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D2.10 Data gathering and analysis of current ERTMS systems

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Further information, deliverables references and cooperating projects:

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Abbreviations and acronyms

Abbreviation / Acronym	Description
AI	Artificial Intelligence
AF	Application Framework
ATP	Automatic Train Protection
ATO	Automatic Train Operation
ATO-OBU	Automatic Train Operation - On Board Unit
ATO-TRK	Automatic Train Operation - Trackside Unit
BTM	Balise Transmission Module
CMD	Common Data Model
DMI	Driver Machine Interface
ETCS	European Train Control System
ERTMS	European Rail Traffic Management System
EU	European Union
EU-Rail	Europe's Rail Joint Undertaking
FRMCS	Future Railway Mobile Communication System
GoA	Grade of Automation
GSM-R	Global System for Mobile Communications – Railway
HTD	Hybrid Train Detection
ICT	Information and Communication Technology
IL	Integration Layer
IoT	Internet of Things
JU	Joint Undertaking
MA	Movement Authority
OBU	On Board Unit
OPTIMA	Operational Platform Testbed for Integrated Mobility Applications (name of a project)
RBC	Radio Block Centre
S2R JU	Shift2Rail Joint Undertaking
TMS	Traffic Management System
TIMS	Train Integrity Monitoring System

Executive Summary

The objective of this deliverable is to provide a comprehensive analysis of the current state-of-the-art of the European Railway Traffic Management System (ERTMS), its implementations, and the progress of research in this domain, highlighting open issues and challenges while describing possible directions for improvement and the technologies that promise the most significant enhancements. The task was carried out as a systematic literature review, following PRISMA guidelines, with queries performed on Web of Science, Scopus, and Google Scholar using the search string "Railway Traffic Management System AND (AI OR Digital Technologies)". After applying exclusion criteria based on publication year, number of citations, language, and a full-text review, 106 papers were selected for in-depth analysis and classification into five macro-areas: Safety, Optimization, Quality of Service, Automation, and Networks.

The analysis reveals that Safety is the most discussed research topic, with 33 papers (31.13% of the total), focusing on anomaly detection, predictive maintenance, digital twins, and risk assessment using artificial intelligence. Optimization follows closely with 40 papers (37.73%), addressing train rescheduling, traffic control, trajectory optimization, and digitalization of core ERTMS components. Quality of Service accounts for 14 papers (13.20%), primarily investigating passenger flow prediction, delay forecasting, and passenger Internet connectivity. Networks also represent 14 papers (13.20%), covering train-to-ground communication performance, intrusion detection systems, blockchain-based security, and train-to-train communication. Automation is the least represented area with only 5 papers (4.71%), focusing on Automatic Train Operation enhancement through AI and cloud-based architectures.

The most cited papers in the corpus demonstrate that Quality of Service topics receive the highest average citations, followed by Safety and Optimization. Notably, only two papers exceed 100 citations, both employing artificial intelligence for defect detection and delay prediction. The analysis identifies several critical gaps in current research, including limited work on train positioning systems, insufficient exploration of virtualization and cloud-edge computing architectures for hosting AI applications, scarce research on passenger connectivity enhancement, and underdeveloped train-to-train communication solutions. These gaps represent opportunities for future research, particularly for enabling higher Grades of Automation and improving the attractiveness of railway transportation. The findings of this deliverable directly inform the continuation of PhD10 activities, which will focus on real-time anomaly detection for train positioning systems, machine learning-based energy consumption estimation, and hybrid virtualized architectures for next-generation ERTMS.

1 Objective/Aim

The objective of this deliverable is to provide an analysis of the current state-of-the-art of ERTMS, its implementation and the progress of research in this topic, highlighting their open issues and challenges, and describing possible directions of improvement of the system and the technologies that candidate to introduce the most promising enhancements. The task has been carried out as a systematic literature review. Proposals, implementations, and direction in research for railway traffic management systems have been gathered, analysed and classified, identifying the main trends in research and the open issues that need to be addressed, leaving space for advanced applications and functions.

2 Background

The PhDs EU-Rail project aims to foster collaboration and innovation in the European railway sector by consolidating a scientific community and conducting research through 10 PhD positions. The project is closely aligned with the goals of the EU-RAIL Joint Undertaking (EU-Rail) and the involved industry partners. The research topics cover a range of areas, such as supporting the implementation of rail technical innovations for decarbonization, promoting gender equality in the rail industry, exploring new education and training methods, enabling rail-based urban logistics, improving fast night train operations, studying the dynamic stability of trains over bridges, enhancing safety-relevant communication in the railway system, calculating societal KPIs of rail research programs, the railway inclusion and accessibility for individuals with intellectual disability and ICT platforms for interoperable and reliable ERTMS systems.

The present deliverable D2.10 *Data gathering and analysis of current ERTMS systems* provides information about the current state of the research in ERTMS. Main trends in research and open issues have been highlighted. The different technologies proposed in research have been analyzed, deepening how they can help in overcoming the current limitations of ERTMS.

