However, in the proposed method, considering that TSI imposes very strict safety requirements on onboard systems, it was decided to limit the integration of an additional module to ETCS onboard. The envisaged system is external. The implications of external STM indicate that the STM will not make the safety-critical decisions, and there will be no direct communication or link between EVC and STM. Instead, the physical connection envisaged is between BTM and STM. This preference enabled the inheritance of performance standards of ETCS onboard. The proposed STM will not replace a certain part of the ETCS onboard sub-component. It will only replace the analogue part of the BTM module to benefit from the Safety Integrity Level 4 decision-making processes of ETCS onboard.

Under Level STM ALSN operation, the required ETCS onboard system sub-components are European Vital Computer (EVC), Balise Transmission Module (BTM), Driver Machine Interface (DMI), Train Interface Unit (TIU), Odometry and External ALSN STM. Other sub-components of ETCS onboard are not required. However, the availability of such components would not affect the operation. The required components from ALSN trackside are code track transmitter, transmitter relay DC, transmitter relay AC and code transformer. The interlocking and CTC are also required as they are the backbone of every railway signalling system. The ALSN STM is required to enable communication between ALSN trackside and ETCS onboard. To define communication, the input and output of the ALSN STM are required to be defined as well. The input of the ALSN STM is the ALSN codes. The ALSN trackside generates ALSN codes to carry movement authority information. The output of the ALSN STM are telegrams that are in the form of digital frequency shift keyed (FSK) signals.

The transition from ERTMS to ALSN is envisaged through fixed balise, as indicated by SUBSET 026. The fixed balise installed right before the transitioning zone will inform the ETCS onboard that now the train enters a railway section where the ALSN trackside signalling system is active. The ETCS onboard will receive a NID_STM / NID_NTC: No. 39 command to activate the ALSN STM from the fixed balise.

As a result of the requirement analysis for ALSN STM, it has been identified that the conceptualisation of the items below will be sufficient to present the conceptual architecture.

- System Requirement Specifications:
 - Components of ETCS onboard
 - Components of ALSN onboard
 - Input data for STM
 - Management of STM data processing
 - Output data for STM
 - Management of STM transition
- Conceptual Form Fit Functional Interface Specification (FFFIS)

- Interface between ETCS onboard and ALSN STM
- Train-to-track communication
- Track-to-train communication

4.3 Proposition of ALSN STM

This section will provide the proposed ALSN STM's conceptual architecture. The sub-components of ETCS and ALSN systems that will be required for ALSN STM Level operation will be shown and the interrelation between sub-components will be summarised. The input and output relationship and STM data processing will be envisaged in “Conceptual System Requirement Specifications” (SRS). On the other hand, track-to-train communication and the new interface will be identified and presented in Conceptual Form Fit Functional Interface Specification (FFFIS).

4.3.1 Conceptual system requirement specifications (SRS)

The conceptual SRS identifies the functions of the ALSN STM and the sub-components of the ALSN STM. The available requirements and subsets about STMs are not fully beneficial, considering that they are only relevant to KER STMs. The proposed system also differs from the defined STMs with its feature of external integration. Considering these facts, the ALSN STM requires a whole new definition. This study will conceptualise the requirements.

The input of the ALSN STM shall be the output of the ALSN trackside. The main aim of the STM is to translate the Class B train protection system's output to the ETCS onboard. Considering this fact, the input of the ALSN STM will be AC-modulated DC impulse signals, in other words, ALSN codes. Each code indicates a different type of movement authority. The rectangular pulses undergo AC modulation with 25 Hz, 50 Hz or 75 Hz carrier frequencies. Equation (3) shows the mathematical representation of the input of ALSN STM. $S_0(t)$ is the rectangular pulse code, and $\sin(2\pi F_N t)$ represents AC modulation.

$$S_1(t) = S_0(t) \cdot \sin(2\pi F_N t) \quad (6)$$

The output of the STM shall be the input of ETCS onboard. The output will be digital telegrams. The output will be either a long-type telegram with 1023 bits or a short-type telegram with 341 bits. (Figure 4.1) The ALSN STM generates the telegram in digital form. In the normal ERTMS operation, the receiver unit of BTM performs the conversion of the FSK signal to a digital telegram. In the envisaged method, the digital telegram (output) is directly integrated into the FPGA board of BTM.

