Impact Assessment of Train-Centric Rail Signalling Technologies

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Summary

The railway industry aims at increasing railway capacity by developing new generations of train-centric signalling such as Moving Block and Virtual Coupling. These railway technologies entail several implications on different criteria related to performance, safety and feasibility. The various challenges of Virtual Coupling need to be addressed to understand whether this technology is worth implementing in real life for different market segments. This thesis provides an overall assessment of the train-centric signalling technologies by proposing several frameworks to tackle different aspects related to modelling, assessment and roadmapping.

About the Author

Joelle Aoun conducted her PhD research in the Department of Transport and Planning at Delft University of Technology. She holds a MSc degree in Civil Engineering from Lebanon with specialization in transport. Her research interests include the impact assessment of complex systems, railway traffic management and railway signalling.

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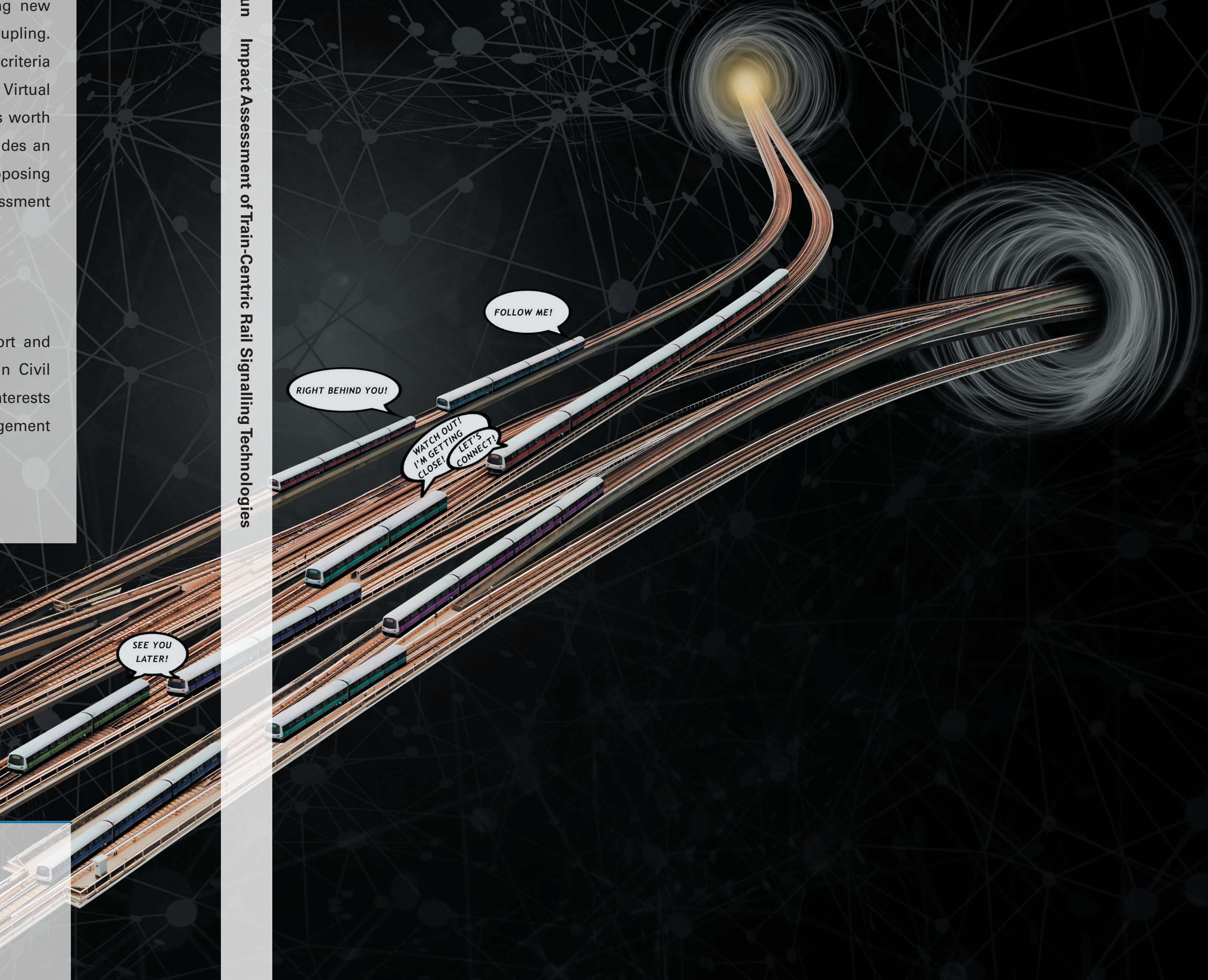

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Joelle Aoun

Delft University of Technology

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Preface

My PhD trajectory was a unique experience full of joy and challenges. I am extremely happy to reach this moment for thanking all the people who believed in me, guided me and supported me throughout my PhD journey.

I firmly believe that the key to a successful PhD depends on the synergy between a PhD's personal effort and his/her supervisors' input from different dimensions. That being said, I want to first and foremost express my deepest gratitude to my promotor Prof. dr. Rob M.P. Goverde and my daily supervisor Dr. ir. Egidio Quaglietta for their extensive guidance, support and encouragement in the past years. I have enjoyed every bit of working with both of you.

Thanks a lot Rob for your support, critical feedback and enthusiasm in my PhD research. I have learned a lot from your detailed comments and the discussions that were inspiring! You always made time for me (despite your extremely busy schedule) and your critical review improved the quality of my work significantly. Thank you for providing me the opportunity to give a lecture on Advanced Train Signalling for Bachelor students and another one in the Master course Railway Operations and Control. Besides, I highly appreciate the freedom you gave me to explore my research interests. Rob, you have truly exemplified what it means to be an outstanding supervisor and professor!

Egidio, thank you very much for giving me the opportunity to conduct research under your (daily) supervision. I am happy to be your first PhD candidate and the first one to graduate. Your trust and professional guidance played a key role in the success of my research. I had the pleasure to assist you in teaching for three consecutive years in the Master course Railway Traffic Management. You gave me sufficient space and freedom to explore different ideas. The discussions we had inspired me with new research insights. Thank you for always being supportive to me professionally and personally. You provided me lots of helpful advice, as well as great opportunities to reach out to professionals in different fields.

Thanks to you, Rob and Egidio, I was able to always boost my inspiration towards achieving high-quality results. Although I had zero experience in railways, you always showed unwavering confidence in me and believed in my abilities right from the start. Because of your enduring support, I had a paper accepted for publication before my Go/No Go meeting, and my progress has been consistently positive ever since.

Besides my supervisors, I would like to thank the rest of my PhD thesis Committee: Prof. dr. ir. Serge Hoogendoorn, Dr. Wijnand Veeneman, Prof. dr. Marjan Hagenzieker, Dr. Valeria Vittorini and Prof. dr. Francesco Flammini. Many thanks for your time on assessing my dissertation and the valuable comments that improved the dissertation. I want to further extend my gratitude to Valeria for your warm hosting and guidance in the Erasmus+ Mobility training where I spent two months of my PhD journey in Naples (Italy). I truly appreciate all the chats and discussions we had, and I am honoured that you are in the evaluation committee of this dissertation. Wijnand, I gratefully acknowledge your valuable feedback on both my Go/No Go and thesis.

Special thanks goes to Serge, the Head of the Department of Transport and Planning (T&P), for creating a wonderful environment that promotes collaboration, open communication and professional growth. Thanks to T&P, I was able to join abundant interesting seminars and international conferences with speakers coming from both academia and industry across the world. I would also like to thank the secretaries of the T&P department, Moreen, Marije, Dehlaila and Priscilla, for your practical support during my PhD.

Moreover, I offer my appreciation to the Graduate School, from which I learned a lot. I was enjoying the learning process to the point that I completed 82/45 credits in total for discipline-related, research and transferable skills. Sincere thanks go to the European Commission for supporting and funding my PhD research. In addition, I am truly appreciative of the TRAIL Research School for their educational services and their practical support during my research, particularly in printing this dissertation.

To all my colleagues in T&P, thank you everyone for your willingness to share knowledge and celebrate achievements together. It has been a delight for me to work in such a friendly and inspiring environment. I appreciate all the group lunches, after-lunch coffee breaks, spontaneous get-togethers and travel trips within and outside the Netherlands. I also enjoyed the many social activities, drinks, dinners, and BBQs. Very distinct acknowledgements go to my (former) colleagues from the Digital Rail Traffic Lab. I enjoyed the countless conversations and activities with many of you that are worthwhile memorizing. Moreover, being part of the PhD Council, I got the chance to develop good relations with colleagues in eight different departments at the Faculty of Civil Engineering and Geosciences. This great opportunity helped me to strengthen collective relationships for building mutually valued results. I was happy to interactively employ constructive changes and maintain a joyful environment with the team.

I want to extend my heartfelt appreciation to special friends who have been by my side and offered me companionship along this challenging journey. Thanks for making my study and life more colourful and joyful.

The deepest gratitude goes to my family. From the beginning of my life, my parents have always been taking care of me, unconditionally loving me, and highly believing in me. Because of you, I never feel hopeless. Words are never sufficient to express my love and gratitude for you. You undoubtedly believe that your daughter is excellent in every aspect and your love empowers me with tremendous strength and confidence. I am also grateful to my brother Jad for always boosting my motivation and highly supporting me in the design of my PhD thesis cover.

Finally, I owe my greatest appreciation to God for illuminating my path and providing me strength and resilience. With a heart filled with joy and reverence, I praise you for you unwavering support and grace to overcome obstacles and persevere towards this remarkable achievement.

Delft, the Netherlands, July 2023
Joelle Aoun

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List of Acronyms and Abbreviations

AHP	Analytic Hierarchy Process
ATO	Automatic Train Operation
CAPEX	Capital Expenditures
COM	Communication
DMI	Driver Machine Interface
EoA	End of Authority
ERA	European Railway Agency
ERTMS	European Rail Traffic Management System
ETCS	European Train Control System
EVC	European Vital Computer
FTA	Fault Tree Analysis
GNSS	Global Navigation Satellite System
GSM-R	Global System for Mobile Communications – Railway
JU	Joint Undertaking
KPI	Key Performance Indicator
L2	Level 2
L3	Level 3
MA	Movement Authority
MAAP	Multi-Annual Action Plan
MB	Moving Block
MCA	Multi-Criteria Analysis
MCDM	Multi Criteria Decision Making
MOVINGRAIL	MOving block and VIrtual coupling New Generations of RAIL signalling
OPEX	Operational Expenditures
PERFORMINGRAIL	PERformance-based Formal modelling and Optimal tRaffic Management for moVING-block RAILway signalling
RBC	Radio Block Centre
S2R	Shift2Rail
SAN	Stochastic Activity Network
SWOT	Strengths, Weaknesses, Opportunities and Threats
TIM	Train Integrity Monitoring
TPR	Train Position Report
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
VC	Virtual Coupling

Chapter 1

Introduction

1.1 Context and background

The railway transport demand increase forecasted in the next 20 years will be hardly absorbed by existing railway networks which might be already operating at nearly saturation conditions. The railway transport demand of passengers and goods is continuously increasing. The European Commission has forecasted the railway travel demand to increase by 30% and 50% in year 2050 compared to year 2000 for passengers and freight, respectively (European Environment Agency, 2012). The currently adopted fixed-block signalling system is not suitable to accommodate the massive railway demand forecasted by the European Commission, which consequently leads to a capacity problem. In conventional fixed-block signalling, the track is physically partitioned into portions named block sections with the rule that a block section cannot be occupied by more than one train at a time. As the railway infrastructure capacity is already saturated in several areas, one of the solutions is to build more railway tracks. However, this requires high investment costs and is not always feasible, especially in densely built areas where land availability is very limited. In addition, current railways need continuous maintenance of signalling trackside equipment. Therefore, new ways must be found for an effective and cost-efficient game changer to increase the capacity.

A better solution to enhance capacity is the migration towards train-centric signalling systems. 'Train-centric' means that the operational and functional signalling procedures of the trains take place onboard of the train instead of relying on trackside train detection equipment and lineside signals. This means that the operational expenditures/costs for maintaining trackside equipment and building more railway tracks would be avoided. Moving Block (MB) is one of the train-centric signalling systems that finds an implementation in the European Rail Traffic Management System/European Train Control System Level 3 (ERTMS/ETCS L3). MB envisages trains equipped with onboard devices for monitoring the train integrity and safe braking supervision. The trains in MB communicate with a trackside signalling component, named Radio Block Centre (RBC), by continuously sending position reports and receiving movement authorities via a Vehicle-to-Infrastructure (V2I) communication. In MB operations, the traditional partitioning of a railway line in fixed blocks is no longer needed. In this setup, traditional block sections can be removed together with corresponding lineside equipment so that train separation can be reduced to an absolute braking distance (i.e., the distance needed to brake to a standstill).

One of the promising solutions that could provide substantial capacity benefits to railway customers is Virtual Coupling (VC), a next-generation railway signalling concept that advances MB. VC is based on the MB principles, but it can also provide substantial capacity benefits over MB, since it allows the trains to move dynamically and synchronously in platoons at a very short separation from each other by means of Vehicle-to-Vehicle (V2V) communication. VC would therefore improve train frequency while lowering costs and strengthening the attractiveness to trains since it has the ability to improve customer's comfort and connectivity. The concept of VC reduces the train separation to a relative braking distance, which takes into account the braking characteristics of the train ahead even when the predecessor executes an emergency braking, while ensuring a safety margin. The minimum train separation between two consecutive trains is therefore either an absolute (for MB) or relative (for VC) braking distance plus a certain safety margin.

In order to deploy VC in real life, we need first to understand whether this system can provide enough benefits over existing railway signalling systems (including MB) and whether it is feasible and safe enough to be implemented. This is achieved by assessing the introduced next-generation railway signalling systems in terms of performance, safety, and feasibility for different market segments. Feasibility refers to the technical, financial, and regulatory perspectives. Design parameter requirements are not yet defined for VC since this concept is still in a conceptual stage and therefore not implemented in real life. Moreover, in the literature, the VC system is mainly assessed in terms of capacity with respect to existing signalling systems but there is no overall evaluation of VC in terms of performance, safety, and feasibility, given the multi-disciplinary challenges of implementing this technology.

Therefore, the railway industry needs to analyse train-centric signalling and assess its impact in terms of multiple criteria for different segments of the railway market, namely high-speed, mainline, regional, urban and freight. In addition, there are no defined critical steps for the development and actual deployment on real networks. It is essential to understand what the actual challenges and benefits are that VC can provide over MB if the same technological developments and safety levels would be achieved. Also, there are no well-established methodological frameworks which could support scientists and practitioners in the analysis and assessment of train-centric signalling, especially for novel concepts such as VC.

1.2 Research objective and research questions

Scientific researchers and railway practitioners need to understand whether VC is worth implementing in real life for different rail market segments. They also indicate the necessity to investigate whether this concept can provide enough benefits over previous railway signalling technologies while guaranteeing safety. The objective of this research is to assess the performance, safety, and feasibility of VC with respect to MB by deriving and evaluating specific design configurations. A design configuration is characterised by a given combination of values of both variables and parameters of the components in a system. For instance, a design configuration of VC would be characterised by a set of values for parameters related to different market segments such as the train length, the maximum speed, and acceleration and braking rates, as well as variables of relevant system components. Those variables can relate to the maximum error and latency of the GNSS-based train location and integrity device (which affect

the Train Position Report–TPR), the RBC processing time, the EVC processing time, the V2V communication delay, and the driver/ATO reaction time.
The main research question is consequently formulated as:

> *How can train-centric rail signalling technologies be assessed in terms of performance, safety, and feasibility for different market segments?*

To answer the main question, the thesis is structured based on the following key research questions:

1. What are the potentials of Virtual Coupling for different rail market segments? (Chapter 2)
2. How to asses the overall impact of train-centric rail signalling systems? (Chapter 3)
3. How to identify potential critical step-changes in the development of train-centric rail signalling systems? (Chapter 4)
4. How can the safety and performance of train-centric rail signalling systems be analysed? (Chapter 5)

1.3 Thesis contributions

This thesis presents contributions for both the scientific community and the society, as described in sections 1.3.1 and 1.3.2, respectively.

1.3.1 Scientific contributions

The main scientific contributions of this thesis are described for each chapter as follows.

Investigating market potentials and operational scenarios of Virtual Coupling railway signalling (Chapter 2)

Market potentials for VC are investigated and new insights into preliminary operational scenarios are defined based on opinions of a significant population of European railway Subject Matter Experts (SMEs) about VC benefits/challenges from operational, technological, and business perspectives. In addition, for the first time, general opinions and stated travel preferences of potential railway customers in futuristic scenarios of VC-enabled train operations are gathered from representatives of various socio-professional categories. This contributes to the understanding of possible changes in modal choices of travellers and potential shifts from other transport modes because of a more frequent and flexible VC train service. The study conducted in this chapter leads to the analysis of 'strengths, weaknesses, opportunities and threats' (SWOT) to identify advantages and disadvantages of VC signalling as well as the resulting limitations to the railway business for five different market segments.

A hybrid Delphi-AHP multi-criteria analysis of Moving Block and Virtual Coupling railway signalling (Chapter 3)

This chapter consists of combining and applying for the first time in the railway literature a multi-criteria analysis (MCA) based on a hybrid Delphi-Analytic Hierarchy Process (Delphi-AHP) approach for assessing the impacts of railway signalling innovations (i.e. MB and VC) in terms of eight different criteria. These criteria include infrastructure capacity, system stability, energy consumption, lifecycle costs, travel demand, safety, public acceptance and regulatory approval. This chapter also presents new Key Performance Indicators (KPIs) represented by indexes for each defined criterion. A novel framework is also developed that encompasses multiple cross-disciplinary methods for evaluating technical, technological, operational and societal/regulatory criteria. Another main original aspect of this chapter is that, KPIs and methods are integrated for quantitative evaluation of different criteria within a hybrid MCA. The purpose of this integration is to comprehensively investigate the impact of train-centric signalling from all relevant perspectives including safety, which is the most crucial for the deployment of railway technologies.

Roadmap development for the deployment of Virtual Coupling in railway signalling (Chapter 4)

A novel framework is built for developing scenario-based roadmaps which are derived from the SWOT (Chapter 2) and MCA (Chapter 3) results. This was done by developing a gap analysis and identifying step-changes between current and future states of the railway sector in terms of operational, technological and business perspectives, towards the development of a radical new concept in railway signalling, i.e. VC.

Analysis of safe and effective next-generation rail signalling systems using an FTA-SAN approach (Chapter 5)

A Fault Tree Analysis-Stochastic Activity Network (FTA-SAN) based approach is proposed to effectively deal with system complexities and behaviour, with the aim of better understanding the impact of failures on safety and performance. In addition, we define in this chapter generic Fault Tree Analyses (FTAs) for MB and VC by highlighting the differences in components' functionalities between the two signalling systems. This chapter also highlights potential failure rates for various functions that adhere to the Safety Integrity Level 4 (SIL 4) specifications. Based on the FTA-SAN analysis, a new KPI is defined as input to the Delphi-AHP MCA for assessing the safety criterion.

1.3.2 Societal relevance

Developing efficient and reliable railway systems is a crucial challenge for many societies worldwide. Over the past years, the greatly increased frequency of railway services has opened an unprecedented opportunity for operators to come up with more advanced planning procedures and operations. However, the integration of multi-disciplinary criteria from a variety of sources is crucial when analysing and modelling new technologies. This thesis helps therefore to unlock the market potentials of VC and to provide for the first time a general evaluation of VC effects, which can support the railway industry in strategic investments/decisions and development plans. This would also ultimately contribute to addressing societal mobility challenges with further advanced railway systems.

More specifically, this thesis offers scientific outcomes that can benefit the railway industry and the user.

From the railway industry's perspective:

- The developed techniques and methods can be used for analysing and assessing next-generation railway signalling systems.
- The application of the developed methodological frameworks and models can support railway stakeholders in evaluating scenarios for developing new rail technologies.
- The developed MCA allows a comparative assessment of railway system performance, safety and feasibility-related criteria for five different market segments.
- The FTA-SAN approach is efficient for assessing the safety and performance of a given design configuration, hence supporting the design of safe next-generation train-centric signalling to different market segments.
- The flexibility and generality of the proposed frameworks can be used as guidance to the railway industry in developing strategic decisions and identifying criticalities for implementing new technologies.
- The investigation of the market potentials of VC has a practical impact on providing a fair market environment to multiple competing train operating companies (TOCs), so that they can gain fair access to the railway infrastructure. Such a non-discriminatory treatment can encourage TOCs to positively participate in the competition. This can provide higher quality services, with the aim of increasing their ridership and raising their revenue.
- VC can be beneficial for the freight market, given that a more flexible freight service could be delivered with self-propelled units that could couple/decouple near merging/diverging junctions to reach delivery destinations of the different commodities more efficiently.

The societal contributions of this thesis from a railway customer's perspective are explained as follows:

- Train-centric railway signalling systems can be developed to enhance safety, comfort, and efficiency. By offering more reliable and efficient train services, the railway transport mode can attract more passengers from other modes. The increase of the market share of the railways is beneficial to the society, because railways are environmentally friendly (consume less energy and emissions than e.g. cars), fast and reliable.
- The exploitation of potential infrastructure capacity is practically relevant to the frequency of train services. The increase of the available capacity can bring more frequent train services to passengers, which can further lead to more options in train connections and can reduce the total travel time of passengers.
- The methods developed in this dissertation have practical relevance in terms of improving service quality (e.g. reliability, high frequency). Providing a high quality service can increase the attractiveness of railways to potential users, which can further increase the share of railways and raise revenue of the railway sector. Consequently, high quality train services can enhance the control of passengers on personal affairs and avoid missed appointments caused by delays or low-frequent train services.

- The proposed tools and methods in this thesis support the design and assessment of a more capacity-effective railway which can increase flexibility and satisfaction of customers' travel needs.

1.4 Outline of the thesis

This thesis is structured based on the visual outline illustrated in Figure 1.1. The following paragraphs provide a brief description of the main chapters.

The VC concept introduces radical changes to current train services and procedures, which calls for a deeper understanding of the possible modes of operation and the impacts on the entire railway business. To this end, **Chapter 2** considers investigating the market potentials and operational scenarios of VC railway signalling to five different market segments. This chapter provides the background on railway signalling systems and highlights the challenges of VC in terms of safety, technology, operation, infrastructure and business. A SWOT analysis of VC is ultimatley performed to understand the benefits and limitations of VC based on survey outcomes derived from experts' opinions and stated travel preferences in futuristic VC applications.

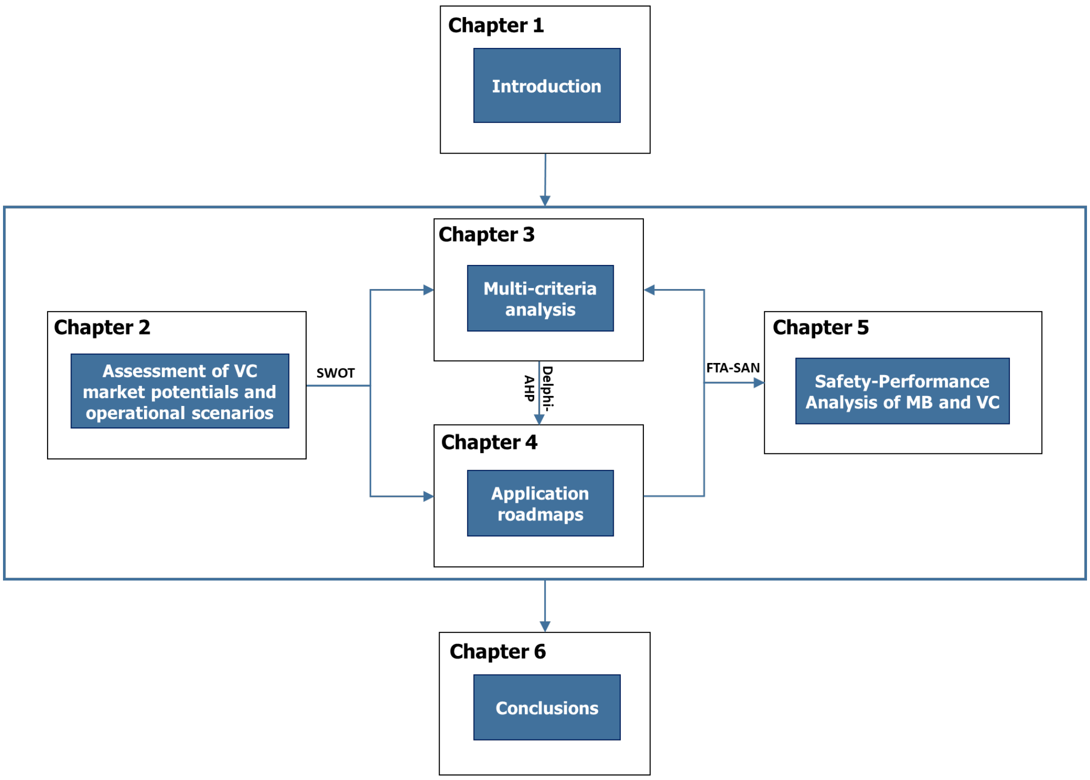

Figure 1.1: Overview of thesis structure

Chapter 3 proposes a novel MCA framework to analyse and compare MB and VC in terms of relevant quantitative and qualitative criteria (e.g. costs, capacity, energy, demand, safety, regulatory approval) for the five market segments defined in Chapter 2. By handling multiple criteria, it is possible to holistically assess the implementation of new alternatives and to find the most crucial criteria based on the weights associated by means of a hybrid Delphi-AHP approach.

Based on the results in Chapter 3, the safety criterion was assessed as the most important with a weight of 45%. However, migrating from the current state to a future desired state necessitates bridging several gaps that are translated into step-changes when performing a roadmap. **Chapter 4** uses results from Chapter 2 and Chapter 3 to generate scenario-based roadmaps for the defined market segments based on optimistic and pessimistic cases. Particularly, the SWOT results are used to develop the strategies and generate ideas on how to close gaps by identifying step-changes in the operational, technological and business domains to ultimately serve a roadmap. Optimistic and pessimistic scenarios are defined for five factors (demand, CO_2 emissions, CAPEX, OPEX and regulatory approval) to indicate how fast the gaps –translated into step-changes identified by a Swimlane roadmap– would be closed based on estimated timelines in consultation with key stakeholders.

Chapter 5 deals with a deeper research on the criticalities found in Chapter 3 and Chapter 4. These refer to the need for a deeper evaluation of the safety-performance aspect of VC. The focus is on developing and analysing fault trees for MB and VC based on causal-effect relationships between the components that constitute each system. To deal with system complexities and behaviours, we consider the interaction between safety and performance for several trains running on a railway track. This chapter also incorporates the effects of system failures derived from the FTA and the system behaviours in real-world conditions by means of an FTA-SAN approach for the five defined market segments in Chapter 2. The outcome of the proposed approach is a KPI that feeds back into the MCA in Chapter 3 in order to ensure a similar level of the most critical criterion –safety– between MB and VC.

Finally, **Chapter 6** concludes the thesis and gives recommendations to future research and practice. It shows the railway practical implications of using an FTA-SAN approach to assess safety in an MCA, and highlights the usefulness of an overall decision-making framework that builds on multi-disciplinary criteria.

Chapter 2

Investigating market potentials and operational scenarios of Virtual Coupling railway signalling

The new concept of Virtual Coupling (VC) envisages autonomous trains running in radio-connected platoons to significantly improve railway capacity and address the forecasted increase in the railway demand. Such a concept will however introduce radical changes to current train services, technologies and procedures, which call for a deeper understanding of possible modes of operation and the impacts on the entire railway business.

This chapter investigates market potentials and preliminary operational scenarios of VC for different segments of the railway market: high-speed, mainline, regional, urban and freight. The research builds on a Delphi method where an extensive survey has collected expert opinions about benefits and challenges of VC as well as stated travel preferences referring to futuristic VC applications, to ultimately build a 'strengths, weaknesses, opportunities and threats' (SWOT) analysis.

Apart from minor changes, this chapter has been published as:

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2.1 Introduction

The railway demand of passengers and goods is continuously increasing, which leads to railway capacity saturation, especially in densely built-up areas. This has been challenging for infrastructure managers (IMs) as well as for railway customers, who are increasingly subject to overcrowding, delays, and limited train service frequencies with a consequent lack of flexibility in adapting their travel alternatives (Quaglietta et al., 2020). Virtual coupling (VC) is a recently introduced concept envisaging a railway with no more block segregation and trackside safety equipment, in which train integrity and safe braking supervision is entirely controlled on board the trains and in which the trains move synchronously in platoons at a relative braking distance from each other (i.e., the distance needed by a train to slow down to a standstill by taking into account the braking characteristics of the train ahead). Such a concept could provide substantial capacity benefits versus plain moving block operations, enabled by the European Train Control System Level 3 (ETCS L3) (Theeg and Vlasenko, 2009), which instead considers trains being outdistanced by an absolute braking distance. The main limitation in capacity for a plain moving block is observed for high-speed lines in which absolute braking distances, and therefore train separations, can reach up to 4–5 km at speeds around 300 km/h (Quaglietta et al., 2020; Quaglietta, 2018).

Although the concept of platoons of vehicles separated by a relative braking distance is already known in the field of road traffic, its adaptation to the railways raises profound challenges. This is mainly because of the much lower rail-wheel adhesion coefficient that makes train operations, such as braking and direction switching, significantly different from cars. The concept of VC introduces safety, technological, and operational issues that need to be brought to the attention of the wider railway industry to understand whether there is potential for market uptake, despite its supposed capacity benefits. Therefore, there is necessity for a deeper analysis of the advantages of VC with respect to fixed- and moving- block signalling and the corresponding challenges to its implementation. The Shift2Rail Programme (Shift2Rail, 2019), funded by the European Commission, is trying to look closely into VC railway technologies addressing a specific stream of research. This chapter contributes to widen such an understanding by investigating market potentials and preliminary operational scenarios for VC train operations. To this aim, the Delphi method has been applied in which a survey was used to collect opinions of a significant population of European railway Subject Matter Experts (SMEs) about VC benefits/challenges from operational, technological, and business perspectives. The survey was extended to representatives of other socio-professional categories to gather general opinions and stated travel preferences of potential railway customers in futuristic scenarios of VC-enabled train operations. Outcomes from this survey supported a preliminary analysis of possible changes in modal choices of travelers and potential shifts from other transport modes because of a more frequent and flexible VC train service. An analysis of strengths, weaknesses, opportunities and threats (SWOT) was then performed to identify advantages and disadvantages of VC signalling as well as the resulting opportunities and limitations to the railway business. The analysis was carried out for the different market segments defined by the Shift2Rail multi-annual action plan (MAAP) (Shift2Rail, 2015), namely, high-speed, mainline, regional, urban, and freight. Advantages and challenges of VC can indeed differ depending on the type of railway market segment, given that speeds and operational characteristics vary substantially.

The following section provide a more detailed description about VC and its corresponding challenges of safety, technology, and operation (Section 2.2). A description of the methodology and survey is given in Section 2.3 along with market case studies used to collect SME opinions and stated travel preferences in Section 2.4. Results are then reported in Section 2.5 and evaluated with preliminary operational scenarios for VC. A SWOT analysis is eventually provided for each of the market segments, followed by conclusions in Section 2.6.

2.2 Virtual Coupling: concept, signalling architecture and challenges

To further increase network capacity to accommodate the forecasted increase in railway demand (ERA, 2019), the concept of VC has been recently proposed (Figure 2.1). VC takes moving block train operations to the next stage by aiming to separate trains by a relative braking distance and allowing them to move synchronously together in platoons of trains that can be treated as a single convoy at junctions, to increase capacity at bottlenecks. As in ETCS L3, train position is reported by radio communication via a Radio Block Centre (RBC). The Movement Authority (MA) is also broadcast to trains by the RBC. Because of the very short distances between trains under VC, sight and reaction times of human drivers are no longer safe; therefore, Automatic Train Operation (ATO) devices shall be fitted to all trains for automated driving. To implement such a concept, trains need to exchange speed, acceleration, and position information via a Vehicle-to-Vehicle (V2V) communication architecture (Mitchell et al., 2016).

A few research attempts have analyzed train operations with a separation based on a relative braking distance. In 1998, Ning (1998) referred to relative braking distance train separation between trains. Quaglietta (2018) introduced preliminary operational concepts for VC by defining an extended blocking-time model for comparing capacity occupation of VC with ETCS L3 moving block operation. In a further work, Quaglietta et al. (2020) developed a train-following model to describe train operations under VC and assess capacity performance under different operational settings.

The train convoy (platoon) concept consists of understanding the behaviour between a leading train and a following train. A leading train is controlled by ETCS L3 (Theeg and Vlasenko, 2009) whereas the following train receives speed and brake command data from the leader. If information is delivered from the leader to the follower, the latest assumes that the leader shall continue on the current trajectory based on high-integrity V2V communication, otherwise it falls back to ETCS L3 (Mitchell et al., 2016).

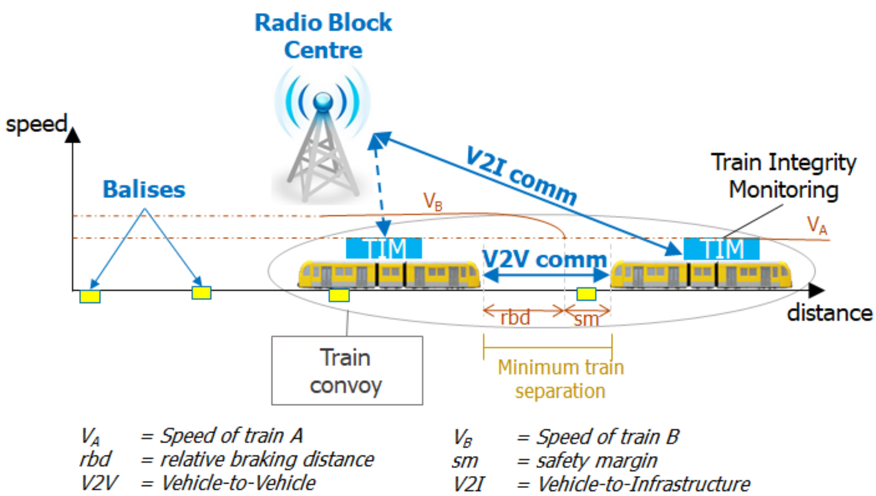

Figure 2.1: Schematic layout of Virtual Coupling train operations

The concept of vehicle platooning has been proved already in the road sector for automated cars under cooperative adaptive cruise control (Herman et al., 2017); however, the much longer braking curves of trains and the presence of moving track elements for direction switching (i.e., points) raise non-negligible safety, operational, and technological challenges that need to be carefully addressed.

2.2.1 Virtual Coupling: safety, technological, operational, infrastructure and business challenges

The purpose of VC is to improve railway capacity and, correspondingly, service frequencies as train headways can be significantly reduced (Quaglietta et al., 2020). However, every newly introduced technology has limitations and potential risks, which require serious investigation by experts. Implementation of VC faces several safety, technological, operational, and infrastructure challenges.

Safety challenges relate to the following:

Diverging junctions at which the shorter separation between trains virtually coupled in a convoy might not provide enough time to move and lock the point, thereby raising derailment risks.

The frequency of the V2V communication layer; if dynamic information about deceleration controls of the leader in a convoy is not timely broadcast and received by the train(s) behind, then potential train collisions might occur.

The heterogeneity of braking characteristics of different trains moving in a convoy, which could raise collision risks if, for example, a train is following another one that has higher braking rates. In this case, it would be necessary to manage braking controls of the trains in a convoy so that all of them brake at the rate of the train with the worst braking performance. Such a challenge is mostly related to mainlines in which different categories of trains run on the same network.

Train separation consists of different components for VC, including relative braking distance and a safety margin (see Figure 2.1). The safety margin mainly depends on the speed and a friction factor, in addition to the V2V communication latency and the GPS location inaccuracy.

Technological challenges mainly refer to the following:

The need to integrate the V2V communication layer with the existing train-to-ground communication ‒also known as Vehicle-to-Infrastructure (V2I)‒ structure between trains and the RBC, and provide high-frequency, integer, and reliable exchange of dynamic information (i.e., position, speed, and acceleration).

Interfaces of the V2V communication layer to be made with the interlocking and traffic management system. Under VC, trains might indeed have an individual autonomous control and no longer be managed by a centralized interlocking and traffic dispatching centre. For instance, routes in interlocking areas could be directly set from on board the trains, or trains could control their speeds based on the information received by the V2V layer about the status of other neighbouring trains.

The upgrade of current ATO functions to react to the broadcast information from the V2V communication layer in addition to that sent by the RBC.

From an *operational* perspective, relevant issues include the following:

The necessity of changing current train planning rules by introducing a different set of norms that no longer depend on a single train but on the entire convoy. For example, in VC, the scheduled running time of a train will depend not just on the characteristics of its own rolling stock and route but also on the operational features of the other trains moving together in the same convoy.

Potential changes in engineering and operational rules, as virtually coupled trains will have a massive impact on procedures for allocating and managing rolling stock and crew to train services; also, shunting procedures at yards, given that multiple units could also be coupled/ decoupled virtually by means of the V2V layer.

Potential modification to the protocols for traffic management and train to trackside or V2I communication, given two possibilities for the communication of MA. The first refers to a centralized process in which all trains communicate with the RBC. The second uses decentralized communication in which only the leader of a train convoy receives MA from the RBC, whereas the trains in the convoy are able to share information via V2V communication.

The railway *infrastructure* might also need adaptations to operate trains under VC. Station platforms would need to be extended to allow multiple trains platooning in a convoy to enter a station and stop at the same platform while queueing one behind each other. In addition, platforms might be segregated into multiple sections delimited by physical barriers (e.g., gates, turnstiles) and platform doors, to provide passengers with a platform layout ensuring comfort and safety of boarding/alighting procedures. Upgraded dynamic information systems are also required to give correct indications to passengers about the right train to board and avoid any confusion that might arise from multiple trains queueing at the same platform but heading to different destinations.

Addressing each of the mentioned challenges could lead to several changes in the railway business, specifically for policies, regulations, capital expenditures (CAPEX), and operational expenditures (OPEX).

2.3 Methodology

The methodology applied to identify market potentials and preliminary operational scenarios for VC is illustrated in Figure 2.2.