Three of the most wide databases have been interrogated to retrieve articles, papers and other document regarding Artificial Intelligence and Digital technologies applied to Railway Traffic Management systems. The works so obtained have been filtered first for relevance and age. Then, a full text review has been performed to select the works more relevant in the area.

The rest of the document is organized as follows:

- Section 3 presents an introduction of the ERTMS and the impact that digitalisation can have on it.
- Section 4 describes the methodology that has been followed to extract and select relevan works, and an overview of research trends. Articles and Journals have been organized and splitted into macro areas.
- Section 5 shows the results of the analysis, highlithing the most relevant contribution for each of the identified macro area
- Section 6 discuss the research trends and current gaps

3 Introduction

The purpose of PhD10 is to study the current evolutions of the ICT platforms for the next generation ERTMS. In this phase of the project, a study on the current state of the art of research in railway traffic management systems has been carried out to identify the main trends and the most interesting technologies explored so far to promote innovation in this field.

The possibility of passengers traveling and the necessity of industries to exchange goods have become a push for more efficient railway connectivity. Furthermore, the sustainability policies supported by developed countries are reviving interest in railway, being this the best transportation mode if emissions of polluting gas and quantity of passengers and goods it can carry are considered.

The reply of the European Union to this situation is the introduction of the European Railway Traffic Management System (ERTMS) as a uniform, standard railway traffic management system suitable to promote interoperability among railways of different countries. However, ERTMS is still evolving and the objective of its different levels of implementation is to introduce new features and functionalities to support the evolution of railway transportation.

Many projects have arisen in Europe to further push innovation in this domain, and many proposals have been put forward to support the development of the railway industry. The purpose of this deliverable is to deepen and summarize the state-of-the-art of research on ICT platforms for ERTMS and Railway Traffic Management Systems in general, with the aim of highlighting the most discussed challenges and issues and the research solutions proposed to solve them.

To address this topic, a systematic literature review has been carried out. Some of the most widely used databases have been queried to find publications about the described topic and the collected documents have been deeply analized based on the problem they try to solve and the used technologies.

3.1 Overview of ERTMS

The European Railway Traffic Management System is nowadays used in many European countries. It has been designed to promote interoperability among different heterogeneous R-TMSs, and to improve the efficiency of international railway travels for both passengers and freight. Since ERTMS is widely adopted, currently the main objective is to enhance it, creating a R-TMS that, beside promoting interoperability, is able to make travels faster, more comfortable, and less expensive for the end user. This can allow to satisfy the growing requests of international exchange of passengers and freight while avoiding increasing emissions as for air and road traffic. Indeed, nowadays ERTMS is still evolving, proposing, for instance, new methods to support continuous communication between train and ground station, ways to better allocate the railway capacity based on the concept of moving blocks, and exploring new technologies able to support the digital transformation and close the gap with other sectors such as automotive and aviation. Furthermore, the digital technologies that are possible to deploy can involve several aspects affecting the same system.

In the last few years, many research topics have been explored through several Joint Undertakings (Shift2Rail [1], EU-Rail [2]) and some flagship projects such as MOTIONAL [3], R2DATO [4], RAIL4EARTH [5]. These initiatives fed the research on innovative solutions in railway to improve efficiency, safety, and security, with the purpose of delivering a better service for passengers and freight. Indeed, innovation in transportation means applying cutting-edge digital technologies to deploy Intelligent Transportation Systems (ITSs) able to make autonomous decisions and automate processes for improving system efficiency and safety. According to this paradigm, the TMS must become increasingly complex, able to deal autonomously with a wide set of problems while keeping, at the same time, safety standards on high level. Thus, it is important to gather all the relevant works in this domain to navigate the complexity of the topic and eventually find gaps in research in order to provide a vision of the possible activities for the next few years in the field.

Furthermore, a special consideration is applied to Artificial Intelligence (AI), which is pervasive in any field, particularly when it comes to process optimization and automation.

The methodology used to retrieve and classify the most relevant works in the section is described in the next section.

4 Methods

The search strategy to gather the research papers is based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, and involved queries to some of the most important and wide databases. Particularly, for this case study, *Web Of Science*, *Scopus*, and *Google Scholar* were considered. The query runs on these databases is: *Railway Traffic Management System* ***AND*** *(AI* ***OR*** *Digital Technologies)*. The results were filtered based on language and document type, year, number of citations, age, and, finally, a full-text review. The study selection is further explained in Chapter 4.1.

4.1 Study Selection

Overall, 447 papers have been selected from the queries on the mentioned databases. A first filter to neglect duplicates and non-English papers has been applied. Afterward, a relevance analysis has been conducted, excluding old papers (publication prior year 2015), nowadays out of date given the rapid progress in ICT and being the survey focused on the latest research trends, and papers with less than three citations. An exception has been made for the papers with a publication year > 2022, which might not yet have had enough time to be cited. Summarizing, these were the exclusion criteria:

- Publication year < 2015
- Number of citations < 3 AND publication year < 2022

After the screening phases, 314 papers were selected that are either recent (published in 2022 or later) or are older (published between 2015 and 2021) but have at least three citations.