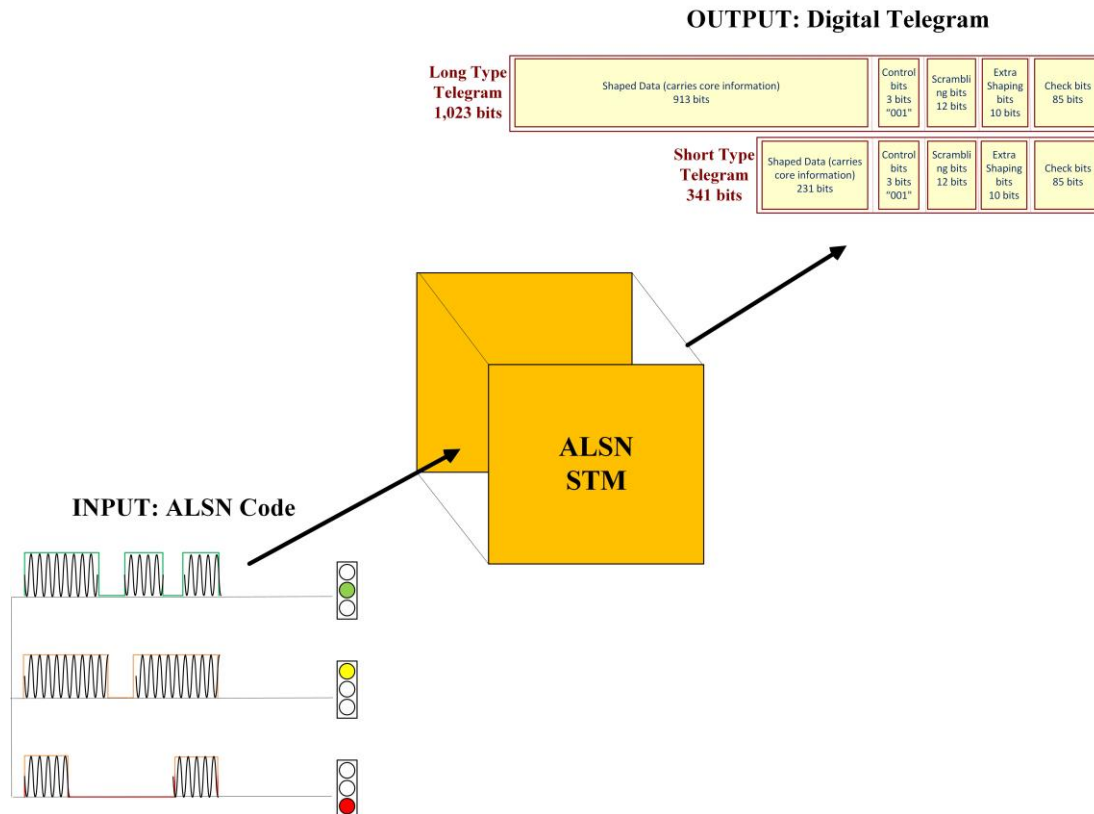


Figure 4.1: Input and output of the ALSN STM.

The identified input and output provide insights into the management of the STM process. The STM shall have the necessary components to pick up the ALSN code to process the information. To perform this action, the ALSN STM shall have receiving coils. The received code needs to be processed by the ALSN STM. As explained in ALSN onboard sub-components, the ALSN STM shall have a filter, amplifier and pulse relay. The filter is a bandpass filter that allows only the frequency with the selected carrier frequency. As explained in detail, the ALSN codes are transmitted through rails, and rails are vulnerable to interferences and disturbances. Considering

the effect of outside distortions, the attenuated signal enters the amplifier after filtering. Pulse relay demodulates the AC modulated signal into rectangular pulse code.

The rectangular pulse code carries the data of movement authority. The identification of the movement authority data from the rectangular pulses requires an additional sub-component. This sub-component is named “conversion unit” (CU). Firstly, the CU counts the DC pulses and decodes the received signal. The decoded signal takes the digital form of Green, Yellow or Red-Yellow. The CU performs the demodulation for three cycles to compare the received results. As ALSN codes will be continuously delivered to the receiving coils, the check for three cycles enables redundancy and prevents hazards. If the consecutively received ALSN code is the same, then the conversion unit matches the received code with the appropriate telegram. As ALSN trackside only provides three types of movement authority, this poses a limitation of available telegram packets. This is also an issue to consider. Further matching needs to be done to inform ETCS onboard of the degraded mode of operation. The only defined degraded mode of operation in ALSN is the “white code”. The white code is only provided when the ALSN code is not available. The conversion unit shall also include some telegram packets that carry information to ETCS onboard regarding degraded mode. Hence, the conversion unit shall have a library of ALSN codes and other results that might be received and matched with the digital telegram packets. E.g. Green ALSN code shall be matched with the packet “transmission of a movement authority for Level 1”. The conversion unit shall be the decoder of the rectangular pulse code and the identifier of the required telegram to be generated. The selected telegram packet is envisaged to be generated by the telegram generator. The telegram generator provides the output of the ALSN STM. Finally, the telegram shall be fed into ETCS onboard via BTM’s FPGA board.

The identified sub-components of ALSN STM also require sub-components from both ETCS and ALSN. The ETCS onboard subcomponents are European Vital Computer (EVC), Balise Transmission Module (BTM), Driver Machine Interface (DMI), Train Interface Unit (TIU), Odometry and External ALSN STM. The BTM is required for the injection of the digital telegram generated by ALSN STM. The generated telegram is connected to the FGPA of the BTM. The ALSN STM requires a separate connection to the FPGA board, considering that the receipt, analogue-to-digital conversion, is performed by the STM itself. The FPGA board of BTM will detect the right telegram,

demodulation and time stamping of the received telegram. The correctness of the telegram context is checked by the ETCS onboard. The time stamp and the movement authority information will be kept in BTM until the EVC reads the data. EVC will process the received data, and the extracted information will be shown in DMI. EVC commands the TIU based on the received data. The use of odometry shall be also available in the ETCS onboard.

The ALSN trackside subcomponents are the code track transmitter, transmitter relay DC, transmitter relay AC and code transformer. These components will receive the movement authority from interlocking and provide ALSN codes as the AC-modulated DC impulses. The code track transmitter generates the code for green, yellow or red-yellow. The transmitter relay DC generates the rectangular pulses in accordance with the generated code. Transmitter relay AC provides the AC modulation with either 25Hz, 50Hz or 75Hz. Finally, the AC-modulated rectangular pulse code is sent to the rails via the code transformer. The generated code will be transmitted through rails.