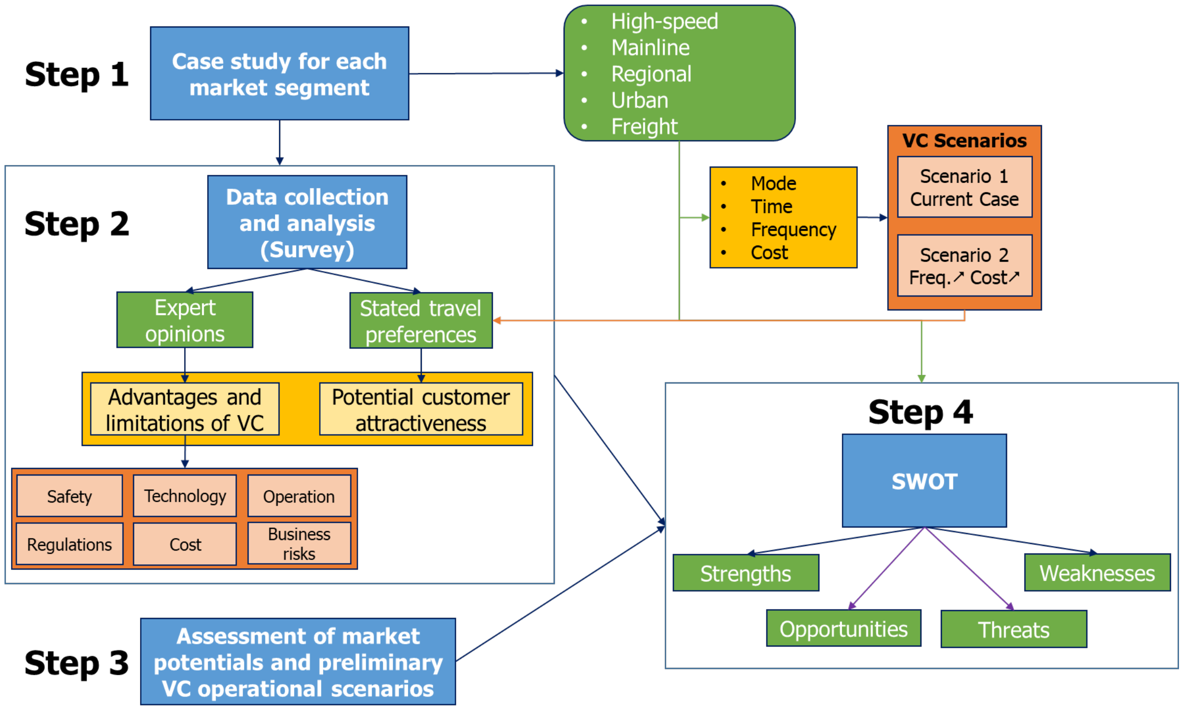

Figure 2.2: Methodology for investigating market potentials and preliminary operational scenarios of Virtual Coupling

As can be seen, four steps are considered as follows:

1. Defining case studies for each of the main market segments.
2. Collecting and analyzing SME opinions and stated travel preferences using a survey that aims at understanding both the potential customer attractiveness of VC operations as well as the main advantages and limitations of VC with regard to safety, technology, operation, regulations, costs, and business risks.
3. Identifying market potentials and preliminary VC operational scenarios.
4. Using results obtained at Steps 2 and 3 to perform a SWOT analysis that determines needs, targets, potential competitors, and barriers to the deployment of VC.

The survey on the advantages, limitations and customer attractiveness of VC is structured in two main sections:
- General section, with questions addressed to collect information about the general public and stated travel preferences.
- Technical section, with questions addressed to SMEs having expertise, advanced knowledge, or both, of the railways to understand potential benefits, challenges, and business impacts of VC operations.

2.3.1 General section

The *general section* contains two parts:

Part 1. Basic information: questions related to age, gender, socio-professional category, and education background.

Travel choice on daily routine trips: questions aimed at collecting information on daily routine trips of the interviewees, such as origin/destination and reason(s) of the trip, travel time and distance, average monthly cost, mean(s) of transport, and reason(s) for that modal choice.

- If respondents do not travel by train but there is an existing railway connection between their origin–destination (O-D) pair, an additional set of questions is formulated. Such questions aim to understand whether in a future scenario in which VC is implemented, interviewees would be willing to shift from their current travel mode to the railways for a slight increase in ticket cost (because of the higher train frequencies provided).
- If respondents do not use the railways on their routine O-D trips, they are asked whether they ever use trains, how frequently, and for which type(s) of activity.

Part 2. Travel choice on market segment case studies: questions related to modal choice of the interviewees in a future scenario in which they have the possibility of choosing an improved railway service thanks to the deployment of VC. Key performance criteria for the different travel alternatives (i.e., travel time, frequency, and cost) and transport modes support interviewees in providing reliable answers about their travel choice.

2.3.2 Technical section

The *technical section* relates to SMEs and includes three parts:

Part 1. Technological and operational scenarios for VC: from a technological perspective, railway experts' opinions were collected about potential technologies (e.g., ATO, V2V) and modes of operations needed for running virtually coupled trains for each of the market segments. From an operational perspective, preferences were collected for more frequent but shorter trains with a limited amount of on-board facilities (e.g., toilets, bar/restaurant), which could be a potential cause of inconvenience for passengers. Questions also addressed whether having queued virtually coupled trains in the same convoy and at the same platform would confuse passengers in boarding the right train. Possible solutions were identified to allow platoons of trains to enter and stop in station areas.

Part 2. Benefits and challenges of VC: questions to gather SME perspectives on potential advantages and limitations of VC for each of the market segments with regard to safety, operation, and technology. SMEs were also asked to provide potential solutions to overcome limitations/challenges that they pointed out.

Part 3. Business impacts of VC: questions to understand and foresee possible impacts of VC on CAPEX and OPEX for each market segment.

2.4 Case studies

To investigate the applicability of VC to each of the different railway market segments defined by the Shift2Rail MAAP, real European railway corridors have been considered as case studies. The use of real case studies supports interviewees in providing more concrete comments and stated travel preferences during the survey. The five case studies are as follows:

1) For the high-speed segment, the Italian corridor Rome–Bologna.
2) For the mainline segment, the route between London Waterloo and Southampton on the South West Main Line in the United Kingdom.
3) For the regional segment, the stretch between Leicester and Peterborough on the Birmingham– Peterborough line in the United Kingdom.
4) For the urban segment, the route London Lancaster–London Liverpool Street on the London Central Line in the United Kingdom.
5) For the freight segment, the Rotterdam–Hamburg corridor between the Netherlands and Germany.

A summary of these case studies is provided in Table 2.1. For each of them, the current scenario is presented with existing travel alternatives and transport modes (e.g., car, airplane, bus, bike, etc.) as well as a future scenario, assuming that VC is operational. The second scenario envisions a VC-enabled train service with a higher frequency and a corresponding higher ticket fee. Interviewees have the same set of modal alternatives as in the current scenario, keeping the same performances and costs, except for the railways that change in cost and frequency by virtue of the deployment of VC. For instance, if the case study for the high-speed market segment is considered, the current scenario includes four different travel mode alternatives for a routine trip from Rome to Bologna: the high-speed train, with a total travel time of 1 h and 55 min, departing every 15 min, with a ticket cost of €45; the bus, leaving every 4 h and taking more than 4 h, but with a decreased ticket price of €14; the car, which could be taken any time for the same cost as the train but with a travel time of 4 h and 20 min; and the airplane, leaving three times a day and taking 55 min at a cost of €66.

The future scenario proposes that the other modes of transport are available with the same performance (i.e., frequency and travel time) and cost, whereas a VC-enabled high-speed train service is available every 6 min (rather than every 15 min) for a 20% increase in the ticket fee (i.e., plus €9.20). The same rationale was followed for the case studies proposed for the other passenger-related market segments (see Table 2.1).

For the freight train line from Hamburg to Rotterdam (503km), the current scenario refers to three available freight trains per day, each transporting 8 containers (i.e., 24 containers per day) at €1,235 per container, with an average travel time of 7 h and 30 min. The road alternative is the truck that, for the same amount and type of goods, would take just half an hour more with a significant price decrease (€505 per container). If goods are transported by means of a ship, the cost per container is around €1,160 for a travel time of 16 h and just one delivery per day. Air cargo can be delivered once a day with a cost of €1,506 per container. In the future scenario, the same travel alternatives are available, again assuming that all modes keep the same performances and costs except the railways. Thanks to VC, railway frequencies increase from 3 to 7 trains per day (i.e., 56 containers per day instead of 24) with shorter trains in length and an increased marginal delivery cost by 20% (€245).

Table 2.1: Summary of Virtual Coupling case studies for each market segment

		Railway Market Segment				
		High-Speed	**Mainline**	**Regional**	**Urban**	**Freight**
Case Study		Rome-Bologna (305 km)	Waterloo-Southampton (127 km)	Leicester-Peterborough (84 km)	London Lancaster-London Liv St. (7 km)	Rotterdam-Hamburg (503 km)
Travel Time (HH:MM)		01:55	01:20	00:55	00:15	07:30
Current Scenario		1 train/15 min €45.90	1 train/30 min €28.45	1 train/60 min €13.45	1 train/2 min €2.80	3 trains/day €1,235
Future Scenario (Cost ↗ Freq. ↗)		1 train/6 min €55.10 (+20%)	1 train/11 min €34.15 (+20%)	1 train/22 min €16.15 (+20%)	1 train/45 s €3.35 (+20%)	7 trains/day €1,480 (+20%)
Travel alternatives						
Available Transport Modes (HH:MM Frequency Cost)	**Bus***	05:00 1 bus/4 hours €14.00	02:20 1 bus/hour €9.00	01:15 2 buses/day €8.20	00:50 1 bus/6 min €1.75	-
	Car	04:20 On-demand €44.15	02:10 On-demand €14.40	01:00 On-demand €15.00	00:45 On-demand €1.10	-
	Bike	-	-	-	00:36 On-demand Free	-
	Walk	-	-	-	01:27 On-demand Free	-
	Plane	00:55 3 planes/day €66.30	-	-	-	-
	Truck	-	-	-	-	08:00 On-demand €504.45
	Ship	-	-	-	-	16:00 1 ship/day €1,160.77
	Air Cargo	-	-	-	-	01:00 1 cargo/day €1,506.20

**For mainline and regional segments, the bus is considered a regional bus, also known as coach.*
HH:MM = 'Hour:Minute' time format.

2.5 Results

The survey on expert opinions and stated travel preferences was made during an interactive workshop in London (UK) held with representatives of the wide European railway industry, including Infrastructure Managers (IMs), Railway Undertakings (RUs), suppliers, transport authorities, consultants and academics. The same survey has then been distributed online to extend the sample to members of other socio-professional categories. The questionnaire was built electronically on a total of 66 questions based on a cascading sequence from previous answers. The survey has been completed by a total of 201 interviewees. More than half of the respondents (56.2%) aged between 22 and 35 years old, followed by 16% for the age range 36-40 and 18.4% for people between 18 and 21 years old. Most interviewees were males (69.2%)

and less than one-third were females. Almost half (53.7%) were students or PhD candidates, followed by 32.3% of employers/employees and 11% of teachers and professors. We have asked the interviewees in the survey if they had any advanced knowledge or expertise in railways and 36.8% said yes.

Due to the particular stratification of the interviewed sample, survey results might be affected by some bias. Part of the bias derives from different perspectives that certain industry representatives (e.g. IMs and RUs) have about the same aspect of the railway business. Another share of the bias might be due to the specific case studies proposed during the interview, which might make obtained results not universally applicable to all railway networks belonging to a given market segment.

2.5.1 Preliminary analysis on Virtual Coupling customer attractiveness and modal share

A specific analysis is performed to have a preliminary understanding of the modal split and the potential shift to railways that VC could bring in a future deployment scenario.
By aggregating stated travel preferences collected in the survey, the resulting modal share has been computed for each of the case studies for the current and the future transport scenario. These are illustrated in Figure 2.3 and Figure 2.4 for the passenger (i.e. high-speed, mainline, regional, and urban) and the freight market segments, respectively.

Modal choices for the current scenario are reported with blue bars, while orange bars represent modal preferences for the future scenario of VC-enabled train service with increased frequency and ticket fares.

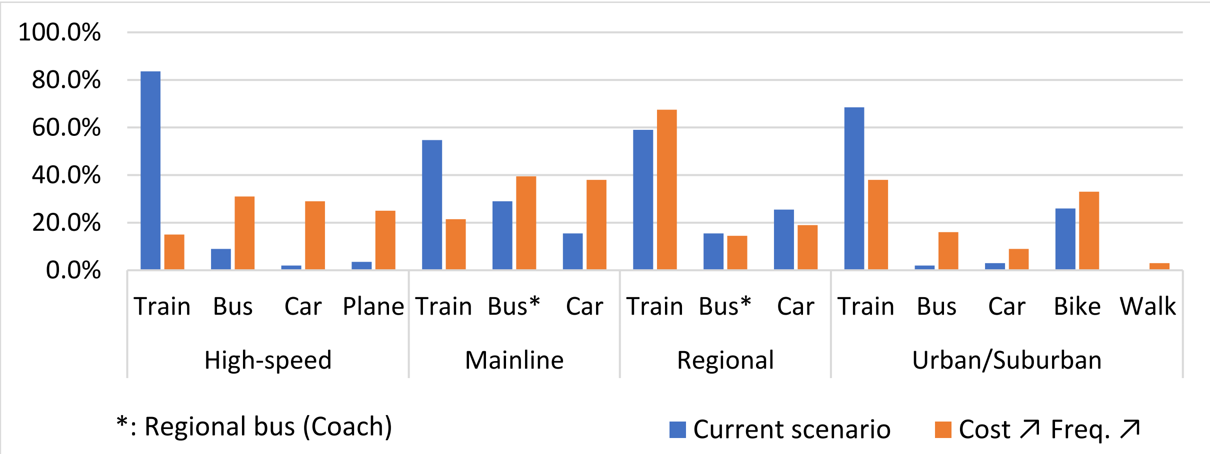

Figure 2.3: Modal share for each passenger-related case study

Figure 2.4: Modal share for the freight-related case study

For the high-speed segment, most respondents (84%) prefer traveling by train in the current scenario for distances higher than 300 kilometres (blue bars in Figure 2.3). The proposed increase of 20% in the ticket fare (to reduce service headways by 10 minutes on a 2 hours journey) is not perceived as attractive to the interviewees. Having high-speed trains every 15 minutes seems already satisfactory for most of the respondents. The increase in the ticket cost proposed in the future scenario of a more frequent VC-enabled train service (every 6 minutes), massively shifts travel preferences towards the car, the bus or the plane, as shown by the orange bars in the histogram. In general, such outcome shows that VC is not that attractive on high-speed corridors having already a service headway of 15 minutes over a given O-D like for the considered Rome-Bologna case. However, VC is not only about shortening headways but also about addressing the headway shortening capabilities with respect to the demand. Therefore, VC is worth applying to address future massive demand in dense areas.

For the mainline segment, almost half of interviewees (55%) opt for railways in the current transport scenario, while only a small share uses the car (see blue bars). A future scenario of a train service offering 20 minutes less waiting time for a ticket increase by 20% is not considered that attractive from many of the interviewees who in that case would prefer shifting to the other modes of transport, as clearly illustrated by the orange bars. Many of them respond that for this kind of journey, they would prefer arranging their travel schedules around a less frequent train service rather than paying that much more to use an improved mainline connection.

For the regional segment, most respondents would use the available railway connection (having a frequency of one train per hour) for the current transport scenario. The remaining part would rely instead on the car, followed by bus users (blue bars). It is interesting to see that for the future scenario of a train every 22 minutes for a ticket cost increase by 20%, a significant share of the sample would shift from cars to railways (orange bars). This means that the proposed market scenario is attractive to passengers, since they are not currently satisfied with the delivered railway service and would be willing to pay more for a more frequent regional railway service.

For the urban segment, the modal share for the current transport scenario is in net favour of the available metro line, having already a good frequency of a train every 2 minutes. By looking at the blue bars, the other used modes are the bike (26%), with a minority travelling by bus or car.

In the future scenario of a metro train every 45 seconds for a ticket increase by 20%, many respondents would shift to other modes of transport, given that they are not willing to pay more for improving a service that is already satisfactory as it currently is. Paying even €0.55 more for a reduction by 75 seconds in the average waiting time, is not an attractive market scenario. Such a little saving in the waiting times is indeed not perceived positively by passengers, who would flexibly arrange their trips around the current service headway of 2 minutes. Those results show that service improvements brought by VC on urban lines might not attract customers with an increase in ticket fares. Deployment of VC on such lines could however benefit railway stakeholders due to the increased capacity and possible mitigation of delay propagation.

For the freight segment, the modal split in the current transport scenario is in advantage of the road trucks as depicted by the blue bars in Figure 2.4. Such a result indeed matches with the modal share observed in real life, given a higher flexibility and cheaper truck delivery. Instead, in the future scenario of more flexible and frequent VC-enabled freight railways, a significant modal shift from road trucks is observed even in the case of an increase by 20% in the marginal delivery cost. Such a shift is mainly dictated by the fact that customers perceive railways as a more reliable mean of transport. Furthermore, a higher flexibility and delivery capacity would be appealing, despite potential raises in the marginal cost, since these raises would be widely compensated by the larger number of units delivered. Such an outcome shows that the implementation of VC on freight railways would be very attractive to the freight transport market with consequent benefits to the environment due to the reduction of trucks on the roads.

2.5.2 Preliminary Virtual Coupling operational scenarios

Preliminary operational scenarios for each market segment have been traced by combining the results from the survey together with outcomes from brainstorming sessions and workshops held with railway experts across Europe. Most SMEs belong to academic institutions and railway signalling/manufacturing companies, followed by infrastructure managers, governmental railway agencies and passenger/freight train operating companies.

Each scenario sketches operational characteristics to enable a safe VC train service that increases market attractiveness of each railway segment from both stakeholders' and customers' perspectives. Main operational characteristics relate to:

- i) planned service headways for O-D pair,
- ii) train composition,
- iii) on-board customer facilities,
- iv) train platforming procedures,
- v) crowd management at platforms,
- vi) train power supply and
- vii) main principles to control virtually coupled train convoys.

Operational ranges are defined for each of the mentioned characteristics and reported in Table 2.2. Validity and effectiveness of such operational scenarios will be further investigated in future research by means of accurate modelling (e.g. simulation) and Multi-Criteria Analysis (MCA) techniques.

Table 2.2: Preliminary operational scenarios of Virtual Coupling to each market segment

OPERATIONAL CHARACTERISTICS			PRELIMINARY MARKET SEGMENT SCENARIOS: High-speed	Mainline	Regional	Urban	Freight
Planned Headways (per O-D pair)			15-25 min	7-20 min	8-20 min	1-6 min	On-demand
Minimum Train Composition			2 locos + 6 cars	2 locos + 4 cars	2 locos + 2 cars	2 locos + 2 cars	Various*
On-board Customer Facilities	Bar/Restaurant car		✓	✓			N/A
	Sufficient no. toilets/seats		✓	✓			
	Sufficient no. seats		✓	✓	✓	✓	
	Mixed 1^{st} & 2^{nd} -class cars		✓	✓	✓	✓	
	Silent cars		✓	✓	✓	✓	
Automation	ATO instead of driver(1)		✓	✓	✓	✓	✓
	Crew at platforms(2)		✓	✓	✓	Optional(3)	N/A
Train Platforming	Destination for trains allowed to queue at the same platform during stop		Same	Same	Different	Same	N/A
Crowd Management at Platforms	Platform segragated into sections delimited by: (a) boards or (b) physical barriers and platform doors		(a) or (b)	(a) or (b)	(a)	(a)	N/A
Power Supply	EMUs	Overhead line (via pantograph)	✓ (4)		✓	✓	✓
		On-board batteries(5)	✓	✓			
		Regenerative braking	✓	✓	✓	✓	✓
	DMUs	Diesel engine (VC optional)	✓	✓	✓	✓	✓
Convoy Control	Safety margin between trains in a convoy		50-300 m	50-200 m	50-150 m	50-100 m	50-200 m
	Coupling/Decoupling process allowed: (i) "on-the-run" or (ii) when at a standstill at stations		(i) or (ii)	(i) or (ii)	(ii)	(ii)	(i) or (ii)

**: Various compositions for freight trains:*
- *Fixed composition of maximum 8 wagons for bulk freight (total length of 250 m including 2 locomotives)*
- *1 automated freight wagon for fixed multi-commodity freight*

(1): ATO also includes on-board telephone/radio and cameras for issue reporting and security surveillance
(2): Crew checks tickets and boarding/alighting procedures at platforms
(3): Crew might manage crowd during special events of intense congestion (e.g. concerts, football matches)
(4): Overhead line used mainly during cruising and braking
(5): On-board batteries are mainly used:
- *during accelerating*
- *when moving in virtually coupled convoy if the distance from pantographs of neighbouring trains <100 m*

N/A: Not Applicable

For the high-speed, mainline and regional segments, train compositions are defined to provide customers with enough seating availability, a standard number of toilets per seats, silent wagons, a bar/restaurant service and the presence of both first- and second- class coaches. For the regional and urban segments, providing a bar/restaurant or a specific number of toilets per seats is no longer necessary because train services on those segments cover much shorter distances. Given the frequencies and lengths defined for high-speed, mainline and urban trains, platforms will need to be dedicated to a certain group of destinations. This means that only trains heading to the same destination are allowed to stop behind each other at the same platform. Because of the lower frequencies of regional trains, platforms can instead allow for trains going to different destinations to queue at the same platform during a stop. To enable such operational changes, platforms of all passenger market segments will need to be extended and segregated into sections delimited by boards and/or physical barriers. Also, platform doors will need to be introduced given full automation of operations. In addition, crew might only be present at platforms to check tickets or manage congestion during special events.

Whilst the use of Diesel Multiple Units (DMUs) would not raise particular issues when trains run in a virtually coupled convoy, specific operational measures need to be introduced instead for Electric Multiple Units (EMUs). High-speed or fast trains on mainline moving at a short distance from each other within a convoy, might generate mechanical oscillations in the catenary that could be dangerous for the overhead line system and for the rolling stock. Such trains can be powered via the pantograph only if the distance from the pantograph of the train ahead is more than 100 metres. Also, the power capacity of the substations might become insufficient to feed many trains moving on the same electrical section. For this reason, on-board batteries need to be introduced together with regenerative braking to recharge the batteries and/or feed the substation back during braking.

The distance between stations or yards on high-speed, mainline and freight networks allows trains operating under VC to couple/decouple when at a standstill in stations or even on-the-run. A coupling/decoupling on-the-run is possible for those segments where distances between interlocking areas are long enough, to allow a train to catch up with a train ahead, or to outdistance from it by an absolute braking distance. Indeed, on-the run decoupling at diverging junctions is (for obvious safety reasons) only possible by imposing an absolute braking distance between trains for switches equipped with current technologies. A shorter train separation (i.e. relative braking distance + safety margin) could only be achieved if advanced technologies for fast switching are installed such as Railtaxi (Büro, 2019) or REPOINT (Bemmet, 2019). In the case of regional and urban railways, the shorter interstation distances only consent trains to be virtually coupled/decoupled while at a standstill at stations.

For the freight market segment, a completely new operational setup is proposed and illustrated in Figure 2.5. Specifically, bulk freight trains going from one source to one single destination will have a fixed composition of 250 metres, that is shorter than today’s freight trains (Figure 2.5a), to allow for higher service frequency and flexibility. A fixed composition of freight trains would also contribute to solve the current limitation of Train Integrity Monitoring (TIM) for variable train compositions. Multi-commodity freight with different types of goods going to different destinations could be instead transported by means of single fully automated freight wagons (25-30 m long) which can virtually couple to a main convoy at merging junctions (so to increase capacity at bottlenecks) and decouple at diverging junctions to reach their specific destinations. Figure 2.5b illustrates an example of how self-propelled autonomous freight wagons going/coming to/from different locations (D1, D2, D3) could virtually couple (represented with radio waves) or decouple (absent radio waves) at merging/diverging junctions.

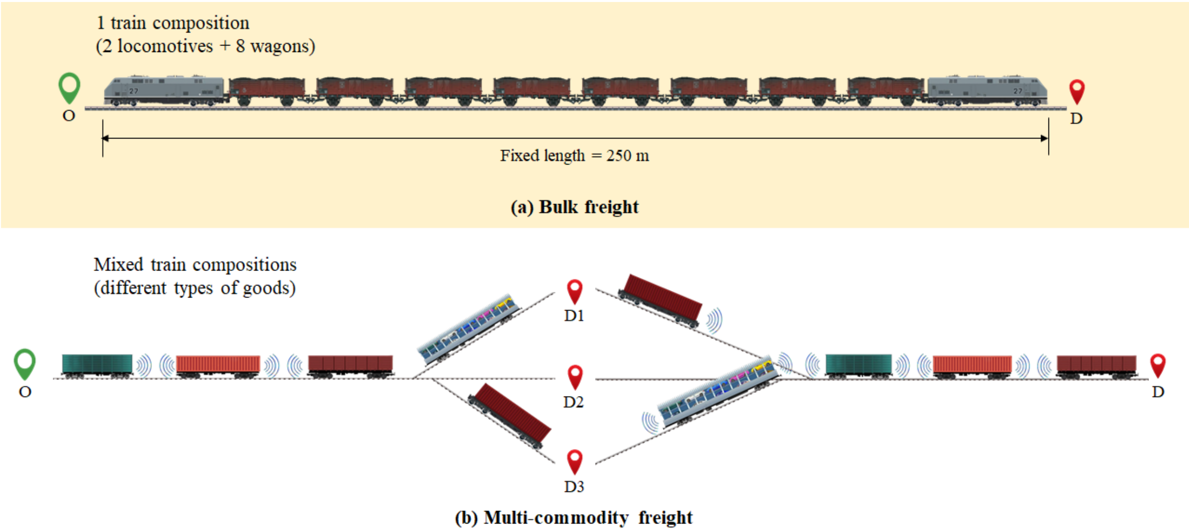

Figure 2.5: Operational scenario example for (a) bulk and (b) multi-commodity freight trains

2.5.3 SWOT analysis

The SWOT was carried out based on the survey results particularly from the technical section (Section 2.3.2) and the brainstorming sessions and workshops held with railway experts across Europe. As described in Section 2.5, we started with an interactive workshop in London (UK) to build the survey based on the needs in the SWOT. The workshop was then followed by a brainstorming session in Manchester (UK) and some online meetings to iterate and validate the SWOT analysis.

The feasibility of VC depends on the possibility of overcoming the challenges previously discussed in terms of safety, technology, operation, infrastructure, and business. To this end, a SWOT analysis has been developed to assess strengths and weaknesses of the VC concept and corresponding opportunities and threats potentially introduced to the railway industry.

VC has strengths and weaknesses that are common to all the considered market segments, and that lead to the same kind of opportunities and threats. Results are shown in Table 2.3.

Main outcomes from the SWOT analysis highlight that VC provides clear advantages over plain moving block for all the market segments. Strengths include an increase in network capacity and reliability, a potential reduction of operation costs (i.e. OPEX) due to full automation of train operations, the reduction of the communication latency, and the mitigation of some types of accidents thanks to the V2V communication. On the other hand, several weaknesses relate to an increase in the capital expenditure (CAPEX) due to additional devices required for the V2V train communication, the updating of rolling stock on-board equipment and the overhead line system (i.e. redesigning the electrical power supply). Other issues concern safety to manage trains with heterogeneous braking performance in the same convoy as well as to control convoys at diverging junctions. VC has the potentials for opening several market opportunities. Higher capacity means more train paths that could be sold by Infrastructure Managers (IMs) and more train services that can be delivered by Railway Undertakings (RUs). At the same time, reduced operational costs are possible thanks to full automation of train operations which strongly reduce costs for personnel salary. This leads to a profit increase for both IMs and RUs and a possible deregulation of the current railway market. The deregulation comes as a direct consequence of an increase in available train paths and a decrease in the operating costs, which makes the railway market affordable also to smaller transport operators, hence more competitive. Also, the train-to-train communication will need a more intense cooperation among several RUs since trains running by different undertakings will need to exchange dynamic information when operating on shared routes. This will open possible scenarios for cooperative consortia of railway operators instead of the current competitive business model, which can lead to higher Benefit/Cost ratios, as reported in Root and Visudtibhan (1992).

VC also offers the railway industry a chance to accelerate the migration of current Control and Command Systems (CCS) towards more future-proof digital railway architectures, as well as an upgrade of current switch technologies to faster and more reliable ones. On the other hand, VC might introduce threats such as a potential increase in ticket fees (needed for delivering a more frequent service) which might not be received well by customers. Moreover, the V2V communication layer could lead to a higher train control complexity than ETCS Level 3, with risks of approval from the railway industry. Other threats regard the need to partially redesign policies, regulations and engineering rules currently adopted in the railways, as well as the necessity of facing additional investment costs to address the safety issues introduced by relative braking distance operations.

Table 2.3: SWOT analysis of Virtual Coupling to all market segments

Strengths	**Weaknesses**
• Increased line capacity due to relative braking distance separation • Improved mitigation of delay propagation • Reduced latency in communication with RBC in moving block due to V2V • High degree of service flexibility • Decreased OPEX thanks to automated operations, removal of trackside equipment and more reliable switch technologies • Potential impact reduction of some accidents due to continuous train-to-train communication.	• Safety at diverging junctions still need full braking distance for current switch technology • Safety risks for handling trainsets having heterogeneous braking rates in the same convoy • Investments needed to install the V2V communication layer • Necessary infrastructure upgrades to the Overhead line system, platforms and possibly switch technologies • Potential increase in ticket fees to support the higher service frequencies.
Opportunities	**Threats**
•Attracting more railway customers due to increased service flexibility • Potential profit increase of Infrastructure Managers and Railway Undertakings, thanks to more available train paths at reduced operational costs • Deregulation of the railway market with opening to smaller transport operators • Restructuring of the railway market from a competitive to a more cost-effective cooperative consortium model for operators • Migration of current Control and Command Systems (CCS) to more future-proof and efficient digital railway architectures • Maximising capacity and further reducing maintenance costs by installing advanced technologies for faster and more reliable switches.	• Potential increase in ticket costs might not be well received by railway customers • Possible increase in train control complexity with respect to moving block, which might raise approval risks from the industry • Additional costs of stakeholders to address safety issues due to relative braking distance separation • Partial redesign of policies, processes and engineering rules, which need agreement and endorsement across the wide rail industry.

Additional Strengths, Weaknesses, Opportunities and Threats captured for each specific market segment are detailed in Table 2.4.

Table 2.4: Additional Strengths, Weaknesses, Opportunities and Threats of Virtual Coupling to each market segment

Market	Strengths	Weaknesses
High-speed	• Significant train headway reduction due to relevant difference between absolute and relative braking distances at high speeds • More efficient platooning because of homogeneous rolling stock characteristics • Coupling/Decoupling can be performed on-the-run due to long interstation distances.	• High safety risks in case of V2V signal loss • Substantial stress of overhead catenary due to high speed EMUs running closer.
Mainline	• Additional capacity increases thanks to homogenisation of travel behaviour of the different train categories when platooning over open tracks • Grouping of trains in a single convoy which might reduce the amount of level crossing closures • Coupling/Decoupling feasible on-the-run on sufficiently long interstation distances.	• High complexity and uncertainty in managing heterogeneous rolling stock in one convoy.
Regional	• Grouping of trains in a single convoy might reduce the amount of level crossing closures.	• Potential longer closure of level crossing to road users to allow the passage of a train convoy with the need of warning devices • Coupling/Decoupling in a convoy potentially allowed only at a standstill due to non-sufficient interstation distances.
Urban	• More efficient platooning because of homogeneous rolling stock characteristics.	• Provision of only marginal capacity improvements to current service headways which are already short.
Freight	• Higher flexibility and capacity of freight delivery • Minimised handling operations at marshalling yards since coupling and decoupling can occur on the tracks • Coupling/decoupling of convoy feasible on-the-run thanks to long interstation distances.	• Complexity in platoon sequencing due to different rolling stock characteristics of freight trains (e.g. torque, brakes, weight).
Market	**Opportunities**	**Threats**
High-speed	• None additional to Table 2.3.	• None additional to Table 2.3.
Mainline	• Migration to advanced systems for automatic traffic control to optimise management of trains with different characteristics.	• None additional to Table 2.3.
Regional	• Substantial increase of customers thanks to massive improvement of current regional service frequencies.	• None additional to Table 2.3.
Urban	• None additional to Table 2.3.	• Investments for VC deployment might not be compensated by a sufficient customer increase.
Freight	• Introducing a revolution to current rail freight transport set to attract a relevant share of market from other modes • Shorter trains with fixed composition overcome limitations of TIM while reducing brake build-up times • Collection and distribution of goods over the last mile can be optimized and automated.	• Legislative rules in terms of weight and length platooning (e.g. number of freight trains per convoy).

2.6 Conclusions

A description of the innovative concept of Virtual Coupling (VC) has been provided in this chapter by detailing main technological and operational characteristics. The core of this chapter provides results from an extensive survey focused on representatives of the European railway industry to collect expert opinions about market potentials and challenges for VC. Preliminary operational scenarios and a SWOT analysis have been produced for different railway market segments to assess feasibility of VC and investigate the applicability of such a concept.

Results of the survey highlight that VC can make the railway transport mode more attractive to customers if the increase in ticket costs (for the higher service frequencies) is restrained. On the other hand, these marginal increases in utilisation costs are compensated or even nullified by full railway automation which removes costs for on-board personnel and for coupling/decoupling trains at stations or yards.

For dedicated high-speed lines with already high service frequencies (around a train/15 min), the use of VC would not have a significant impact on the modal shift to railways. However, VC can be extremely beneficial to high-speed lines currently operating with lower frequencies. A negligible attractiveness to customers has been observed for urban lines where passengers seem to be already satisfied with the current train services having headways of 1-2 minutes. VC operations are instead very appealing to customers of regional and freight market segments, where a manifest willing to pay more for using a more frequent train service has been recorded. In other words, if VC is proposed to improve the customers' satisfaction, then the ticket price increase would not be perceived as negative, since VC would not just merely increase capacity but improve the entire customer experience by delivering a more flexible service more in line with passengers' travel needs.

Preliminary operational scenarios have been defined for each market segment by combining survey outcomes with brainstorming sessions and workshops held with representatives of different sectors of the European railway industry. Ranges of "market-effective" service headways have been identified for each segment, together with main operational characteristics such as train compositions, on-board customer facilities, train platforming and crowd management, power supply, and control of virtually coupled convoys.

The SWOT analysis provides clear advantages of VC in terms of reduced OPEX and communication latency. Weaknesses result mainly from increased CAPEX and safety at diverging junctions especially for trains with heterogeneous compositions. Some threats are introduced by the VC implementation due to potential increased ticket fees, higher complexity from train-to-train communication, safety issues due to the relative braking distance operations as well as the market deregulation. On the other hand, VC opens opportunities to both IMs and RUs. Benefits include reduced operation costs and increased profits, a deregulated and more competitive railway market as well as potentials for cooperative consortia of railway operators leading to higher Benefit/Cost ratios. VC can also result in a possible migration towards more digital railway architectures with upgraded technologies, potentially increasing the number of railway customers. Additionally, VC would facilitate the implementation of on-demand train services which could possibly revolutionize the entire idea of timetabling. An economic analysis for capacity increase will be performed in future research work by means of a Multi-Criteria Analysis.

Chapter 3

A hybrid Delphi-AHP multi-criteria analysis of Moving Block and Virtual Coupling railway signalling

In Chapter 2, a Delphi method has been applied where a survey has collected opinions of a significant population of European railway Subject Matter Experts (SMEs) about VC benefits/challenges from the operational, technological and business perspectives to five different market segments. The railway industry has an urgent need to investigate limitations and advantages of VC over plain moving block (MB) before proceeding with potential investment decisions. An overall analysis is hence necessary to identify the effects that VC could have in terms of technical, technological, societal and environmental criteria. This chapter contributes to address this necessity by performing an extensive multi-criteria impact analysis of VC in comparison with ETCS Level 3 MB and traditional fixed-block signalling systems for the different railway market segments defined in Chapter 2.

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3.1 Introduction

The railway industry urges to increase transport capacity of existing networks to address the forecasted growth in the railway demand. Research is hence focusing on reducing the safe train separation distances of traditional fixed-block railway operations by introducing train-centric signalling concepts which migrate more and more trackside vital equipment to train-borne equipment using radio communication.

Moving Block (MB) signalling (Theeg and Vlasenko, 2009) envisages that the train is equipped with devices for continuous train positioning, Train Integrity Monitoring to guarantee a safe train-rear position, and dynamic braking curve supervision, as well as wireless communication for sending position reports and receiving movement authorities from Radio Block Centres (RBCs). In this setup, traditional block sections can be removed together with corresponding lineside equipment so that train separation can be reduced to an absolute braking distance (i.e. the distance needed to brake to a standstill). An implementation of MB signalling for conventional railways finds an implementation in the European standard: European Train Control System (ETCS) Level 3. Therefore, new railway signalling and control technology are being developed that can significantly increase railway capacity and overall performance.

The concept of Virtual Coupling (VC) advances MB operations by reducing train separation to less than an absolute braking distance using Vehicle-to-Vehicle (V2V) communication. By mutually exchanging dynamic information (e.g. position, speed, acceleration), trains can be separated by a relative braking distance (i.e. the safe distance of a train behind the rear of the predecessor taking into account the braking characteristics of the train ahead) even when this predecessor executes an emergency braking, while ensuring a safety margin. This is particularly beneficial when trains move synchronously together in a virtually coupled state within a platoon. Those platoons could hence be treated as a single train at junctions thereby greatly increasing capacity at network bottlenecks.

Several critical safety issues are however still unaddressed for the VC concept. Crucial is for instance the risk of splitting platoons at diverging junctions where a switch must be locked before a train is at the absolute braking distance so that it can still brake in case of failure. The railway industry has an urgent need to investigate limitations and advantages of VC over plain MB before proceeding with potential investment decisions. An overall analysis is hence necessary to identify effects that VC could have in terms of technical, technological, societal and environmental criteria. This chapter contributes to address this necessity by performing an extensive multi-criteria impact analysis of VC in comparison with ETCS Level 3 MB and traditional fixed-block signalling systems for different railway market segments. The analysis has been made in the context of the European project MOVINGRAIL (MOVINGRAIL, 2018) funded by the Shift2Rail programme (Shift2Rail, 2020). An innovative multi-criteria analysis framework is introduced to evaluate impacts of VC on lifecycle costs, infrastructure capacity, energy consumption, service stability and travel demand as well as on qualitative criteria such as regulatory approval, public acceptance and safety.

The main contributions of this chapter are: *i)* the application for the first time in railway literature of a hybrid Delphi-Analytic Hierarchy Process (Delphi-AHP) approach to assess impacts of railway signalling innovations; *ii)* the definition of a multi-criteria framework encompassing multiple interdisciplinary methods for evaluating technical, technological, operational and societal/regulatory criteria; *iii*) the definitions of new indexes that –to the best of our knowledge– were not identified in previous published works, and *iv*) for the first time a general evaluation of VC effects is reported which can provide the railway industry with more elements to support strategic investment and development plans.

In Section 3.2 of this thesis, a literature review on train-centric signalling systems and multi-criteria methods is provided. The Multi-Criteria Analysis (MCA) methodological framework introduced in this study is described in Section 3.3. Section 3.4 presents operational scenarios and the methods used to compute each criterion. Section 3.5 displays case studies considered for the different railway market segments and reports the final results of the MCA. Conclusions and recommendations are eventually provided in Section 3.6.