After that, a full text review has been carried out and, finally, 106 papers have been selected. These papers will be the basis to extract data and statistics useful to understand the current research direction and to feed the analysis of the main promising and deepened trends, how the focus is changing throughout the years, and whether there are areas not covered yet. The papers have been classified by areas such as: safety, optimization, Quality of Service, Automation and Networking, and the analysed based on the proposed approach.

4.2 Data Extraction

The first analysis is focused on the distribution of the publications over the years, to highlight the trend of the research interest in the evolution of ERTMS systems. The results are illustrated in Figure 1.

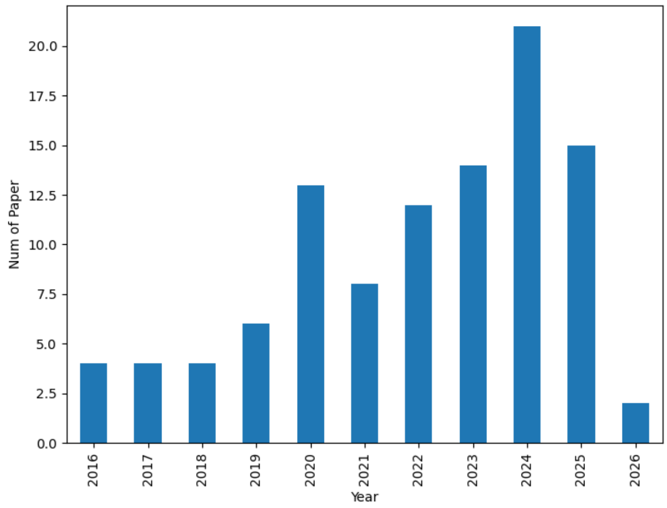

Figure 1 Number of selected papers per year

In the year 2020, there was a sharp increase in published papers. Notice that the 31st of December 2021 (originally 2020, then extended), the Shift2Rail Joint Undertaking (S2R JU) [1], part of the Horizon 2020 program, ended, contributing thus to the increase of works published in the last phase of the projects founded during this framework. A significant decrease in publications appears in 2021 compared with the previous year, possibly due to the slowdown of both industry and the academia during the COVID pandemic. On the other hand, in the years between 2016 and 2019, the publications included in the analysis are less than half compared them with the period after 2022, showing how only a few articles on this topic manage to gain recognition.

The distribution of publications among journals, conferences, and theses is shown in Figure 2.

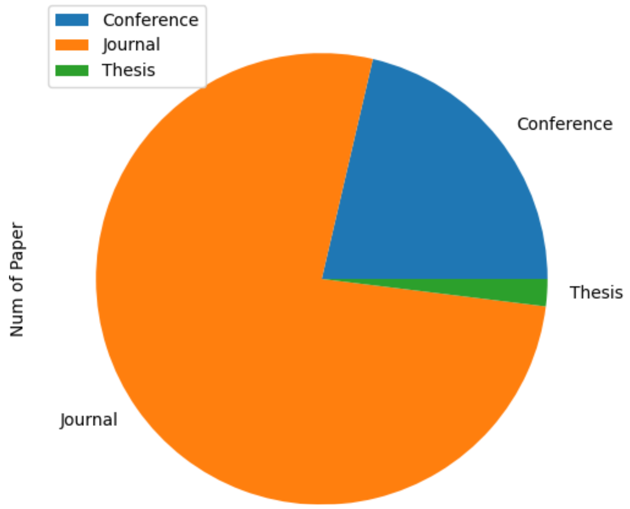

Figure 2 Publication type: Conference papers, Journal articles, Theses

Most of the documents are published in journals, although there is a consistent fraction of conference papers. Two works are instead theses, both published in 2016.

After the review and analysis of the articles' content, some major areas of study within the railway domain have been identified, which are classified as follows:

- **Automation**: the works focused on the automation of rail operations, particularly on Automatic Train Operation (ATO) related to ERTMS, or on enhancing the capabilities of R-TMS to run several automated tasks.

- **Network**: the works focused on the improvement of the connectivity Train - Ground Station. Particularly, up to now, in ERTMS GSM-R is used, which is based on 2G technologies, but currently the objective of railway industry for the next generaio ERTMS is to switch to Future Rail Mobile Communication System (FRMCS), based on 5G technologies.
- **Optimization**: the works focused on reducing operational costs, enhancing the capacity of the railway lines, or optimizing the train schedules also in real-time.
- **Quality of Service**: the works focused on solutions aiming at improving the experience of the users.
- **Safety**: the works with the goal to improve the passenger safety or increase the railway systems dependability .