The block diagram of the ALSN STM is provided in Figure 4.2. The block diagram identifies the conceptual architecture of ALSN STM. There are five main areas to this architecture;

- Underlying signalling system: This area refers to CTC and interlocking. This area is the common part for both ETCS and ALSN as these two systems do not replace interlocking, both of them only enable trackside and onboard components.
- ALSN Trackside: This area comprised of the typical sub-components of ALSN trackside
- ETCS Onboard: This area is the generic ETCS onboard system
- External ALSN STM: This area is the proposed method to solve the interoperability problems between ERTMS and ALSN signalling systems and to develop STM technology for the ALSN system.
- Optional: This area contains fixed balise only. This section is optional and proposed as an additional upgrade to the ALSN trackside.

- Filtering the received signal with the bandpass filter
- Amplifying the attenuated signal
- Demodulating the AC modulated signal to the DC rectangular pulse signal
- Decoding of DC rectangular pulse signal to digital green, yellow or red-yellow
- Performing the decoding three cycles and compare the results (if all three are the same, proceed)
- Matching the decoding results with the set of digital telegram packets
- Generating the matched telegram packet in the form of digital telegram (either short or long-type)
- Sending the digital telegram to the FPGA Board of BTM

4.3.2 Conceptual form fit functional interface specification (FFFIS)

FFFIS is an interface specification that usually covers all communication levels. This study proposes a conceptual FFFIS to specify the interface between ALSN STM and ETCS onboard and train-to-track and track-to-train communications. The available FFFIS STM (SUBSET-035, 2015) provides insights regarding the implications; however, the ALSN STM interface and communications require a new interface definition.

Some requirements are identified as valid for ALSN STM as well. The identified general FFFIS requirements are summarised below (SUBSET-035, 2015),

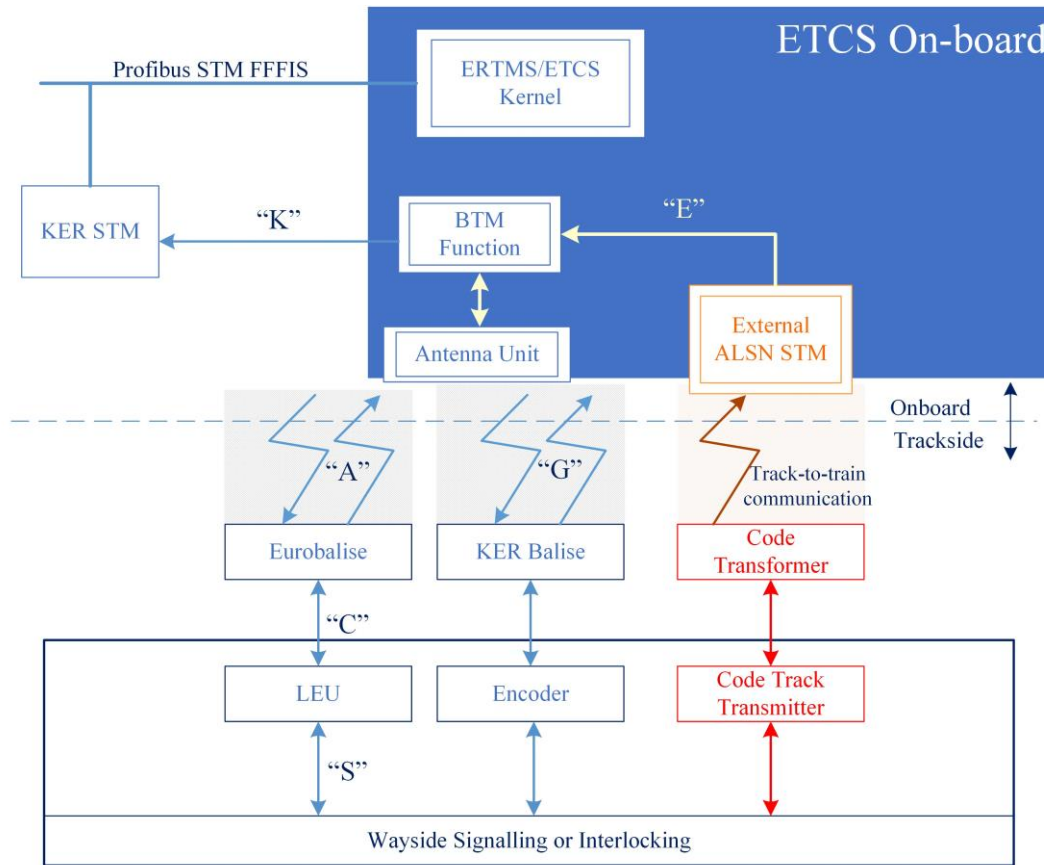
- Use of unique NID number as NID_STM: 39 for ALSN
- Use of common time information as ETCS onboard and it is communication through STM interface
- Only active STM shall be ALSN STM at a specified time
- ETCS onboard shall actively check the ALSN STM for failures
- The STM can be isolated from ETCS onboard with the defined interface.

No connection shall be made between two systems with lower safety integrity level. ETCS onboard and BTM is the safety integrity level 4. The STM ALSN shall also be a system with the safety integrity level 4 (SIL 4).