3.2 Literature review

3.2.1 Train-centric signalling systems

In traditional fixed-block signalling systems, trains are separated by one or more block sections with movement authorities provided by lineside (multi-aspect) signals or radio-based cab signalling like ETCS Level 2 (Theeg and Vlasenko, 2009). MB signalling reduces train separation to an absolute braking distance by removing track block sectioning and migrating vital track-clear detection equipment to onboard integrity monitoring. The ETCS Level 3 standard gives requirements for MB railway operations (Figure 3.1a). A trackside Radio Block Centre (RBC) sends Movement Authorities (MAs) to the trains indicating the maximum distance that the train can safely run based on regularly updated Train Position Reports (TPRs). The onboard European Vital Computer (EVC) ensures that the MAs are respected by computing and supervising dynamic speed profiles including continuous braking curves. Verification of train integrity is performed by an onboard device called Train Integrity Monitoring (TIM) which is still an open challenge for trains with variable composition such as freight trains. The British and Dutch railway infrastructure managers propose a hybrid version of ETCS Level 3 which leaves in place track-clear detection devices to monitor train integrity for trains unequipped with TIM (Furness et al., 2017). Legrand et al. (2016) propose instead an integrity monitoring technology that can meet required safety standards by combining Global Navigation Satellite Systems (GNSS) with Inertial Navigation Systems (INS). Biagi et al. (2017) show how missed train integrity and/or position reporting due to communication break-up in ETCS Level 3 can drastically reduce network capacity.

MB operations made possible by ETCS L3 have been upgraded recently by the concept of VC which postulates the possibility that trains could just be separated by a relative braking distance plus a safety margin, so to increase even further infrastructure capacity utilisation. As illustrated in Figure 3.1b, VC enriches the basic MB architecture with a V2V communication layer to allow trains exchanging dynamic information (e.g. position, speed and acceleration) which is needed to supervise relative braking and keep a safe separation. The virtually coupled trains form a train convoy that is treated as a single train at junctions, so that switches remain locked until the entire convoy has passed. VC also enables the formation of platoons where trains can move synchronously with each other at close distance, thereby increasing capacity. Due to the very short train separation, automatic train operation becomes essential for VC given that human driving reaction times would no longer be safe in this setup.

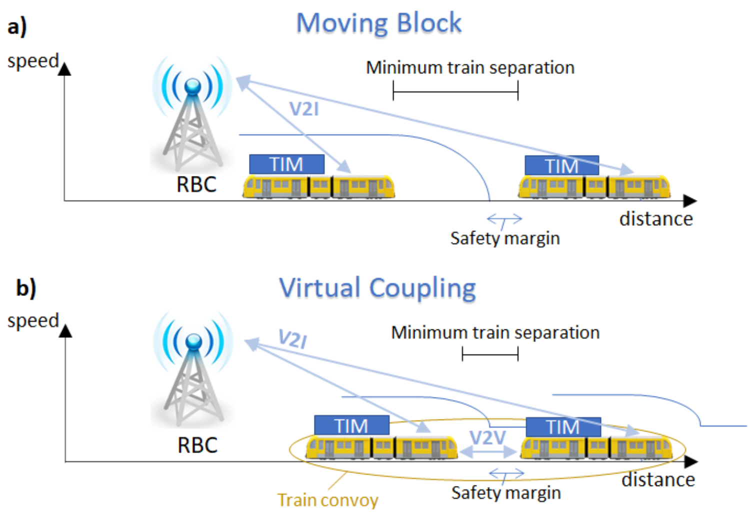

Figure 3.1: Schematic architecture of train-centric signalling systems: (a) Moving Block and (b) Virtual Coupling

Several challenges still need to be addressed for VC. One main issue regards diverging junctions where a separation shorter than a full braking distance is not yet possible as it could lead to unsafe train movements in case of longer switch setup times or switch locking failures. Another issue relates to the V2V communication architecture that requires high levels of reliability and low latency for the exchange of safety-critical information among trains. European projects such as X2Rail-3 (X2RAIL-3, 2018) and MOVINGRAIL (MOVINGRAIL, 2018) have been investigating safe operational principles, scenarios and reliable communication architectures for the feasibility of VC. Fenner (2016) presented steps and scenarios for closer running, i.e. VC. Schumann (2017) simulated the 'Shinkansen' scenario to increase line capacity on the Tokaido high-speed line in Japan by following the VC principles. Flammini et al. (2019) proposed a quantitative model to analyse the effects of introducing VC according to the extension of the current ETCS Level 3 standard, by maintaining the backward compatibility with the information exchanged between trains and the trackside infrastructure. Felez et al. (2019) developed a preliminary Model Predictive Control approach for virtually coupled trains using a predecessor-following information structure that minimizes a function of desired safe relative distance, the speed of the predecessor train and the jerk. Di Meo et al. (2019) studied operational principles and communication configurations of VC in several stochastic scenarios by using a numerical analysis approach. Quaglietta et al. (2020) illustrated preliminary capacity benefits of VC over MB for a British mainline case study, by applying a multi-state train following model. The main question that literature has not clarified yet is whether the trade-off between overall benefits and costs of VC are more advantageous to the transport industry than MB signalling. This chapter tries to address this fundamental research question by implementing an innovative multi-criteria analysis framework to compare impacts of VC with MB and traditional fixed-block signalling systems.

3.2.2 Multi-criteria analysis methods

Multi-Criteria Analysis (MCA) is a scientific method to support practitioners in making effective decisions with respect to several conflicting criteria (Kumru and Kumru, 2014; Miettinen, 2012). An MCA is similar in many aspects to a Cost-Effectiveness Analysis (CEA) that compares the relative costs and effects of different alternatives, but involving multiple indicators of effectiveness (Pearce et al., 2006).

The Multi-Criteria Decision Making (MCDM) methods provide decision makers with some tools to solve a complex problem where different points of view are taken into account (Vincke, 1992). The first step for performing an MCA is to correctly identify the main criteria which need to be assessed to address a specific design/evaluation problem. One of the main approaches applied in literature to determine critical evaluation criteria is the Delphi method which has been firstly introduced in 1950s (Dalkey and Helmer, 1963). Delphi consists of combining points of view and opinions from a group of individuals by means of iterative questionnaires with controlled feedback. Four key features are regarded as necessary to define a 'Delphi' procedure: anonymity, iteration, controlled feedback and statistical aggregation of group responses (Rowe and Wright, 1999). The Delphi technique has been extensively used in various sectors including forecasting, planning, curriculum development (Thangaratinam, 2005), health care (Morgan, 1982) and transportation (Da Cruz et al., 2013). Once the main criteria are identified, several MCDM methods are available in literature to an objective criteria assessment. The Analytic Network Process (ANP) facilitates feedback and interaction capabilities among different cited elements within and between groups (Saaty, 2001). The ELimination Et Choix Traduisant la REalité (ELECTRE) method is used to choose the best actions from a given set of actions. Main applications of the ELECTRE are usually found to solve three types of problems: choosing, ranking and sorting. The main limitation of this approach is due to the high subjectivity of calculated ELECTRE thresholds which might lead to unreliable results (Gavade, 2014). The Weighted Sum Method (WSM) is one of the earliest and simplest techniques that supports single dimensional problems and where overall results are provided in a qualitative form such as 'good, better, best' (Singh and Malik, 2014). The Multi-Attribute Utility Theory (MAUT) is a "rigorous methodology to incorporate risk preferences and uncertainty into multi-criteria decision support methods" (Loken, 2007), but it has the shortcoming of being data intensive requiring an incredible amount of input at every step of the procedure in order to accurately record the decision maker's preferences (Velasquez and Hester, 2013). The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) was developed by Hwang and Yoon (1981) and is based on selecting the shortest distance from the positive ideal solution (i.e. best possible combination of criteria) and the longest distance from the negative ideal solution (i.e. worst criterion values). TOPSIS is an easy deterministic method which does not consider uncertainty in weightings (Gavade, 2014).

A more objective and comprehensive MCA method is the Analytic Hierarchy Process (AHP) developed by Saaty (1980a) which is a compensatory scoring method that eliminates incomparability between variants built on a utility function of aggregated criteria (Xu and Yang, 2001). The AHP is considered as a systematic and terse method (Li, 2017) applicable to decision-making problems with complex hierarchies. Applications of the AHP are found in different areas ranging from the socio-economic sector (Kumru and Kumru, 2014) to transportation (Macharis and Bernardini, 2015). Feretti and Degioanni (2017) identified the AHP to be particularly appropriate to railway management related problems. Barić and Starčević (2015) showed that more than 18% of railway MCA projects make use of the effective AHP method (e.g. Gerçek et al., 2004; An et al., 2011; Kumru and Kumru, 2014).

Based on the outcomes of this literature review, AHP has been selected in our research as the most appropriate MCA method to assess the impacts of VC railway signalling which is considered as an innovative and at the same time complex step-change for the railway sector. Specifically, we will be relying on a hybrid Delphi-AHP approach to have a more objective identification of the most relevant assessment criteria and ensure consistency in the pairwise comparison matrix for criteria weighting, which is required for the calibration of the AHP technique.

3.3 Methodology

In this section, the MCA framework is introduced where the focus is on the AHP and the Delphi methods. Sections 3.3.2 and 3.3.3 are part of existing theories available in the literature review (Section 3.2), whereas the innovative framework is built on combinatorial methods, consolidated mathematical techniques, engineering procedures, and extensive Subject Matter Expert (SME) interviews and workshops to assess each of the criteria defined in Section 3.1. The elements of this framework are further detailed in Section 3.4 where the developed methodologies are applied in Section 3.5.

3.3.1 MCA framework

The described MCA framework is illustrated in Figure 3.2. The MCA builds on two main elements: alternatives (derived from options) and criteria (derived from objectives). An alternative is a choice defined between two or more possibilities (i.e. options). A criterion instead is generated based on the objectives that the decision-maker would like to achieve. For example, the selection of a 'population' criterion could be based on the objective of engaging alternatives where the population is greater than a value "x". The set of alternatives and criteria is usually specified by a group of decision makers, mainly stakeholders or SMEs. Each alternative possesses its own values of criteria which can be either quantitative or qualitative depending on the defined objective(s). Criteria for buying a new car could for example be quantitative such as cost and engine power or qualitative such as user's comfort and overall look. Assume that an individual hesitates about the car to buy and there are five alternatives available (Alternative A1 for car 1, A2 for car 2, …, A5 for car 5). The decision-maker needs to choose the suitable car based on a set of criteria (e.g. cost, engine power, durability, comfort, etc.). Each alternative m possesses its own value of Criteria n (i.e. $X_{m,n}$). For instance, alternative A1 possesses its own value of the first criterion cost for alternative A1 (i.e. $X_{1,1}$), A2 possesses its own value of cost $X_{2,1}$, etc. In the same manner, alternative A1 possesses its own value of comfort $X_{1,2}$, A2 is assigned with $X_{2,2}$, etc.

In this chapter, the interactions between alternatives and almost all of the quantitative criteria (i.e. infrastructure capacity, system stability, lifecycle costs and energy consumption) depend on different operational scenarios described in Section 3.4. Stated preference surveys are involved to assess travel demand distribution, and stakeholders' judgement is used for safety, public acceptance and regulatory approval. After combining the different combinations of criteria values per alternative, a performance matrix is constructed. Criteria are weighted by means of the hybrid Delphi-AHP method (Section 3.3.3). Based on the set of expertise required for the survey, a panel of experts is accordingly selected. Then a round of the Delphi survey is performed and survey results are analysed in terms of consistency of the AHP pairwise comparison matrix. In case the consistency ratio of the relative criteria assessment is above the threshold of 0.1, all the respondents providing inconsistent matrices are required to re-do the survey so to give consistent responses (i.e. Consistency Ratio $CR \leq 0.1$). After each round of the AHP pairwise comparison matrix, the survey results are distributed anonymously to the interviewed panel for further feedback until final consistent results are returned. The Delphi rounds are further discussed in Section 3.5.3 and the number of rounds has been limited to three as Walker and Selfe (1996) claim that "repeated rounds may lead to fatigue by respondents", and most studies use two or three rounds (Arof, 2015). After the first round of the hybrid Delphi-AHP method, we further guided the interviewees to provide consistent responses. Particularly, we created a dynamic Excel sheet that automatically syncs the matrix with the final value of the consistency ratio, so that the interviewees can alter the values of their matrices accordingly until reaching a $CR \leq 0.1$. Then, decision matrices are normalized and weighted to ultimately provide an overall value for each alternative. In this chapter, the examination process consists of enabling cohesion among the different points of view of the involved SMEs, and evaluating consistency to reach a reasonable consensus matrix by statistically aggregating responses. Finally, results are evaluated and shared with the respondents. This framework can be also applicable to other fields by just modifying the alternatives and criteria in Figure 3.2 according to the investigated study.

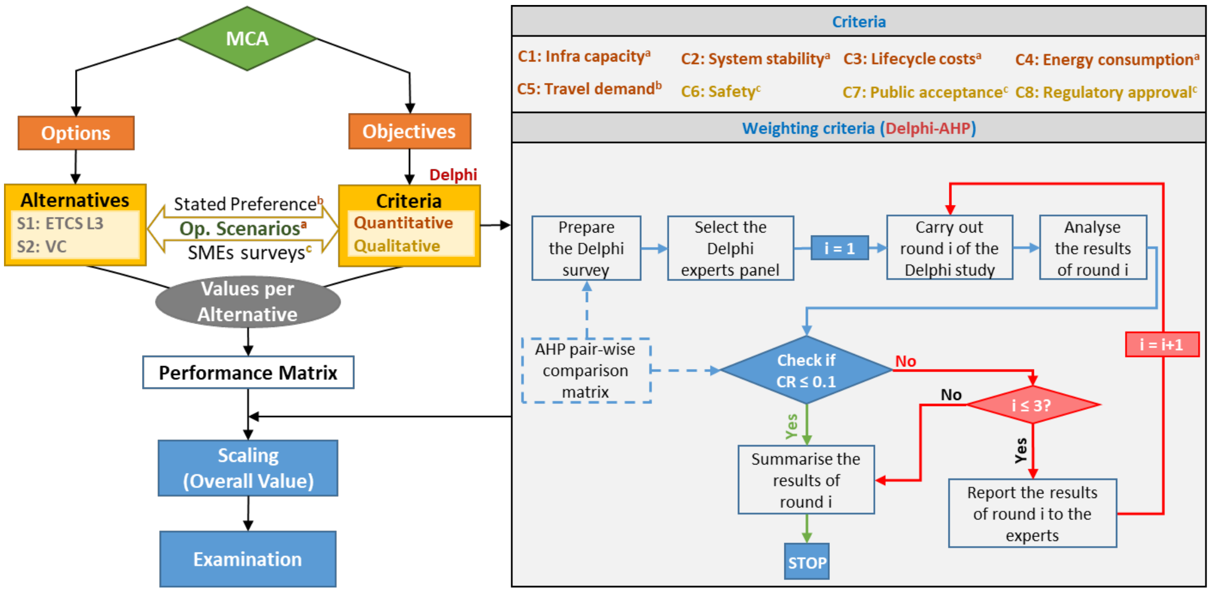

Figure 3.2: MCA Framework

3.3.2 The Analytic Hierarchy Process (AHP)

Three main steps are involved in the determination of weights in the AHP technique:

1) Building the hierarchical model
2) Constructing the pairwise comparison judgment matrix
3) Checking consistency.

Step 1: Building the hierarchical model

The hierarchical model consists of three main layers. The top layer represents the overall goal for determining the ranking of importance. The middle level displays the multiple criteria which influence the goal. Those criteria are used for evaluating the alternatives that constitute the bottom level of the hierarchical model (Bhushan and Rai, 2004). In other words, each alternative has its own values of criteria associated with it. Figure 3.3 shows the AHP model where the goal layer is denoted as A, the middle level consists of n criteria denoted as C_1, C_2, …, C_n and the bottom level consists of m (signalling) alternatives denoted by S_1, S_2, …, S_m.

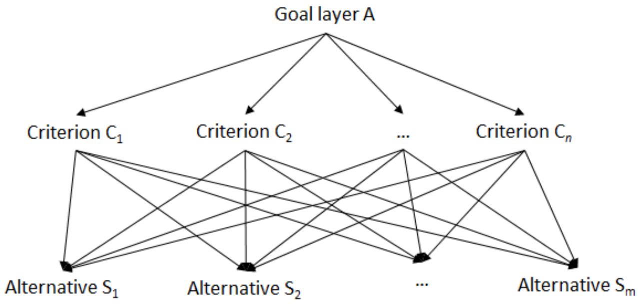

Figure 3.3: Analytic Hierarchy Process model

Step 2: Constructing the pairwise comparison judgement matrix

A judgement matrix evaluates and prioritizes a list of options where the decision-maker provides weighted criteria that are assessed with respect to each other in a $n \times n$ matrix. The judgement matrix for criteria weighing is constructed by pairwise comparing two elements (Saaty, 2008; Dieter and Schmidt, 2013). The pairwise comparisons are used to determine the relative importance of each element of one layer to the element of the above layer. In this chapter, we consider one level of pairwise comparison which consists of determining the relative importance of each criterion C1, C2, …, C_n with respect to the goal A (see Figure 3.3). The other level of assessing each alternative S1, S2, …, S_m with respect to each criterion C1, C2, …, C_n is out of the scope of this analysis since decision makers considered railway signalling alternatives equally important with respect to each criterion. The decision-maker has to express his/her opinion about the value of one single pairwise comparison at a time based on a scale of relative importance that ranges from 1 to 9 where a value of 1 means that the compared criteria are of equal importance. The lower bound of 2 signifies weak or slight importance whereas a value of 9 refers to absolute or extreme importance. The remaining values are uniformly intermediate ranging from 3 (moderate importance) to 8 (very strong importance). The judgment value of the importance of element i with respect to element j is r_{ij}, the reciprocal value is $1/r_{ij}$. For instance, a matrix value of 9 means that the criterion on the row is absolutely more important than the one on the column, whereas a value of 1/9 means that the criterion on the column is absolutely more important than the one on the row. The number of comparisons within the level is based on the equation: $n(n-1)/2$ where n is the number of comparable elements (i.e. in this case the number of criteria).

Step 3: Checking consistency

After constructing the pairwise comparison matrix, matrix values $C_{i,j}$ on row i of criterion i and column j of criterion j are normalized (as the term $\bar{C}_{i,j}$) by the sum of the values on all rows of column j where n is the total number of comparable elements:

$$\bar{C}_{i,j} = \sum_{l=1}^{n} \frac{C_{i,j}}{C_{l,j}}, \quad i, j \in \{1, \dots, n\}. \tag{3.1}$$

Weights $C_{w,i}$ for a criterion on row i are then computed as the average of the normalized values $\bar{C}_{i,j}$ across the total number of comparable elements n on that row:

$$C_{w,i} = \sum_{j=1}^{n} \frac{\bar{C}_{i,j}}{n}, \quad i \in \{1, \dots, n\}. \tag{3.2}$$

The vector of weights is called priority vector or 'normalized principle Eigenvector' (Kumru and Kumru, 2014). An eigenvector is computed based on the normalized judgement matrix.

However, inconsistencies might arise when many pairwise comparisons are performed (i.e. high number of criteria). For example, if a decision-maker evaluates criterion C_1 as more important than criterion C_2 and criterion C_2 more important than criterion C_3, an inconsistency arises if criterion C_3 is assessed as more important than criterion C_1. The purpose of matrix consistency is to ensure that the judgement is rational and avoid conflicting results.

Before computing the Consistency Ratio (CR) of the consolidated pairwise comparison matrix, the maximum eigenvalue λ_{max} needs to be calculated. This eigenvalue is defined as the average of the ratios obtained from the weighted sum on row i and the corresponding criterion weight $C_{w,i}$. Here, the weighted sum is defined as the sum of the relative importance values $C_{i,j}$ multiplied by the corresponding criterion weight $C_{w,i}$ over the columns j of row i. Hence, λ_{max} is computed as:

$$\lambda_{max} = \sum_{i=1}^{n} \frac{\lambda_i}{n}, \quad \text{with } \lambda_i = \sum_{j=1}^{n} \frac{C_{i,j} C_{w,j}}{C_{w,i}}. \tag{3.3}$$

Note that $\lambda_{max} \geq n$ and $\lambda_{max} - n$ measures the deviation from the judgements from the consistent approximation. A Consistency Index (CI) is then calculated as:

$$CI = \frac{(\lambda_{max} - n)}{n - 1}. \tag{3.4}$$

Finally, the Consistency Ratio (CR) is obtained by dividing CI by the Random Index (RI) associated with the number of comparable elements n with values as displayed in Table 3.1 (Saaty, 1980a), i.e.,

$$CR = \frac{CI}{RI}. \tag{3.5}$$

Table 3.1: The RI values

No. Elements	1	2	3	4	5	6	7	8	9	…
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	…

For each criterion, performance values $X_{m,n}$ obtained for criterion n and signalling alternative m have been normalized ($\bar{X}_{m,n}$) with respect to the maximum (for beneficial criteria) or the minimum (for non-beneficial criteria) value over all the signalling alternatives:

- For beneficial criteria: $\bar{X}_{m,n} = X_{m,n} / \max_l(X_{l,n})$.
- For non-beneficial criteria: $\bar{X}_{m,n} = \min_l(X_{l,n}) / X_{m,n}$.

Finally, the ranking of alternatives is obtained by computing the weighted MCA performance scores P_m (3.6) defined as the weighted sum (by the criterion weights $C_{w,n}$) over the total number Nc of criteria n per signalling alternative m, for a given market segment.

$$P_m = \sum_{n=1}^{Nc} \bar{X}_{m,n} \cdot C_{w,n}. \tag{3.6}$$

3.3.3 A hybrid Delphi-AHP approach

The hybrid Delphi-AHP approach aims at combining the Delphi technique with the AHP MCDM method described in Sections 3.2.2 and 3.3.2. This technique has been traced in many research areas such as project management (Lee and Kim, 2001), logistics (Cheng et al., 2008), shipping (Lee et al., 2014), forecasting (Mishra et al., 2002) and safety (Chung and Her., 2013). However, to the best of our knowledge, it has not been used in the railway sector. Arof (2015) showed that usually the number of participants involved in a Delphi survey is different than those involved in an AHP survey. The number of panellists generally depends on the level of expertise required, the availability of experts and their willingness to participate in the study.
In this study, the Delphi technique has been used for a double purpose. First to identify the most prominent criteria with respect to the AHP goal, second to evaluate a consistency check in the pairwise comparison matrix of the AHP technique.

The advantages of this hybrid technique include:

- The possibility of conducting the analysis without needing a minimum required number of participants.
- Collaboration among multidisciplinary experts in selecting and assessing the different criteria.
- Suitability for geographically dispersed experts thanks to the globalised nature of railway transport operations.

The adopted approach ensures the following:

- In-depth cooperation among Subject Matter Experts (SMEs) who are willing to contribute to the study, given the number of rounds involved to reach consistent results.
- Better focus in selecting the most prominent criteria with respect to the investigated study.
- A more flexible compilation and assessment of the matrix for relative criteria importance.
- A more objective calibration of criteria weights due to comparison between all possible pairs of identified criteria.
- Less biased decisions even when experts are from different backgrounds due to the controlled feedback on the AHP matrices and the share of statistical aggregation of group responses.

3.4 Operational scenarios and criteria

Five market segments are defined by the Shift2Rail Joint Undertaking Multi-Annual Action Plan (S2R JU MAAP, 2015), namely high-speed, mainline, regional, urban and freight. Operational scenarios are used to compute the quantitative criteria listed in Section 3.3. They are based on different combinations of train manoeuvres (with or without stops) and configurations of the signalling system. We consider three types of train manoeuvres, namely on a plain line, at a merging junction or a diverging junction (Figure 3.4). The combination of manoeuvres, stopping patterns and system configurations is based on the defined market segment. For instance, the infrastructure layout of the urban market segment is usually simplistic (i.e. very few junctions or crossings), and metro trains stop frequently on the line. Therefore, for this specific market segment, we only consider the plain line manoeuvre with stopping patterns. For the regional market, trains indeed stop frequently but the infrastructure layout is more complex than the one for the urban market, as it also includes merging and diverging junctions. For stopping train manoeuvres, both trains will dwell at the station for the case of a plain line (M1). In the case of the merging junction (M2), the station is assumed to be located 500 meters from the switching point where both trains will be stopping. In the case of the diverging junction (M3), the leading train (i.e. train in front) stops at the station located 300 meters from the switching point and the follower carries on over the other track overtaking the leader while this latter is dwelling at the station. Configurations selected for the signalling systems are instead based on a combination of three main design variables typical of a given signalling system and/or the selected market segment. Those design variables are the safety margin (SM), the system update delay or system reaction time (ΔT) and the setup time (ts) to change the switch in the desired direction if needed, set and lock a route. More details on the definition of operational scenarios and each of the design variables can be found in MOVINGRAIL (2020).

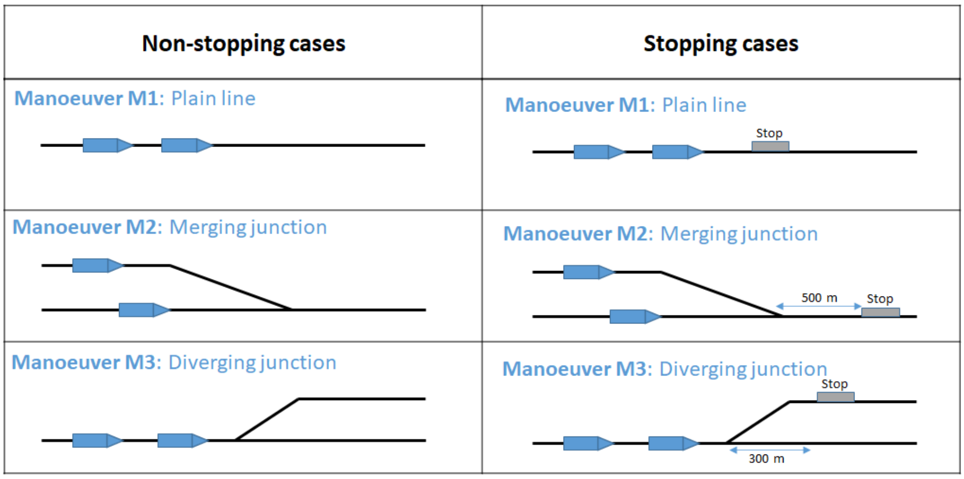

Figure 3.4: Manoeuvres for investigating the benefits of Virtual Coupling over previous railway signalling systems

In this chapter, a total of 66 operational scenarios are analysed. In the MCA, the comparison between MB and VC has been carried out mainly referring to differences in the signalling equipment, hence excluding potential extra investments which might be thought of under VC to expand the fleet size. Rolling stock investment costs are hence considered the same for both MB and VC. VC could operate a more frequent train service by using the same fleet size of ETCS L3 and by having a shorter composition (e.g. a train composed by a single MU rather than two coupled MUs as operated under MB).

The baseline system configuration is the conventional signalling system currently installed for a given market segment. For the mainline, regional, urban and freight markets, we refer to a three-aspect fixed-bock signalling. For the high-speed segment, the baseline signalling system is ETCS L2. In the MCA (Section 3.5), the alternative system configuration S1 refers to the migration from a baseline system configuration to ETCS L3 MB signalling system while the alternative system configuration S2 corresponds to the migration from baseline to VC. The number and distribution of the operational scenarios among manoeuvres and system configurations for each market segment are summarized in Table 3.2.

Table 3.2: Definition of operational scenarios for each market segment

Market Segment	No. Operational Scenarios	Manoeuvres	Stopping Trains	System Configurations
Urban	3	Plain	Yes	3-Aspect, ETCS L3, VC
Regional	9	Plain, Merging, Diverging	Yes	3-Aspect, ETCS L3, VC
Mainline	18	Plain, Merging, Diverging	Yes and No	3-Aspect, ETCS L3, VC
High-speed	18	Plain, Merging, Diverging	Yes and No	ETCS L2, ETCS L3, VC
Freight	18	Plain, Merging, Diverging	Yes and No	3-Aspect, ETCS L3, VC

3.4.1 Quantitative criteria

The evaluation of the defined quantitative criteria for the different signalling alternatives are reported from Section 3.4.1.1 to Section 3.4.1.5.

3.4.1.1 Infrastructure capacity

Capacity is the maximum number of trains that can operate with a chosen level of service on a section of infrastructure during a period. The level of service is determined by the imposed traffic and the operational condition for a given timetable. So capacity depends on both the timetable and the infrastructure. The classical method to determine the capacity is the timetable compression method from the UIC Code 406 (UIC, 2013), which reveals the excess buffer time in a timetable. We estimate the impact on capacity with VC by considering no changes in the infrastructure.

However, the change of the infrastructure can be calculated via the occupation time as the signalling principles must change to accompany VC. The occupation time of a small infrastructure section can be seen as "atoms" of a timetable. One atom contains a change in a time-speed-distance diagram from the blocking-time theory (Hansen and Pachl, 2014). The combination of atoms will then form manoeuvres (Figure 3.5). The combination of manoeuvres with operational parameters are then operational scenarios where a headway between the involved trains can be calculated. Preliminary aspects of manoeuvres and operational scenarios can be found in Aoun et al. (2020a, 2020b). The manoeuvres (Figure 3.4) can then be used to represent the component of a timetable in the capacity assessment. The impact of VC and MB on infrastructure capacity is then expressed in terms of the minimum headway computed as the minimum time between two consecutive trains which allows for the safe completion of their manoeuvres over a given infrastructure location. For example, in the diverging junction illustrated in Figure 3.5, the minimum headway is computed for a reasonable reference point between the fronts of two trains; in this case, the danger point at the turnout. Next, the decisive point was determined, by marking where the rear of the first train clears the turnout. From the decisive point, the calculation occurred in two directions. Forward via the train length and along the braking curve. Backwards starting with the length of the turnout, the safety margin, the absolute braking distance, adding the time components of the system time to clear the signal and the reaction time for the train to acknowledge information and further along the running curve.

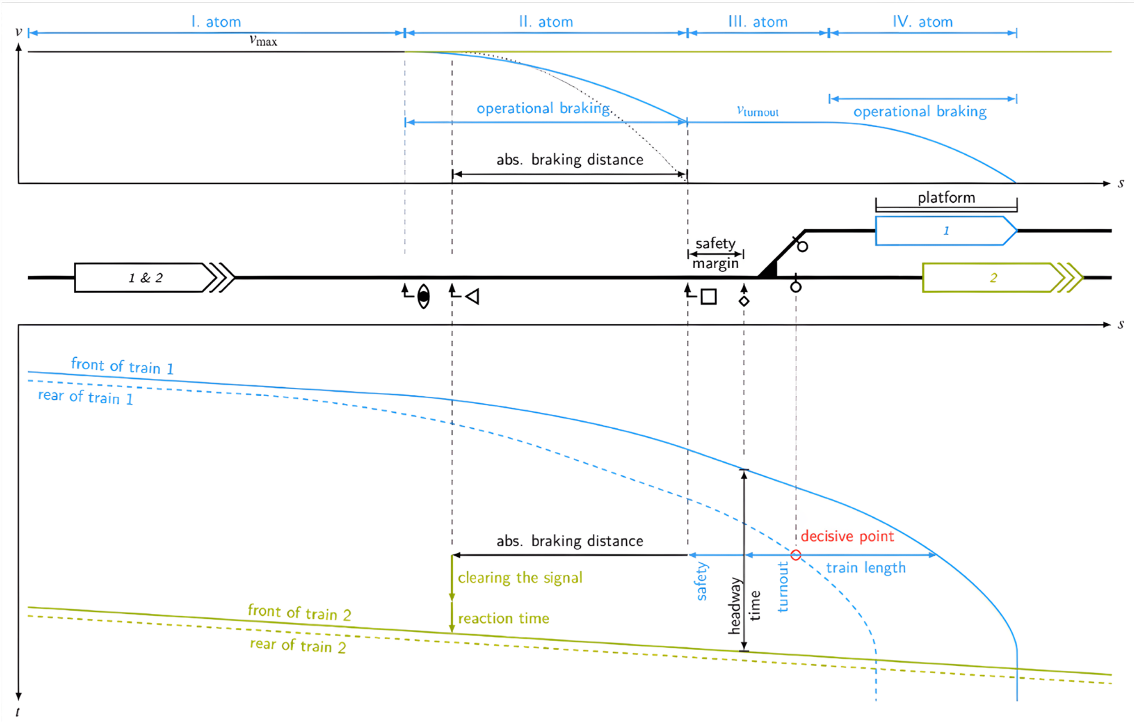

Figure 3.5: Diverging junction manoeuvre with stopping case including atoms, speed-distance diagram, time-distance diagram and blocking-time theory

A capacity index $I_{cap}(S_k)$ has been defined to compare capacity effects of the signalling alternatives S_k (for $k = 1,2$) versus the baseline S_0. The capacity index is used in the MCA results (Section 3.5) and represents the reciprocal of the ratio between the minimum headway H_i of operational scenario i for signalling alternative S_k and baseline S_0, averaged over the total number of operational scenarios N_k applicable to S_k, i.e.,

$$I_{cap}(S_k) = N_k \left(\sum_{i=1}^{N_k} \frac{H_i(S_k)}{H_i(S_o)} \right)^{-1}, \qquad k \in \{1,2\}. \tag{3.7}$$

3.4.1.2 System stability

System stability is evaluated based on the UIC Code 406 recommendations (UIC, 2013) on maximum thresholds of occupation time to have stable train operations on a given market segment. In this study, we aim at deriving a generic measure for system stability for the various market segments without focusing on a case-specific infrastructure layout or timetable. Therefore, we define here a stability index based on an average minimum headway over the various operational scenarios defined in Section 3.4 and a given typical train frequency per hour. For each market segment, it is considered that an hourly timetable runs the same amount of trains that are currently operated in the peak hour on the representative case study corridors (Section 3.5.1). A compressed timetable has been obtained for the baseline S_0 and the two futuristic signalling alternatives, S_1 for ETCS L3 and S_2 for VC, based on minimum line headways computed for the different manoeuvres and stopping patterns in Section 3.4.1.1. Specifically, for both stopping and non-stopping train patterns, an average minimum line headway has been calculated as a mean value across all manoeuvres.

The average minimum line headways have been used to compress the hourly timetable according to the UIC Code 406 and to calculate a corresponding average infrastructure occupation rate. A stability index $I_{stability}$ is considered the complementary of the infrastructure occupation rate, averaged over all of the operational scenarios:

$$I_{stability}(S_k) = 1 - \frac{1}{N_k}\sum_{i=1}^{N_k}\frac{N_T H_i(S_k)}{3600}, \quad k \in \{0,1,2\}. \tag{3.8}$$

The stability index is computed for each of the signalling systems S_k considering the total number of train services N_T operating in a reference hour multiplied by an average minimum line headway across all the operational scenarios $i \in \{1, \dots, N_k\}$ applicable to S_k. The minimum headway times $H_i(S_k)$ of each operational scenario i in signalling system S_k are computed in seconds, so the division by 3600 translates the minimum headways to a fraction of an hour (3600 s). The stability index can also be given in percentage by multiplying them by 100%.

3.4.1.3 Lifecycle costs

Lifecycle costs refer to the entire cost to install (CAPEX) and operate (OPEX) a signalling alternative. Estimates for investment costs (CAPEX) have been assessed based on reference unit costs provided based on field knowledge of Park Signalling Ltd. as a signalling system supplier, as well as from official national/international sources and specific literature on unitary expenditures for railway personnel, maintenance and energy. Assessments relative to operational costs (OPEX) derive from projections relying on available cost data for MB signalling mainly adopted in urban areas, e.g. Communication-Based Train Control (CBTC), and official reports on unitary costs for track and rolling stock maintenance, as well as personnel salaries. Energy provision expenses instead refer to average unitary kWh costs in Europe as reported by Eurostat (2019). Both CAPEX and OPEX items have been assessed to migrate the baseline signalling system S_0 to either ETCS L3 (Signalling alternative S_1) or VC (Signalling alternative S_2). For both types of signalling migration (i.e. S_0 to S_1 and S_0 to S_2 (via S_1)), costs include fees for approval and deployment authorisation from Railway Regulatory Bodies ranging between €300M and €360M (Network Rail, 2016). An average of €330M has been used in this analysis.

Capital costs (CAPEX)

The capital expenditures have been computed for each market segment based on the number of multiple units (MUs) composing a trainset for each case study. The total number of multiple units (N_{MU}) needed to operate the railway service for the baseline, the MB and VC signalling systems has been computed based on the following equation:

$$N_{MU} = \frac{2\,T_r + 2T_w}{H_S}\,N_{MU_{train}}. \tag{3.9}$$

The waiting time of rolling stock to turn around at terminal stations (T_w) is considered 15 minutes for all cases, whereas the scheduled one-way running time (T_r) and the number of MUs per train formation ($N_{MU_{train}}$) depend on each case study (Section 3.5.1). The scheduled service headway (H_S) for a given signalling system has been assumed to be corresponding to the line headway of a typical railway network with a varied infrastructure topology including plain lines, merging and diverging junctions. By setting the scheduled headway equal to the line headway, it is possible to identify the maximum number of MUs that are required when the network is utilized at its maximum capacity. Based on this assumption, the service headway considered for the computation of MUs coincides with the most critical train headway across all manoeuvres calculated for the infrastructure capacity scenarios (Section 3.4.1.1) for a given signalling system. As mentioned before, we consider the same fleet size, therefore the same number of MUs for both ETCS L3 and VC so to compare these systems only from the differences in terms of installation costs for the signalling equipment. It should be noted that for the practical number of multiple units required to operate a railway service, it is necessary to increase the number of MUs provided by the above equation by 10% to consider additional spares for facing unforeseen failures, and by another 20% for spares to allow vehicles in the depot for ordinary maintenance.

Operational costs (OPEX)

The operational expenditures (OPEX) are computed based on four components: the average infrastructure maintenance, the average rolling stock maintenance, the energy provision and personnel wages. Since operational costs are held on a yearly basis over the lifecycle of a signalling alternative, the computation has considered discounting of future costs by using a yearly discount rate of 5% over a total lifecycle period of 30 years.

- The average infrastructure maintenance costs are considered to be the same as ETCS Level 3 MB, i.e. €1.7k/km (European Commission, 2019), unless there is a significant change to point equipment. Track/infrastructure maintenance costs may be however increased through greater wear from increasing capacity. For three-aspect signalling, the average cost of infrastructure maintenance is considered €2.0k/km whereas for ETCS Level 2, the cost is €1.8k/km.
- The average rolling stock maintenance costs $C_{RSmaint}$ are computed as:

  $$C_{RSmaint} = CU_{RSmaint} \cdot D_{oneway} \cdot O_{RS} \cdot \frac{60}{T_r + T_w} N_{MU_{train}}, \tag{3.10}$$

  where $CU_{RSmaint}$ is the average rolling stock maintenance cost per kilometre, D_{oneway} is the one-way travelled distance, and O_{RS} is the number of rolling stock operating hours on average in one day. The variables T_r and T_w represent the scheduled running time and waiting time for turning around at terminals respectively, and $N_{MU_{train}}$ is the number of MUs per single train formation.
- The energy provision costs C_{Ep} are considered per train service and computed as:

  $$C_{Ep} = CU_{Ep} \cdot D_T \cdot N_T \cdot N_O, \tag{3.11}$$

  where CU_{Ep} is the unitary electricity cost per train/km, D_T is the total travelled distance by a train service in 1 hour, N_T is the number of train services operated in an hour and N_O is the number of operating hours in one day.