However, it is important to notice that those areas are not mutually exclusive. In some cases, the difference between one area and the other can be subtle, and a work can cover more than one domain. Anyway, for the ease of reading, whenever an article can fit two or more areas, the best fit according to the performed analysis has been chosen.

The papers organized for each topic are summarized in Table 1, where are reported the number of papers for each topic, their bibliographic information, and the related share with respect to the total amount of selected papers. This allows to highlight the sectors with a greater interest of the academic and industrial communities, such as Safety and Optimization, which occupy the greater shares of works

Table 1 Classification on the papers by topic

Main Topic	Num	References	Total shares
Automation	5	[21], [18], [11], [82], [30]	4.71%
Optimization	40	[45], [23], [51], [91], [34], [13], [14], [67], [80], [77], [110], [94], [58], [16], [55], [68], [52], [83], [104], [59], [99], [89], [65], [86], [109], [96], [28], [54], [15], [17], [26], [60], [35], [61], [42],[72],[31], [98], [85], [84]	37.73%
Network	14	[103], [25], [12], [37], [49], [100], [29], [73], [95], [74], [111], [50], [20], [106]	13.20%
Safety	33	[97],[79], [87], [78], [24], [7], [70], [9], [92], [53], [108], [40], [6], [105], [63], [102], [69], [47], [48], [93], [8], [62], [101], [90], [88], [43], [81], [32], [27], [76],[71], [19], [56]	31.13%
Quality of Service	14	[107], [10], [66], [75], [57], [44], [39], [22], [64], [46], [33], [41], [38], [36]	13.20%

From Table 1, it emerges that one of the most discussed research topics related to digitalization and AI in R-TMS is safety. Railways, indeed, being a critical system, must guarantee the highest safety standards. Thus, it is not surprising that a high portion of research documents focus on how to deploy new digital technologies to improve the dependability of the system, deploying for instance mechanisms of monitoring and predictive maintenance. Optimization is the other relevant topic for the railway industry: to reduce the costs and allow greater railway capacity, it is necessary to optimize the line allocation and the trains schedule. Also, trajectory optimization to reduce braking and accelerations are crucial process to reduce cost and energy consumption.

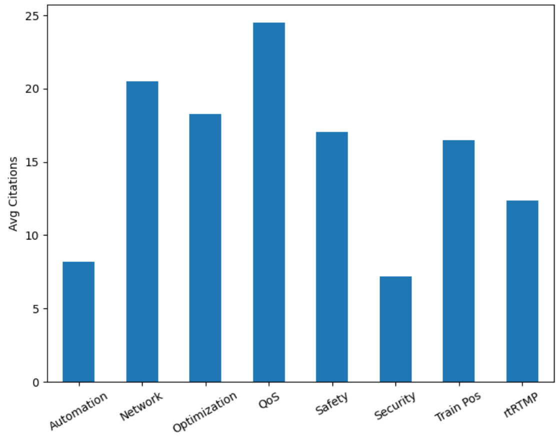

Figure 3 Average number of citations per Main Topic

To deepen this analysis, in Figure 3 the average number of citations per topic is illustrated: the publications related to the Quality of Service are the most relevant in research, having a higher number of citations, demonstrating the interest of the academic community.

To further extend this analysis, the top ten most cited papers are listed in Table 2. : only two papers have more than 100 citations. Both use AI, although in different ways.

No paper regarding automation and network is present in Table 2, while two of the first three papers regard Quality of Service, proposing methods for predict train delays and predict passengers' flow. This is not surprising since it has been assessed that this topic is the most cited on average, whereas automation and network were the less cited arguments. The other papers in the list deal with Safety (three out of ten) and Optimization (four out of ten), assessing the high interest if academy and industries in those topic too.

Table 2 Most cited articles.

Title	Citations	Area
Real-time detection system for rail sur Face defects based on machine vision [69]	138	Safety
Stochastic prediction of train delays in Real-time using bayesian networks [46]	129	QoS
Multi-graph convolutional-recurrent Neural network (mgc-rnn) for short- term forecasting of transit passenger flow [39]	86	QoS
Digital twins for anomaly detection in the industrial internet of things: conceptual architecture and proof-of- concept [27]	84	Safety
Train trajectory optimization for improved on-time arrival under parametric uncertainty [99]	70	Optimization

Communication-based train control system performance optimization using deep reinforcement learning [110]	66	Optimization
Blockchain-enabled virtual coupling of automatic train operation fitted main- line trains for railway traffic conflict control [72]	57	Optimization
Deep learning for short-term origin-destination passenger flow prediction under partial observability in urban railway systems [44]	57	QoS
A deep learning approach towards railway safety risk assessment [7]	48	Safety
Deep deterministic policy gradient for high-speed train trajectory optimization [77]	45	Optimization

5 Results: analysis of the main areas of research interest

5.1 Safety

Safety is one of the most important topics in the context of railway systems. Indeed, as explained above, many of the recent applications of digital technologies concern improving passenger safety. In Table 3, the different works on Safety applications are showed, grouped by their aim, and the proposed methodology to reach their objective.