The STM FFFIS also provides insights regarding the functional interface. The functional interface for the available FFFIS is defined for DMI, Brake Interface, TIU, Juridical Data and Odometer (SUBSET-035, 2015). However, the proposed interface for ALSN STM does not envisage any functional interface with the above-mentioned ETCS onboard sub-components. The ALSN STM is connected to BTM's FPGA board. The proposed method does not allow direct communication with EVC via Profibus. Instead, the evaluation and critical decision-making are left to ETCS onboard, thus EVC. As this is an external STM, the only interface is planned between the BTM function and STM. The interface proposed in this study is a novelty. The defined interfaces do not envisage a physical interface between BTM and STM.

The defined interfaces for the ERTMS signalling system are namely "K", "A", "G", "C", and "S". The "S" interface defines the connection between LEU and the interlocking system. The interface "C" is the connection between LEU and switchable balise. The "S" and "C" interfaces are available for ERTMS Level 1 operation; both have physical bi-directional connections via wires and cables. On the other hand, the interface "A" indicates the air-gap interface where no handshakes are envisioned, but the flow is bi-directional. The "A" interface is used for fixed and switchable balise, which means it is used in Level 1, 2 and 3 operations. The additional interfaces called "G" and "K" are defined for KER STM, as explained in the former section. The "G" interface defined an air-gap interface between KER balise and BTM. This is not valid for ALSN STM, since the standard of BTM has been configured to generate activation signal for KER balises. The "G" interface enables BTM- KER Balise direct bi-directional communication. This communication is embedded in BTM through available specifications. This is not valid for ALSN STM. The interface "K" is envisaged to transmit the data received from KER balise by BTM to KER STM. This interface is unidirectional, and it is from BTM to KER STM. The evaluations and decision-making conducted by KER STM are connected to the ETCS onboard via Profibus. The defined interfaces are not the counterpart of the envisioned interface for ALSN STM. The receiver and analogue processing is performed on the ALSN STM, and the digitalisation, decoding, matching and digital telegram generation are also performed on the same module. The interface required is a digital port connection to the FPGA board of BTM. This new interface is identified as a unidirectional interface from ALSN STM to BTM. The new interface is called the "E" interface. Figure 4.3

shows all the interfaces defined by the standard and the new “E” interface. Figure 4.3 also indicates the train-to-track and track-to-train communications. The train-to-track and track-to-train communications for ETCS levels 1, 2 and 3 are performed by air-gap interface “A”.



References:
ERTMS/ETCS reference architecture SUBSET-100

Figure 4.3: All defined interfaces and the proposed interface "E" are shown as a diagram.

The Euroradio interface is not shown here as it is classified under GSM-R. The track-to-train communication is the telegram that is sent to the Antenna unit as a digital telegram. The train-to-track communication is the tele-powering signal sent to the balise to wake the balise. The defined communication is almost the same for the interface “G”; the communication is both from and to train since KER balise also requires a non-toggling tele-powering signal. The proposed method employs ALSN trackside for train-to-track communication. The transmission medium is rails. This communication can also be referred to as air-gap as no handshake or physical connection is envisaged. The train-to-track communication is not available, and it is not needed. The ALSN trackside code transmitter is automatically activated once the

train enters a track section. So, there is no need for a tele-powering signal. The communication method is on-spot transmission for interface “A” and “G”, but for interface “E”, the communication method can be categorised as semi-continuous.

The conceptualised FFFIS identified a new interface called the “E” interface. The track-to-train communication is presented, revealing that the train-to-track communication is not required for ALSN STM.

4.4 Applicable International Railway Networks

The ERTMS and ALSN signalling system border crossing is common in international railway networks. The NEAR2 (Network of European – Asian Rail Research Capacities) project was initiated in December 2012 and ended in November 2014. This project was funded by the European Union, and the main aim is to identify the Trans-Eurasian Rail Research Networks’ needs for rail transport. As Asia is developing daily, the rail transportation networks connecting Europe to Asia are gaining importance. There are 13 partners in this project from Greece, Germany, the Czech Republic, Lithuania, Russia, China, India, Ukraine and Poland. This project's outcome was identifying the network’s capabilities, technological gaps and barriers to interoperability. The identified Trans-Eurasian Railway routes are provided below(Cheotsov et al., 2013);

- **Route A:** Connection between Western Europe – Russian Far East – Japan / via main Trans -Siberian

This route crosses Poland – Belarus or Ukraine – Russia - Japan.

- **Route B:** Connection between Western Europe – China / via Trans-Siberian Route and its branches

- Route B1 / via a branch of the Trans-Siberian railway network – the Manchurian route

This route crosses Poland – Belarus or Ukraine – Russia - China

- Route B2 / via a branch of the Trans-Siberian railway network – Trans-Kazakh route

This route crosses Poland – Belarus or Ukraine – Russia – Kazakhstan – China

- Route B3 / via a branch of the Trans-Siberian railway network – Mongolian network

This route crosses Poland – Belarus or Ukraine – Mongolia - China
- **Route C:** Connection between Western Europe – China via the TRACECA corridor (Silk Road)
 - Route C1.1 / via the TRACECA – Turkmenbashi rail route (1)

This route crosses Western Europe- Slovakia- Hungary- Romania- Bulgaria- Turkey - Azerbaijan- Caspian Sea- Turkmenbashi- Uzbekistan- Kazakhstan - China
 - Route C1.2 / via the TRACECA – Turkmenbashi rail route (2)