  Unit costs per km for rolling stock maintenance ($CU_{RSmaint}$) and electricity (CU_{Ep}) have been collected by official sources and available literature, and have been accordingly discounted based on yearly inflation rates starting from the source documentation year. The number of working/operating hours is considered 18 per day with a 15 minutes waiting time at terminal.

- Average personnel salaries have been computed by referring to the European Benchmarking of the rail Infrastructure Managers-IMs (Office of Rail Regulation, 2012), as well as the costs, performance and revenues of Great Britain (GB) Train Operating Companies-TOCs (Baumgartner, 2001). For all market segments, salary costs for a conductor are considered 20% less than those of a driver. For the baseline and ETCS L3 scenarios, one driver and two conductors are assumed in the computation, whereas for VC, the driver cost is removed given that the driver will be replaced by automatic train operation.

3.4.1.4 Energy consumption

Consumed energy has been computed in terms of mechanical power by microscopic simulations of representative traffic for each market segment and signalling alternative by using the simulator EGTRAIN (Quaglietta, 2014). The energy consumption has been measured in terms of an energy consumption index $I_E(S_k)$ defined as the average across the total number of operational scenarios N_k of the ratio between the unitary train energy consumption per km $E_i(S_k)$ for a scenario i of a signalling alternative S_k with respect to the baseline signalling system S_0:

$$I_E(S_k) = \frac{1}{N_k}\sum_{i=1}^{N_k}\frac{E_i(S_k)}{E_i(S_0)}, \quad k \in \{1,2\}. \tag{3.12}$$

EGTRAIN has been used to compute train energy consumption by considering two trains following each other under a given signalling alternative. Simulation experiments have referred to typical rolling stocks circulating on the representative case studies used for each market segment (Section 3.5.1), in line with the input data used for capacity computation in Section 3.4.1.1.

3.4.1.5 Travel demand

Travel demand distribution is forecasted by means of a statistical analysis based on stated travel preference surveys distributed over a sample of 229 interviewees for the passenger-related case studies and of 47 SMEs for the freight case, to capture potential modal shifts to railways that the introduction of MB and VC could lead to. More than half of the respondents (54.5%) aged between 22 and 35 years old, followed by 18% for the age range 36-40 and 16.6% for people between 18 and 21 years old. Most interviewees were males (71.5%) and less than one-third were females. Almost half (49%) were students or PhD candidates, followed by 37% of employers/employees and 10% of teachers and professors. We have asked the interviewees in the survey if they had any advanced knowledge or expertise in railways and 40% said yes. By aggregating stated travel preferences, the resulting modal shifts have been computed for each of the case studies (Section 3.5.1) in the current and future transport scenarios.

Modal preferences for ETCS L3- and VC- enabled train services consider a certain headway decrease with respect to the baseline signalling system extracted from Quaglietta et al. (2020). Train services equipped with ETCS L3 impose a 10% increase in ticket fares whilst for VC the increase is 20%. For ETCS L3 MB, the headway reduction is 50% compared to the baseline signalling system that considers three-aspect signalling on mainline, regional and urban market segments. The baseline configuration for high-speed railways is ETCS L2 with a headway reduction of 47% if ETCS L3 is implemented. For VC, the headway decrease is of 63% compared to three-aspect signalling and of 61% compared to ETCS L2 (Quaglietta et al., 2020).

In the MCA results (Section 3.5.2.5), we consider an aggregation of travel demand shares that would shift from all other motorized modes of transport (i.e. car, bus/coach and/or airplane for the passenger-related markets, and truck for the freight market) to railways in the case of no ticket cost increase for using a train service enabled by either ETCS L3 or VC. A more detailed analysis on the demand trends of both ETCS L3 and VC with an increase in ticket fees can be found in Aoun et al. (2020b).

As an additional investigation, based on the modal shifts from motorised transport modes that a certain railway signalling alternative would induce, environmental impacts have also been measured in terms of CO_2 emissions. For each market segment, savings in CO_2 have been computed based on the modal shifts for using more frequent train services under the two signalling alternatives (with no increase in ticket fees). Initial values of CO_2 emissions for each case study have been extracted from publicly available online sources such as EcoPassenger (2020), CostToTravel (2020) and the UK government (2019).

3.4.2 Qualitative criteria

Three criteria were evaluated qualitatively using a Delphi technique where 15 railway SMEs – from both academic institutions and railway companies– have been asked to predict and evaluate the issues which might influence the feasibility and deployment of MB and VC signalling. The following three sub-sections describe the methods used to assess the qualitative criteria.

3.4.2.1 Safety

The level of safety and the perception of safety were evaluated through a survey of stakeholders and experts who were asked to rank the significance based on a number of statements. The values were grouped in tables that show the evaluated priority levels and the likelihood of the defined safety issues for being solved in the next five years. The higher the number, the higher the priority of the issue. Likewise, an evaluation of 5 indicates confidence (from the individual that made the entry) that the issue will be resolved or closed out within five years. By gathering this data, the arithmetic mean of the numerical assessments was computed. A further feature of this analysis was measured by looking at the standard deviation of the inputs.

The values used in the MCA results (Section 3.5.2.6) are based on the safety index I_{safe} computed in (3.13), where $S_{5,safe}$ is the mean score defined for the likelihood of safety issues to be solved in the next five years and $S_{Pr,safe}$ is the assessed priority mean score of all safety issues. A similar/analogous indicator is used for public acceptance and regulatory approval in Sections 3.4.2.2 and 3.4.2.3, respectively.

$$I_{safe} = \frac{S_{5,safe}}{S_{Pr,safe}}. \tag{3.13}$$

3.4.2.2 Public acceptance

The question of public acceptance and regulatory approval is closely related to safety as the benefits that flow from VC will in effect be automatically banked or assumed to work by the public and passengers, while any realization of the potential risks could influence the public to have a low tolerance of technical failures. The interviewees were asked to provide scores for the priority of each public acceptance issue as well as its likelihood to be solved within five years.

The values used in the MCA results (Section 3.5.2.7) are based on the public acceptance index I_{pubacc} computed in (3.14). $S_{5,pubacc}$ is the mean score defined for the likelihood of public acceptance issues to be solved in the next five years and $S_{Pr,pubacc}$ is the assessed priority mean score of all public acceptance issues.

$$I_{pubacc} = \frac{S_{5,pubacc}}{S_{Pr,pubacc}}. \quad (3.14)$$

3.4.2.3 Regulatory approval

Stakeholders were asked to identify potential issues and barriers to regulatory approval, and then the potential interventions that would help to secure or promote regulatory approval. Given that railways have always been controlled through mechanisms that are designed around maintaining safe braking distances between trains, it is non-trivial to ask regulators to accept that this fundamental signalling principle can be modified. However, the thinking that has gone into the development of VC is recognised as an innovation that could achieve benefits for the railway and its users. An evaluation of the factors that will have an impact on the safety of the system, involving the regulatory community directly, could therefore get to the position where the basic principle can be proposed for amendment through the Technical Specification for Interoperability (TSI) and Standards development processes.

The values used in the MCA results (Section 3.5.2.8) are based on the regulatory approval index $I_{regappr}$ computed in (3.15). $S_{5,regappr}$ is the mean score defined for the likelihood of regulatory approval issues to be solved in the next five years and $S_{Pr,regappr}$ is the assessed priority mean score of all regulatory approval issues.

$$I_{regappr} = \frac{S_{5,regappr}}{S_{Pr,\,regappr}}. \quad (3.15)$$

3.5 MCA results for Moving Block and Virtual Coupling

3.5.1 Case studies

Five market segments are defined by the S2R JU MAAP (2015). In this chapter, we consider five case studies corresponding to a specific corridor in Europe for each of the market segments:

1. For high-speed: Rome-Bologna (Italy) – 305 km;
2. For mainline: London Waterloo-Southampton on the South West Main Line (United Kingdom) – 127 km;
3. For regional: Leicester-Peterborough on the Birmingham-Peterborough line (United Kingdom) – 84 km;
4. For urban: London Lancaster-London Liverpool Street on the London Central Line (United Kingdom) – 7 km;
5. For freight: Rotterdam-Hamburg (between the Netherlands and Germany) – 503 km.

The values adopted in this chapter for maximum speed, block section length, three design variables (i.e. safety margin, system reaction time and setup time), and three headway variables (i.e. turnout branch speed, turnout length and dwell time) are displayed in Table 3.3 for each market segment. The system configurations represent the migration from the baseline signalling system S_0 (ETCS L2 for high-speed and 3-aspect block signalling otherwise) to either ETCS L3 (Signalling alternative S_1) or VC (Signalling alternative S_2). In our study, we have made the assumption to have the same safety margins for both MB and VC to keep the capacity comparison of these two signalling systems consistent. In this way, we were able to assess the impact of the reduction in train separations just due to the transition from an absolute braking distance in MB to a relative braking distance under VC, while keeping the same SM. The design variables are assumed and used to analyse the operational scenarios defined in Section 3.4 whilst the other parameters are input for the infrastructure capacity computation.

Table 3.3: Values of parameters and design variables for each market segment

Market segment	Maximum speed (km/h)	Block section length (m)	Safety margin (m)	Sight reaction time (s)			Setup time (s)	Turnout branch speed (km/h)	Turnout length (m)	Dwell time (s)
Syst. Config	S0,S1,S2	S0	S1,S2	S0	S1	S2	S0,S1,S2	S0,S1,S2	S0,S1,S2	S0,S1,S2
High-speed	300	5000	200	2	2	2.02	9	130	140	240
Mainline	160	1000	120	4	2	2.02	8	80	76	60
Regional	120	700	100	4	2	2.02	7	60	63	60
Urban	80	400	80	4	2	2.02	5	80	76	30
Freight	100	1000	100	4	2	2.02	7	60	63	120

3.5.2 Criteria assessment per market segment

3.5.2.1 Infrastructure Capacity

The method from section 3.4.1.1 was used to calculate the capacity gain for VC for each manoeuvre. The calculation was done via the headway times with the maximum utilization of the infrastructure. The decisive point in the time-distance diagram was determined for the headway times (Figure 3.5). The outcome of this procedure is a compressed path-time calculation of two trains in one operational scenario without any buffer time. All results should be considered carefully since the infrastructure in front and behind the manoeuvres was neglected.

Figure 3.6a compares the capacity indexes of ETCS L3 MB and VC per market segment based on Equation (3.7). VC provides relevant capacity improvements over MB for mainline railways (+14%), freight lines (+13%) and high-speed (+11%). VC would have a positive homogenising effect on mainline railways due to the possibility for trains to follow each other in synchronised platoons. For high-speed railways, VC can provide significant capacity benefits for following train movements. However, headway reductions due to VC are only marginal (in the order of 10 s) with respect to ETCS L3, if stopping high-speed trains on a plain line are separated by a relative braking distance. Significant headway reductions (up to 1 min) are instead observed when high-speed trains can move synchronously at a quasi-constant separation in a coupled platoon, as the headway comparison between VC and ETCS L3 shows for the plain line manoeuvre with non-stopping trains (Table 3.4). Train platooning can be also particularly beneficial for freight trains which usually have non-stopping operations. Despite the relatively low running speeds, VC can still provide capacity gains over MB thanks to platooning where trains can keep synchronous stable movements over long distances with relative braking distances. For the regional and the urban segments, VC only shows a little capacity improvement of 1.8% for the former and 5.8% for the latter. This is mainly due to frequent stopping and low operational speeds where a relative braking distance separation would not significantly reduce headways with respect to an absolute braking one. For these two markets, VC could still be beneficial over MB due to platooning, thus enabling stable cooperative operation. However, given the short interstation distances and the frequent stopping patterns of these railway segments, composition/decomposition of platoons would need to occur when trains are at a standstill at stations instead of coupling/decoupling operations on-the-run (i.e. as is the case for manoeuvres with non-stopping patterns). This also entails that the first deployment of VC could be made on these two market segments since they would only require algorithms for synchronous train movements, instead of additional algorithms for controlling trains when shifting between absolute and relative braking distance under VC signalling.

Table 3.4: Headway times of the operational scenarios and their change for different signalling systems compared to current technology

	Minimum headway times per market segment (s)											
Market segment	**High-Speed**						**Mainline**					
Manoeuvres	**Plain**		**Merging**		**Diverging**		**Plain**		**Merging**		**Diverging**	
Stopping patterns	✔	✘	✔	✘	✔	✘	✔	✘	✔	✘	✔	✘
Baseline	481.2	134.9	418.4	99.5	205.9	80.7	182.5	62.3	191	72.4	56.1	55.8
ETCS L3	334.1	74	332.2	92.3	200.9	75.7	133.2	46.5	125.8	56.2	53.3	53.1
VC	329.8	11.4	326.1	92.3	200.9	75.7	130.2	12.3	120.1	56.2	53.3	53.1

	Minimum headway times per market segment (s)									
Market segment	**Regional**			**Urban**	**Freight**					
Manoeuvres	**Plain**	**Merging**	**Diverging**	**Plain**	**Plain**		**Merging**		**Diverging**	
Stopping patterns	✔	✔	✔	✔	✔	✘	✔	✘	✔	✘
Baseline	156	163.1	64.3	114.4	350.1	103.4	357.4	114.9	212.4	90.1
ETCS L3	112.5	105	56.8	84.2	284.4	81.8	270.1	86.2	211.4	89.1
VC	110.7	100.4	56.8	79.6	276.9	27.2	258.2	86.2	211.4	89.1

✔: Stopping trains
✘: Non-stopping trains

3.5.2.2 System stability

As can be seen in Figure 3.6b, MB can greatly improve system stability over the baseline signalling systems for all market segments. Particularly significant is the increase in stability for the urban market where the high frequency service strongly requires MB operations to avoid capacity saturation that occurs if a three-aspect fixed-block signalling system is adopted. VC can provide a further improvement to MB system stability –computed by Equation (3.8)– which is however marginal with respect to stability gains that MB brings over baseline signalling. The biggest stability enhancements brought by VC over MB are observed for the urban (+12%) and the mainline (+5%) market segments. This is because those two markets are characterised by a high number of hourly trains where delays are easily propagated in a snow-ball effect. Reducing the safe separation from an absolute braking distance to a relative braking distance would therefore contribute to further mitigate delay transmission. VC could improve by 5% MB stability for the freight market and by only 2% for the high-speed market. However, system stability gains for VC over MB are much higher when considering only following movements in a platoon of virtually coupled trains (where the corresponding headway is given by the plain line manoeuvre with non-stopping trains). In the case of the regional segment, VC does not provide any practical stability improvement over MB (only 0.3%), mostly because of a combined effect of the lower number of hourly regional train services (much lower than the urban market) and the low speeds that make differences between absolute and relative braking distance only marginal.

3.5.2.3 *Lifecycle costs*

The total deployment costs for ETCS L3 are lower than VC given that the latter signalling system requires the installation of additional intelligent software solutions such as automation, European Vital Computer (EVC) software upgrades and the V2V communication layer. Railway Authority deployment costs and infrastructure costs represent the highest share of CAPEX where the latter depend on the distance between a specific origin and destination (see Section 3.5.1 for the case studies considered in this chapter). However, the technological upgrades for VC would only be up to 11.5% higher than the costs of migrating from baseline to ETCS L3. This percentage was found based on the analysis discussed in Section 3.4.1.3. Total operational expenditures for VC are a few thousand euros lower than MB for all market segments, given the reduced number of crew which is needed to operate a train because of the automation. This means that similar operational costs to VC could be achieved when deploying automatic train operation over plain MB. Differences in lifecycle costs of the two signalling alternatives are very limited since total migration costs from baseline to ETCS L3 or VC are almost the same (Figure 3.6c).

3.5.2.4 *Energy consumption*

Values of the energy index (Figure 3.6d) show that on average VC can slightly reduce energy consumption with respect to MB. If under VC a train slows down to cruise at a lower speed, then the train behind has the possibility to slow down and cruise synchronously with the train ahead. Under MB when a train slows down to cruise at a lower speed, the train behind will initially decelerate as it approaches the End of Authority and then will reaccelerate to the maximum allowed speed instead of cruising at the same speed of the train ahead (unless optimal control algorithms manage the traffic). This behaviour might hence cause repetitive braking/acceleration phases that make MB more energy consuming than VC which has a movement control paradigm between trains in the same convoy.

3.5.2.5 *Travel demand*

For the high-speed case study, it is clear in Figure 3.6e that a significant modal shift from other modes of transport would already happen with the introduction of ETCS Level 3 MB (38%) while VC would only lead to an additional 4% (for a total of 42%). This is because a 15 minutes headway in the current situation (Rome-Bologna) was already satisfying to most respondents, while the service frequency increase proposed by VC was only slightly higher than the one of ETCS L3. Similar results are observed for the mainline and urban railways, where VC would only bring an additional modal shift of 7.8% and 7.1% with respect to ETCS Level 3, respectively. Almost all interviewees who would shift from other modes to VC for the mainline and the urban markets, stated that one of the main reasons behind that would be the possibility of availing of a service that is on-demand or better adaptable to passengers' travel needs. Remarkable results are observed for regional trains where VC could increase the modal shift by 19% over ETCS L3 MB. This is because of the unsatisfactory level of the currently delivered regional service from Leicester to Peterborough, which encourages interviewees towards a service that could be better adapted to an on-demand paradigm or more effectively respond to daily demand variations. Also for the freight market, VC is considered more beneficial than ETCS L3 MB given that a more flexible freight service could be delivered with self-propelled units that could couple/decouple at merging/diverging junctions to reach delivery destinations of the different commodities more efficiently. Results show that a total of 46.6% of the respondents would consider shifting from road trucks to trains in the case of VC signalling (Figure 3.6e).

Based on Section 3.4.1.5, CO_2 emissions results showed that the introduction of ETCS L3 might bring today's emissions down to 70.2% for cars, 67.2% for buses, 62.5% for planes and 70% for trucks. This brings to an expected reduction of today's CO_2 emissions by 36.5% on average across all motorised transport modes. The deployment of VC would instead contribute to an even deeper reduction of today's emissions to 61.7% for cars, 58.1% for buses, 57.8% for planes and 53.4% for trucks. Current CO_2 emissions could be therefore reduced by 42% on average across all motorised transport modes with the introduction of VC, which would greatly help in achieving the goal set for 2050 by the EC white paper on transport (European Commission, 2011) of 60% reduction in Green House Gases (GHG) emissions from transport.

3.5.2.6 Safety

There was near unanimous agreement among stakeholders that the key risk to achieve public and regulatory acceptance is in the safety of VC, and that a wrong side failure during development/testing/early deployment could undermine public and regulatory confidence. There is also awareness that the technical trade press will be very interested in the development phase, and will focus on how confident the solutions will be effective and 'fail safe'.

The main identified safety issues include harmonised non-functional requirements on train integrity, the risk of having trains not being able to stop within their MAs, having MAs exclusively issued for a given section of track for only one train at a time, and the reliability of the communications system. In addition, stakeholders identified as a major issue the central coordination of the switching system in software to find dynamically the appropriate balance between capacity utilization, safety and energy consumption, together with system behaviour and operations defined for degraded situations.
The arithmetic averages of the assessments showed that the experts rated the priority for each of the technical issues as very high with a general finding that most stakeholders did not expect the technical issues to be fully resolved within five years. The standard deviation (SD) of the input showed that the experts are much more confident of the nature of the technical issues that need to be resolved and their high importance ($S_{Pr,safe}$), than they are of the likelihood of the issues being resolved in the next five years ($S_{5,safe}$). This observation applies to both MB (SD = 1.16 with a mean of 3.61) and VC (SD = 1.48 with a mean of 3.25). The SD value for VC reflects significant uncertainty in the confidence of experts on the likelihood of achieving solutions within five years. Therefore, the system under VC has a higher demand for safety compared to the system under MB.

3.5.2.7 Public Acceptance

By gathering the data collected from the stakeholder survey, the arithmetic average of the different assessments showed that most experts do not expect the public acceptance issues to be resolved fully within five years. Issues regarded fear of passengers from collisions due to the safety issues whilst remaining unresolved for VC, mainstream media raising fears, public apathy to the benefits of VC, skepticism of the public towards the maturity of platooning in railways vs road sector, or expectations for similar capability, etc. Stakeholders rated the priority for each of the public acceptance issues ($S_{Pr,pubacc}$) as high with an arithmetic mean of numerical assessments equal to 4.1 and a standard deviation of 1.01. Observations reflected uncertainty in the confidence of experts on the likelihood of achieving solutions within five years ($S_{5,pubacc}$) as scores ranged from 1 to 5 for the different introduced issues, resulting in an average arithmetic mean of 3 and a standard deviation of 1.12.

3.5.2.8 Regulatory Approval

Stakeholders identified a number of strategies to achieve regulatory approval, and they all depend upon the assumption that the system as designed will work towards a very high level of reliability and safety, and that there will be no wrong side failures during the full scale testing phase. The regulatory approval issues reported by the stakeholders include safety incidents that have the potential to set back approval, as well as the requirements for headways and the maximum train length of a convoy. In addition, there is a need for a clear system definition and specifications, and a valid testing system through simulation and pilot/prototypes. Another important issue that needs to be solved concerns the description of operations and the sponsorship of specifications/standards throughout EU Processes. Those issues were symbiotically related to safety and public acceptance (e.g. safety challenges due to technical complexity, approval within the European Railway Agency (ERA), etc.). In addition, regulators are unlikely to take risks upon themselves by approving technologies that the public has concerns about.

The key features of the strategies for achieving regulatory approval are early engagement with relevant regulator (EUAR), development of a very clear system definition, development of the specifications and standards that will apply to the system (to enable Notified Body and EUAR sign off), and the ability to test systems in simulation or test track mode to ensure that failures don’t have an impact on railway/customers and public acceptance. There is a low level of confidence that regulatory approval can be gained within five years ($S_{5,regappr}$), with most stakeholders putting the likelihood in the range of 1 (low confidence) to 3 (medium) and a mean value of 2.82. However with a standard deviation of 1.42, the analysis demonstrates a significant variance in the experts’ confidence of achieving regulatory approval.

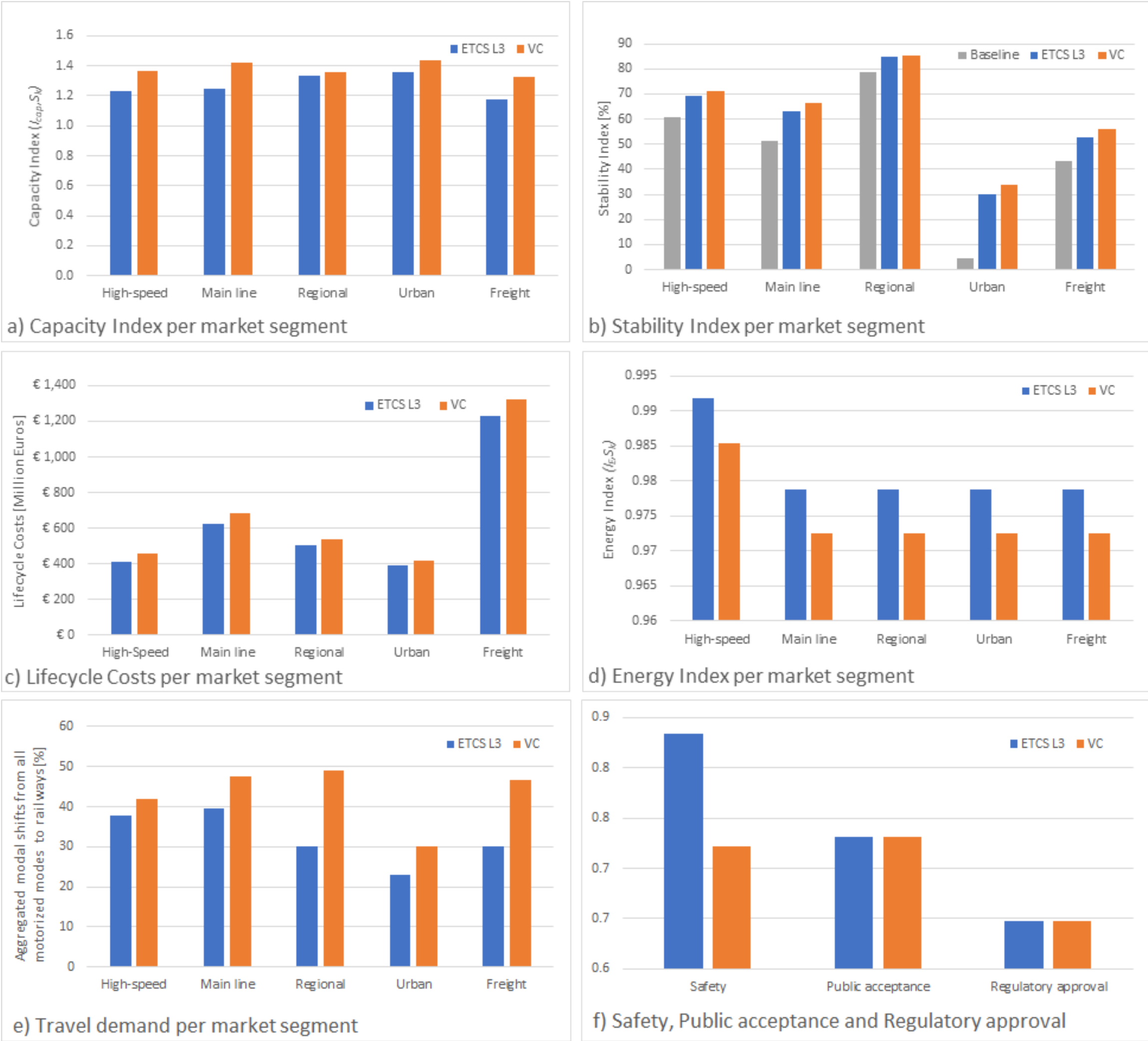

Figure 3.6: Results of criteria assessment

3.5.3 Multi-criteria impact assessment

The multi-criteria analysis of MB and VC has been performed by combining the results obtained for each of the considered criteria and assessing them in a pairwise comparison matrix. This matrix contains relative importance weights among the different criteria as provided by railway experts and stakeholders. The relative importance weights have been collected through surveys of 15 railway SMEs from both academic institutions and railway companies, including experts of the MOVINGRAIL Advisory Board (MOVINGRAIL, 2018). The Delphi-AHP technique has been used to gather a consistent pairwise criteria comparison matrix of relative importance weights where three survey rounds were necessary to achieve a consensus among the experts. The first Delphi survey round started with a workshop gathering railway experts across Europe and members of the MOVINGRAIL Advisory Board. The second round consisted of a follow-up by email to all stakeholders to fill-in matrices of relative criteria importance weights with the objective of providing a matrix with a Consistency Ratio (CR) lower than 0.1. For those experts who did not manage to give a consistent pairwise matrix (i.e. with CR $\leq$ 0.1) at the second round, a third one-by-one email round was needed for the interviewees to adjust their matrices so to be consistent.

According to the hierarchical model defined in Section 3.3.2, the 8x8 pairwise criteria comparison matrix (where the row-column dimensions are given by the eight criteria) with respect to the goal of choosing the appropriate signalling system to each market segment has been built. A geometric mean has been used to consolidate all the consistent pairwise comparison matrices provided by the interviewed railway SMEs. The consolidated pairwise comparison matrix is shown in Table 3.5. The weights of relative criteria importance have been computed based on the hybrid Delphi-AHP technique (see Sections 3.3.3, 3.1), and are given as a ratio between a criterion on the row and a criterion on the column of the matrix using the AHP scale of relative importance as explained in Section 3.3.2.

Table 3.5: Consolidated pairwise comparison matrix

		Infra capacity C1	System stability C2	Lifecycle costs C3	Energy consump C4	Travel demand C5	Safety C6	Public acceptance C7	Regulatory approval C8	Criteria Weights
Infra capacity	**C1**	0.960	1.770	1.000	5.284	2.201	0.142	1.588	0.152	**0.0564**
System stability	**C2**	1.000	2.539	1.042	6.322	1.707	0.117	1.138	0.090	**0.0329**
Lifecycle costs	**C3**	0.394	1.000	0.565	3.503	1.914	0.049	0.634	0.081	**0.0591**
Energy consumption	**C4**	0.586	0.523	0.454	2.783	1.000	0.063	0.848	0.095	**0.0150**
Travel demand	**C5**	0.158	0.285	0.189	1.000	0.359	0.041	0.570	0.084	**0.0293**
Safety	**C6**	8.564	20.412	7.064	24.398	15.796	1.000	13.533	1.442	**0.4499**
Public acceptance	**C7**	0.879	1.578	0.630	1.755	1.180	0.074	1.000	0.150	**0.0372**
Regulatory approval	**C8**	11.118	12.347	6.600	11.911	10.520	0.694	6.664	1.000	**0.3202**
Total		**23.66**	**40.45**	**17.54**	**56.96**	**34.68**	**2.18**	**25.98**	**3.09**	**1**

The matrix values $C_{i,j}$ on row i and column j are normalized over the rows for each column to $\bar{C}_{i,j}$ and then weights $C_{w,i}$ for a criterion on row i are computed as the average of the normalized values $\bar{C}_{i,j}$ over the columns of that row.

Before computing the Consistency Ratio (CR) of the consolidated pairwise criteria comparison matrix, the maximum eigenvalue λ_{max} needs to be calculated as the average of the values λ_i over the rows i, with λ_i the sum of $\left(C_{i,j}C_{w,j}\right)/C_{w,i}$ over the columns j.

The Consistency Index (CI) can now be calculated based on the maximum eigenvalue λ_{max}= 8.3408 and the matrix dimension $n = 8$ as $CI = (\lambda_{max} - n)/(n - 1) = (8.3408 - 8)/(8 - 1) = 0.0487$. The Consistency Ratio (CR) is now finally obtained using the Random Index $RI = 1.41$ for $n = 8$ elements as given in Table 3.1:

$$CR = \frac{CI}{RI} = \frac{0.0487}{1.41} = 0.0345 \leq 0.1$$

Since CR is lower than 10%, the final weights associated with each criterion are then confirmed as listed in Table 3.5.

The consolidated performance matrix for each market segment per signalling alternative is displayed in Table 3.6. Each number of the performance matrix is represented by a value $X_{m,n}$ which is the performance value of the m-th alternative over the n-th criterion based on the criteria assessment per market segment (Section 3.5.2).

Table 3.6: Consolidated performance matrix

		Market Segment	Criteria							
			Infra capacity $I_{cap}(S_k)$	System stability $I_{stability}(S_k)$	Lifecycle Costs	Energy consump $I_E(S_k)$	Travel demand(%)	Safety I_{safe}	Public acceptance I_{pubacc}	Regulatory approval $I_{regappr}$
Alternatives	ETCS L3	High-Speed	1.230	69.19	€413,459,260	0.992	0.378	0.834	0.732	0.648
		Mainline	1.247	63.16	€623,243,784	0.979	0.396	0.834	0.732	0.648
		Regional	1.334	84.76	€503,301,732	0.979	0.302	0.834	0.732	0.648
		Urban	1.359	29.83	€391,992,601	0.979	0.231	0.834	0.732	0.648
		Freight	1.178	52.64	€1,228,503,378	0.979	0.300	0.834	0.732	0.648
	VC	High-Speed	1.367	71.22	€455,924,040	0.985	0.419	0.722	0.732	0.648
		Mainline	1.423	66.54	€685,158,503	0.973	0.474	0.722	0.732	0.648
		Regional	1.358	85.12	€536,778,293	0.973	0.491	0.722	0.732	0.648
		Urban	1.437	33.67	€420,792,215	0.973	0.302	0.722	0.732	0.648
		Freight	1.330	56.06	€1,321,960,368	0.973	0.466	0.722	0.732	0.648

The decision matrix is normalized by consideration of beneficial and non-beneficial criteria. Beneficial criteria are those that the higher the value the better is the performance while non-beneficial criteria are those which on the contrary the higher the value the lower is the performance. For instance, the capacity index is a beneficial criterion since a high value means a larger infrastructure capacity provided by the signalling alternative. The lifecycle cost is instead a non-beneficial criterion since a high value is not beneficial to the choice of a given signalling alternative that would be an expensive option. Therefore, beneficial criteria in this analysis are: infrastructure capacity, system stability, travel demand, safety, public acceptance and regulatory approval. The non-beneficial criteria are: lifecycle costs and energy consumption.

For each criterion, performance values $X_{m,n}$ obtained for criterion n and signalling alternative m have been normalised ($\bar{X}_{m,n}$) with respect to the maximum (for beneficial criteria) or the minimum (for non-beneficial criteria) value over all the signalling alternatives as provided in Section 3.3.2. Performance values for each criterion are then multiplied by the corresponding criterion weight computed by means of the hybrid Delphi-AHP method. The weighted normalized decision matrix per market segment is given in Table 3.7.

Table 3.7: Weighted normalized decision matrix

		Market Segment	Criteria							
			Infra capacity	System stability	Lifecycle costs	Energy consump	Travel demand	Safety	Public acceptance	Regulatory approval
Alternatives	ETCS L3	High-Speed	0.051	0.032	0.059	0.015	0.026	0.450	0.037	0.320
		Mainline	0.049	0.031	0.059	0.015	0.024	0.450	0.037	0.320
		Regional	0.055	0.033	0.059	0.015	0.018	0.450	0.037	0.320
		Urban	0.053	0.029	0.059	0.015	0.022	0.450	0.037	0.320
		Freight	0.050	0.031	0.059	0.015	0.019	0.450	0.037	0.320
	VC	High-Speed	0.056	0.033	0.054	0.015	0.029	0.390	0.037	0.320
		Mainline	0.056	0.033	0.054	0.015	0.029	0.390	0.037	0.320
		Regional	0.056	0.033	0.055	0.015	0.029	0.390	0.037	0.320
		Urban	0.056	0.033	0.055	0.015	0.029	0.390	0.037	0.320
		Freight	0.056	0.033	0.055	0.015	0.029	0.390	0.037	0.320

Finally, the ranking of alternatives is obtained by computing the weighted MCA performance scores P_m defined in Section 3.3.2. The computed scores of the two signalling alternatives (ETCS Level 3 MB and VC) per market segment are graphically reported in Figure 3.7a.

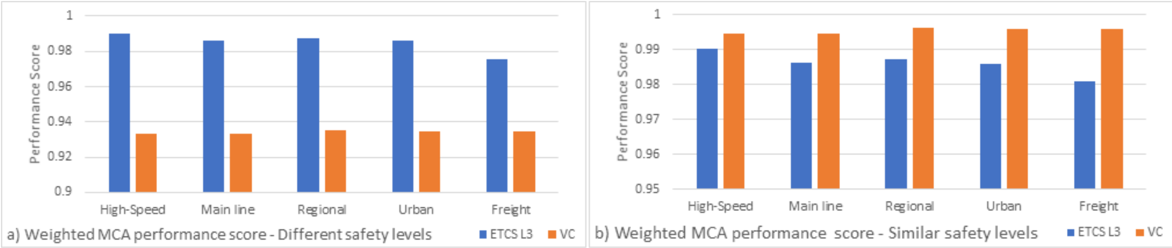

Figure 3.7: Weighted MCA performance score P_m of ETCS Level 3 and VC per market segment for (a) different safety levels and (b) “same safety levels

The MCA performance scores show that ETCS Level 3 MB outperforms VC for all market segments, despite the analysis of individual criteria such as capacity, stability, travel demand and energy consumption that show the opposite (i.e. VC more beneficial than ETCS Level 3) for all the market segments. The reason behind this result is mainly due to the very high weight (45%) associated by the interviewed stakeholders to the criterion “safety” where VC scores are lower than ETCS Level 3 due to its lower technological maturity level and the consequent higher number of open safety-critical issues.

In order to avoid the bias of comparing two signalling technologies with different levels of safety (holding a significant percentage of criteria weight), the MCA has been reiterated considering a future point in time where VC would have the same technological maturity of ETCS L3 MB and therefore a comparable safety performance. Results of the repeated MCA are displayed in Figure 3.7b, clearly showing that VC would outperform ETCS Level 3 for all market segments. This result mainly derives from the much shorter train separations that VC can provide over plain lines with respect to MB, which leads to a reduction of the capacity index that is bigger than the corresponding increase in the lifecycle costs. The slight increase in CAPEX is due to the installation of the V2V communication layer, the automatic train operation and the EVC updates, while the OPEX remains basically the same as for MB. Therefore, parameters like shorter braking distances, shorter communication delays, and relatively small additional CAPEX items make VC more advantageous than MB if the same safety levels are considered. The highest performance score is associated to the regional market segment, mostly because the deployment of VC would provide the service flexibility required by the customer demand over this segment, thereby attracting more travellers from other transport modes.
It must be noted that since the MCA is based on input from stated preferences, particularly from the travel demand analysis, the reported results should be treated carefully given the fact of hypothetical bias where stated-preference methods rely on respondents’ hypothetical responses, which might not accurately reflect real-world behaviour. This is because people’s stated preferences may differ from their actual choices in practical situations. Fifer et al. (2014) stated that individuals tend to overstate their valuation of a particular service, good, or outcome, which can lead to misleading estimates of relative value. Moreover, given external validity (Burford et al., 2013), findings from stated-preference studies may not be generalizable to all contexts or populations. Another key question relates to the temporal stability, which means to what extent these preferences are stable over time (Fuguitt and Brown, 1990). As preferences can change over time, stated-preference methods may not account for dynamic shifts in individual preferences. Therefore the obtained outcome is the best we can currently have, but far from being a reliable prediction in the future.

3.6 Conclusions

This chapter consists of applying for the first time in railway literature a hybrid Delphi-Analytic Hierarchy Process (Delphi-AHP) approach to assess impacts of railway signalling innovations by defining a framework encompassing multiple interdisciplinary methods for evaluating operational, technological and business domains. The possibility that Virtual Coupling (VC) provides for trains to follow each other at a distance shorter than an absolute braking distance can reduce headways especially if trains are allowed to move synchronously at a constant distance in a platoon. This is also reflected in terms of system stability and energy given that running at a shorter safe separation while being continuously informed about position, speed and acceleration of neighbouring trains facilitates delay mitigation and energy efficiency. An increased modal shift to railways is observed for VC, especially for the regional and freight markets where a more flexible train service would better satisfy customer needs currently poorly addressed on those segments.

VC would also allow a more demand-responsive train service that could not be possible with other signalling systems including MB. The possibility provided by VC of composing/decomposing convoys on-the-run, depending on their origin/destination pair and the demand patterns, would allow more homogeneous stopping patterns within the hour, offering on-demand services even to customers of minor stations. A more flexible service would not necessarily entail a higher investment cost for vehicles than MB, since with the same fleet, VC could operate more frequent train services by just having a shorter composition (e.g. running one single MU or even a self-propelled unit in the case of freight). Deployment of VC could also benefit railway stakeholders due to the increased capacity (so higher revenues from train path selling) and possible mitigation of delay propagation (hence less penalties to pay).