Table 3 Classification of works on Safety

Aim	Methods	Articles	Oldest	Newest
Anomaly detection and predictive maintenance	AI	[47], [97], [6], [69], [43], [63]	2023	2026
Anomaly detection and predictive maintenance	AI/ Cloudification	[105]	2021	
Anomaly detection and predictive maintenance	AI/ Data Analysis	[24], [40], [8], [9], [102], [70], [62], [87], [53], [93], [101], [71]	2020	2025
Passenger Evacuation	AI	[90]	2022	
Railway systems modeling	AI	[79]	2025	
Railway systems modeling	Optimization /Modeling	[78]	2025	
Risk assessment	AI	[7], [92], [48]	2020	2024
System Monitoring	AI/ Digital Twin	[27], [88], [76], [32], [108], [81]	2023	2024
Improvement of Train Positioning	AI	[19], [56]	2017	2022

One of the most faced challenges in railway systems by researches, is how to deploy anomaly detection and predictive maintenance. These methods leverage AI to improve safety and reduce maintenance costs. In particular, anomaly detection aims to spot possible misbehaviour of the system before a failure happens, allowing for taking countermeasures. On the other hand, predictive maintenance estimates the wear of components, allowing timing maintenance, repairing, or substituting components before they have a negative effect on the whole system, but not too early which would increase maintenance costs. Many research study propose AI algorithms to face these problems ([47], [97], [6],[69], [43],[63]). For instance, in [6], the authors propose a text analysis algorithm trough unsupervised learning to gain valuable information of previous accident, such as root couse, and helping in anticipating future ones. [69] and [47] proposed both algorithms to detect defects based on image recognition. Particularly, in [47] images are captured and features extracted. Those features are then used to feed an AI model to recognize rail defects more quickly. Instead, [69] uses computer vision to gather and analyse images of the rail surface. Both methods show promising results, although while the first is specifically designed for rail fastner, the second one shows a grater capability for generalize rail surface defects.

Some other articles propose to couple different AI algorithms with different Data Analysis techniques such as data fusion to improve the performance of the models of different systems ([24], [40], [8], [9], [102], [70], [62], [87], [53], [93], [101], [71]).

The monitoring of the system through the usage of Digital Twin (DT) is another problem that is currently under investigation by researches. A DT is a digital copy of a physical system, in this case, a Train. The difficulty of deploying a DT is considering all the interactions the physical system has with the external environment and properly modeling the response on a digital copy. Capturing all these interactions might be unfeasible; therefore, Digital Twin solutions are often coupled with AI. One of the most relevant works is shown in [27]. Here, the authors argue that the Industrial Internet of Things (IIoT) is an approach that is bringing an enormous number of benefits to different industries. At the same time, , as the complexity grows, the probability of failures is growing as well . To cope with that problem, an anomaly detection architecture for IIoT is proposed and discussed within the scenario of ERTMS. A Digital Twin is proposed, representing the real-environment in a virtualized way, and it is coupled with K-Nearest-Neighbour (KNN) algorithm to assist in anomaly detection. This solution allows easy monitoring on the virtual reprensentation of trains, enhanced by artificial intelligence to anticipate possible faults.

5.2 Optimization

This chapter contains all the papers aiming at improving railway efficiency. The selected papers on this topic are summarized in Table 4. One of the most explored problems is train rescheduling. The main reasons why a train might be rescheduled is due to a disruptive event that can cause propagation of delays: a fault of a train can lead to a cascade of delays. To avoid this propagation a reschedule of the train on the flight is necessary. Many articles propose AI to solve this problem ([28], [109], [54], [35], [26], [96]), but statistical methods are used as well, such as in [17], [61], [42], [86], [89]. One of the most relevant article dealing with the rescheduling problem is [47], where the authors propose a Machine Learning (ML) approach to perform root cause analysis of train delay. The authors argue that their model predicts the reason of delays with 83% accuracy, helping in resolving and adjusting the timetable rescheduling.

Traffic control and conflict management are other relevant topics. The focus here is to manage the brake and acceleration of trains to avoid conflicts and optimize punctuality, efficiency, and safety. This is solved in ERTMS through the usage of the Radio Block Center (RBC), which provides Movement Authority (MA). Anyway, this solution is not very efficient: the current RBC implementation is indeed based on the concept of blocks, which is a section of the line that can be either free or occupied. According to this paradigm, a section is occupied until the whole train leaves the block, forcing the following train to slow down or stop, even if it has space ahead to move. The articles analyzed in this work propose to deploy AI approaches, such as Neural Netwokrs [65], Reinforncemente Learning [67] or unsupervised learning [91], to optimize this process.