This route crosses Western Europe- Slovakia- Hungary- Romania- Bulgaria- Black Sea- Georgia- Azerbaijan- Caspian Sea- Turkmenbashi- Uzbekistan- Kazakhstan - China
 - Route C2.1 / via the TRACECA – Aktau route (1)

This route crosses Western Europe- Slovakia- Ukraine – Russia - Georgia- Azerbaijan- Caspian Sea- Turkmenbashi- Uzbekistan- Kazakhstan - China
 - Route C2.2 / via the TRACECA – Aktau route (2)

This route crosses Western Europe- Slovakia- Ukraine – Russia - Georgia- Azerbaijan- Caspian Sea- Turkmenbashi- Uzbekistan- Kazakhstan (different route) - China
- **Route D:** Connection between Western Europe – China via the Central Corridor in Kazakhstan / the Trans-Asian railway route

This route crosses Western Europe- Poland – Belarus or Ukraine – Russia - Kazakhstan – China
- **Route E:** Connection between Western Europe – India via the Trans – Asian railway route / via the Central Corridor in Kazakhstan

This route crosses Western Europe- Slovakia- Hungary – Bulgaria – Turkey – Iran – Pakistan – India.

The identified routes under the scope of the NEAR2 project are the available railway networks that connect Western Europe to Asia. There are multiple barriers to achieving interoperability in those rail networks. As this study focuses on signalling interoperability, the signalling systems along the identified international railway networks are analysed. The analysis showed that Routes A, B1, B2, B3, C1.1, C1.2, C.2.1, C.2.2 and D require a signalling system transition from ERTMS to ALSN in the direction of Europe to Asia. Table 4.1 shows the two countries where transition is envisaged. Figure 4.4 shows the percentage allocation of the signalling systems per total kilometres of the routes. The ALSN signalling system is operational in almost every railway line that the rail network of Western Europe is connecting to. The majority of the signalling systems used along these international corridors are also ALSN Signalling. The percentages of ALSN and ERTMS signalling systems in kilometres are provided below (Cheotsov et al., 2013);

- For Route A: ERTMS Signalling 4%, ALSN Signalling 96%, Total length: 12,970 km
- For Route B1: ERTMS Signalling 4%, ALSN Signalling 77%, Total length: 11,670 km
- For Route B2: ERTMS Signalling 5%, ALSN Signalling 55%, Total length: 10,440 km
- For Route B3: ERTMS Signalling 4%, ALSN Signalling 89%, Total length: 11,560 km
- For Route C1.1: ERTMS Signalling 12%, ALSN Signalling 39%, Total length: 11,360 km
- For Route C1.2: ERTMS Signalling 42%, ALSN Signalling 36%, Total length: 12,440 km
- For Route C2.1: ERTMS Signalling 5%, ALSN Signalling 83%, Total length: 11,765 km
- For Route C2.2: ERTMS Signalling 4%, ALSN Signalling 60%, Total length: 12,585 km

- For Route D: ERTMS Signalling 4%, ALSN Signalling 60%, Total length: 11,945 km

Considering the application of ERTMS in Europe as an interoperability constituent, the STM development for ALSN would also be perceived as an indication of interoperability for the international corridors. The proposed ALSN STM will improve the rail network connectivity between Europe and Asia.

4.5 Financial Implications of The Proposed Method

The proposed ALSN STM contributes directly to interoperability between Europe, Caucasus and Asia and indirectly to the whole world. The former section summarised the alternative routes available connecting Europe to Asia. Understanding the complex financial implications of the proposed ALSN STM requires extensive study since the first and secondary effects, including global peace and prosperity, need to be researched. It is not the initial question of this research. However, to understand the possible financial outcomes, the transition of ERTMS to ALSN and from Turkey to Georgia will be analysed as an example.

Among these routes, category C is also part of the international TRACECA (Transport Corridor Europe, Caucasus and Asia). Route C1.2 crosses the TRACECA – Turkmenbashi rail route starting from Slovakia, Hungary, Romania, Bulgaria, Turkey, Armenia, Georgia, Azerbaijan, Turkmenistan, Uzbekistan, Kazakhstan and China. This route has a missing link since the border is close between Turkey and Armenia. Another alternative has been proposed to this missing link by Turkey, Georgia and Azerbaijan with the protocol signed in 2007(Özpay, 2018). This agreement envisaged the Baku – Tbilisi and Kars Railway Line (BTK). This initiative aimed to increase the railway freight and passenger volume, thus increasing the import–export volume between these three countries. The investment cost of the BTK railway line was planned as 422 million USD for reconstruction works and 178 million USD for new construction costs. The expected freight volume of the railway line is 6.5 million tones, and the passenger volume is 1 million.

Table 4.1: List showing ERTMS - ALSN transition requirements for routes A, B, C and D (Cheotsov et al., 2013)