The qualitative assessment by stakeholders shows that safety is a major issue for all market segments, that the risk of a significant failure could jeopardise both public and regulatory acceptance, and that early clarification of the regulatory process and engagement with the relevant regulators is critical to achieving successful implementation of the technology. The experts proposed engagement with the European Union Agency for Railways (EUAR) as they develop revisions to the Command Control and Signalling Technical Specification for Interoperability (CCS TSI) to permit the introduction into operational systems. In general, there was greater confidence in the identification of important factors and issues that would need to be resolved to implement VC, than there was over the likelihood of those issues being resolved in the next five years.

MCA scores show that when considering the current technological maturity of VC and MB, the latter would be more beneficial than VC although an opposite conclusion is drawn when criteria like capacity, stability, energy consumption and travel demand are analysed individually. With a similar technological maturity level to both signalling alternatives and hence comparable safety performance, VC would outperform ETCS Level 3 for all market segments.

Future research will be investigating the crucial factor of VC safety from a quantitative perspective in order to identify potential issues that might prevent/limit the actual deployment of this technology. A quantitative safety analysis would also allow a more effective calibration of the corresponding AHP weights based on an objective comparison of safety risks of MB and VC. The outcomes of the MCA performed in this study are also used to delineate a roadmap to the potential deployment of VC for the different railway market segments in Europe.

Chapter 4

Roadmap development for the deployment of Virtual Coupling in railway signalling

In Chapter 2, market needs and preliminary VC operational scenarios were assessed based on the outcomes of a SWOT analysis. In Chapter 3, an MCA for ETCS L3 MB and VC consisted of using a hybrid Delphi-Analytic Hierarchy Process (Delphi-AHP) approach to weight eight different criteria, i.e., infrastructure capacity, system stability, lifecycle costs, energy consumption, travel demand, safety, public acceptance, and regulatory approval. The outcomes of the SWOT analysis (Chapter 2) and MCA (Chapter 3) have been used as input to the current chapter to introduce and apply a methodological framework for developing roadmaps, considering uncertainties represented by scenarios for five different railway market segments.

This chapter aims at capturing operational, technological and business differences between traditional railway signalling systems and future train-centric signalling systems, as well as identifying potential optimistic and pessimistic roadmaps to migrate railway operations to VC signalling.

Apart from minor changes, this chapter has been published as:

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4.1 Introduction

The implementation of new railway technologies necessitates well-developed strategies that move forward the current state of railways. Virtual Coupling (VC) is an advanced railway signalling technology that requires the need of developing actions and step-changes towards its real deployment. Several gaps arise from the implementation of this technology mainly relating to communication, safety and cooperative train control. Therefore, there is a need to understand the different railway system components that will be affected by VC, and identify the step-changes that allow the migration from the current state to the desired state by means of a roadmap.

The business and societal benefits of VC mainly come from the significant reduction of headways between trains, which consequently increases the railway capacity and allows higher train frequencies and shorter arrival and departure intervals. Additionally, with VC a train can virtually couple and decouple on the run, as opposed to fixed train formations, allowing an increased service flexibility which can attract a relevant share of customers from other modes of transport to railways. This in turn increases the profit of railway undertakings (RUs) and infrastructure managers (IMs) as their turnover would raise while operational costs would potentially reduce or remain the same. The latter is because when migrating from fixed-block signalling to VC, the increased track maintenance due to higher traffic volumes would be compensated by the removal of trackside equipment (e.g. signals, track-clear detection) and the installation of faster more reliable switch technologies. The revenues of RUs would increase as more tickets would be sold with a marginal increase in the fees for delivering a more frequent service. Additionally, IMs will gain higher productivity of the railway network due to the larger availability of train paths to be sold.

The MOVINGRAIL European project assessed operational procedures and advanced testing methods for the European Rail Traffic Management System Level 3 (ERTMS L3) Moving Block (MB) signalling, as well as communication technologies and market potential of VC. MB signalling (Theeg and Vlasenko, 2009), or the European Train Control System Level 3 (ERTMS/ETCS L3), substitutes vital trackside equipment with onboard devices to monitor train integrity (i.e. all cars are safely held together), next to train positioning, and continuous speed and braking supervision. In this way, train separation is reduced from a given number of fixed-block sections to an absolute braking distance (i.e. the safe distance needed to brake to a standstill). The concept of VC advances moving block operations by reducing the train separation to less than an absolute braking distance. When forming a Virtually Coupled Train Set (VCTS) or convoy, the distance between consecutive trains can be reduced to a relative braking distance (i.e. the safe distance of a train behind the rear of the predecessor taking into account the braking characteristics of the train ahead) using Vehicle-to-Vehicle (V2V) communication and cooperative train control while ensuring a safety margin. This concept is analogous to the automotive industry where the V2V communication can support a significant capacity increase via cooperative adaptive cruise control (CACC) while enabling the preservation of much shorter, though still safe, gaps (Diakaki et al., 2015). In railways, the V2V communication is particularly beneficial when trains move synchronously together in a platoon, and consequently a safety margin would be sufficient between the trains in a VCTS (Quaglietta et al., 2022).

VC is still under development by the railway industry due to safety-related issues as well as the need of developing specific technologies such as the V2V communication and a cooperative automatic train operation system. The railway industry hence urges to understand the set of tasks and technological developments which ought to occur before VC could be deployed.

In MOVINGRAIL (2019) and Aoun et al. (2020a), market needs and preliminary VC operational scenarios were assessed based on the outcomes of a 'Strengths, Weaknesses, Opportunities and Threats' (SWOT) analysis. A multi-criteria analysis (MCA) for ETCS L3 MB and VC consisted of using a hybrid Delphi-Analytic Hierarchy Process (Delphi-AHP) approach to weight eight different criteria, i.e., infrastructure capacity, system stability, lifecycle costs, energy consumption, travel demand, safety, public acceptance and regulatory approval. The outcomes of the SWOT and MCA analyses have been used as input to the current study to build roadmaps. The goal of using both a SWOT and MCA is to assess criteria and critical step-changes for developing VC.

There are several types and visual representations for a roadmap. Roadmaps can have various levels of granularity, from components to complex systems, to sectors or fields of science (Phaal and Muller, 2009). The architecture of a roadmap must be configured to suit the focus and scope of the investigated technology towards its implementation. Roadmaps have a wide spectrum of applications including science/research, industry, technology, product, project, etc. (Kostoff and Schaller, 2001). Since our main focus in this chapter is on the development of a technology roadmap, we provide more details on the types of technology roadmaps in Section 4.2.1. We use a Swimlane visualization functionality as a supportive tool to show how to bridge gaps though a list of step-changes that can be assessed in terms of priorities and time order for the deployment of VC. The Swimlane was developed on the Roadmunk software and is defined as "a theme-oriented visualization of roadmap items that works best for 'no dates' roadmaps or more agile roadmaps that can be pivoted on themes, sprints, or epics" (Roadmunk, 2022). The Swimlane was shared in a workshop with railway stakeholders for easily identifying step-changes, together with their priorities and time order in a theme-domain oriented visualization. In addition, as this tool is flexible and allows plotting items on a dynamic grid, modifications were made online during the workshop by dragging and dropping items and changing the properties they belong to based on the stakeholders' feedback.

The aim of this chapter is to provide a methodology for developing roadmaps for the introduction of VC considering uncertainties represented by scenarios for five different railway market segments. We focus on five factors relevant to the European Commission goals and the deployment of VC, namely demand, CO_2 emissions, CAPEX, OPEX and regulatory approval. The main contributions of this chapter are as follows:

i) Identifying the main railway system components that will be affected by VC;
ii) Developing a gap analysis and step-changes between current and future states of the operational, technological, and business domains for the introduction of VC;
iii) Proposing a generic roadmapping framework based on various approaches to derive scenario-based roadmaps;
iv) Applying the proposed framework to generate VC deployment roadmaps for different market segments that support stakeholders in the practice of technological forecasting and planning.

Section 4.2 presents a literature review on roadmapping with particular interest in technology roadmap, scenario planning and scenario-based roadmap. Section 4.3 explains the methodology proposed in this chapter. Section 4.4 focuses on fundamentals of VC operations and introduces necessary changes and gaps to current operational rules and technologies. Section 4.6 presents the results of the Swimlane for the phased deployment of VC, as well as the scenarios and the corresponding scenario-based roadmaps, with particular focus on the mainline case study (described in Section 4.5). Section 4.7 provides a discussion on the results. Finally, conclusions and future works are provided in Section 4.8.

4.2 Literature review

This section presents a literature review on technology roadmap, scenario planning and scenario-based roadmaps. It provides the reader with a better understanding of the concepts that are used in this chapter, as well as the adopted approach in the upcoming section. The methods described below are used as a basis for developing a new framework for roadmap design.

4.2.1 Technology roadmap

A roadmap has been explained in several ways where for instance Phaal et al. (2004) define it as “a means to communicate intent and associated plan”. Ricard and Borch (2011) define a roadmap as a visual representation of layers of information related to developments of technologies in the explored context. A recent publication states that a roadmap is “a structured visual chronology of strategic intent” (Kerr and Phaal, 2022). The same authors mentioned that a roadmap is a critical artefact for onward communication within an organization and across various stakeholders. DeGregorio (2000) mentioned that roadmaps provide a “compact method” of visually summarizing and communicating information.

A distinction shall be made between roadmap and roadmapping. Particularly, Kerr and Phaal (2022) define roadmapping as “the application of a temporal-spatial structured strategic lens”. In their research, roadmapping is represented by a governing framework which allows for a generic structure to be applied across temporal-spatial canvas. The roadmapping methodology has an integrative functionality which is useful for explaining the role of the other methods involved in this research and how they relate, including scenario planning and the SWOT analysis. Roadmaps represent the future, a vision that is achieved through possible routes. A roadmap is used to illustrate and communicate alignments of technology and product development with market requirements and the right timing guided by a common vision (Phaal et al., 2004). The aim of a technology roadmap is to provide a strategic framework for aligning and prioritizing market trends and drivers with technology developments and Research and Development (R&D). Phaal and Muller (2009) consider roadmapping as a useful graphical tool to structure the development of a strategic plan within the broader picture of a sector. Duin et al. (2016) state that roadmapping is a powerful and flexible technique for supporting strategic planning. Roadmapping is therefore useful as a structural and strategically flexible tool when navigating in uncertainties.

Roadmaps are mostly represented in a layered structure of solution strategies together with a time dimension (Lee et al., 2015). Roadmaps can also be used for illustrating the sequence of actions in time (Phaal et al., 2004; Phaal et al., 2009; Robinson and Propp, 2008). The main layers identified in a roadmap are market/business, service/product, technology/science and resources (Yang and Yu, 2005; Ricard et al., 2011; Hussain et al., 2017). Duin et al. (2016) consider roadmapping as a useful graphical tool to structure the development of a strategic plan within the broader picture of a sector. The focus on condensing the complex information into a graphical framework is considered as a key-benefit of technology roadmaps, allowing for visualization of market pull and technology push and checking the consistency in alignments.

We refer to the eight categories of a technology roadmap in Phaal et al. (2001), where our scope fits into the third, sixth and eighth categories: strategic planning, programme planning, and integration planning, respectively. From the strategic planning perspective, our study includes a strategic dimension in terms of supporting the evaluation of different opportunities or threats derived from the SWOT, typically at the business level. The roadmap focuses on the development of the EU vision in terms of business, operation and technology domains. Gaps are also identified by comparing step-changes that are explored to bridge the identified gaps and migrate railways from the current state to the desired future state. In terms of programme planning, Phaal et al. (2001) state that this type of roadmap focuses on the implementation of strategies, and relates more directly to project planning like R&D programmes. Our roadmap includes an entire theme dedicated to Research and Innovation (R&I). Furthermore, our roadmap focuses on the management of the development for next-generation railway signalling systems between technology development, and programme phases and milestones. Finally, from the integration planning perspective, we focus on the integration and evolution of the technology, since VC builds on MB railway signalling and follows several of its business and operational standards, based on a certain ‘technology flow’. It must be noted that the development of the VC technology also requires integrating various technologies (i.e., software, communication system) besides the ones that are developed for MB signalling.

As a means of communication, Kerr et al. (2012) mention that a roadmap visualization conveys information, connects stakeholders and mobilizes action. Roadmap visualizations can have different forms such as tables, bars, graphs, Gantt charts, bubble charts, multilayer block diagrams, tree diagrams, flow-based schematics or metaphor-based illustrations (Phaal et al., 2001; Kerr and Phaal, 2015). A technology roadmap provides a graphical means for exploring and communicating relationships between markets, products and technologies over time (McCarthy et al., 2001; Lee and Park, 2005). A condensed visual format of a roadmap provides a ‘one-page’ high-level view of the system by incorporating various key perspectives for developing consensus, aligning step-changes or actions, and identifying risks. This kind of roadmap is thought as a general-purpose ‘strategic lens’, through which a complex system can be viewed. The aim of this lens is “to structure and represent multiple interrelated perspectives on the evolution of the system, providing a framework to support understanding and dialogue” (Phaal and Muller, 2009). In this chapter, we consider the bars representation for each layer to simplify and unify the required outputs to migrate railway signalling business, operation and technology domains, and consequently deploy VC.

In the past decade, dynamic roadmaps have been used to overcome the key challenge for technology managers and practitioners for implementing a robust roadmap and keeping it alive (Phaal et al., 2001). Das (1987) states that strategic planning is “dynamic by nature”. Duin et al. (2016) adopted a dynamic roadmap where they use a quantitative approach in a qualitative way, since it provides a step-by-step approach to map dynamic actions. They mentioned that the stakeholders involved in the research need guidance to turn their awareness of the system vulnerabilities and insights into actions, and therefore the need for a roadmap. Results show that dynamic roadmaps should be designed by involving strategic planners and that validation is important if the roadmap should be respected by strategic planners. Phaal et al. (2005) mention that a roadmap is dynamic due to the inclusion of the time dimension. Gerdsri and Kocaoglu (2007) used the Analytic Hierarchy Process (AHP) to build a strategic framework for technology roadmapping. They presented a new methodology called the Technology Development Envelope (TDE) to transform the roadmapping approach to the level in which it is dynamic, flexible and operationalizable. Quiceno et al. (2019) showed that the robust strategy focuses on transforming the current business with existing resources and the development of new capabilities. In addition, the process to construct the strategy requires systems' thinking, as the scenarios present a variety of different dynamics that must be considered and compared.

4.2.2 Scenario planning

In the past decades, scenario planning has gained increased attention in both academia and practice as an effective method to examine future uncertainties (Schwartz, 1991). Murray (1965) defines a plan as "a conscious attempt, made in advance, to identify a desirable end, and to specify how this end is to be achieved". The concept of planning is broadly articulated by Dauten (1958) as the "determination of what is to be done". A scenario is defined as a (hypothetical) sequence of events constructed for the purpose of focusing attention on causal processes and decision points (Kahn and Wiener, 1967). The work of the mentioned authors relates to the sequence of events. Troch et al. (2017) define a scenario as an exploration of hypothetical future events, highlighting the possible discontinuities from the present and used as a tool for decision-making. Thus their approach concerns future states. Both approaches of Kahn and Wiener (1967) and Troch et al. (2017) can be related to the timeline presented in the roadmaps, and provide insights to define plausible future states and pathways to bridge the current state to the future one. Lobo et al. (2005) mentioned that scenario-building is important as a powerful tool to broaden perspectives and to explore the universe of possibilities for the future. They also stated that scenario building is an interesting bridge between citizens and decision makers, helping to identify present critical branch points for a sustainable future. Scenario building is used to help thinking about possible futures and their implications (European Commission, 2007). Lindgren and Bandhold (2003) define scenario planning as an effective strategic planning tool for medium- to long-term planning under uncertain conditions. It helps to sharpen up strategies, draw up plans for the unexpected and keep a lookout in the right direction and the right issues. Geum et al. (2014) state that scenario planning can be applied as an effective approach to deal with a complex and rapidly changing business environment. Duin et al. (2016) showed that scenarios are developed to help people empathize in plausible futures.

Several methods have been integrated with scenario planning. A multi-objective system architecting and design integrates single aspects into a complete system that fits the customers' context and needs (Phaal and Muller, 2009). Hickman et al. (2012) indicate that there is an emerging set of methodologies, including scenario analysis, which can be combined with more conventional approaches such as the MCA, to offer much promise for the evaluation and implementation of sustainable transport futures. As an example, they define a framework that combines scenarios with a multi-actor discussion and a simulation tool (INTRA-SIM), to assemble and appraise future potential scenarios. Troch et al. (2017) explored scenarios for the development of a Belgian rail transport system based on a SWOT analysis. The results showed that the obtained scenarios allow the quantification and measurement of the impact of future developments and decisions towards the Belgian rail freight market. A SWOT analysis is at the core of all strategic planning processes, explicitly or implicitly. Wiehrich (1982) provided a structured method for relating the SWOT factors/components, leading to a balanced set of strategic options, and considered time explicitly. He also refers to the TOWS matrix which serves as a conceptual framework for future research about the combination of external factors (Threats and Opportunities) and those internal to the enterprise (Weaknesses and Strengths), and the strategies based on these variables. Soria-Lara and Banister (2018) integrated the MCA with transport scenario analysis to assist policy-makers in deciding how the implementation of transport policy schemes can be made more central to the scenario building process.

4.2.3 Scenario-based roadmap

Scenarios must be used to design a robust roadmap. Moreover, using scenarios in an early stage of roadmapping ensures that risks and uncertainties are considered, and that the roadmap is more robust (Wise et al., 2014; Ilevbare et al., 2014; Duin et al., 2016; Hansen et al., 2016). A roadmapping process should accommodate those uncertainties associated with forecasts by means of scenario planning or other methods such as a sensitivity analysis. Courtney et al. (1997) define a framework to determine the level of uncertainty surrounding strategic decisions and to tailor strategy to that uncertainty. Geum et al. (2014) proposed a three-step combined approach to support scenario planning consisting of scenario building, technology roadmapping and system dynamics simulation. They considered three scenarios (i.e. optimistic, pessimistic and neutral) for a case study of carsharing services in Korea to demonstrate the applicability of the proposed approach. The main strength of this paper is that it provides a systematic combination of technology roadmap and system dynamics to support scenario planning. However, their study did not include the development of technology roadmaps for each scenario. Cheng et al. (2016) used a scenario-based roadmapping method (SBRM) for strategic planning and decision-making to incorporate the scenario planning (macro level) and roadmapping (micro level) perspectives. Results showed that the proposed method allows companies to externalize their insights of practical future scenarios with positive and negative impacts at micro level for strategic planning and forecasting. It also helps companies – specifically dealing with strategic planning and technology management– to visualize the future action plan according to the plausible future scenarios in an effective way. Lee et al. (2015) used a scenario-based roadmapping approach to help decision makers in assessing the impacts of changes on organizational plans. They propose an approach to make scenario-based technology roadmapping more robust by assessing the impacts of future changes on organisational plans. However, their approach does not include the analysis of internal factors of organisational plans. In addition, they do not integrate different methods and processes for building scenarios.

4.2.4 Proposed approach

Results in Aoun et al. (2021) showed that VC entails regulatory approval barriers since a number of strategies depends upon the assumption that the system as designed will work towards a very high level of reliability and safety, and that there will be no wrong side failures during the full scale testing phase. The regulatory approval issues reported by the stakeholders included safety incidents that have the potential to set back approval, as well as the requirements for headways and the maximum train length of a convoy. In addition, a set of engineering and operational rules should be defined and approved as VC will also change procedures in planning, management and control of railway traffic (MOVINGRAIL, 2018). There is also a need for a clear system definition and specifications, and a valid testing system through simulation and pilot/prototypes. Another important issue that needs to be solved concerns the description of operations and the sponsorship of specifications/standards throughout EU processes. Those issues are symbiotically related to safety and public acceptance, e.g. safety challenges due to technical complexity and approval within the European Railway Agency

(ERA). In addition, regulators are unlikely to take risks upon themselves by approving technologies that the public has concerns about.

The roadmapping process can be expert-based, computer-based or hybrid (Kostoff and Schaller, 2001). Our study builds on a hybrid roadmapping process since on one hand the results draw on the knowledge and experience of the participants and railway experts to subjectively identify the relationships and dependencies among the step-changes as well as the identification of timelines. On the other hand, objectivity arises from the involvement of a hybrid Delphi-AHP MCA since this approach identifies the most relevant assessment criteria and ensures consistency in the pairwise comparison matrix for criteria weighting, which is required for the calibration of the AHP technique. In addition, scenarios are quantified based on EU targets and real-data on quantitative factors, namely demand, CO_2 emissions, CAPEX and OPEX. In addition, a SWOT can provide an objective evaluation of the strengths, weaknesses, opportunities and threats of VC based on the functionalities of the system.

The discussed methods in Sections 4.2.1, 4.2.2 and 4.2.3 support the development of a generic methodological framework to design a roadmap. Scenario planning is a useful tool to put forward strategies, seize opportunities and offset the threats presented by the uncertain changes in technologies and the business environment. Based on the existing literature, the SWOT has been used for scenario planning whereas the AHP was adopted for technology roadmapping. In this chapter, we use two approaches, namely a SWOT and a Delphi-AHP MCA, together with expert judgement, in a single framework to define scenario-based roadmaps. The SWOT supports in the development of appropriate processes for strategic planning whilst the Delphi-AHP approach helps in identifying key factors and their quantitative importance towards the implementation of a certain product or technology. Delphi consists of combining points of view and opinions from a group of individuals by means of iterative questionnaires with controlled feedback. The AHP is a multi-criteria decision-making method that consists of weighting criteria by means of a pairwise comparison judgement matrix (Saaty, 1980b). It is a compensatory scoring method which eliminates incomparability between variants and builds on a utility function of aggregated criteria. This approach has been considered as the most appropriate Multi-Criteria Decision Making (MCDM) technique for solving complex cases (Lee and Kim, 2000). AHP has been widely applied for solving several decision-making problems such as socio-economics (Kumru and Kumru, 2014), manufacturing systems (Yang et al., 2009), roadway maintenance (Li et al., 2018), technology evaluation (Lai and Tsai, 2009) and various transportation fields (Barić and Starčević, 2015; Aoun et al., 2021).

Existing literature for developing roadmaps does not entirely involve decision makers in expressing their preferences for the type of strategies/step-changes that need to be evaluated in terms of priority, time order, durations and criticality with respect to other step-changes. They also do not consider always future scenarios by looking at different factors and durations for variant case studies. In addition, our study involves stakeholders and experts since the beginning of the design of the strategies to evaluate because we used their input for developing the SWOT and MCA which were in turn used as input to develop the scenario-based roadmaps. Therefore, our approach can support future thinking and the development of strategic values as it involves different stakeholders in various ways. It also develops consensus among decision makers on a set of research and technological needs. In particular, we look first at system components and their functions to identify gaps between current and future states, and generate the related step-changes to close those gaps by looking at the 'SWOT' of the investigated technology. In addition, case studies and criteria weights, which derive from a hybrid Delphi-AHP through stakeholders' judgement, help to determine how important the identified step-changes are by assigning their priorities. Those priorities were also set based on surveys and a workshop with sector experts. For the first time in literature, we apply the proposed framework for the deployment of VC to different market segments with particular focus on mainline railways. It must be noted that a roadmap can always be subject to changes given prevailing conditions and circumstances. It is therefore important to critically review the roadmap by analysing various dynamic options of moving forward and reaching a certain goal with respect to a certain context and situation. The term 'dynamic' is therefore used in our chapter to reflect the fact that roadmaps do explicitly include the time dimension and are useful for mapping system change based on specific defined scenarios for different case studies. The scenarios help in keeping pace with the step-changes, exploring alternative paths, bringing attention to timely options, and dealing with the unexpected. Indeed, the preferred route corresponds to optimistic scenarios. However, as uncertainties in the business, operation and technology domains are unavoidable, outlining a 'Plan-B' option, hereafter referred as pessimistic scenario, would provide more depth of thinking behind the question 'what if?'. For instance, the rate of change to which the VC system is subjected or the pace of technology advancements in wireless communication or the structural change in the railway market can cause several amendments in the built roadmaps, and consequently impact the five factors considered in Section 4.6.2.

4.3 Roadmapping methodology

The roadmap is used as a strategically flexible tool to visualize timelines and priorities of market trends, actions and steps towards the real deployment of VC. The most general and flexible approach to develop roadmaps is a visual time-based, multi-layered chart that enables several functions and perspectives to be aligned. An example can be found in Phaal and Muller (2009) based on typical perspectives for industrial applications, and three key questions that must be answered for any coherent strategy: where do we want to go, where are we now, and how to get there.

The outputs of the SWOT analysis (MOVINGRAIL, 2019; Aoun et al., 2020a) and the hybrid Delphi-AHP multi-criteria analysis (MOVINGRAIL, 2020a; Aoun et al., 2021) are applied in this chapter to close technological, operational and business gaps, as well as to assign priorities for the resulting step-changes. An action plan is built to address the benefits (strengths and opportunities) and drawbacks (weaknesses and threats) to each market segment (i.e. high-speed, mainline, regional, urban and freight) in optimistic and pessimistic scenarios. Several factors are considered in the identification of scenarios where values are defined optimistically or pessimistically based on policy goals, real data and certain assumptions.

Phaal and Muller (2009) state that a practical way to impart a progressive story arc is to use a series of "stepping stones that lead from the current situation to the desired future state". The proposed roadmapping methodology in this chapter applies a gap analysis in the operational, technological and business domains that identifies differences between current and future states and the step-changes that need to occur to migrate each of the domains towards VC. Based on the step-changes identified in these three domains, a roadmap is then developed which details transitions that need to occur to progressively deploy VC.

Figure 4.1 illustrates the framework developed to design roadmaps based on a SWOT, a hybrid Delphi-AHP multi-criteria analysis, and expert judgement. The gap analysis consists of determining the step-changes to be taken to migrate from a current state to a desired future state.

The first step to design a roadmap is to define objectives and a common vision (i.e. where we want to go). In this chapter, this corresponds to the EU vision in addressing demand and consequently increasing railway capacity, reducing CO_2 emissions and decreasing lifecycle costs. The second step consists of understanding the current situation (i.e. where we are now) where in our study fixed-block signalling is mainly adopted. The third step in-between is the gap analysis that fits into the strategic management process when reviewing how well a current strategy is working with the necessary steps and actions (i.e. how to get there). Proceeding on with the current strategy gives rise to a gap that needs to be covered to reach the desired goal. As a result, a knowledge gap arises between what we know from the current state (i.e. the state-of-the-art, definition, scope, etc.) and what we must know to cope with the future changes and decide which direction/scenario to follow.

The definition of step-changes is achieved by four interacting elements related to knowledge and strategy. The initial principle is based on Zack (1999) and Tiwana (2002) who aimed at precisely identifying what knowledge the organization and its people possesses currently and what knowledge they would require in the future in order to manage their needs and meet their goals. According to the last two mentioned references, the knowledge strategy link describes the overall approach an organization intends to take to align its knowledge resources and capabilities to the intellectual requirements of its strategy. This relates to the link between what we know in terms of definition and scope and the overview of what can be done. The Strategy knowledge link is based on the organization's identification of the knowledge required to execute the intended strategy, and compare that to its actual knowledge, thus revealing the gaps between knowledge and strategy. This link relates to what we must do by following a certain action plan and the direction towards why we must expand the current knowledge. Figure 4.1 shows how the gaps can be bridged by means of certain step-changes, referred also as 'actions', which are then analysed in different scenarios for various cases (in our study rail market segments). The knowledge strategy link is based on the knowledge gaps discussed in Section 4.4 which motivate the railway business market to apply specific step-changes (Do-what). The strategy knowledge link stems from the fact that we get to know which research is required to increase the knowledge based on the action plan. After developing the scenarios, we get to know what is the most critical market segment for which a particular attention would be given from regulatory bodies and suppliers of signalling technologies.

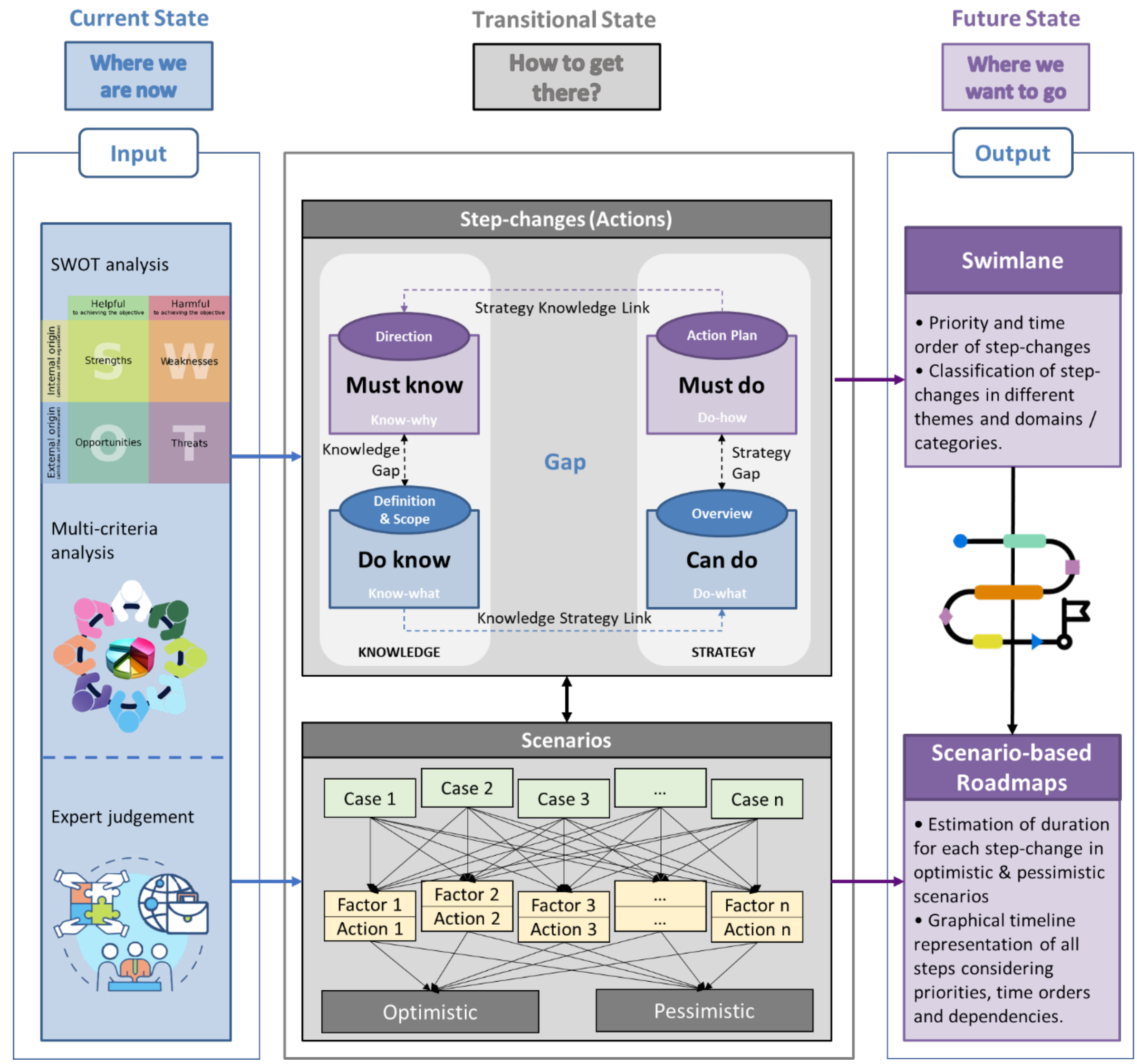

Figure 4.1: Roadmapping framework

The relations between the four elements in the 'Step-changes' box of Figure 4.1 are based on three components: the core (middle text in each box), the aim (the upper text in the oval) and an identifier (the bottom text in each box). The connections between those elements are explained as follows:

1) We define the 'Do know' because we aim at understanding the definition and scope of the strategy that we want to build. To do that, we need to investigate what we know in the current state to be able to build what we can do (knowledge strategy link).
2) We define the 'Must know' because we aim at a certain direction by looking at what must be known. To do that, we need to understand why there is a need for new knowledge. This is an identifier to determine the 'Must know' based on what we do know.
3) We define the 'Can do' because we aim at having an overview of the current strategy to be able to build a futuristic one. To do that, we need to understand what can be done in the current state.

4) We define the 'Must do' because we aim at building an action plan that leads to the desired direction (strategy knowledge link). To do that, we need to look at how we can do what we can do.

A strategy gap is the gap between what we must do in the future state and what we can do in the current state. It arises between the current performance and the desired performance towards a common vision and well-defined objectives. The strategy for achieving them stems from what must be done and what we could actually do given the facts and limitations of the current circumstances. The action plan provides a strategic link to the future knowledge that interacts with the current knowledge state.

This process is supported by understanding the SWOT of a certain technology or vision. The SWOT is useful for strategic planning as it provides a clearer overview on what we can do in a current situation by taking into account the knowledge in the current state. The ‘Can do’ element can be affected by threats encountering a certain technology as they can engender business risks that hamper the effective development of an application roadmap. Drucker (1994) mentions that “the central challenge facing management” is “what to do”. The SWOT results are therefore used to develop the strategies and generate ideas on how to close the gaps by identifying step-changes in the operational, technological and business domains to ultimately serve a roadmap. To develop a good strategy, we need to build on the strengths, address or remedy the weaknesses, grasp the opportunities, and avoid or minimise the threats.

The development of scenarios for each market segment (Section 4.6.2) includes baseline values which are initially derived from MOVINGRAIL (2020a) that consists of implementing a hybrid Delphi-AHP MCA for ETCS L3 and VC. Other baseline values derive from data collected through surveys and publicly available governmental sources. The size of the gaps (i.e. how big/important the problem is) is assessed by means of priorities and time order for a set of steps and actions in the operational, technological and business domains, as illustrated in the Swimlane (Figure 4.2). In this chapter, the Swimlane is used as a domain/theme-oriented visualization of roadmap items on dynamic grids where fields can be moved, ordered and prioritized based on stakeholders’ feedback. The identification of gaps that stem from the SWOT are addressed by means of the Swimlane through a list of step-changes that are categorized based on defined domains and themes.

Outcomes from the SWOT analysis, the MCA and expert judgement were used as input to define the step-changes in the roadmap. The scenarios presented in this chapter are a collection of plausible future events to assess their impacts over a long-term strategy. The different defined scenarios are interrelated since on one hand, the scenario-based roadmaps vary in terms of optimistic and pessimistic timelines for different market segments. On the other hand, optimistic and pessimistic scenarios represented in terms of five factors (i.e. demand, CO_2 emissions, CAPEX, OPEX and regulatory approval) are crucial within the developed scenario-based roadmaps since they represent the desired vision (i.e. the why) or the market pulls set by the European Commission. Those five pulling factors are hence the targets VC aims at. Therefore, the optimistic and pessimistic scenarios in the developed scenario-based roadmaps vary for each market segment (case) in terms of *(i)* durations for each step-change (action) based on expert judgement, and *(ii)* prediction uncertainties represented by five factors related to the VC market pulls that are estimated based on the European Commission targets, policy goals and data collected from the MCA developed in MOVINGRAIL (2020b) and Aoun et al. (2021). Section 4.4 is devoted to the knowledge and strategy gaps for VC. It considers what we know and what we must know about the main operational and technical railway system components, and thus also provides the knowledge-strategy link towards what we can do to make VC happen. To close the loop, the strategy gap must be explored to understand what we must do by providing the strategy-knowledge link and defining the direction of the knowledge development in the roadmap for the introduction of VC.

Optimistic and pessimistic percentages are defined for each factor (Section 4.6.2) to understand the impacts of the estimated timelines (defined in consultation with stakeholders) on market pulls. In particular, the higher the positive impact of the factors (e.g. more demand, less costs), the faster is the development of the technology. Reciprocally, the longer the estimated duration of the step-changes defined for each market segment (pessimistic case), the lower would be the overall positive impact on the societal, environmental and economic factors. The evaluation of the strategies in the roadmap allows us to see if they will be able to bridge the gap (e.g. they are sufficient to reach the EU vision) by developing scenario-based roadmaps (Section 4.6.2). Timeline roadmaps are therefore developed for each market segment based on the Swimlane by means of the project management software Primavera P6 Pro. The built roadmaps provide a step-by-step approach to map dynamic actions based on the defined optimistic and pessimistic scenarios for different market segments.

4.4 Virtual Coupling scope and gaps

This section discusses the scope of VC and the knowledge gaps that need to be filled for the main operational and technical railway system components. In particular, the communication, safety, interlocking and control technology are emphasized, including communication structures, platoon planning, and integrated railway traffic management.

All of these components are critical for the real deployment of VC, in the sense that each of them needs to be sorted out or it will halt the implementation as a whole. In interlockings, when a train (usually the leading train -henceforth addressed as “leader”- in a convoy) gets exclusive right to control and occupy the points, the request is declined for all other trains until relevant elements have been released by the last train of the convoy. The control time for points is the time to request the points, to get them assigned and to move them. Moving points is only possible in the gaps between train convoys, and assigning points to the leader requires action from a traffic control centre. The main function of this control centre is to regulate the train (convoy) sequences and timings to avoid conflicting train paths. The VCTS train protection system supervises the relative braking distances for each train in a convoy, while the cooperative train operation system guarantees stable operation in a platoon under the constraints of relative braking distances. The interactions between these two components are comparable to Automatic Train Protection (ATP) and Automatic Train Operation (ATO) under fixed-block and moving block systems. Smooth performance of trains in a platoon is only possible when these two components work seamlessly together. Communication (COM) structures require peer-to-peer capability between all trains and over large distances (> 1 km), low latency and high availability. In addition, specifications for VC COM should be as open and abstracted as possible to maximize equipment independence. Cellular 5G/evolving 3GPP standards are also needed to address current COM solutions obsolescence, cost-effectiveness and avoid clashes between the other system components. One of the main challenges of the cooperative train protection of train convoys is to have carefully monitored and coordinated virtually coupled trains in a VCTS and avoid collisions within the convoy. A safety and performance analysis should be developed for the integrated system rather than for separate components. For instance, safety and performance of the entire system depend on the interactions between communication structures (train-to-train and train-to-trackside), the safety systems (e.g. interlocking, convoy route locking and route release, cooperative train protection within convoys), and automated train operation and traffic control systems (e.g. traffic management and cooperative train operation), which may differ for the different market segments. Capacity performances of VC and potential gains over state-of-practice signalling systems have been addressed on a portion of the South West Main Line (UK) by Quaglietta et al. (2020). VC will change railway traffic planning as the capacity allocation may incorporate relative braking distances and therefore reduce train headways. In addition, platoons may have to be carefully planned including the type and order of trains. More details about the various railway system components and their challenges can be found in MOVINGRAIL (2020b). The main gaps identified for each of those components are summarized in Table 4.1.