The topic of optimization is closely related also to trajectory and speed optimization. An algorithm able to compute the best acceleration and braking profile for the train, providing not only a speed limit but also a suggested speed has the potential to strongly reduce the cost of a single ride by reducing the energy required. In [110] for instance, an AI-based method to reduce energy consumption is proposed. The AI method is based on reinforcement learning, and safety rules are applied to ensure that no dangerous operation is proposed by the AI model. Some other article uses other formalisms, such as in [99]. Here the author proposes to formulate the optimization problem as a Markov decision process to determine energy-efficient driving strategies. AI can be used for the energy consumption estimations, as deepened in [114], where a method based on linear regression is proposed.

While all the aforementioned works propose solutions and algorithms to improve the optimization of trains run and schedule, some other works focus on creating a computing architecture able to host complex AI algorithms. The authors that focuses on this topic propose a Multi-Agent System and Cloud Computing ([58], [16], [13], [14], [60], [15]) to face this challenge, suggesting distributed architectures, dividing the responsibility of certain tasks among several Intelligent Agents, a software able to intercat with irs environment and taking action accordingly. To support this paradigm switch, also digitalization of railway components has been explored as solution ([83], [80], [98], [85], [84], [112], [113]). In [80] for instance, the authors suggest a digital interlocking, arguing that, accordingly with their findings, it can help in speed up the processes it manages. In the same direction, in [84] and [85], the authors proposed to use Network Function Virtualization and Cloud computing for deploying the future ERTMS. Those architectural choices can provide the next generation railway traffic management system with greater flexibility, scalability and interoperability thanks to the property of virtualization and cloud computing, that allows for a fast deployment and enhanced reliability thanks to the possibility of quickly allocate new resources when needed, or moving virtual component across different physical machines.

Table 4 Classification of works on Optimization

Aim	Methods	Articles	Oldest	Last Year
Real-Time monitoring of the stations for security and crowd management	AI	[23]	2025	
Real-Time rescheduling after a disruptive event	AI	[28], [109], [54], [35], [26], [96]	2016	2025
Real-Time rescheduling after a disruptive event or based on passenger flow	Statistical Methods	[17], [61], [42], [86], [89]	2017	2024
Traffic control and conflict management	AI	[68], [67], [91], [34], [104], [65]	2020	2025
Conflict Management	Blockchain	[72]	2022	
Optimize train trajectories and reduce time and energy consumption	AI	[110], [77], [55], [45], [51], [94], [114]	2017	2025
Planning Maintenance	Optimization Algorithms	[59]	2016	
Optimize train trajectories and reduce time and energy consumption	Optimization Algorithms	[52],[99], [31]	2020	2024
Manage large-scale AI	AI/ MAS/ Cloudification	[58], [16], [13], [14],	2018	2025

model for a scalable train schedule optimization		[60], [15]		
Improve the performance of core components	Digitalization	[83], [80], [98], [85], [84], [112], [113]	2020	2025

5.3 Quality of Service

The research papers that fall in this area, shown in Table, 5, propose improvements for user experience. Similar to train rescheduling, also in this case, passenger flow prediction is one of the most investigated topics. The purpose of passenger flow prediction, in this case, is to perform crowd regulation, operation management, and support decision-making processes to offer a better service to the passengers. A very interesting work about this topic is [39], where the author proposes a Multi-Graph Convolution Recurrent Neural Network to forecast the passenger flow. Multigraph particularly, means that the Neural Network (NN) is fed with different graphs, each one capturing a different type of relationships among the stations.

Other works focus on predicting the delays ([46], [57]) or improve the punctuality ([36], [66]). All the solution proposed in these works, are based on a strong use of AI to estimate delays based on patterns already seen. Finally, recently, some research has been carried out to improve passenger connectivity to the Internet. Keeping a solid Internet connection is particularly hard in high-speed trains, even if they offer Wi-Fi on board, since the fast movement forces devices to connect to different cells too often. In this case, the used technologies include, but are not limited to, AI to predict and anticipate the moment of the handover (switching the cell the train is connected to provide Internet connectivity). Indeed, the research in [107] and [75] propose to couple AI with Software Defined Networks/Network Function Virtualization (SDN/NFV) over 5G. SDN/NFV provides greater flexibility compared with traditional networks, leveraging the ease of virtual components to be quickly reconfigured. Using this approach, together with AI, allows for a fast handover in high-speed trains. In this way, it would be possible for passengers to experience better connectivity while traveling.

Table 5 Classification of works on Quality of Service

Aim	Methods	Articles	Oldest	Last Year
Enhance the precision of arrival	AI	[36]	2024	
Predict train delay and delay propagation	AI	[46], [57]	2018	2023
Providing advises to minimize effect of disruptive event	AI	[66]	2016	
Predict passenger flow	AI	[39], [44], [10], [33], [41], [64].	2020	2024

		[22], [38]		
Improve passenger connectivity	AI/ SDN/NFV / Protocols	[107], [75]	2024	2024

5.4 Automation

Automation in railways is a crucial topic that has the potential to affect all the aspects seen so far. The research in this area aims to improve the Automatic Train Operation (ATO) component of ERTMS to obtain possibilities of self-driven trains. In this case, most of the research, see Table 6, focuses on building architectures or investigating technologies that have the potential to increase the computational capacity of ERTMS. Among all these, only one work focuses on using AI to improve the capabilities of the ATO component. In [21] the authors propose a deep reinforcement learning algorithm to deploy an intelligent control method for ATO. A Deep Q-Network (DQN) is proposed as learning model to adjust in real-time the train automatic driving strategy based on the train operating state and the environment, showing that the DQN manage to reduce the energy consumption of the train and parking accuracy.