Route A	Route B1	Route B2	Route B3	Route C1.1	Route C1.2	Route C2.1	Route C2.2	Route D
Poland (ERTMS) ↑↓	Poland (ERTMS) ↑↓	Poland (ERTMS) ↑↓	Poland (ERTMS) ↑↓	Slovakia (ERTMS)	Slovakia (ERTMS)	Slovakia (ERTMS) ↑↓	Slovakia (ERTMS) ↑↓	Poland (ERTMS) ↑↓
Ukraine (ALSN)	Ukraine (ALSN)	Ukraine (ALSN)	Ukraine (ALSN)	Hungary (ERTMS)	Hungary (ERTMS)	Ukraine (ALSN) ↑↓	Ukraine (ALSN) ↑↓	Ukraine (ALSN) ↑↓
Belarus (ALSN)	Belarus (ALSN)	Belarus (ALSN)	Belarus (ALSN)	Romania (ERTMS) ↑↓	Romania (ERTMS)	Russia (ALSN)	Russia (ALSN)	Belarus (ALSN)
Russia (ALSN)	Russia (ALSN)	Russia (ALSN)	Russia (ALSN)	Georgia (ALSN)	Bulgaria (ERTMS)	Azerbaijan (ALSN)	Azerbaijan (ALSN)	Russia (ALSN)
	China (CTCS)	Kazakhstan (ALSN)	Mongolia (ALSN)	Azerbaijan (ALSN)	Turkey (ERTMS) ↑↓	Water Transport	Water Transport	Kazakhstan (ALSN)
		China (CTCS)	China (CTCS)	Water Transport	Armenia (ALSN) ↑↓	Turkmenistan (ALSN)	Kazakhstan (ALSN)	China (CTCS)
				Turkmenistan (ALSN)	Georgia (ALSN)	Uzbekistan (ALSN)	China (CTCS)	
				Uzbekistan (ALSN)	Azerbaijan (ALSN)	Kazakhstan (ALSN)		
				Kazakhstan (ALSN)	Water Transport	China (CTCS)		
				China (CTCS)	Turkmenistan (ALSN)			
					Uzbekistan (ALSN)			
					Kazakhstan (ALSN)			
					China (CTCS)			

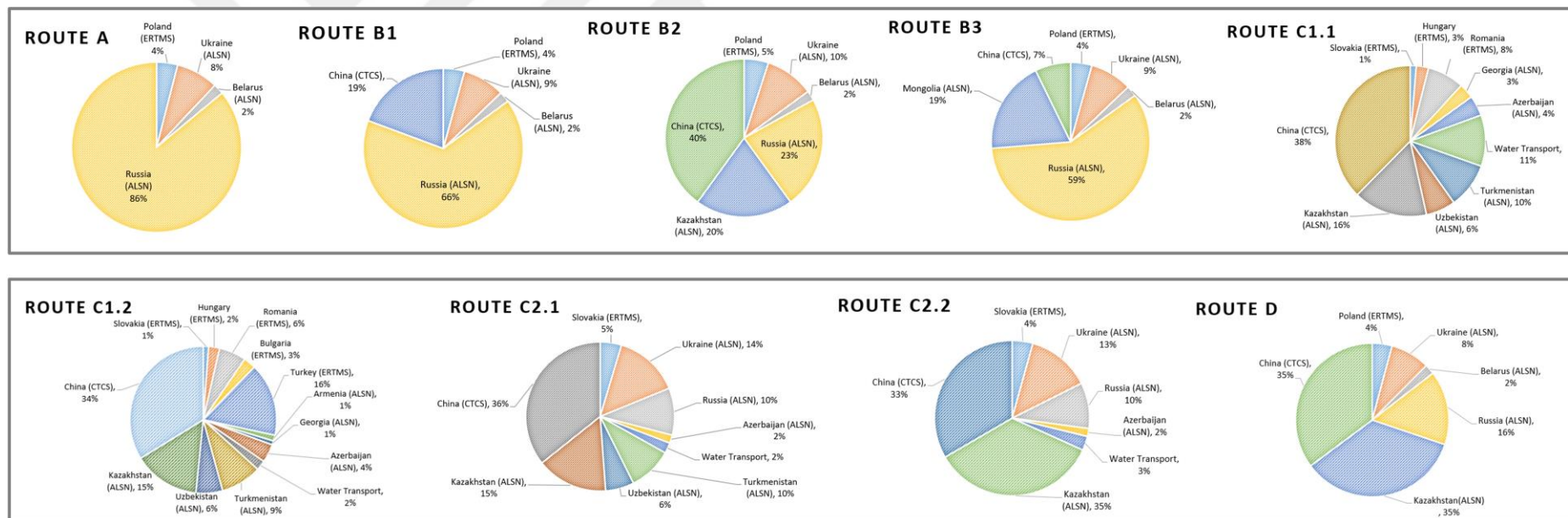


Figure 4.4: Charts showing the percentages of signalling system along the routes A, B, C and D (Cheotsov et al., 2013)

The investment includes the new construction of a 73 km-long railway line connection between Georgia and Turkey and a 29 km-long railway line in Georgia as well as the rehabilitation of the Akhalkalaki – Tiflis railway line (Üzümcü & Akdeniz, 2014). The works also included the reconstruction of the Baku – Böyük Kesik railway line. The works on the BTK railway line started in 2009 and opened to operation in 2017(Özpay, 2018). Since the railway line's opening, Turkish authorities declared that 2 million 405 thousand tonnes of freight had been carried through the BTK railway line. The transportation of goods from Asia to Europe has dropped to 15 days. The aim is to reach 17 million tonnes of freight by 2035 (TRT Haber, 2023).