Table 4.1: Gaps for the implementation of Virtual Coupling

Component	Gaps
Interlocking	• Developing the optimal interaction between train-centric train operation and trackside route setting management concerning fixed and dynamic routes, direction control, flank protection and level crossings. • Establishing a new route release procedure for trains separated by a relative braking distance. • Examining the duty and authority of traffic control to prioritise trains, routes, direction control and updating onboard timetable data.
COM structures	• Analysing acceptable communications' latency in relation to distance and speed. • Investigating the need for equipment redundancy in the context of operational availability. • Confirming feasibility of implementations of Virtual Coupling communication structures. • Developing and specifying communications protocols for use with Virtual Coupling, including safety and security aspects.
Cooperative train protection of train convoys	• Defining various cooperative modes of VCTSs. • Developing protocols and algorithms for determining cooperative braking curves and relative braking distances. • Defining procedures for updating ATP braking characteristics for running trains. • Defining the interfaces between safety-critical functions and train operation functions. • Developing an appropriate safety analysis for virtually-coupled trains in a convoy.
Cooperative train operation of train convoys	• Developing a cooperative train operation method for stable and optimal platooning. • Developing a cooperative approach trajectory algorithm to join a platoon. • Developing a cooperative platoon splitting train trajectory algorithm. • Developing a cooperative platoon dissolving algorithm with trains diverging to different platform tracks. • Investigating energy-efficient train platooning.
Railway traffic planning and management	• Extending the blocking time theory with relative braking distances and Virtual Coupling principles. • Including the extended blocking time theory in conflict detection models for railway timetable planning and railway traffic management. • Developing models for platoon planning. • Developing integrated cooperative train operation and traffic management. • Developing passive switch technology for merging and diverging at relative braking distance.

As mentioned in Section 4.3, the strategy gap is the gap between what we must do in the future state and what we can do in the current state. It must be noted that so far, nothing has been done for developing VC but only actions have been taken to implement MB which components are considered a pre-requisite for VC. The several strategy gaps for developing VC are mainly highlighted in the identified step-changes (see Section 4.6) based on the knowledge gaps identified in Table 4.1. These gaps are specifically about the step-changes identified by the experts, which might vary in terms of technological developments for different market segments. From the technological point of view, the strategy misses at the moment concrete deployment / test installations for VC as its deployment cannot be made if regulatory bodies do not approve this technology and authorize testing or a real-scale proof-of-concept.

4.5 Case study

VC is considered to be deployed over several rail market segments such as high-speed, mainline, regional, urban and freight. In this chapter, we present the optimistic and pessimistic scenarios for different market segments with a particular focus on the mainline market as the different components (Section 4.4) for this market are the most critical compared to the other segments. Particularly, mainlines have heterogeneous traffic that requires advanced systems for automatic traffic management and cooperative train operation to optimise the management of trains with different characteristics. This needs to be addressed by considering all the uncertainties that might arise from heterogeneous rolling stocks in one convoy. In addition, mainline railways are characterised by a higher complexity of junction station layouts due to branches from other rail networks of other categories (e.g. regional, freight or even high-speed) which connect to it, with a consequent elevated complexity of train manoeuvres at junctions/stations. This level of complexity and traffic heterogeneity requires longer development and deployment processes before VC could be deployed on mainline railways. The scenarios for the other market segments can be found in MOVINGRAIL (2020b).

The mainline case study considers the South West Main Line in the United Kingdom (UK) where a train runs from Waterloo to Southampton (127 km) every 30 minutes for 1h20' compared to a headway of 60 minutes for a 2h20' trip by coach (regional bus) with €28.45 and €9.00 ticket fees, respectively. A trip for the defined Origin-Destination (OD) pair by car takes 2h10' and costs €14.40. In MOVINGRAIL (2020a), the travel demand analysis indicated that based on a survey conducted with 229 respondents in year 2019-2020, the modal share in railways for this particular case study is 58%.

The total transport CO_2 emissions for the considered case study are 16.928 kg per passenger, i.e., 13.904 kg for traveling by car and 3.024 kg for traveling by coach/regional bus. The initial emissions values were extracted from publicly available online sources such as EcoPassenger (2020), CostToTravel (2020) and the UK government (2019). In MOVINGRAIL (2020a), modal shifts were computed based on stated preference surveys to collect potential customer attractiveness for the introduction of VC. Modal shifts from motorized transport modes to railways were used to compute CO_2 emissions assuming that there is no increase in ticket costs. By further expanding this analysis, results showed that VC can reduce CO_2 emissions by 46.7% on average. Based on the report by the UK Government on "2019 UK Greenhouse Gas Emissions, Final Figures" (UK GOV, 2021), transport was the largest emitting sector in the UK in 2019 and is responsible for over a quarter of all greenhouse gas emissions in the UK (27%).

Due to increased road traffic that has largely offset improvements in vehicle fuel efficiency, transport emissions were estimated to have been around 5% lower in 2019 than in 1990.

CAPEX provides a marginal increase to migrate from ETCS L3 to VC (10.7%) while OPEX is considered almost equal for the two signalling alternatives. The OPEX for VC with respect to the multi-aspect signalling system is 27.4% (MOVINGRAIL, 2020a).

In the case study, the knowledge strategy link is set by the outcomes of the feasibility study and represents the link between what we know from developments and technologies currently implemented in railway signalling (in our case studies, this refers to ETCS L2 for high-speed and multi-aspect signalling for the other market segments) and how we can bridge the knowledge gaps in Table 4.1 to bring the railway market to VC through a set of step-changes which build a strategy. On the other hand, the strategy-knowledge link mainly provides input to the 'Direction' (see Figure 4.1) that the knowledge will be extended. Given the time to implement a certain strategy, we get to know what are the most critical rail segments and the knowledge required by stakeholders such as regulatory bodies and signalling system suppliers to overcome strategy-related challenges.

4.6 Results

This section presents results of the roadmapping analysis. The process consists of developing the technology roadmap (Section 4.6.1), then defining generic and market-specific scenarios with a specific focus on the mainline market segment (Section 4.6.2). Optimistic and pessimistic scenarios are defined based on the required durations for the different step-changes and on prediction uncertainties represented by five factors related to the VC market pulls. A Swimlane is defined by assessing priorities and times orders of step-changes towards the deployment of VC. Finally scenario-based roadmaps are developed based on the outcomes of sections 4.6.1 and 4.6.2.

4.6.1 Stakeholder survey and swimlane roadmap for Virtual Coupling

A key initial step when designing a roadmap architecture is to understand the strategic context in terms of focus, scope and aims (Phaal and Muller, 2009) as shown in the 'Do know' element in Figure 4.1. In addition, it is crucial to define goals, explore strategic options or scenarios, and implement step-changes as described in Section 4.3. These are developed by a process team -which represents a small group of people- that liaises with other key stakeholders.

The priorities of the step-changes were defined based on MCA criteria weights and the expert judgment. A survey was distributed to the MOVINGRAIL partners to assess priorities and time order for a set of steps defined in a workshop with the MOVINGRAIL project partners and members of the advisory board, and to collect further steps/actions relative to the implementation of VC. The involvement of the members of the advisory board provides less bias on the results since they are considered external to the project. Both priorities and time order were based on a score from 1 to 20. The highest priority is represented by number 1 while the lowest priority is assigned a value of 20. For time order, the steps were ranked by starting with number 1.

From the MCA perspective, the priorities for the different step-changes were developed based on previous results from a hybrid Delphi-AHP MCA (MOVINGRAIL, 2020b; Aoun et al., 2021). For instance, we found that the safety criterion had a weight of 45% when compared to the weights of seven other criteria. Therefore, the step-change 'Research on longitudinal motion control systems within train convoys, including convoy stability and relations to ATO' (see Figure 4.2) has a very high priority because it should guarantee a safe distance between the trains before being able to move to the next step-change. In addition, the ATO should interact with the onboard safety system to promptly respond to the indication of position, speed and acceleration communicated by a predecessor to its follower within a convoy. Similarly, the regulatory approval criterion had a weight of 33% which is assigned a high priority when compared to the weights of the other seven criteria. This is reflected in the step-changes related to the concept of operations and requirements as regulatory bodies would be able to approve the VC technology and authorize testing or real-scale proof-of-concept only after the requirements, the concept of operations and the systems architectures are supported by them. We found in our study that the input provided by the stakeholders in the survey and workshop was aligned with the priorities assigned to the step-changes based on the MCA results.

The aim of the Swimlane is to show how to bridge the gaps discussed in Section 4.4 through a list of step-changes towards the real deployment of VC. A Swimlane was developed to group time order and priorities collected from the survey into different themes and domains. The survey results were revealed and further expanded during an online workshop (given the Covid-19 circumstance) scheduled on the 6th of May 2020 with 22 participants representing project partners and railway experts in both academia and industry. The criteria adopted for the selection of the stakeholders included the type of professional background/company and the level of expertise, i.e. limited, practitioner, expert. The development of roadmaps requires the involvement of stakeholders, often with very different perspectives. Kostoff et al. (2004) mention that identifying appropriate participants to be involved, particularly in workshops, is a key consideration during the planning phase. We mainly focused on the five most important types of stakeholders in the railway field including: 9 representatives from academic institutions, 5 from infrastructure managers, 3 from railway signalling/manufacturing companies, 3 from passenger/freight train operating companies and 2 from governmental agencies. The workshop process which we adopted was based on the Delphi method where the roadmap was created in multiple iterations. The Delphi approach ensures controlled feedback and statistical aggregation of group responses to avoid biased outcomes. First, the process team determined the scope of the roadmap and shared a list of initial step-changes with the stakeholders. The stakeholders were asked to come up with further step-changes and to share feedback on the provided step-changes. Scenarios, facts and brainstorming helped in identifying different roadmapping opportunities, and we updated the roadmap during the workshop based on the received feedback and brainstorming discussions. The survey's participants all attended the workshop which had the aim of reaching consensus about the chronological sequence and priorities of each action step in the roadmap towards VC. The iterations between the survey and workshop ensured feedback between the why, what and how perspectives. Survey results highlighted that respondents who defined themselves as experts provided a more consistent opinion across all the questions formulated in the survey. After both the survey and the workshop, the collected information was synthesized and consolidated in a set of visualizations which are packaged in this chapter in a strategic roadmap relating to the why, what, how and when, as illustrated in Figure 4.5.

The results were grouped into six themes (Feasibility study; Research and Innovation; Requirements; Specifications; Design, Develop and Build; and Deploy) and three domains (i.e., Operation, Business and Technology). Based on the priorities and time order extracted from the survey results, the step-changes were sorted chronologically per group (i.e., theme/domain box) while assessing priority based on the following colours: red – very high priority; orange – high priority; yellow – medium priority; green – low priority; blue – very low priority; grey – no priority. The items in the 'Feasibility study' theme were not assessed in terms of priority since these steps are related to tasks of the MOVINGRAIL project. However, those steps are crucial to bridge the gap between the current and future states and are listed below:

- Definition of VC, scope and boundaries Operation
- Identification of operational scenarios Operation
- Market analysis and use cases Business
- Cost-effectiveness analysis, including capacity analysis Business
- Technology roadmap to develop VC Business
- Business risk analysis Business
- Analysis of communication solutions for Virtual Coupling Technology
- Proposals for Virtual Coupling communication structures Technology

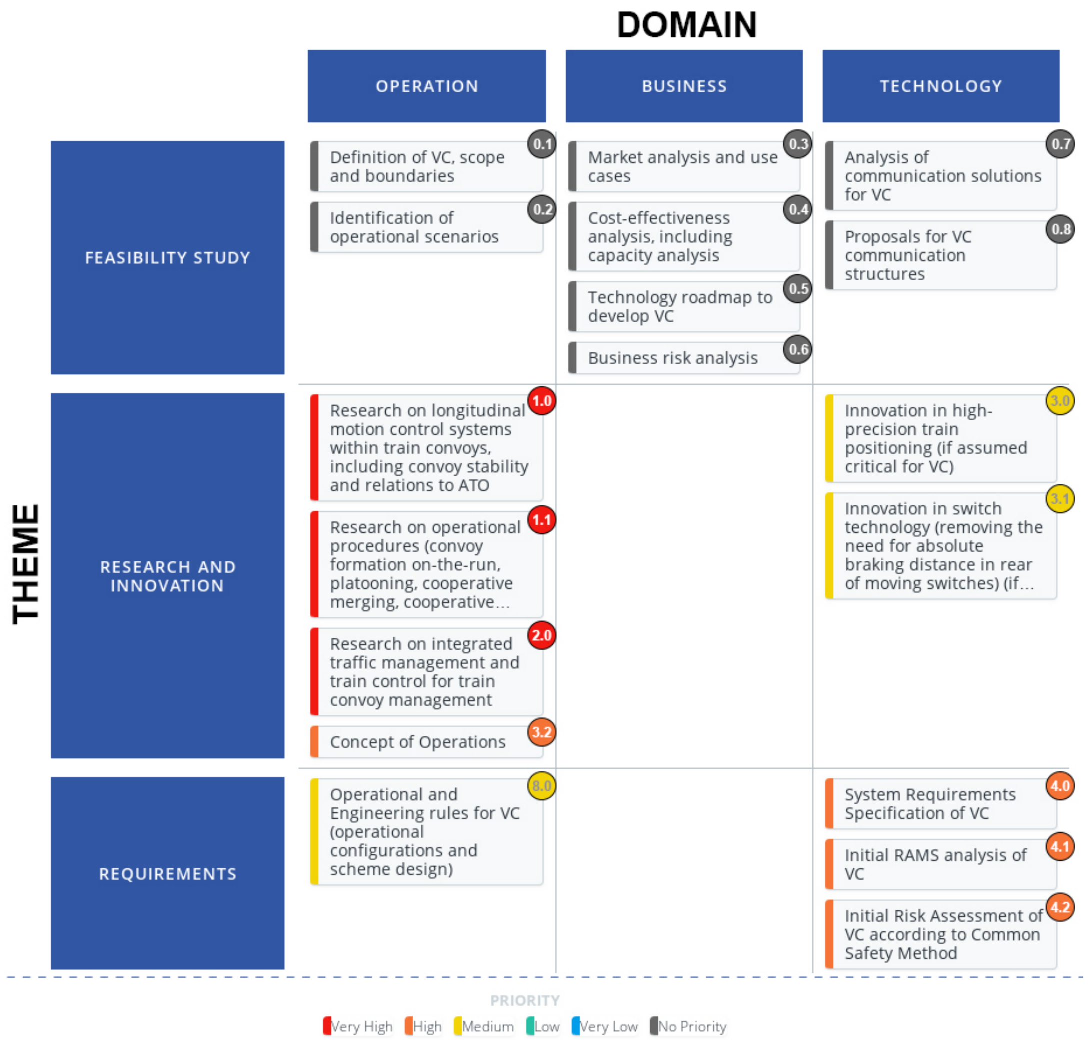

Figure 4.2: Part of the Swimlane for the implementation of Virtual Coupling

Figure 4.2 shows part of the Swimlane. All the step-changes, themes, domains, priorities and time order among the steps are illustrated in Section 4.6.2. The results showed that the major steps that represent the highest priorities are all within the R&I theme and are related to the longitudinal motion control systems in convoys, operational procedures, as well as the integrated traffic management and train control. These steps were assessed as first in time order and are considered as input to the upcoming actions. The high priority steps are related to the concept of operations, the system requirement specifications, the initial Reliability, Availability, Maintainability and Safety (RAMS) analysis, and the initial Risk Assessment of VC according to the Common Safety Method (CSM-RA). In addition, specifications related to system architectures for VC (i.e., integrated communication and control architecture intra & inter convoys) were considered of high priority and require as input two specifications of medium priority related to the operational procedures in interlocking (IXL) areas and the operational procedures for coupling, coupled running and decoupling. All the other specifications were assessed as medium priority and emphasize the communication protocols (including safety and security), as well as the communication models for V2V, and RBC/Vehicle-to-Infrastructure (V2I). System architectures were considered as input to the last two mentioned medium-priority steps. Standardization (e.g., within ERTMS) requires input from operational and engineering rules within the 'Requirements' theme which was also assessed as medium priority. In the 'Design, Develop and Build' theme, all the steps were considered of medium priority except the final RAMS analysis, and the final CSM-RA that were allocated to low priorities. Regulatory approvals were also represented by a green colour (low priority). This is most probably because respondents assessed the steps looking at the current knowledge and strategy (see Figure 4.1). This means that although very low priorities were provided to the deployment of ETCS L3 and VC, this is just for the time being, as there are other priorities that require dedication and attention to be able to successfully reach the lower-priority steps that are indeed crucial for the real implementation of VC.

4.6.2 Scenarios for Virtual Coupling implementation

This section develops scenarios that are used to describe various expected or assumed future situations to different market segments. A scenario considers alternative characteristics based on certain assumptions and conditions. The aim of the scenarios is to evaluate the most prominent factors/criteria for the deployment of VC by considering their pros or cons, and to build scenario-based roadmaps based on estimated durations (see Table 4.2). We analyse five measures or factors that affect the real (business) deployment of a certain technology or transportation project, i.e., demand, CO_2 emissions, CAPEX, OPEX and regulatory approval.
Two scenarios have been defined for each market segment: optimistic and pessimistic. The scenarios were grouped into two categories: generic and market specific. In this section we describe the generic scenarios and the ones related to the mainline market. Details on the scenarios defined for other market segments can be found in MOVINGRAIL (2020b). The goal is to fulfil the European Commission's strategic target set in the White Paper on Transport towards the deployment of a more competitive, capacity-effective and sustainable railway by 2050 (European Commission, 2011). In this study, we assume that the achievement of the EC's targets entails a necessary deployment of the VC concept within 2050. The baseline values of the defined factors are derived from Aoun et al. (2021) and from publicly available governmental sources.

Default percentages for demand and CO_2 emissions in the optimistic scenarios are based on the European Commission vision in the White Paper on Transport (2011) and the Shift2Rail MAAP (2015). The European Environment Agency (EEA) forecasted a big increase in the number of passengers that must be accommodated by the railways in the next 30 years. This corresponds to a 30% increase in passenger transport demand in 2050 compared to the year 2000 (European Environment Agency, 2012). The railway demand is estimated to increase by 50% for freight in 2050 compared to 2010 (European Commission, 2011). In addition, the European Commission has a strategic vision to railways to cut down the greenhouse gas emissions by 60% within year 2050 compared to year 1990, and envisages a massive modal shift of passengers and freight from road, air and water transport to railways (European Commission, 2011). Optimistic costs consider a 40% less value with respect to the baseline percentage. The regulatory approval criterion is described qualitatively in generic scenarios for all market segments. We also represent this quantitatively in Figure 4.3 based on the criterion index of 0.320 computed in Aoun et al. (2021) by adding a 40% increase in the case of the optimistic scenario.

The pessimistic scenarios are based on 'pessimistic' trends of the defined criteria. In this case, the values are considered to increase or decrease by 50% compared to the optimistic scenario, depending on whether the defined criterion is beneficial (e.g. demand) or non-beneficial (e.g. costs). The railway demand for passenger trains is considered to increase by just 15% and for freight trains by only 25%. Similarly for CO_2 emissions, we assume a percentage decrease in CO_2 emissions by 30% instead of 60%, and for regulatory approval, the increase is by 20% instead of 40%.

4.6.2.1 Generic scenarios for all market segments

Generic scenarios are applicable to all market segments and defined as follows.

Generic optimistic scenario: The railway demand is considered to significantly increase and the CO_2 emissions to notably decrease for all market segments. An optimistic percentage of a 40% decrease is assumed for CAPEX and OPEX with respect to baseline percentages extracted from the cost analysis in MOVINGRAIL (2020a). The incentives between IMs and RUs are well aligned and support the deregulation of the railway market by opening to smaller transport operators. The railway market enhances cooperative and positively competitive consortia of railway undertakings. Consequently, mobility is improved, and railway services are easier to access by the customers who can choose route alternatives from different operators. This would support standardization and interoperability by providing a better choice for customers to improve quality and variety while enjoying all services in the railway market. In addition, a simple booking platform can be beneficial to customers who can book their railway trips with transparency in ticket prices (as is the case for airlines). In this scenario, digitalisation creates new models and service providers where the railway industry would embrace liberalisation and establish new ways for setting efficient prices and improving data sharing and trust of information in the market by developing new regulation mechanisms. The share of data among different railway undertakings would provide a more comprehensive understanding of mobility systems and people's needs where rail would become part of an entire mobility chain. With such cooperation, regulatory approval is fast, and policies are aligned with the five scenarios defined in the White Paper on the future of Europe (European Commission, 2017).

Generic pessimistic scenario: The railway demand is considered to increase by only 15% instead of 30%, and CO_2 emissions are considered to decrease in value by 50% with respect to the optimistic scenario. This is because it is expected that road transport will also become more sustainable due to technological evolutions (e.g., electric vehicles, battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV)). The cooperative train control complexity is full of uncertainties that might arise from heterogeneous braking rates in one convoy. This scenario considers misalignment between the incentives of IMs and RUs and does not easily support the deregulation of the railway market with opening to smaller transport operators. The 'pessimistic' percentages of CAPEX and OPEX consider a 50% decrease in cost compared to the percentage in the optimistic scenario (0.5 x 0.4 = 20%). Mobility challenges arise from both institutional and regulatory perspectives; railway undertakings would have to migrate from their traditional monopolistic approach when it comes to data sharing, and it is crucial to understand how regulators will make use of the data and the security measurements that need to be undertaken. Therefore, the railway market is uncooperative in this scenario and regulatory approval is considered critical (i.e., requires a longer time compared to the optimistic scenario).

4.6.2.2 Scenarios for the mainline market segment

In an optimistic scenario, an increase of 30% in the demand results in 75% of the total modal share for train users from Waterloo to Southampton that was initially 58% (see Section 4.5). The homogenisation of travel behaviour of the different train categories when platooning over open tracks facilitates coupling and decoupling on-the-run due to sufficiently long interstation distances, which provides additional capacity benefits. Travellers' satisfaction can be maximised by means of a personalised on-demand travel experience if swarming trains (composed of a single powered car unit) are introduced for the passenger trains (mixed with freight trains). In the case of the pessimistic scenario, the railway demand for mainline railways is considered to decrease by 15% less than the optimistic scenario, resulting in a total demand of 67% of train users between Waterloo and Southampton, since it is expected that road transport will also become more sustainable due to technological evolutions.

Since the European Commission has a strategic vision for railways to cut down the greenhouse gas emissions by 60% within year 2050 compared to year 1990 and based on Section 4.5, we consider in this chapter that the optimistic transport-related CO_2 emissions are reduced by 55% from year 2019 to 2050 (from 27% to 12.2%). In the case of the pessimistic scenario, the reduction is equivalent to 27.5% (50% of 55%) resulting in 19.6% emissions by the year 2050. In the optimistic scenario, the CAPEX increase of 10.7% in VC investment costs compared to ETCS L3 is further decreased by 40% resulting in just a 6.4% increase. OPEX for VC with respect to the multi-aspect signalling system is decreased from 27.4% to 16.4%. In the pessimistic case, CAPEX is increased by 8.6% and OPEX by 22%.

As mainlines have heterogeneous traffic, the cooperation between IMs and RUs is an important step-change towards the speed-up of regulatory approval for the effective implementation of VC. The Shift2Rail MAAP mentions that there is a need for developing and implementing wider and more sophisticated applications for mainline operation. Given the above, the mainline market segment would indeed profit from migrating to advanced systems for automatic traffic management and cooperative train operation to optimise management of trains with different characteristics. On the contrary, a pessimistic scenario considers that given the high uncertainty and complexity in managing heterogeneous rolling stocks in one convoy and the crucial planning of collaboration between IMs and RUs, more time would be needed for regulatory approval.

A summary of the results is illustrated in Figure 4.3.

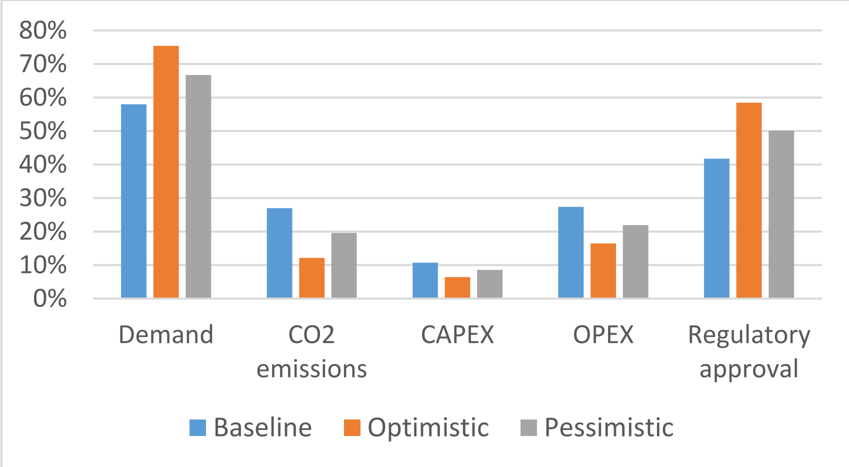

Figure 4.3: Scenarios for the mainline market segment

4.6.3 Scenario-based roadmaps for each market segment

The main reasons for developing the scenario-based roadmaps relate to the goals of the VC deployment which can satisfy the EU vision. The main objective of VC is to increase line capacity by reducing headways, as well as to increase operational flexibility by insuring interoperability between all railway vehicles. VC also aims at improving the use of the existing station platforms by adopting several platform tracks. Costs are reduced with the implementation of VC since this technology relies on onboard equipment and electronic systems instead of lineside signals and/or the need to build new tracks or applying major infrastructural changes. Another reason that reduces costs is the reduced operational expenditure (OPEX) due to automatic operations (Aoun et al., 2021).

In this section, roadmaps are illustrated for optimistic and pessimistic cases by estimating timelines for the step-changes defined in Table 4.2. If the five factors defined in Section 4.6.2 are optimistic, e.g., demand will be increased by 30% for passengers and by 50% for freight by year 2050, the deployment of VC would indeed be accelerated. Similarly, if CO_2 emissions will be significantly decreased by 60% and costs will be decreased, policies and regulations would foster the deployment of VC. On the other hand, short timelines mean that the environment would rapidly become less pollutant and that the need for high investment costs and payments for staff would be reduced. Reciprocally, the longer the estimated duration of the step-changes defined for each market segment (pessimistic case), the lower would be the overall positive impact on the societal, environmental and economic factors. Based on the results in sections 4.6.1 and 4.6.2, indicative durations to each of the steps were estimated for optimistic and pessimistic scenarios. Since the durations regarding the actual deployment of VC depend on the corridor length and in order to provide generalised roadmaps that are not just applicable to the case studies defined in MOVINGRAIL (2020a), the timelines were estimated based on an online workshop held with stakeholders across Europe and professional experiences by sector experts.

Actions can start simultaneously or consecutively. Dependencies among the different steps are related to the time order derived from the stakeholder survey and the Swimlane (Figure 4.2), where one item can be considered as an input to the following step, resulting in a cascading sequence of timelines. The generation of roadmaps has been executed with the project management software Primavera P6 Pro.

The results show that the deployment of VC can be fulfilled to all market segments in optimistic and pessimistic scenarios, except for the mainline pessimistic scenario where VC would be deployed by 2054 instead of 2050 (see Figure 4.4). This is because for mainline railways there is a high uncertainty and complexity in longitudinal cooperative motion control and managing heterogeneous rolling stock that have different braking rates in one convoy. Consequently, there is a need for further time extension for R&I in integrated traffic management and train control for both freight and passenger trains that operate on the same lines. In addition, regulatory approval might engender further delay since there is a need for crucial cooperation and agreement between IMs and RUs due to the heterogeneous traffic conditions. The duration of steps for each market segment in optimistic and pessimistic scenarios is shown in Table 4.2. The gradual colours of the estimated values denote that the reddish cells are the most critical, i.e., require the longest duration. The resulting scenario-based roadmap for the pessimistic scenario of the mainline market segment is illustrated in Figure 4.5. Note that this figure is just an example of one scenario for one market segment. However, the roadmap builds on two scenarios for each market segment towards the deployment of a visionary concept that is not yet implemented in real life, i.e. VC. The scenario-based roadmaps for the deployment of VC to each of the defined market segments in both optimistic and pessimistic scenarios can be found in MOVINGRAIL (2020b).

The roadmap in Figure 4.5 represents a high-level, strategic plan that aims to communicate the VC project goals and vision. Particularly, each step-change represents a goal. In our research, we do not make a detailed and linear schedule of tasks, but we rather look at the bigger picture since each of the step-changes shown in Figure 4.5 requires further investigation and has several uncertainties in terms of the adopted methodology or technology. This figure also shows the high-level domains, themes and dependencies between the step-changes, in addition to the priorities associated to each step-change.

In the illustrated roadmap, we follow the two key dimensions of a roadmap structure, namely timeframes (i.e. when) and layers/sub-layers, as discussed in Phaal and Muller (2009). The aspects of why, what and how are attributed to the layers of the structured roadmap. First, we show the current situation, mainly related to the step-changes under the theme 'Feasibility Study'. We then progressively illustrate the step-changes in the short-, medium- and long-terms towards the vision of deploying VC. A long-term strategy enables key uncertainties and scenarios to be articulated, and shifts in the operation, business and technology domains, to capture and assess long-term issues that affect current decisions and plans, like R&I. The strategic lens provided by this roadmap magnifies and focuses on the issues and areas of the VC system which are of most importance. Those are assessed by means of priorities, time order, dependencies and durations. As mentioned previously, the main objective is to fulfil the European Commission's strategic target set in the White Paper on Transport towards the deployment of a more competitive, capacity-effective and sustainable railway by 2050 (European Commission, 2011), represented in our study by the deployment of VC. The middle layer (what) constitutes the evolution of the technology, we represent this by sub-layers or intermediate layers to highlight key enablers and barriers/gaps which must be overcome through step-changes that lead towards the deployment of VC, and consequently benefit both customers and stakeholders. Therefore, the *what* in Figure 4.5 corresponds to the step-changes to migrate from current state to future state (see Figure 4.1). Those step-changes can be related to functions (e.g. RAMS analysis), features (e.g. ATO), performance (e.g. operational procedures in interlocking) and knowledge (e.g. operational procedures). Finally, the bottom layer *how* deals with the resources required to develop the VC system. Based on Phaal and Muller (2009), those resources can be related to knowledge (e.g. technology, skills, competences) or other resources (e.g. finance, alliances/partnerships, facilities). In our study, the *how* corresponds to the resources and the regulatory bodies responsible for the validation of the safety and engineering rules of VC, consequently leading to its deployment.

The Swimlane developed in Section 4.6.1 helps in understanding how each theme will evolve for each layer and sub-layer, and how the layers relate to each other. Figure 4.5 portrays pushing and pulling perspectives as it supports the identification and discussion of the general requirements and capabilities offered or needed, respectively. The market pull leads from the *why* to the *what*. In the case of VC, it corresponds to the business and market needs for increasing capacity due to the significant increase in population and rail demand growth. Another main pull is given by the strategic EU vision for a competitive and sustainable transport envisaging a significant increase in current railway capacity, as well as a decrease in CO_2 emissions and lifecycle costs. The market pulls represented in optimistic and pessimistic scenarios (Figure 4.1) are based on the percentages obtained in Section 4.6.2. The technology push is the relation between the *how* and *what.* Technology pushes in the case of VC are given by advances in telecommunications, informatics and rail signalling technologies whose increasing efficiency and capabilities are pushing railway operations towards a higher level of digitalization and automation of traffic management and train control. The latest developments relate to high-accuracy satellite-based vehicle positioning, high-speed / high-capacity signalling systems like ERTMS/ETCS, high-frequency long-range radio communication systems, and algorithms for automatic train operation. These developments are pushing the upgrading of railway operations towards a digital future where train separation could be reduced (hence capacity increased), as automation will potentially improve driving reaction times, hence reliability and safety of current trains.

The time estimates of all step-changes must be viewed as rough expert opinions based on experience with past technology, whereas governmental policy may change the speed of developments. Therefore, the total estimated time until deployment must be taken as indicative. More important are the lessons from the dependencies, orders and critical paths illustrated in the roadmaps. These may give guidance to put emphasis on certain step-changes. In particular, the roadmaps showed that R&I must be done in the beginning and was assessed as a lengthy process. It is therefore important to start these R&I topics in parallel as soon as possible. The business risks that entail those step-changes are discussed in detail in MOVINGRAIL (2020c).

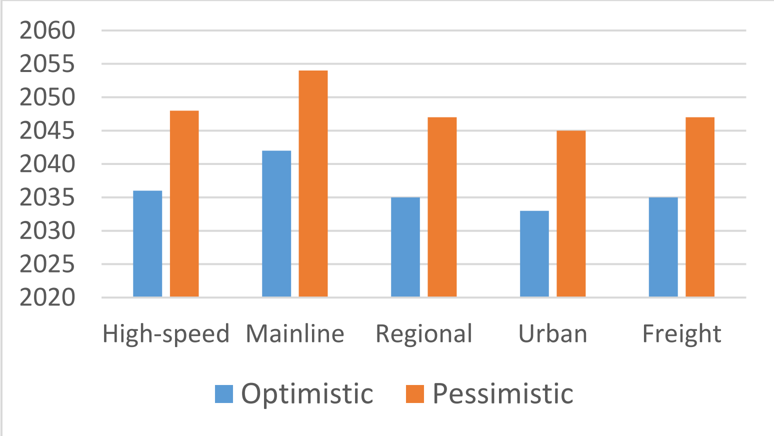

Figure 4.4: Time until deployment of Virtual Coupling for each market segment in optimistic and pessimistic scenarios

4.7 Discussion

The research conducted in this chapter proposes a novel roadmapping approach by developing a framework that supports various tools, scenarios and data flow. We applied the proposed framework for the first time to generate roadmaps for the VC deployment to different railway market segments to support stakeholders in the practice of technological forecasting and planning. The practical perspective is also highlighted in the critical aspects shown by the roadmaps which need to be considered both on the technological and regulatory sides to support regulators and policy makers in satisfying the market needs.

The policies and strategies that can be supported by the developed roadmaps include changes in engineering rules and operational principles for operating railways. Based on the feasibility study performed on VC in the MOVINGRAIL project, a set of enhanced engineering and operational rules have been drafted to support the IMs and regulatory bodies in writing VC and MB related rules (MOVINGRAIL, 2018). The responsible for approving these principles is the European Railway Agency (ERA) together with IMs and RUs. The roadmaps also provide the necessary elements that would need to be incorporated to reach approvals from the railway industry when it comes to technological developments and regulations. The ERA specifies which kind of certification process needs to be set to make the future technologies compliant to the current safety standards. In addition, rail system suppliers can avail of the outcomes of the roadmap to define strategic investment plans for research and developments of required signalling technologies enabling the deployment of VC to the market. In terms of the societal implications, the developed roadmaps help in understanding the required costs, time to deployment and the impact on the environment. Particularly, the scenario-based roadmaps show how the introduction of the VC technology can change the modal shifts between available transport modes and railways. Consequently, modal shifts would have an overall implication on energy consumption, CO_2 emissions and costs. The findings of this chapter can also be used by the society for internal learning to redesign an intervention, improve approaches to interact with customers, or deliver an action or step-change. The identification of the scenario-based roadmaps as well as the SWOT analysis can support in developing tailored interventions to achieve better outcomes.