Other works focus on the architectural design of digital platforms to enable automation. In both the works in [11] and [82], the authors argue that digitalization, virtualization and programmability are the key point to design an ICT platform able to support Intelligent Transportation Systems. Those features also enable the possibility of embedding Machine Learning in the virtualized components creating an intelligent railway controller. The possibility of embedding real-time analytics and intelligence in railway components is, indeed, the enabler for higher degree of automation.

Table 6 Classification of works on automatic train operation

Aim	Methods	Articles	Oldest	Last Year
Implementing ATO and improving the punctuality, parking accuracy, and energy saving	AI	[21]	2023	
Enhance the capabilities of R-TMS	Digitalization	[30], [11], [82], [18]	2019	2024

5.5 Networks

The ability of trains to share information with the ground station is a crucial feature to enable a higher degree of automation, improve safety and performance, and reduce costs. A solid and reliable Train-to-Ground connection is vital to provide the Traffic Management System with all the data it needs to make decisions.

As in many other areas and illustrated in Table 7, AI is the most investigated technology to improve network connectivity; however, the problems that researchers are trying to solve are numerous and are referred to both performance and security.

How to improve network performance is one of the most deepened topics. Here, the proposed solutions involve the use of AI to perform the handover of the access point ([37], [12]), spectrum allocation on the radio communication ([103], [49]), and congestion control ([25]).

On the other hand, security in the network is also a crucial aspect to keep in mind to prevent malicious attacks that might affect the safety of the system. The proposals here include the use of AI to boost Intrusion Detection Systems (IDSs) and perform anomaly detection to spot possible attackers or faults on the connections. One of the most interesting work is [20], where the authors leverage adaboost, and ensemble learning method which uses an ensable of week classifier, to spot pattern of attacks and support the IDS, showing how their model is able to recognize more than 96% of attacks. On the other hand, in [29], the authors focus on the attack on the balises, using AI models for intrusion detection, particularly, Multi-Layer Perceptron (MLP), Support Vector Machine (SVM) and Adaptive Neuro Fuzzy Inference System (ANFIS) are used, showing promising results in terms of accuracy.

AI is not the only tool used to improve security, but Blockchain is also considered. The Blockchain can be seen as a distributed, immutable database, where the insertion of new data requires the consent of more than the majority of network resources. This feature is used to ensure confidentiality by managing keys through the immutable blockchain.

Finally, another relevant topic is Train-to-Train (T2T) communication. Currently, the trains cannot communicate directly with each other; however, enabling a connection T2T would allow a more fine-grained control and a better allocation of the line, passing from a fixed block paradigm to a moving block paradigm for the segmentation of the line. Some proposal for T2T communication exists: in [100] the authors propose to use a wireless technology based on LTE and using as metric for the quality of services the Quantized Age of Information (QAoI), meaning the "age" of the data, in order to always obtain the most updated data. Moreover, Q-learning is used to improve the performances in terms of AoI by supporting decision making and network resources allocation.

Table 7 Classification of works on Network and Connectivity

Aim	Methods	Articles	Oldest	Newest
Train- to-Train (T2T) communication	AI/ Protocols	[100]	2020	
Improve network performances	AI	[37], [12], [103], [49], [25]	2019	2023
Network anomaly detection	AI	[50], [111]	2024	2025
Intrusion Detection Systems	AI	[20], [29]	2022	2025
Network security requirements formalization	AI	[95]	2024	
Ensuring data confidentiality	Blockchain	[106], [73], [74]	2021	2022

6 Discussion on the analysis of the current state-of-the-art of ERTMS, their implementations and the related progresses in research, open issues, challenges and possible directions of improvements

After a careful analysis of the most studied technologies for R-TMS, it is clear that most of the research focuses on how to improve safety and optimize railway processes. Safety is the most delicate topic when talking about railway system: whatever proposed improvement requires a safety assessment to be sure that it does not interfere with crucial railway processes, such as, for instance for ERTMS the computation of movement authority. It is therefore not surprising that much research focuses on how to improve the safety of the systems by exploiting new technologies. Particularly promising is the predictive maintenance that allows anticipation of dangerous situations by estimating degradation of components and allowing providers to take countermeasures before a fault happens. Anomaly detection is the other complementary approach. In this case, the system is monitored to detect faults before they propagate into a failure of the overall system. The two approaches allow not only for enhancing the safety, but also for strongly reducing maintenance costs and unavailabile time.