As indicated, the BTK railway line passes through Turkey, Georgia and Azerbaijan as part of the main international route. Turkey's railway lines have a 1435 mm railway gauge. The adopted signalling system is ERTMS. Azerbaijan and Georgia's railway lines have 1520 mm railway gauge, and the adopted signalling system is ALSN. Azerbaijan has renewed the connecting railway section's electrification to 25 kV AC; however, Georgia's section is still under operation with 3 kV DC electrification. Turkey's connecting railway line between Kars – Çıldır tunnel is non-electrified. The interoperability between Turkey, Georgia and Azerbaijan is very low, considering track gauge, signalling system and electrification status. To overcome these barriers, the authorities envisaged special facilities at border crossings. There is an AC-DC changing facility in Böyük Kesik, where Azerbaijan's railway line connects to Georgia, and an automatic track gauge changing facility at Akhalkalaki station in Georgia before entering Turkey. These facilities improve the train operation in borders. The AC-DC changing facility improves the movement between Georgia and Azerbaijan. Azerbaijan has also procured Stadler locomotives that can operate with AC and DC electrification. The automatic track gauge changing station improves the movement between Georgia and Turkey. The special wheelsets can pass through this specific station where the train moves from 1520 mm to 1435 mm or vice versa. The issues of track gauge and electrification have been improved with these facilities. However, there is no attempt to improve the incompatibility of signalling systems, namely; ERTMS and ALSN. Considering that the proposed method ALSN STM will improve the train movement along BTK and increase the volume of freight and passenger trains by decreasing the cost and time spent on border crossing. ALSN STM will contribute to lowering the barriers faced in border crossing and increase the

competitiveness of BTK railway. Thus, it will contribute to the target of 2035, which is 17 million tonnes. The railway shall be competitive to attract volume from other modes of transport such as road and air. Compared to other alternative international roads, the corridor's attractiveness needs to be increased. The railway shall be competitive to attract the modal split from other modes of transport in the existing route and to attract freight movement from alternative international corridors. As explained in the former sections, interoperability is important to achieve the referred attractiveness. This study focuses on signalling interoperability and identifies an international corridor where signalling interoperability or an attempt to ameliorate cross-border operation in terms of signalling is neglected. The financial implications of such neglect could be predicted by comparison. There are similar cross-border issues in Europe, and the financial implications were studied.

The München – Verona railway line over the Brenner Pass is part of the Scandinavian-Mediterranean Core Network and Rail Freight Corridor 3, and it connects Italy, Austria and Germany. The Brenner action plan was initiated as a plan for a modal shift from road transportation to railway transportation for 2009 - 2022. The plan aimed to increase the attractiveness of cross-border railway operation between the München – Verona railway line. There are certain interoperability issues along this railway line. The railway section between Verona – Brennero is 3kV DC electrified, and the Brennero – Munich section is 15kV AC electrified. There are three different signalling systems along the section. The section on Italy has a command-and-control system called SCMT, the section on Austria has ERTMS, and the section on Germany has a PZB signalling system (ERA, 2022). These are the major issues that impose hardships on cross-border operations. The problems that were faced on this line are very similar to the problems faced on the BTK railway line. The European Union Agency for Railways's (ERA) report on cross-border rail transport potential identifies a couple of issues and their financial implications. The issues identified are as follows(ERA, 2022);

- Train braking rules and documents
 - Time Lost per train: 20 minutes
 - Cost Spent per train: 66 – 100 EURO
- Technical checks at border stations and mandatory checks

- Time Lost per train: 30 minutes
- Cost Spent per train: 86 – 122 EURO
- Real-time communication
 - Time Lost per train: 116 minutes
 - Cost Spent per train: 258 - 313 EURO
- New train number
- Two people cabin crew
- Equipment of border stations with commutable electric power supply
- Restriction for the train length (and/or weight)

Among the identified issues, “train braking rules and documents” and “real-time communication” issues can be resolved or minimised with the help of a harmonised signalling system and standardisation of rail operator’s cross-border operations. According to ERA, due to these issues, the München – Verona railway line cross-border operation is losing 399 minutes per train at each border crossing. The financial implication of this loss is approximately 470 EURO per train. The annual loss of only these issues was calculated as 10.5 million EURO. EU has decided to invest in this railway line with a new alternative to the 55 km long Brenner Base Tunnel, with ERTMS signalling and 25kV and 15kV AC electrification. This decision proves that the countries are willing to invest in major infrastructure projects to increase the competitiveness of the international corridors’ border crossings. The implications on the BTK railway line would be higher than The München – Verona railway line since the BTK railway line is located in the middle of the international corridor connecting Europe to Asia.

The example of the München – Verona railway line is provided to make a similar projection in the context of the BTK railway line. The BTK railway line is utilised as an example of the ERTMS – ALSN transition. As indicated in these examples, it is clear that the proposed ALSN STM is crucial for international railway operations, and it has great potential to save billions of EUROS each year for the economy. In addition to cost savings, it promises to attract freight and passengers from other modes of transport, such as road, air and seaways. This means ALSN STM greatly impacts social and economic development, which can promote peace and prosperity in the world.



5. CONCLUSION

As the introduction indicates, the ALSN system is categorised under Group 3 train protection group, whereas ERTMS Level 1 is grouped under Group 4. The ALSN signalling system enables continuous cab signalling with braking supervision; however, ERTMS signalling is more advanced with the spot transmission system for location reference and enriched data informing the track status and dynamic speed supervision. ERTMS signalling is more advanced and standardised than the ALSN signalling system. These two systems are major operational signalling systems in the World.