Table 4.2: Duration estimation of optimistic and pessimistic scenarios for each market segment

	Short title of step	Time order & priority	Optimistic Scenario (months)					Pessimistic Scenario (months)				
			HS	ML	RGN	URB	FRT	HS	ML	RGN	URB	FRT
Feasibility Study	VC, scope and boundaries	0.1	2					5				
	Operational scenarios	0.2	2					5				
	Market analysis & use cases	0.3	3					6				
	CEA including capacity analysis	0.4	5					8				
	Technology roadmap	0.5	2					4				
	Business risk analysis	0.6	2					4				
	COM solutions	0.7	5					8				
	VC COM structures	0.8	4					8				
Research & Innovation	Longitudinal motion ctrl systems in convoys	1.0	24	30	24	18	24	36	40	36	30	36
	Operational procedures	1.1	6	12	6	6	6	12	18	12	12	12
	Integrated traffic mgt & train ctrl	2.0	24	30	24	18	24	36	40	36	30	36
	Train positioning	3.0	24	24	12	12	12	36	36	24	24	24
	Switch technology	3.1	24	24	12	12	12	36	36	24	24	24
	Concept of Operations	3.2	6	12	6	6	6	18	24	18	18	18
Requirements	System Requirements Specs	4.0	12	18	12	12	12	18	24	18	18	18
	Initial RAMS analysis	4.1	3	6	3	3	3	6	10	6	6	6
	Initial CSM-RA	4.2	3	6	3	3	3	6	10	6	6	6
	Operational & Engineering rules	8.0	10	12	10	10	10	20	24	20	20	20
Specifications	Operational procedures in IXL	5.0	6	10	6	6	6	12	20	12	12	12
	Operational procedures for coupling, coupled & decoupling	5.1	8	10	8	8	8	18	24	18	18	18
	Systems architectures	6.0	8	12	8	8	8	18	24	18	18	18
	COM protocols including safety and security	7.0	12	18	12	12	12	18	24	18	18	18
	COM models: V2V & V2I	7.1	8	12	8	8	8	18	24	18	18	18
	Standardization (e.g. ERTMS)	9.0	12	18	12	12	12	24	30	24	24	24
Design, Develop & Build	Develop COM system	10.0	8	12	8	8	8	12	18	12	12	12
	Upgrade RBC & EVC software	10.1	6	10	6	6	6	18	24	18	18	18
	Develop ATO	10.2	12	18	6	3	6	24	30	12	6	12
	Develop testing methods	10.3	12	12	12	12	12	20	20	20	20	20
	Early deployment & trial	11.0	6	10	6	4	6	12	18	12	10	12
	Final CSM-RA	12.0	6	8	6	4	6	12	18	12	10	12
	Final RAMS analysis	12.1	6	8	6	4	6	12	18	12	10	12
	Safety case	12.2	4	6	4	4	4	8	10	8	8	8
Deploy	Safety approval	13.0	6					18				
	Regulatory approval process (inclusion in TSI)	13.1	18					30				
	Deployment of ETCS Level 3 MB	14.0	18	24	18	12	18	24	30	24	24	24
	Deployment of VC	15.0	12	18	12	8	12	18	24	18	16	18

Legend

Priority scale	Market segment		Duration
Very high	HS	High-Speed	short → long
High	ML	Mainline	
Medium	RGN	Regional	
Low	URB	Urban	
Very low	FRT	Freight	

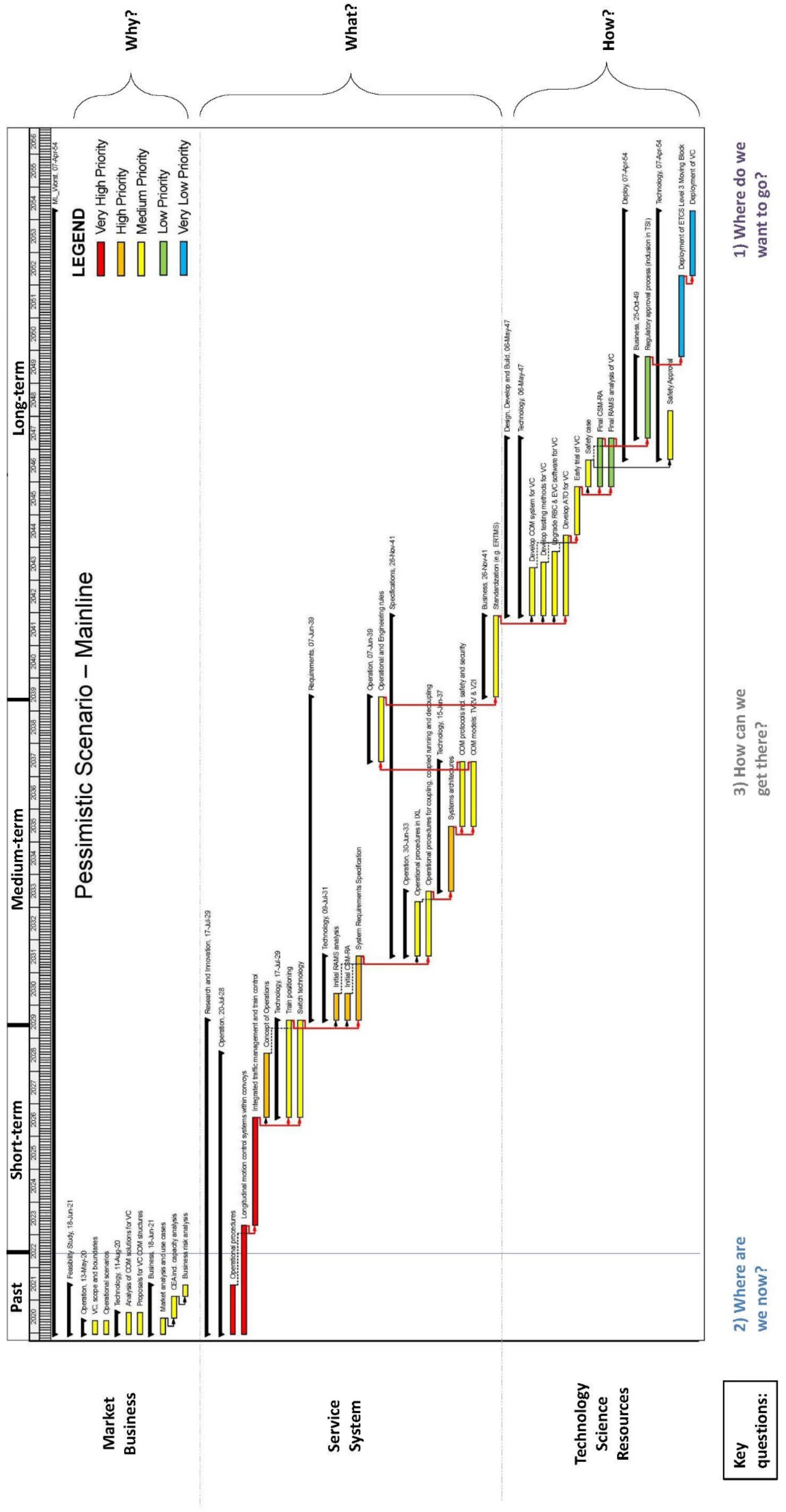

Figure 4.5: Mainline – Pessimistic scenario (16/12/2019 – 07/04/2054)

The SWOT was useful in determining the required step-changes for migrating from the current state to the future state towards deploying VC for each market segment. Based on the MCA results (MOVINGRAIL, 2020a; Aoun et al., 2021), we found that the urban market segment is ranked first in terms of cost and capacity. This is because this railway market is the simplest in terms of infrastructure layout and operation and therefore requires less investment and operational costs. In addition, since trains operate autonomously on a single track that does not involve complexities in land profile, the CO_2 emissions can be reduced. Metro systems also have the ability to transport a lot of passengers with short headways. With the implementation of VC, capacity benefits will increase to very frequent train services (e.g. every 30 seconds). In terms of regulatory approval, as automated metro systems are already implemented in an increasing number of cities worldwide, such as London, Lille, Beijing and Singapore, this process takes relatively less time than for other railway markets. This is mainly due to the same characteristics that enabled Automatic Train Operation Grade of Automation 4 (ATO GoA4) in these metro systems, such as slower speeds, closed environments and no to limited crossing tracks.

The future time horizons are associated with uncertainties represented in the roadmaps. In the framework from Courtney et al. (1997) where the levels of uncertainty can be related to timeframes, the research conducted by Kahn and Weiner (1967) seems to fit Level 2 of the Courtney et al. framework (options and branching pathways), while the definition of Troch et al. (2017) looks more relevant to Level 3. Our work relates to the Kahn and Weiner (1967) definition as the end point is clear (EU goals), with the timing and impacts to achieve these goals uncertain, represented by optimistic and pessimistic scenarios for five different market segments.

Two main toolkit configurations are identified based on the following. On one hand, when strategic planning is dominated by future uncertainty, future-oriented scenarios can be used to resolve this uncertainty, which will define an end state towards which a roadmap can be developed. These scenarios have common and different elements and can potentially be combined to create branching pathways. On the other hand, when future uncertainty is not dominant, a baseline roadmap can be developed subject to a sensitivity analysis using scenarios, which leads to mitigations and options. Our research relates to both toolkit configurations since the uncertainty arises from the fact that we are not sure whether by 2050 VC can be deployed to all market segments given the various challenges that need to be resolved for its deployment. On the other hand, depending on the complexities involved by each market segment, durations are affected by optimistic and pessimistic scenarios.

The challenges faced by the stakeholders represent different perspectives on the feasibility and challenges of the VC technology itself, the value and usability of VC for the railway market customers, and the skills and competences for creating and developing the VC concept. In addition, although the participants had different opinions about the durations for each step-change, the workshop helped in developing a consensus among all the stakeholders based on both expert and scientific judgement.

The technology roadmap developed in this chapter can be used by other groups of people or fields to make decisions, or customers who are interested in the deployment of VC in the railway market. Other disciplines and applications such as logistics, supply chain, aviation and road transport could follow similar approaches for roadmapping and for the introduction of a new technology or process from start to market uptake. Furthermore, given the susceptibility of the developed framework to support a wide range of scenarios and case studies, it can help to plan and coordinate technological developments at any organizational, national or international level. Additionally, the roadmapping methodology defined in this chapter can be used as input to decision makers where synchronisation and flexibility are enabled for redefining focus and direction, based on the variability of inputs from a SWOT analysis, MCA results and stakeholders.

Future recommendations include the enhancement of visuals that support the development of roadmaps based on the considered technology and its requirements. In addition, a limitation concerns the use of the same level of priority of the step-changes to all the market segments. This might not always be adequate since different stakeholders may have diverse needs and priorities depending on the investigated scenario for each market. Therefore, the concept of dynamic scenarios can be introduced to allow for more flexibility with the dependencies between step-changes, priorities, scenarios and market segments. Moreover, the developed framework in this chapter can be integrated with other management tools and methods to provide a deeper investigation of systems' dynamics and areas from different sociological and technological fields. For instance, the integration of a Technology Development Envelope (TDE) can support the determination of an optimum path of technology development to maximize its benefits.

4.8 Conclusions

This chapter developed a technology roadmap for the implementation of Virtual Coupling (VC) with a particular focus on the mainline market segment. It aimed at capturing operational, technological and business differences between traditional railway signalling systems and future train-centric signalling systems, as well as identifying potential optimistic and pessimistic scenario-based roadmaps to migrate railway operations to next-generation signalling.

The main challenges of VC were identified along with the required step-changes to the safety, communication and control technology, interlocking, Vehicle-to-Vehicle communication, cooperative train protection and control, and integrated traffic management. A Swimlane was developed by associating step-changes identified by stakeholders in a survey and workshop to assess priorities and time order for a set of future operational and technological steps, as well as business actions relative to the implementation of VC. This was supported by means of a gap analysis that consists of determining steps that must be undertaken to improve a present state towards a desired state. Particularly, the results of a SWOT analysis could be adapted to highlight the enablers for the implementation of VC and to generate ideas on how the gaps can be closed in different market segments through a list of step-changes.

The results of a hybrid Delphi-Analytic Hierarchy Process (Delphi-AHP) Multi-Criteria Analysis (MCA) were used to define the priorities of the step-changes and to explore quantitatively optimistic and pessimistic scenarios for the development of VC to different market segments. The chapter focused on the impacts of five prominent factors for the deployment of new transportation technologies, namely demand, CO_2 emissions, capital and operational costs, and regulatory approval. For all market segments, the need for an initial investment might not be well received by infrastructure managers and local governments. Results showed that both optimistic and pessimistic scenarios fulfilled the target of deploying VC by 2050, except for the pessimistic scenario of mainline railways where VC could only be deployed by 2054. The main bottleneck is here the development of integrated cooperative train operation, traffic management and interlocking for train convoys. This market segment would also involve high coordination between railway undertakings and infrastructure managers to enable VC of trains belonging to different train operators (where train information exchange is essential), as well as to provide a better choice of travel alternatives, crowd management and mobility promotion.

The defined scenario-based roadmaps provide support to identify potential risks and criticalities that could arise when migrating towards VC operations. Results from this study can therefore be used as a tool for stakeholders to setup strategic investment plans which can steer the technological developments, and the necessary regulations facilitating the migration to VC rail operations.

The proposed approach helps in effectively visualizing a future action plan according to plausible future scenarios. This is particularly important when companies attempt to manage market and technology activities for both strategic planning and technology management. In practice, companies can use the developed roadmapping methodology at a corporate level for the management of toolkits to foster business growth and organizational changes. The integration of SWOT, MCA, expert judgement, gap analysis and scenarios in the framework also provides a means for addressing corporate challenges and exploring new opportunities. Moreover, the developed roadmap framework provides a coherent and holistic architecture within the development and evolution of not only the VC system but also other dynamic businesses or systems where step-changes can be explored, mapped and interpreted based on distinct scenarios. Therefore, the methodology developed in this chapter is generic and can be adapted to different business processes and integrated to other management frameworks and disruptive technological game changers. As a next research step, the interactions of the essential system components for VC will be investigated in a system safety and performance analysis.

Chapter 5

Analysis of safe and effective next-generation rail signalling systems using an FTA-SAN approach

In Chapter 3, safety was assessed as the most critical criterion with a weight that exceeds 45% of the total MCA score in the overall impact assessment of the train-centric signalling technologies. Results also revealed that VC can outperform MB if both signalling alternatives reach the same level of technological maturity. In addition, findings in Chapter 4 showed that the Reliability Availability Maintainability and Safety (RAMS) analysis and the Risk Assessment according to Common Safety Method (CSM-RA) are attributed to a high priority and are critical step-changes towards the deployment of VC. However, no study has been conducted to quantitatively evaluate the safety and performance of train-centric signalling technologies to ensure a similar level of technological maturity.

In this chapter, we study the different components that constitute MB and VC railway signalling systems, their functions and failure dependencies. In particular, we apply a fault tree analysis to understand the cascading effect of one or more failures on a certain top event of a fault tree. To deal with system complexities and behaviours, this chapter considers the interaction between safety and performance for several trains running on a railway track. It also incorporates the effects of system failures derived from a Fault Tree Analysis (FTA) and the system behaviours in real-world conditions by means of a Fault Tree Analysis-Stochastic Activity Network (FTA-SAN) approach for the five defined market segments in Chapter 2. A KPI is determined to feed back the MCA for ensuring a fair impact comparison between MB and VC.

Apart from minor changes, this chapter has been submitted as:

Aoun, J., Goverde, M.P., Nardone, R., Quaglietta, E., Vittorini, V. (2023). Evaluating the safe and efficient behaviour of rail signalling technologies based on FTA-SAN.

5.1 Introduction

Next-generation train-centric signalling systems like Moving Block (MB) and Virtual Coupling (VC) are currently being considered by the railway industry to meet strategic goals of increased network capacity and service efficiency. While MB reduces train separation to an absolute braking distance, VC would enable trains to move at a relative braking distance and potentially in synchronous fashion when forming radio-linked platoons. Both the concepts of MB and VC aim to migrate vital trackside equipment (e.g., track circuits, signals) to the onboard and remove the conventional track apportioning from open lines while still using interlocking at junctions/stations. A radio-based communication layer enables a trackside Radio Block Centre (RBC) to receive position reports from the trains and to send them Movement Authorities (MAs), i.e., the maximum distance that a train can safely cross. MAs are used by the onboard European Vital Computer (EVC) to dynamically supervise train separation while the Train Integrity Monitoring (TIM) checks that trains are integer, and no car is accidentally detached and stranded on the tracks. On top of such a complex system architecture, VC also features a Vehicle-to-Vehicle communication (V2V) layer by which trains inform each other on their current position, speed and acceleration, to allow a separation shorter than an absolute braking distance or move synchronously in a platoon.

Given the shorter train separation enabled by MB and VC as well as the higher technological complexity, the railway industry urges to assess potential impacts on rail service effectivity and safety where the latest is by far the most important factor to authorise operations. A shift to VC requires major changes to the assumptions and system boundaries of the safety case for railway operations. So far, several attempts have been made to assess the safety and effectiveness of MB signalling. Qualitative studies were made by European projects such as ASTRail (2019) and X2Rail-1 (2019) which proposed hazard mitigation measures for MB and a corresponding update of signalling requirements and/or operational and engineering rules. Zafar et al. (2012) conducted a quantitative formal analysis of MB safety properties to prevent collisions/derailment at interlocking areas. Aoun et al. (2021) reported a preliminary qualitative safety assessment for both MB and VC based on expert interviews. However, to the best of our knowledge, no attempt has been made yet to quantitatively analyse the effectiveness of MB and VC in supervising safe train separation under both nominal and degraded operational conditions. Especially for degraded operations, it is crucial to consider the influence of MB and VC component failures and related cascading effects on the capability of the overall signalling system to guarantee safe train movements. Therefore, the work in this chapter contributes to bridge the literature gaps by proposing a novel combined approach of Fault Tree Analysis (FTA) and Stochastic Activity Networks (SANs) to assess the effectivity of MB and VC in safely supervising train movements in case of stochastic component failure for different market segments including high-speed, mainline, regional, urban and freight rail. The proposed analysis attempts to address main challenges related to the complexity of interactions among the different MB and VC signalling components (trackside and onboard) and the statistical distribution of component faults. These faults are variable over time and heterogeneous across components, as they are influenced by e.g., maintenance regimes, service intensity and rail market-specific operational conditions.

The main challenge for deploying advanced train signalling technologies is to ensure a safe and effective operation on existing railway networks. However, none of the existing studies in the literature has tackled this aspect by considering different sets of design variables and modelling the behaviour of the investigated systems under different scenarios.

Aoun et al. (2021) showed that among eight criteria assessed through a hybrid Delphi-Analytic Hierarchy Process (Delphi-AHP) approach, the safety criterion was evaluated as the most relevant with a weight of 45%. Results also revealed that VC can outperform MB if both signalling alternatives reach the same level of technological maturity, i.e., safety. In addition, findings in MOVINGRAIL (2020b) and Aoun et al. (2023) showed that the Reliability Availability Maintainability and Safety (RAMS) analysis and a Risk Assessment according to the Common Safety Method (CSM-RA) are attributed to a high priority and are critical step-changes towards the deployment of VC.

It is crucial to investigate the effects of faults in MB and VC system component design variables and functionalities on the operation of trains and to understand their behaviour under different configurations. However, to the best of our knowledge, this gap has not been addressed yet in the literature. Therefore, we aim in this chapter at finding the thresholds of design variables with particular focus on the TPR network delay in a way that guarantees an effective and safe train movement (i.e., without an overshoot of the ETCS braking curve indication). We then evaluate the maximum failure rate that VC can occupy to ensure a similar technological maturity with MB by performing a sensitivity analysis on the TPR error.

After an extensive literature review on various safety and performance methods, we found that combining FTA and SAN is an effective approach in dealing with system's complexities and behaviour to better understand the impact of faults on safety and performance. The methodology is further explained in Section 5.3.

An FTA is defined for modelling components' interactions and cause-effect relationships which could lead to unsafe train movements in both MB and VC. The FTA is used to apportion a Safety Integrity Level (SIL) 4 failure rate across the different MB and VC signalling components. The resulting component failure rates are then used as input to a SAN-based simulation for assessing safe train supervision effectiveness of MB and VC in an example of a Train Position Report (TPR) error. Safe supervision effectiveness is measured in terms of the total number of times that we consider the number of times that a train brakes according to the permitted braking curve which uses a service braking rate. The main contributions in this work are:

(i) Identifying the effects of signalling component failures on the effectivity of MB and VC in safely supervising train operations for five railway market segments.
(ii) Proposing a novel approach which combines FTA and SAN for a quantitative analysis of signalling system configurations.
(iii) Defining a Key Performance Indicator (KPI) for the evaluation of effective signalling supervision of safe train movements.
(iv) Determining practical implications for MB and VC component configurations which could support the railway industry in investment and design decisions.

The chapter is structured as follows. Section 5.2 highlights the MB and VC concepts and the main safety and operational challenges for implementing VC. It also provides a literature review on the SAN modelling formalism. Section 5.3 describes the FTA-SAN methodology adopted in this chapter. A description of the FTA and SAN models for MB and VC is provided in Section 5.4. Finally, Section 5.5 outlines the results followed by conclusions in Section 5.6.

5.2 Literature review and background

To achieve the contributions defined in Section 5.1, there is a need first to understand next-generation railway signalling systems and the purpose of combining FTA and SAN models. This section provides the reader with a better understanding of the systems and concepts that are used in this chapter as well as the proposed approach for developing a novel framework that aims at evaluating the safe and effective behaviour of advanced transportation technologies, with particular focus on the railways field. It must be noted that the number of times the train brakes according to the permitted braking curve which uses a service braking rate –hereafter referred as braking applications– is used in this chapter as an indicator for safety. Therefore, we do not focus on accidents that relate to collisions or derailments but rather on the failures of the railway signalling system functionalities that lead to the undesired event of an unsafe train movement.

5.2.1 Next-generation railway signalling systems

In the past decades, research has focused on investigating different aspects of next-generation train-centric signalling systems like MB and VC in terms of capacity evaluation and hazards identification. Figure 5.1 gives a schematic view of the MB and VC concepts. Both MB and VC signalling can improve capacity and reduce maintenance costs since the train separation in both systems is no longer based on fixed blocks where the rule is that a block section cannot be occupied by more than one train at a time. In addition, lineside signals are removed, and trackside track-vacancy detection equipment is migrated to onboard TIM (Aoun et al., 2021). The TIM verifies that a train is complete while it is in operation. It also guarantees a safe train-rear position for dynamic braking curve supervision. In MB (Theeg and Vlasenko, 2009), such as proposed in the European Rail Traffic Management System/European Train Control System Level 3 (ERTMS/ETCS L3), the train separation depends on Train Position Reports (TPRs) which are regularly sent from train to trackside, i.e., the RBC. The RBC sends Movement Authorities (MAs) to the trains to indicate the maximum distance that a train can safely run represented by the End of Authority (EoA). In MB, the train separation is reduced to an absolute braking distance which is needed by a train to brake to standstill. VC can reduce further the separation between the trains to a relative braking distance by taking into account the braking characteristics of the train ahead. VC can therefore allow trains to move efficiently in platoons by forming a Virtually Coupled Train Set (VCTS) or convoy where trains communicate with each other by means of V2V and cooperative train control to ensure a safety margin. The highest capacity benefits for VC are in the case of trains running in a virtually coupled state where a safety margin would be sufficient between the trains in the VCTS. The Global System for Mobile Communication Railways (GSM-R) is used for the bi-directional exchange of messages between an onboard EVC and the RBC represented by the Vehicle-to-Infrastructure communication (V2I) in Figure 5.1. GSM-R V2I applies to both MB and VC while the additional functionality of the V2V is specific for the VC technology and requires (5G) low-latency high-availability communication. As the sight reaction time of a human driver would not be safe in the setup of a very short train separation among trains, Automatic Train Operation (ATO) becomes essential for VC.

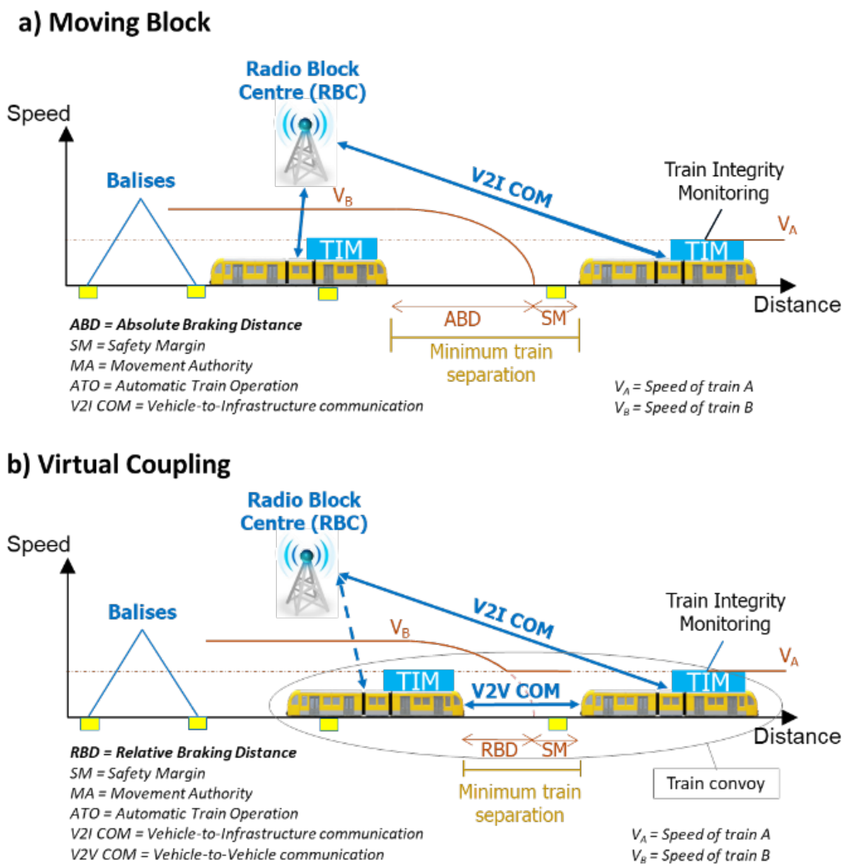

Figure 5.1: Schematic architecture of train-centric signalling systems: (a) Moving Block and (b) Virtual Coupling

Flammini et al. (2019) proposed a quantitative model to analyse the effects of introducing VC according to the extension of the current ETCS Level 3 standard, by maintaining the backward compatibility with the information exchanged between trains and the trackside infrastructure. Di Meo et al. (2020) studied operational principles and communication configurations of VC in several stochastic scenarios related to the transitions between different VC operating modes by using a numerical stability analysis of the closed-loop system to study platooning in the automotive field. Quaglietta et al. (2020) developed a train-following model to describe train operations under VC and assess capacity performance under different operational settings. In Aoun et al. (2020), several challenges for the implementation of VC have been discussed particularly related to safety, technology, operation, infrastructure and business. Aoun et al. (2021) found that the safety criterion weighs almost the same as seven other criteria together, namely infrastructure capacity, system stability, lifecycle costs, energy consumption, travel demand, public acceptance and regulatory approval. In addition, Aoun et al. (2023) found that the most critical step-changes towards the deployment of VC are the longitudinal motion control systems within convoys and the integrated traffic management and cooperative train operation. This is because there is a need to guarantee a safe distance between trains before being able to develop the concept of operations, as well as the train positioning and the switch technology. To guarantee a safe relative distance, several issues need to be solved. They can relate to the frequency of the V2V layer. For instance, if dynamic information about braking control of the leader in a convoy is not timely sent and received by the trains behind, then train collisions might occur. Another constraint can potentially arise from the heterogeneity of braking characteristics of different trains moving in a convoy which could also raise collision risks if for instance the train ahead within a convoy has a higher braking rate. In addition, an accurate dynamic safety margin (Quaglietta et al., 2022) needs to be considered between the trains based on the speed, a friction factor, the RBC and V2V latencies, the control delay or ATO reaction time, and the location inaccuracy.

5.2.2 The SAN modelling formalism

Stochastic Activity Networks (SANs) are a stochastic extension of Petri Nets (PN). They provide a high-level modelling formalism and enable the specification of performance, dependability and performability models (Meyer et al., 1985). Therefore, SAN has been widely used for dependability and performability evaluation of complex systems (Sanders and Malhis, 1992; Bertolino et al., 2011; Fantechi et al., 2022). A modular approach to modelling of complex systems is possible by leveraging hierarchical specification of models.

In the following, the main notations and concepts used in the chapter are introduced. SAN consists of four primitives: places/extended places, activities (with or without cases), input gates and output gates, as illustrated in Figure 5.2. *Places* represent the state of the modelled system, they can contain a number of *tokens*. The number of tokens in a place represents the *marking* of that place. The distribution of tokens over places in the model is the *marking of the network* and represents the state of the model. *Extended places* differ from 'ordinary' places for the type of tokens they may contain: the tokens in a place do not provide any kind of information, instead in the extended places they can represent atomic variables or data structures.

Activities represent actions in the modelled system, they are of two types: *timed* and *instantaneous*. Timed activities represent time-consuming actions, instantaneous activities represent logic conditions or actions that complete in a negligible amount of time. Places and activities are connected through arcs so that an activity may have a set of input places and a set of output places. *Cases* are used to model uncertainty associated to the completion of an activity: each case represents a possible different outcome. Each activity has a probability distribution (*the case distribution*) associated with its cases. The case distribution may be dependent on the marking of the model at the activity completion. If no cases are present, a default with a probability equal to one is assumed. Graphically, cases are represented as circles on the right side of an activity (see Figure 5.2). Each timed activity has an *activity time distribution function* associated with its duration, which can be associated to general distributed random variables (e.g., exponential, normal, binomial) and can be marking dependent.

The dynamics of the model is provided by the firing of the activities according to the *enabling and completion rules.* The firing of an activity models the execution of the activity and causes a state change in the SAN producing a new marking (hence it represents a state change in the modelled system): tokens are removed from the input places of the transition and generated in the output places according to the completion rule.

Input and output gates are introduced to allow greater flexibility in defining enabling and completion rules. Only enabled activities may fire, input gates control the enabling of the activities and define the marking changes when the activities complete. An *input gate*, if present, is placed between the activity and its input places and connected by arcs where *an enabling predicate* and an *input gate function* are defined. *An activity is enabled* when the predicates of all input gates connected to the activity are evaluated to true, and each 'ordinary' place connected to the incoming arcs contains at least one token. The input gate function specifies how the marking of the input places changes upon the completion of the activity. In case an activity is directly connected to an input place, the activity is enabled if there is at least one token in that input place and the marking of the place is decremented when the transition fires. An *output gate*, if present, is placed between the activity and its output places and connected by arcs to the cases of the activity and to the output places. An *output gate function* is defined which specifies how the marking of the output places changes upon the completion of the activity. In case an activity is directly connected to an output place, the firing of the activity increments the marking of the place.

With the aim of dealing with complex system models, a hierarchical specification of SAN is possible through the *replicate and join* operations. The Replicate/Join formalism allows to build composed models from sub-models called *SAN atomic models*. The atomic models are composed through place superposition. The replicate operation generates more instances of an atomic model, and the join operation composes different types of atomic models. In both cases, the sub-models communicate by sharing the global variables represented by the common (superposed) places.

SAN models are developed and solved by using the multi-formalism multi-solvers tool Möbius (Sanders, 1999; Clark et al., 2001). Da Silva et al. (2021) mention that the Möbius tool is the only available mature tool that can edit and solve SAN models by integrating both analytical solvers and a discrete event simulator.
In Möbius some of the primitives of the SAN models are based on the C++ programming language. Specifically, the types used to define the extended places, and the functions and distributions associated to the activities and to the input and output gates are written in C++.

To accurately evaluate the effects of VC in terms of network safety, realistic conditions need to be considered such as the minimum headway times and the type of rolling stock. Recent studies (Flammini et al., 2021) indicated that the SAN can be used to effectively evaluate the safety of VC. The authors used SAN to represent all performance and dependability aspects of interest for the analysis of railway VC in real-world scenarios. Based on their results, they proposed to extend their research to reliability, safety and security modelling due to the modularity of the adopted SAN approach.

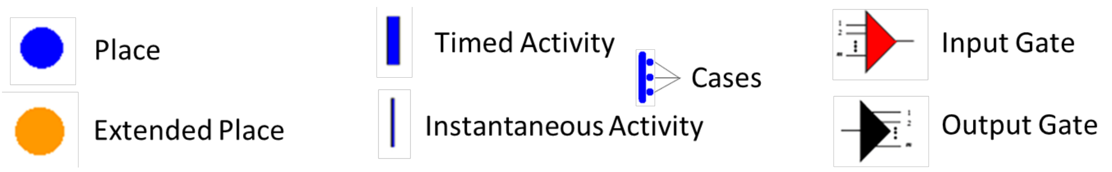

Figure 5.2: Primitives of SAN modelling formalism

5.3 Methodology

In this section, we introduce a novel methodological framework (Figure 5.3) on the integration of an FTA with a SAN approach (Section 5.2.2). The FTA is a deductive, structured methodology to determine the potential causes of an undesired event (Khakzad et al., 2011; Limnios, 2007; NASA, 2002). Mahboob and Straub (2011) define the FTA method as a common technique used for logical representation of a technical system for the purpose of safety and reliability analysis. In this deductive method, an undesired event – called Top Event

(TE) – is postulated and the scenarios leading to the TE are identified. They originate from basic events and are described by a series of logical operators and intermediate events leading to the TE.

In this chapter, we provide an aggregated high-level FTA for modelling the causes of unsafe train movement. We then integrate the failure rates derived from the developed FTA in the cases of activities in the SAN models by conducting a sensitivity analysis on the failure rate to analyse the effect of perturbations on the train movement in degraded operations. These degraded operational conditions relate to potential faults in the design variables of MB and VC railway signalling. The perturbations refer to the number of violations of ETCS braking applications, while the goal is to maintain a safe separation (minimum headway) and to avoid an emergency stop in case of faults in the values of the design variables. A variable is defined as an element, feature or factor that is liable to vary or change. A design variable is a numerical input that is allowed to change during the design process or optimization. In this chapter, we vary the values of the variables that allow the design of train-centric signalling systems (Table 5.1).

To develop an FTA, the system components are first identified and evaluated based on their corresponding functionalities and interdependencies. Then, a cascading sequence of system component failures and cause-effect relationships are analysed to understand how a failure or fault in one component impacts the other components. We used a Tolerable Hazard Rate (THR) apportionment (see Section 5.4.1.2) to compute the failure rates of all the elements of the fault tree. Part of the detailed FTA developed for MB and VC can be found in Aoun et al. (2022).

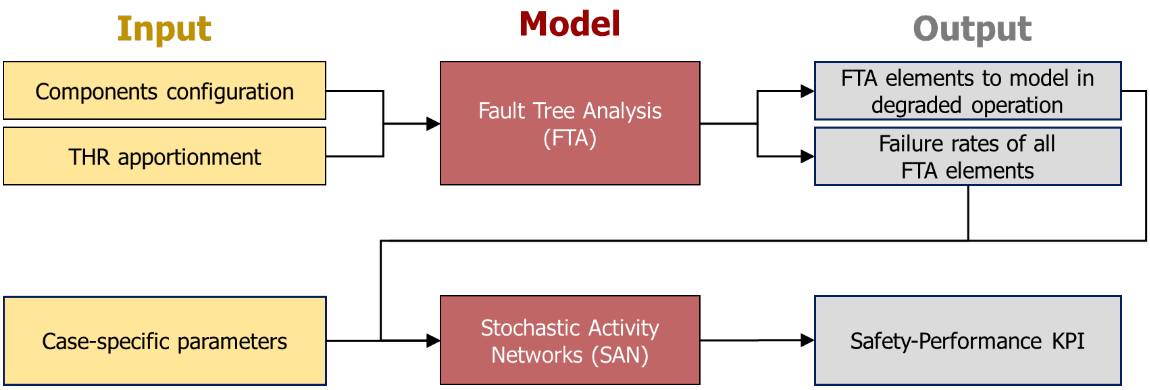

Figure 5.3: FTA-SAN methodology framework

Two simulation analyses are conducted in this chapter. Within the SAN modelling tool, Möbius, a sensitivity analysis on different design variables that constitute the investigated system is performed while taking into account the minimum headway between trains. The purpose of this analysis is to find the threshold of the design variables to allow a safe train movement based on a specific safety-performance KPI. In this chapter, we particularly focus on the TPR delay design variable which is the communication time from the train to the RBC (TPR broadcasting time). In the second analysis, we apply a sensitivity analysis on the failure rates in the FTA which are introduced in the cases of the activities in the SAN models. The focus of this chapter is on analysing the failure rate of the TPR error for both MB and VC in a way that guarantees a similar level of maturity between both systems. In both analyses, the objective is to search for a threshold variation of the design configuration before leading to a violation of the permitted braking curve, so to evaluate an effective and safe deployment of MB and VC.

5.4 Modelling for Moving Block and Virtual Coupling

5.4.1 FTA modelling of unsafe train movement for Moving Block and Virtual Coupling

5.4.1.1 System Components and Functions

The first step in developing an FTA is to define the scope of the study. This is achieved by defining the systems' components and identifying their related functions. Figure 5.4 illustrates the breakdown structure of the components that constitute MB or ETCS L3 (blue colour) and VC (orange colour). The elements that have both the blue and orange colours are applicable to both MB and VC.

Some of the MB components are also included in ERTMS/ETCS Level 2 systems. At this level of abstraction, the main differences between ETCS L2 and the MB systems are the following: 1) the onboard system includes a new component, TIM, 2) the trackside track-clear detection is no longer necessary as in fixed-block signalling; 3) trackside functions are new or modified. All the trackside and onboard equipment are common to both MB and VC. However, VC is characterised by the additional V2V component.

Intuitively, the fewer number of trackside components may increase the system reliability and decrease costs, as it is also envisioned by the European rail initiatives Shift2Rail and EU-Rail (2022). On the other hand, the introduction of new components has to be considered. In the following, a brief description of the components introduced in Figure 5.4 is given.

Both MB and VC systems have RBCs and Eurobalises as trackside equipment. The RBC is a computer-based system that elaborates the messages that need to be sent to the trains. A main goal of the RBC is the management of the MA. The MA provides the maximum distance that a train can safely cross without colliding with another train on the route. In VC, the MA associated to VC, MA_{VC}, combines information from both the RBC and the V2V communication channel, and the speed associated to the End of Authority for VC (EoA_{vc}), is either equal to the speed of the train ahead (if trains are running in a coupled stage), or zero (if trains are decoupling). The Eurobalise is a transmission device placed between the rail tracks. It is defined as a trackside transponder or electronic beacon acting as a fixed geographical reference point. The main functions of the Eurobalise are to report the train position and to provide the up-link for sending messages to the train onboard system.

The ERTMS/ETCS onboard system is a computer-based system that supervises the movement of a train, on basis of the information exchanged with the trackside system. It is composed of the European Vital Computer (EVC) where kernel functions are stored, the Driver Machine Interface (DMI), the Balise Transmission Module (BTM), the Train Integrity Monitoring (TIM), the Radio Transmission Module (RTM), the Train/Brake Integrity Unit (TIU/BIU), odometry and the Juridical Recording Unit (JRU). The EVC monitors continuously the train location by means of an onboard odometer that is regularly calibrated any time the train crosses a balise. It also elaborates MA messages and supervises in real time a dynamic speed profile including braking curves that ensures that the train does not overrun the EoA. However, in the case of VC, further functions of the EVC are implemented by considering the supervision of both the EoA_{vc} and the standard EoA (in the operational state of an (un)intentional decoupling). In addition, the EVC for VC predicts the distance traversed by the leader during a certain coordination time that is required by the follower to catch up with the leader's speed at the location indicated by the EoA_{VC} within a certain safety margin from the latter's rear. The DMI provides a bi-directional interface with the train driver and displays relevant information and instructions to the driver. The TIM verifies that a train is complete while it is in operation. It also guarantees a safe train-rear position.

The BTM detects the presence of a balise and processes the up-link and down-link data. The BTM is interfaced with the ERTMS/ETCS kernel and onboard antenna unit (i.e., Global System for Mobile communications-Railway (GSM-R)). The RTM provides a bi-directional interface with the trackside. The TIU and BIU are used as interfaces with the EVC to the train and/or the locomotive for submitting commands or receiving information. The BIU is used for implementing braking instructions. The odometry represents the entire process of measuring the train's movement (speed and distance) during a journey along the track.The JRU is used as a device to record defined data relating to the train's movements for legal purposes. The recorded data shall allow analysing the cause of an accident, incident, or hazardous situation.

The communication components include the GSM-R onboard which applies to both MB and VC and the additional functionality of the V2V communication that is specific for the VC technology. The GSM-R onboard radio system (antenna) is used for the bi-directional exchange of messages between the onboard EVC and RBC. The V2V communication onboard allows the trains to be separated by a relative braking distance. Via onboard antennas, the trains are able to exchange route and kinematic information (e.g., speed, acceleration) and to form a convoy of virtually coupled trains, also known as Virtually Coupled Train Set (VCTS).

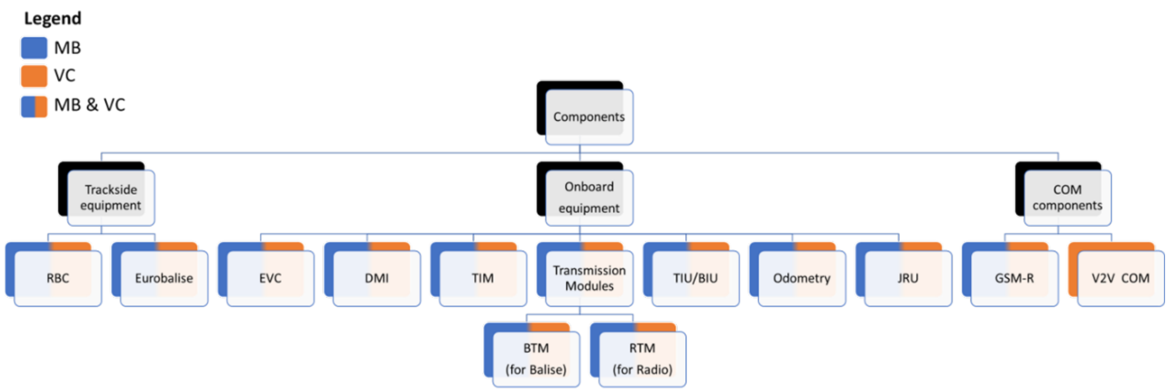

Figure 5.4: Signalling Components' breakdown structure of Moving Block (MB) and Virtual Coupling (VC)

5.4.1.2 *Fault Trees Development*

One of the main advantages of an FTA is that it provides a logical framework for understanding and assessing the scenarios leading to system failures. We apply the principles of the FTA in this section by looking at a high-level perspective of the cause-effect relations leading to an unsafe train movement of both MB and VC. The MB specifications have been defined by the Shift-to-Rail (S2R) X2Rail-1 (2019) and X3Rail-3 (2020) projects and they are publicly reported in the project deliverables. VC is still a visionary concept. The application conditions of VC have been investigated in S2R X2Rail-3 (2020) and further research is planned within Europe's Rail (2022), the successor of the S2R Joint Undertaking.