The other area that attracts most of the researches is "optimization". This is a wide term that includes many aspects of the railway industry, such as traffic control, rescheduling of train runs based on some unexpected event (such as disruptive events or a station more crowded than expected), optimizing train trajectory, or improving the capabilities of core components of ERTMS to allow a faster and more precise train control. In particular, optimizing train trajectory has the potential to significantly reduce costs by limiting the number of accelerations followed by braking, which results in wasted energy and higher costs for suppliers that are ultimately passed on to the end user. Enhancing ERTMS core components is often achieved through digitalization, which is a delicate topic. This process would allow for cheaper and more flexible components, with higher capabilities, but at the same time, would introduce extra layers of complexity that should be carefully managed to not affect the dependability of the system.

In order to enhance the a high level of Quality of Service for passengers, one of the most investigated topics is passenger flow prediction. Understanding in advance how the passengers are going to move from one station to the other is crucial for dimensioning the fleet of trains serving one specific line, for the crowd management, and transit control. This would also allow for higher safety for passengers in transit in overcrowded stations. This is particularly relevant for urban rail, but it could also be applied to long-haul trains in the future, allowing for the deployment of more rolling stocks whenever a consistent number of passengers is predicted to move in a specific station. Another topic often underestimated is the connectivity for passengers. Especially in high-speed trains, with frequent hand-overs and long distances, the connectivity of passengers to the Internet can be cumbersome. Some work exists on the topic, proposing solutions based on Software Defined Networks/Network Function Virtualization, coupled with AI, to ensure a smooth handover and guarantee continuous connectivity to passengers. At any rate, not many studies have been found on the topic, highlighting a gap in the research that, if filled, could provide a better experience for passengers and support the choice of trains over other transportation modes.

Another topic closely related to optimization and QoS is automation. In this category fell all the articles that discuss methods to make automatic decisions and enhance the Grade of Automation (GoA), currently stuck at level 2. In this case, only one of the retrieved works focuses on enhancing the Automatic Train Operation systems through AI. Other works focus on proposing architectures based on cloud computing and microservices to provide the computational capacity for making decisions in real-time with high dependability.

Train connectivity is a very relevant topic to enhance the railway capability and support automation. This topic involves two branches of research: improving the network capability of the trains and enhancing the security of the communication. Like in the previous cases, AI is the most used approach for both situations. It can be used both to boost Intrusion Detection System and to improve network performance by using it to deal with handover and load balancing. About the security, the use of blockchain to manage cryptography keys and ensure confidentiality is also very interesting. An underappreciated topic is Train-to-Train communication, which would represent a huge breakthrough, allowing trains to communicate directly with each other, enabling a fast exchange of information that will not require a complex logic at the trackside to compute the authorization to the movement. In this case, the real challenge is to establish a reliable connection among two or more trains that are moving at high speed (greater than 300 km/h). Fast movements can indeed impair the quality of the connection between trains.

Based on the conducted analysis, it is possible to deduce that, despite the increase in research material in the last few years focused in reliable and interoperable ERTMS, some gaps still exist, such as the lack of research for improving the connectivity for passengers or for deploying a Train-to-Train communication. Both these aspects have the potential to increase the attractiveness of railway transportation, the first one by providing a better service to the passengers and the second one by enabling a fine-grained communication between trains that will be able to make decisions locally rather than rely on a remote ground station, unlocking higher safety thanks to the reduced latency to compute the next action, and a higher grade of automation. AI/ML is the game-changer in almost all the identified areas, being the most explored and used solution. Despite that, not so many works on the architecture needed to host those complex applications exist. Concepts such as cloud-edge computing and virtualization are not properly explored. Those topics are crucial to enhance the power of R-TMS and push towards a greater Grade of Automation.

After a careful analysis of the state of the art of the research for Railway Traffic Management Systems, some interesting trends has been highlighted. Litterature about train position is poor, despite it being a crucial topic for implementing self driving train. Also, topic such as virtualization and architectural design to deploy applications to enhance the GoA have not yet been explored properly.

7 Current and future activities of PhD10

Since the aim of PhD10 is to study reliable and interoperable ICT platforms for ERTMS, in line with the illustrated analysis, the current open issues on this matter have been explored and further discussed with Rete Ferroviaria Italiana (RFI), the Italian provider of railway infrastructure, that support this PhD providing tutoring actions and feedback on the evolution of the activities. Some interesting use cases have been outlined, particularly it emerged the interest of industry in systems able to detect anomalies in the train positioning system at run time. Therefore, in the continuation of the work, a model able to spot anomalies and/or errors in the on-board position sensors (namely odometers) in real-time, with low and predictable latency, will be studied and proposed. Furthermore, a Machine learning-based estimation of train energy consumption has been deepened based on the suggestions provided by RFI [114]. Finally, coherently with the deductions about the evolution of research on ICT platform for ERTMS, the introduction of hybrid virtualized architectures has been deepened during the first year of the project and was and will be presented at international conferences [98], [112], [113].

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