The literature review performed in this research indicated that more research and development efforts are available for ERTMS. However, the academic interest and research are comparably low for ALSN. The open access standards and requirements of ERTMS can explain the main reason behind this gap. The standards and requirements of the ALSN signalling system are not publicly available and not organised as ERTMS. The academic research in both systems is categorised as modelling, optimisation and issues & problems. For the ERTMS system, modelling attracts more attention than optimisation and issues & problems are more focused on implementation. For the ALSN system, the optimisation attracted more attention than modelling and issues & problems referred to operation. The literature on ALSN is trying to address the issues regarding ALSN code distortions and interferences. The weakness of ALSN is the lack of standardisation, RAMS target values and vulnerabilities towards interferences. On the other hand, the disadvantage of ERTMS is the process of transition from a national signalling system to ERTMS. It has its own hardships, considering the required investments, training etc. Even Europe could not finalise the transition from each member country's legacy signalling system to ERTMS. To facilitate the transition period, ERTMS proposes a solution as one of its operational levels: Level STM. This level enables the integration of a module to be able to operate in another signalling system's trackside. It is reviewed that although ALSN is defined in ERTMS specifications as a Class B train protection system, there is no STM defined for ALSN. Considering the fact that international corridors connecting Europe to Asia require cross-border transition and train operation of ALSN, the proposition of ALSN STM appears as a need. A train that is carrying either

goods or passengers shall transition from ERTMS to ALSN to CTCS when travelling from Europe to Asia. Thus, a novel proposition of ALSN STM proposes signalling interoperability between countries that employ ALSN and ERTMS. The main purpose is to enable the operation of a train with the ETCS onboard in a railway line where the ALSN trackside is operational.

To propose an ALSN STM, every component of both of the signalling systems is analysed; on-board and trackside. The sub-components of on-board and trackside are also identified and their interrelation is presented. To understand the concept of signalling interoperability, the technical specifications for interoperability are analysed for control command signalling. The analysis showed that for the development of ALSN STM, system requirements and the definition of a new interface are needed. To identify this information, a requirement analysis is performed. Later on, the conceptual framework is drawn for the system requirement specification of the newly proposed ALSN STM. The module receives the input as ALSN codes and decodes the data received. The decoded message is matched with the telegram database in the module, and the digital telegram is generated by the module. The module has a newly defined interface called the “E” interface that is directly connected to the FPGA board of the BTM. The conceptual framework of ALSN STM is developed with the construction of this framework.

The applicable international railway corridors are identified. The proposed ALSN STM would be used in nine different international corridors since all of them require a transition from ERTMS to ALSN or vice versa. The majority of the railway network is operated by either ERTMS or ALSN. The financial implications are also attempted to be projected. The example of the Baku – Tbilisi – Kars railway line is analysed in terms of cross-border train operation compatibility and a financial projection is made with the study performed by ERA.

As a result of this research, a new ALSN STM framework is proposed. The conceptual system requirement and interface are defined. This method’s contributions to seamless train operation across continents and international freight transport as well as the economy are underlined. As this study is the first step towards ALSN STM, further studies are required to perform an in-depth financial contribution to the country’s economy and the increase in railway line attractiveness in terms of modal split and alternative railway corridors. To identify more on the ALSN STM equipment itself,

more technical studies are also needed for the modelling of ALSN STM. The future studies may focus on the integration methodology with the FPGA board of BTM, modelling ALSN STM with UML, State Charts, Petri Nets or Markov Chains, and constructing a library of digital telegram to be matched with ALSN codes while classifying additional degraded mode of operations.





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CURRICULUM VITAE

Name Surname : Çağla Kivılcım Çiftcioğlu

EDUCATION :

- **B.Sc.** : 2015, Bilkent University, Engineering Faculty, Electrical and Electronics Engineering Department
- **M.Sc.** : 2017, University of Surrey, Faculty of Arts and Social Sciences, International Business Management Department

PROFESSIONAL EXPERIENCE AND REWARDS:

- 2014 – Present : PROYAPI Engineering and Consultancy Inc.
- 2016 – 2018: Burdur - Antalya High Speed Railway Line Design Services (238 km)
- 2018 – 2022: Bilaceri - Yalama Railway Line Rehabilitation Works Design Services and Engineering Consultancy - Azerbaijan (192 km)
- 2018 – 2022: Alat - Osmanlı - Qasımlı - Astara Railway Line Rehabilitation Works Design Services and Engineering Consultancy- Azerbaijan (254 km)
- 2023 - Present: Halkalı - Ispartakule High Speed Railway Line Design Services (8 km with 7 km long twin tube tunnel)
- 2023 - Present: Ispartakule - Çerkezköy High Speed Railway Line Design Services (66 km)

PUBLICATIONS, PRESENTATIONS AND PATENTS ON THE THESIS:

- **Çağla Kivılcım Çiftcioğlu, Mehmet Turan Soylemez** 2023: On The Trail of West – East Signalling Interoperability: A Novel Proposal for STM and an Interface Proposal for ETCS Onboard Operations on Class B Trackside Signalling Systems. (14th INTERNATIONAL CONFERENCE on ELECTRICAL and ELECTRONICS ENGINEERING, Turkey)
- **Çağla Kivılcım Çiftcioğlu** 2023. ETCS level operation and interrelations between ETCS infrastructure and ETCS on-board components (12th B&H CONGRESS ON TRANSPORT INFRASTRUCTURE AND TRANSPORT, Bosnia and Herzegovina)

OTHER PUBLICATIONS, PRESENTATIONS AND PATENTS:

- **Çağla Kivılcım Kuru** 2016 Internationalization of SMEs: Target Country Selection of Turkish Born-Global Design and Engineering Firms