The generated combined fault tree for MB and VC is illustrated in Figure 5.5. The model has been developed on the Isograph Reliability Workbench 15.0 software . The circles are basic events where no further breakdown is possible. All the used gates are OR gates except for EVC-WRONG which represents an AND gate. In this particular case, a wrong computation of the EVC arises from both a wrong computation of the EoA and a wrong computation of the braking curves. The transfer gate (triangular shape) represented by the GSM-R communication error (GSMR-ERR) in Figure 5.5 is an extension to another location or sub-tree within the main tree. In this case, the developed elements under the referred transfer gate are RADIO-FREQ-ERR OR RADIO-BROAD-LIMIT. The elements in blue are common to both signalling systems. The orange elements are specific for the VC technology as they deal with the extra V2V component that characterizes the platooning concept. The items represented in green are modelled in SAN (Section 5.4.2.1).

We first started by developing an FT for MB, then we extended it to VC by considering the potential failures that might arise from the additional V2V communication component (represented by solely the orange colour). The potential main causes for an unsafe train movement could arise from a communication fault, a trackside fault or an onboard fault. The driver error was not considered since we consider that the automatic train protection (ATP) would always interfere whatever the reason of driver error is. The potential causes that lead to a communication fault relate to a broadcasting time delay of the MA from the RBC to the train, or a broadcasting time delay of the TPR from the train to the RBC, or a V2V error which is only specific to the VC system. The reasons that lead to the latest can be a loss of the V2V, or a V2V frequency coverage error, or a V2V limited broadcasting capacity. The loss of V2V can be a consequence of a lack of coverage of the V2V technology to the entire distance between two communicating trains or an interruption of the V2V. In the case of trackside fault, the causes can be associated to an RBC fault or a TPR error. It must be noted that a TPR error can result from two different categories of failures: *(1)* a failure of the onboard system that is caused by an odometry error resulting from an inaccurate wheel diameter or a BTM error, or a train integrity error which is a consequence of a fault in the TIM sensors or an error in a satellite or a GNSS signal, *(2)* a consequence to a trackside failure due to a fault occurring on the balises, given an error in the up-link data transmission or a fault in the power supply. In addition to a TPR error, other causes could also lead to an onboard fault, namely a fault in the EVC or an anomaly in the reaction time. It must be noted that the term anomaly in the FTA is used to include either message integrity errors, wrong variable values (e.g., erroneous computation of the EoA or corresponding braking curves), as well as delayed reception/broadcasting of necessary messages/information or unexpectedly extended processing times of onboard and trackside signalling components. Given that the analysis of all possible anomalies would lead to a very complex experimental setup, we focus in this chapter on a selected set of anomalies whereby preliminary observations showed to be particularly interesting to investigate with respect to safe train movement supervision. Anomalies referring to delays or extended processing times might be more relevant than wrong/erroneous value computation as redundancy of equipment will lead to a direct activation of emergency brakes if at least 2 out of 3 (2oo3) components do not find the same values (this is for instance the case of EVC redundant processors). If the anomaly would instead be a delayed computation or a delayed delivery of necessary information which is still below the threshold for fail-safe brake application, then those delays might induce violations of indicated ETCS speeds corresponding to a given ETCS braking curve. That might hence lead to non-smooth train movements with sudden deceleration or even potentially unsafe movements under certain conditions.

The failure rates of the main events related to the faults of onboard, trackside and transmission (i.e., communication) functions were preliminary derived from a Tolerable Hazard Rate (THR) apportionment approach by UNISIG (2019). Particularly, the following apportionment was used:

- 10^{-9} / hour for ETCS onboard (installed on a train), and
- 10^{-9} / hour for ETCS trackside (installed in an area visited by a train during a reference mission).

Considering that the transmission functions are offered by the joint work of onboard and trackside equipment, UNISIG empirically apportions 1/3 of each hazard rate to the transmission functions. Hence, the THR for ETCS onboard is apportioned as 0.67×10^{-9} / hour to the onboard functions and 0.33×10^{-9} / hour to (onboard) transmission functions. Similarly, the THR for trackside functions is apportioned as 0.67×10^{-9}/ hour to the trackside functions and 0.33×10^{-9} / hour to (trackside) transmission functions. With the increasing complexity of the onboard transmission equipment, which has to support the V2V and additional functionalities, the onboard transmission functions should rely on increased quality equipment to fulfil this rate. Following a reverse engineering approach and by using the FTA principles, the failure rates of all the elements of the fault tree in Figure 5.5 were computed. The values of the elements highlighted in green in the FTA were evaluated in the cases of the activities modelled with SAN for MB and VC by developing a sensitivity analysis on the failure rates.

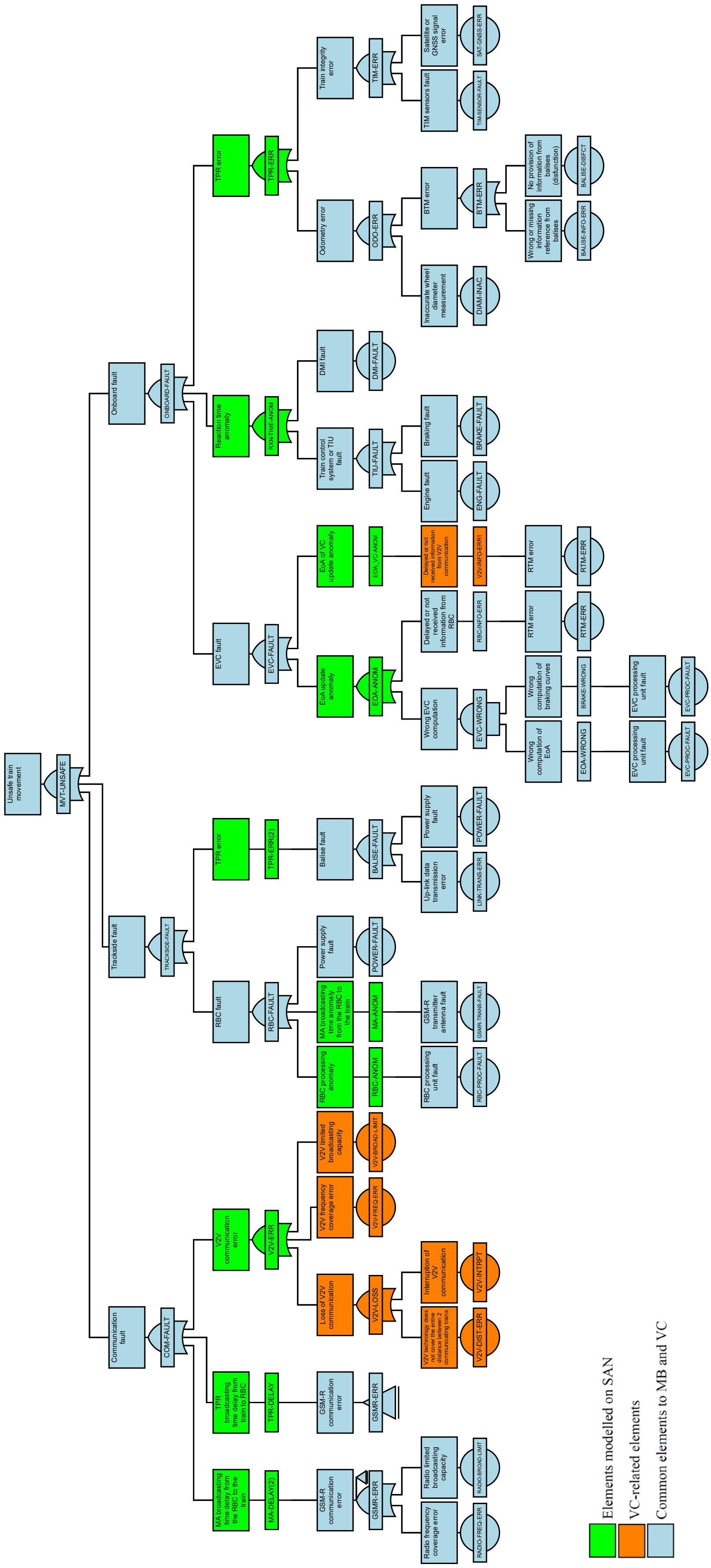

Figure 5.5: FTA for modelling an unsafe train movement for Moving Block (MB) and Virtual Coupling (VC)

5.4.2 SAN modelling for next-generation railway systems

5.4.2.1 SAN modelling principles for Moving Block and Virtual Coupling

The SAN models introduced in this chapter aim at analysing the system behaviour of MB and VC with the objective to estimate the frequency of braking applications (i.e., indication, permitted, warning and emergency) according to several design configurations. The SAN models take into account:

a) Some potential probabilities of failure that affect the performance of the systems;
b) Different railway market segments, specifically high-speed, mainline, regional, urban and freight railways.

The modelling approach composes reusable atomic SAN sub-models modelling the train onboard unit and railway signalling components. The VC model is obtained by extending the MB model with the V2V communication and properly modifying the model variables.

A global MB or VC model is obtained by considering a fleet of trains moving along the track. The introduction of sub-models facilitates their reuse, development and maintenance. For instance, they can be applied to different topologies with different sequences of routes and junction areas.

A braking curve is a prediction used by the ETCS onboard unit to compute in real time the braking distance. The onboard unit predicts the decrease of the train speed against a distance that must not be exceeded according to a mathematical model (ERA, 2020).

In ETCS L3 MB, the driver or the ATO must keep the speed below the permitted speed. The ETCS onboard unit continuously supervises the permitted speed and indicates when braking is required, followed by a braking intervention if the driver or the ATO does not follow up, to avoid that the train exceeds the supervised dynamic speed profile or overruns the allowed limit represented by the EoA.

The analysis considers four different braking curves described in ERA (2020) as follows:
- Indication (I): “the I supervision limit leaves the driver enough time to act on the service brake so that the train does not overpass the permitted speed”.
- Permitted (P): “the P supervision limit in case of overspeed leaves the driver an additional time to act on the service brake so that the train will not overshoot the point beyond which ETCS will trigger the command of the brakes”.
- Warning (W): “the W supervision limit provides an additional audible warning after the permitted speed has been overpassed”.
- Emergency (EBI): “the braking curve related to the speed decrease due to the emergency brake is the Emergency Brake Intervention (EBI) curve”.

To evaluate the effective and safe behaviour of the systems, we use the overshooting of the ETCS speed supervision limits as a Key Performance Indicator (KPI). The values for the braking rates of each market segment are given in Table 5.2.

Several input parameters are needed to enable the computation of the braking curves and the onboard supervision. To compute the braking curves, information is needed, such as the train instantaneous position, speed and acceleration, as well as the driver/ATO reaction time, the track profile, the MA and the braking rates referring to each of the above mentioned ETCS curves. For the onboard supervision computation, the required input parameters are the train data providing the necessary information about the vehicle's braking dynamics and track data. The model analysis aims at quantitatively evaluating the impacts of a selected set of variables (see Table 5.1) on the service offered by the system. Table 5.1 shows the minimum values for each model design variable that were used as input in the SAN models. The developed models also allow to evaluate the effect of possible failures on the behaviour of the system.

We apply a sensitivity analysis to provide indications about the impact of the MB and VC signalling system functionalities on a safe train movement. We mean by "safe" situations where failures can occur but do not lead to collisions or derailment. Therefore, we study the impact of fluctuations in signalling design variables on the behaviour of trains based on the number of triggered braking applications during operation. These variables are used as input to our analysis and include the RBC processing time, the RBC to train (MA) communication time, the MA update time, the EVC processing time of the MA, the TPR and integrity update time, the train to RBC (TPR) communication time, the period between subsequent TPRs, and the additional V2V communication (frequency coverage and broadcasting capacity) only in the case of VC. An additional design variable is the driver or ATO reaction time. For a fairer comparison between the outcomes of the MB and VC systems, we consider the ATO reaction when modelling the behaviour of both MB and VC. In the following sections 5.4.2.2 and 5.4.2.3, a detailed description of the SAN models for MB and VC is provided, respectively.

Table 5.1: Model design variables and their minimum values

Model Name	**Description**	**Min. Value**
RBCprocessingTime	Computation by the RBC	0.2 s
EVCprocessingTime	Onboard translation of received MA into speed profile and speed indication computation by the EVC	1.5 s
TPRnetDelay	Communication time from the train to the RBC (TPR broadcasting time)	0.5 s
MAnetDelay	Communication time from the RBC to the train (MA broadcasting time)	0.5 s
V2VcommDelay	Communication delay in V2V communication	0.1 s
TPRupdatePeriod	Train position and integrity reporting time including GSM-R and GNSS	4 s
driverReactionTime	Includes the onboard translation of received MA into speed indication, i.e. visualization by the EVC, and the time for the driver to interpret and react to the indication	4 s
ATOReactionTime	Includes the onboard translation of received MA into speed profile performed by the ATO, and the speed indication computation by the EVC.	0.5 s

5.4.2.2 SAN model for Moving Block

The SAN introduced in this section provides a high-level representation of the behaviour of the MB system. *Two sub-models have been developed*; the first models the *trackside* sub-system (namely, the *trackside* SAN atomic model which represents the RBC), the second models *the onboard sub-system and the communication* between the trackside and the onboard (namely, the *obuComm* SAN atomic model). They are composed to build the complete SAN model, by instantiating more replicas of the *obuComm* model (one per each train in the fleet) and just one trackside model, which are integrated by the join operation as depicted in Figure 5.6.

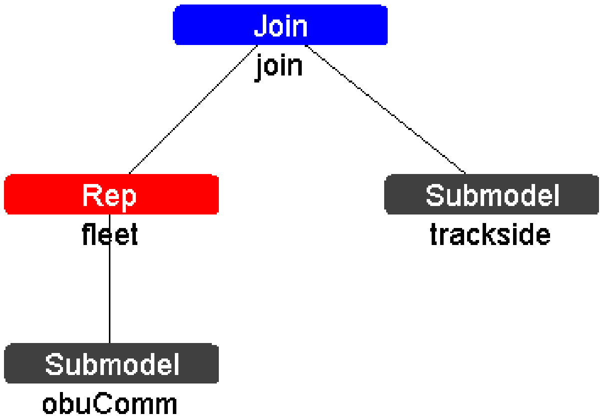

Figure 5.6: SAN composed model for Moving Block signalling

Figure 5.7 illustrates the obuComm SAN atomic model, it represents the movement of a train on a railway track in MB signalling. The extended places (orange circles in Figure 5.7) represent all the information needed by a single train such as the arrival time, the train rear position, the train head position, the train speed and acceleration, as well as the EoA, and the TPR and MA messages. Some of them are superposed in the replica and join operations.

In the left part of the model, a unique ID is assigned to the train (from 0 to N-1): the initial marking of the place *Start* is 1, therefore the instantaneous activity *assigningID* is enabled; when it fires the ID is assigned to the train through the output function of its output gate *assignID* and a token is generated in the place *waitforEntering* to enable in turn the timed transition *trainArrival* whose rate is given by the time distribution function which is deterministic and returns the train arrival time. When the activity *trainArrival* completes, the marking of the place *waitForFreeLine* is incremented and the timed activity *freeLine* is enabled if the associated predicate of the input gate *evaluateFreeLine* evaluates true. The predicate function of the input gate checks the value of the EoA. In case the train is authorized to move, two paths go in parallel; the first on the lower part of Figure 5.7 models the movement of the train on the line. When *freeLine* fires, the output gate *initialPositionAndSpeed* is executed, which in turn updates the marking of the place *trainMovement*. Then the train computes its distance to the EoA and the speed at the next step by means of the timed activity *updatePosition* which is enabled by tokens in the place *trainMovement*. This activity executes the output gate *updatedPositionAndSpeed*, which aims at updating the position and speed of the train. More specifically, the train has to brake if its speed distance coordinates hit one of the braking curves computed backward from the EoA. If for a certain amount of time, the current train position hits the permitted speed, then the train would start braking according to a permitted braking curve. In case of emergency braking, tokens are added in the place *emergency* and *emergencyBrakingActivated.* Finally, when the train reaches the end of the line, it has to exit it and a new token is added in the place *trainHasToExit*. It is worth noting that in the proposed model, a fine-grained discretization of the railway track is used that allows to represent the MB concept by a step-by-step movement of the trains.

Along the second path, on top of the timed activity *freeLine* in Figure 5.7, the train continuously computes and sends its TPR to the RBC (the trackside) via the communication network. The elements of the FTA that are displayed in green in Figure 5.5 are modelled in the cases of the activities in the SAN models. For instance, the TPR is generated by means of the timed activity *updateTPR*. When the activity *updateTPR* fires, two cases are possible. The first case is when the train confirms its integrity. This enables the execution of the output gate *createTPR,* which in turn updates the marking of the place *sendTPR* and the extended place *TPRmsg* according to the output function associated with the activity. However, the problem is that this function could fail, i.e., cannot know whether the train confirmed its integrity. In that case (i.e., case 2 that enables the output gate *createTPR_NoIntegrity*), the train would need to resend another TPR to the RBC via the communication network. If the train does not deliver a new TPR, the message is lost, and the RBC processes the next received message. Similarly, when the activity *TPRNetworkDelay* fires, two cases are possible. The first enables the execution of the output gate *deliverTPR* which in turn updates the marking of the place *TPRtoRBC.* The second enables the execution of the output gate *notDeliverTPR* which returns zero markings.

At the top part of the figure, an MA is generated by the RBC and sent to the train. Here, a failure could also potentially arise. Therefore, two cases are defined where in the degraded condition, if the MA message is not delivered, the train does not update its EoA and the message is cancelled. The input gate *MAmessageForTheTrain* is to show that there is an MA message ready to be sent from the RBC to the train. The RBC model is developed in a trackside atomic model in Figure 5.8.

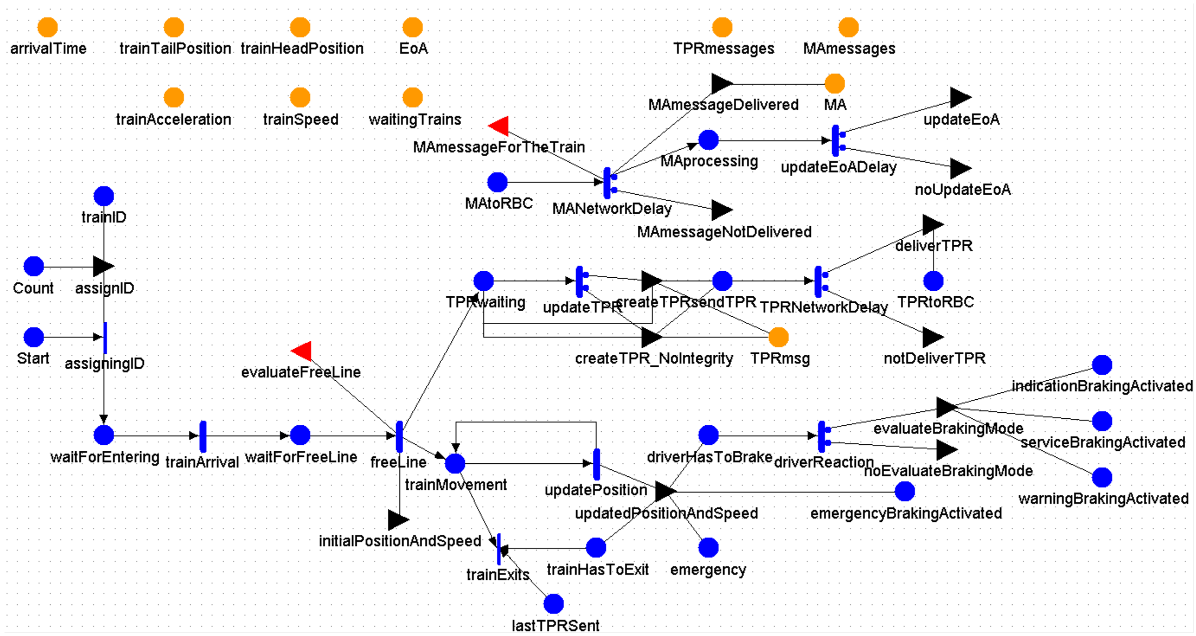

Figure 5.7: SAN model for train movement in Moving Block signalling

The trackside atomic model mainly models the exchange of messages between a train and the RBC. In particular, it aims at evaluating the TPR messages received by the train, processing them, updating the track status areas and sending back MA messages to the train (see Figure 5.8).

The extended places *TPRMessages* and *MAmessages* are shared with the replicas of the *obuComm* models, and represent the messages on the communication network. The extended places *trackStatusAreasHeads* and *trackStatusAreasTails* model the track status variables of the trackside. Each extended place contains an array of short values, which represents the front and the back position of a track status area, respectively. The values in the i^{th} position of the arrays represent the track status area associated with the train whose ID is *i*.

A token in the place *TPRtoRBC* means that a TPR message is ready to be analysed. The activity *RBCprocessing* models the processing time of the RBC. The output gate *updateTSAsAndgiveMAs* is executed. When the activity *RBCprocessing* fires, its output function updates the track status areas (and stores the values in the proper extended places) and generates the MA for the train on the basis of the "known" position of the preceding train.

The trackside has been modelled as a shared resource able to process a single TPR message at a time, this is modelled through the place *idle* which is an input place of the activity *evaluateOlderTPR* and whose initial marking is 1: the token in the place idle is consumed when the TPR message is processed and regenerated after the activity *RBCprocessing* completes.

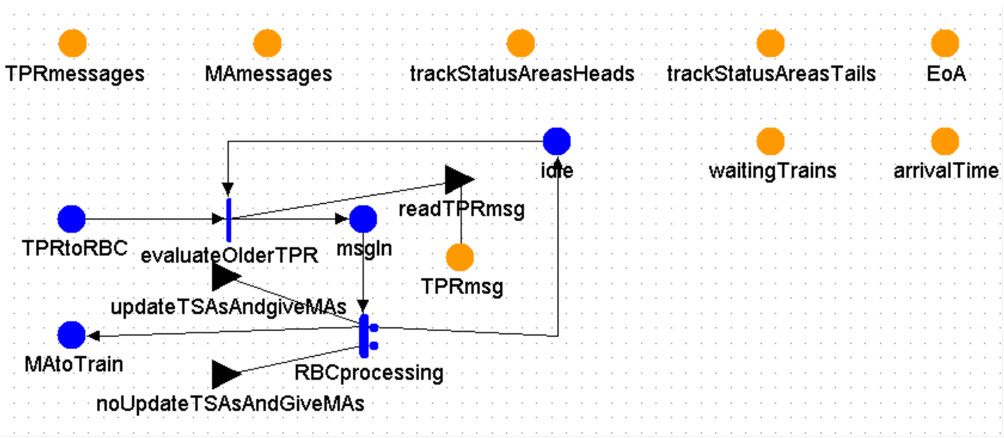

Figure 5.8: SAN model of RBC in Moving Block signalling

5.4.2.3 SAN model for Virtual Coupling

Similar to what is described in the SAN model for MB, the VC model developed in this section (Figure 5.9) models the movement of successive trains on a railway track. The model analysis aims at quantitatively evaluating the impact of a selected set of variables on the service offered by the system. Those variables apply also to the MB system except for the additional V2V-related variables that are only specific to VC. Note that the V2V additional functionalities were also updated in the RBC atomic model.

Hence, the VC SAN model is based on the MB model but adds a subnet modelling the V2V between trains and some parameters to define the number of convoys moving on the track and the number of trains in the convoys. The new structural elements are in the yellow box in Figure

5.9. The first train in the convoy sends the TPR message not only to the trackside but also to its preceding train through the activity *V2Vnetwork* and the *V2V* place, and each train in the convoy propagates the message back to its predecessor. The output function of the *deliverTPR* gate and the extended place *V2Vmsg* are used to model this behaviour and the message exchange. Hence, we consider that only the first train in the convoy sends the TPR to the trackside, the following trains just communicate with their immediate neighbours. The V2V network can possibly fail as modelled by the cases of the *V2Vnetwork* activity. Therefore, the developed model also allows to evaluate the effect of possible failures on the behaviour of the trains under VC operation.

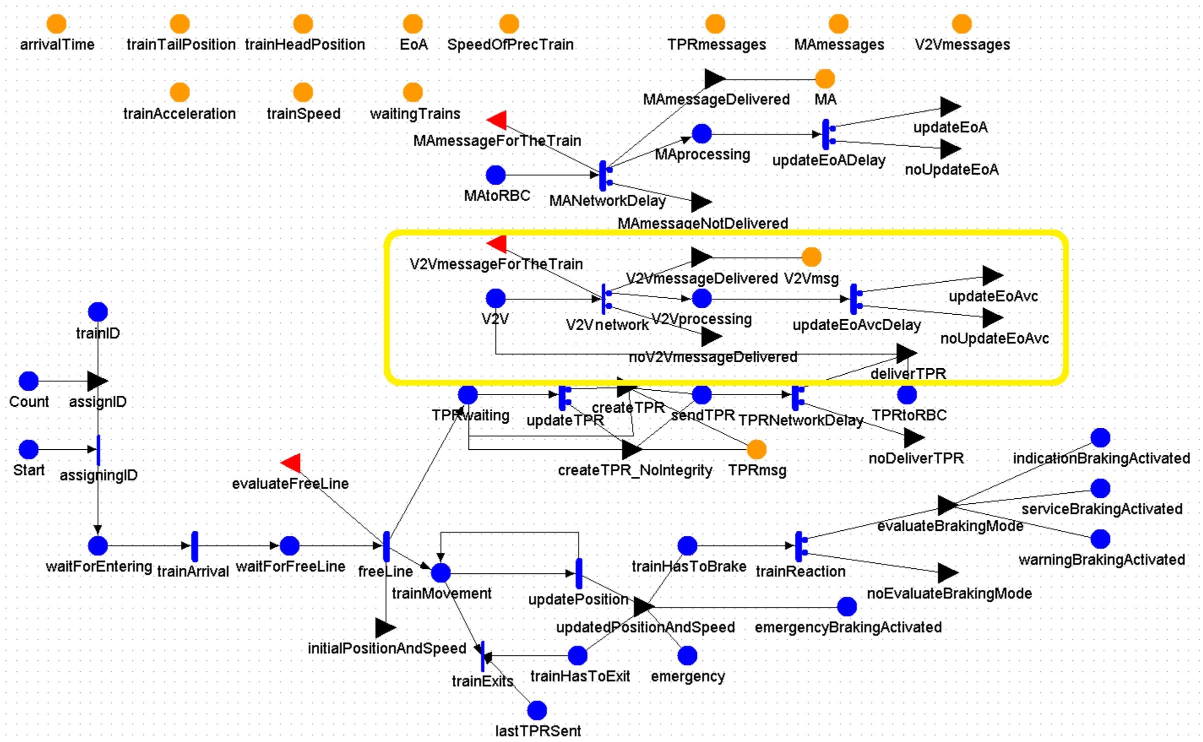

Figure 5.9: SAN model for train movement in Virtual Coupling signalling

5.5 Results

The methodological framework in Section 5.3 is applied by starting with the identification of the different system components of MB and VC and the evaluation of their functionalities and dependencies. More details can be found in Aoun et al. (2022) where a breakdown structure of interacting signalling components in both MB and VC is provided.

That breakdown is extended in this work by introducing a cascading sequence of system failures and cause-effect relationships to capture the effect of a component's failure across other components. For instance, a delayed or not received MA from the RBC can lead to a fault in the EVC. As a KPI to measure the safe train supervision effectiveness of MB and VC, we consider the number of times that a train brakes according to the permitted braking curve which uses a service braking rate. As we refer to the ETCS signalling standard, the KPI will hence report the number of overshooting the speed relative to one of the supervised braking curves, namely Indication, Permitted, Warning, and Emergency (ERA, 2020).

This section provides the simulation results and discussion for five case studies (Section 5.5.1) based on the developed models and outcomes in Sections 5.4. We first set up the simulations. Then we perform the two simulation analyses as explained in Sections 5.5.3 and 5.5.4.

5.5.1 Case studies

Five case studies are defined in this chapter corresponding to a specific corridor of each market segment, namely:

1. For high-speed: Rome-Bologna (Italy).
2. For mainline: London Waterloo- Southampton (United Kingdom).
3. For regional: Leicester- Peterborough (United Kingdom).
4. For urban: London Lancaster–London Liverpool (United Kingdom).
5. For freight: Rotterdam–Hamburg (between the Netherlands and Germany).

For all the analysed market segments, the SAN-based effectiveness analysis of MB and VC signalling will be performed on a route stretch of 24 km and a total number of 4 trains for the sake of computational efficiency. A time-step of 0.15 s is used to update kinematic variables of simulated trains such as speed, position and acceleration. For each rail market segment, specific values are considered for train length, maximum speed, maximum acceleration and various braking rates as provided in Table 5.2.

Table 5.2: Market-specific model parameters

Parameters		**Market segment**				
		High-speed	**Mainline**	**Regional**	**Urban**	**Freight**
Train length (m)		327.6	115	96	130	670
Maximum speed (m/s)		83	44	33	22	28
Maximum acceleration (m/s^2)		0.54	0.53	0.6	0.8	0.2
Braking rates (m/s^2)	**Indication**	1	0.7	0.6	0.5	0.4
	Permitted	1	0.7	0.6	0.5	0.4
	Warning	1.25	0.875	0.75	0.625	0.5
	Emergency	1.5	1.05	0.9	0.75	0.6

5.5.2 Setting up the simulations

The SAN models introduced so far provide a practical means to analyse the MB and VC systems' behaviour at a high level of abstraction with respect to different variables and parameters. Here information is provided about the simulation in the Möbius tool to introduce the experimental trials. The composed model defines a stochastic process allowing for the evaluation of performance/performability measures of interest. Performance variables relate the stochastic process to such measures, in particular they are reward variables.

A reward variable relates to state markings or activity throughputs, and it is defined through a reward function. Two types of rewards are possible: impulse reward, associated with state changes (at activity completion), and rate reward assigned to markings. A difference is given between Interval-of-Time or Instant-of-Time measures. In particular, for rate reward variables, the former measures accumulate over the interval of time that the model spends in those markings, whereas the Instant-of-Time measure gives the rate reward associated with the markings at time t. Based on the reward model, discrete event simulation is performed. Confidence intervals are generated for the performance variables defined in the reward model using the replication method for terminating simulation. The simulator will run several batches to generate data for the confidence interval. It will continue to run more batches until all the reward variables have converged to their specified confidence interval or the maximum number of batches is reached. A minimum number of batches is specified to cope with rare events. For the MB and VC SAN models, both impulse and rate reward variables are defined:

- The performance variables related to *braking events* are rate rewards on the markings of the onboard sub-model. The rate reward is defined to be an Instant-of-Time measure *evaluating the marking of the places modelling the activation of braking* (e.g., the place *emergencyBrakingActivated* in Figure 5.7) at time t for each instance of the *obuComm* atomic model.

- The performance variables measuring *the number of trains exiting the line* in the time interval are instead Interval-of-time rate reward. They provide *the throughput of the activities modelling the trains that exit the line* (e.g., the activity *trainExits* in Figure 5.7) in the given interval of time, over all the instances of the the *obuComm* atomic model.

5.5.3 Analysis of the minimum headway and maximum TPR net delay in Moving Block and Virtual Coupling

The first analysis aims to estimate the minimum service headway in free-flow nominal traffic operational conditions, yielding conflict-free train movements. For this analysis, we consider a minimum processing time of the RBC and onboard as well as minimum communication delays, as reported in Table 5.1. It is assumed that under VC signalling, trains can form convoys/platoons of up to four trains. More are deemed to be unlikely to operate because of incompatibility with infrastructure characteristics of existing rail networks (e.g., platform lengths, length of interlocking areas).

The results are displayed in Table 5.3. It is evident from the obtained outcomes for MB that the most critical market segment is high-speed, where the highest maximum speed of the trains requires a high minimum headway and consequently train separation (of around 53 s and 4 km, respectively). On the contrary, trains in the urban segment could run significantly closer one to another (with a minimum separation of 728 m). Regional and mainline railways offer intermediate performance, with a minimum headway of 40 – 43 s and consequently a train separation between 1 and 2 km, respectively. The freight segment also requires high separation of around 1.3 km and 69 s, where the highest length is combined with the lowest braking rate of the trains.

In VC, the minimum separation between two convoys is equal to the one without VC, i.e., under MB operations, but great benefits are evident in the separation among trains in a convoy (see VC in Table 5.3). In fact, in high-speed, the minimum headway could be reduced by around 77% (to 12 s). Analogously, the minimum headway in the urban market segment could be reduced by 56% (to 17 s), which is equivalent to a reduction of 66% in terms of train separation (244 m). For mainline and regional, the minimum headway could be reduced by respectively 72% and 68%. Furthermore, the freight segment could benefit also from the introduction of VC; in fact, the minimum headway could be reduced by 51% (to 34 s). Hence, with the considered variables, we could say that the advantages are higher for high-speed and mainline railways since the VC offers a significant minimum headway reduction.

The Max TPR delay results show that for all the market segments, the threshold allowed for MB is higher than for VC. This means that to ensure a safe train movement, VC cannot absorb a TPR delay of longer than 1.5 s, which corresponds to the mainline market segment. For MB instead, the results show that the maximum TPR delay can reach 3.9 s for high-speed and freight railways, followed by 3.8 s for mainline railways.

In the case of MB, the max TPR delay follows the minimum headway, which means that the higher the minimum headway, the higher the max TPR delay is. For VC instead, the TPR delay does not follow the minimum headway but the braking rate of the trains assumed per market. This means that on a general trend, a higher braking rate (better braking performance) can tolerate a higher TPR delay. For instance, for high-speed and mainline, the TPR delay can be larger than in the case of urban and freight railways.

Table 5.3: Results of market-specific minimum headway and max TPR for Moving Block and Virtual Coupling

	Market segment	**MB**	**VC**
Minimum Headway (s)	**High-speed**	53	12
	Mainline	43	12
	Regional	40	13
	Urban	39	17
	Freight	69	34
Max TPR net delay (s)	**High-speed**	3.9	1.2
	Mainline	3.8	1.5
	Regional	3.3	1.4
	Urban	2.7	0.9
	Freight	3.9	0.8

5.5.4 Impact of a TPR error in Moving Block and Virtual Coupling

In this analysis, the goal is to assess the impact of a TPR error on the overall service offered by the system. We remind that the “TPR error”, according to the FTA, can be the effect of two different failures: *(1)* a failure of the onboard system that is either unable to evaluate the train integrity or an error of the odometry subsystem, *(2)* a consequence to a trackside failure due to a fault occurring on the balises. The combination with the FTA helps in the identification of the possible rates of this event, which are then used as an input to the SAN to evaluate the effects on the systems, specifically on the activation of braking.

From the FTA, we estimated that this event shall occur with a maximum rate of 5.58×10^{-10}. We used this value in the SAN and performed a sensitivity analysis by varying it in the range $[10^{-10}, 5\times10^{-5}]$ (with a logarithmic step). In fact, for all market segments, we identified the presence of braking with values of failure rates higher than 10^{-7}. This means that the system well tolerates the occurrence of this possible failure, without tangible effects on the service. The analysis is conducted by considering the system at its highest capacity (i.e., trains running at the minimum headway) for the different market segments, to understand the mutual relationships between the considered values of the model variables.

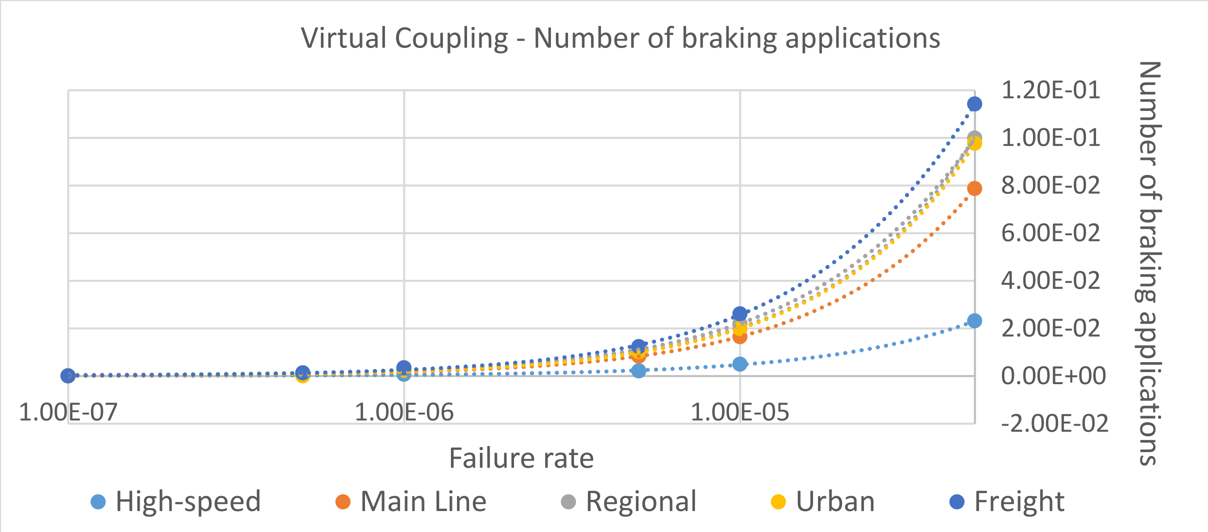

Figure 5.10: Number of braking applications vs. TPR error failure rate for Virtual Coupling

The graph in Figure 5.10 shows the relationship between the failure rate of a TPR error (x-axis) and the corresponding number of braking applications (y-axis) which would be triggered under VC train operations. The analysis is performed for each of the five market segments depicted with specific colours as indicated in the legend. The number of braking applications obtained by the SAN-based simulations are represented by the coloured large dots, which are connected by a polynomial regression of the braking curve trend versus the TPR error failure rate.

Based on the experiments that we performed for VC which considered trains moving synchronously at the same speed, we observed that the number of braking applications has a trend that depends on the braking rates of the trains. Specifically, market segments with a higher braking performance result in having on average a lower number of braking applications. Therefore, the influence of a TPR error in VC becomes higher for market segments with lower braking performances, specifically regional and freight railways.

Figure 5.11 illustrates a comparison of the number of braking applications for MB and VC. For the sake of brevity, we report in this chapter the comparison for the high-speed case as similar trends were observed for the other market segments. The results provided by the FTA-SAN experiments match our expectations as VC shows a higher number of braking applications with respect to MB for the same TPR error failure rate. This means that for VC to effectively supervise the train separation at the same safety level as MB, we would need to have a much higher reliability of the TPR. For instance, we have observed that to obtain a number of braking applications of 2×10^{-4} which is obtained for MB for a failure rate of 10^{-6}, we would need a TPR failure rate of VC equal to 3.25×10^{-7}. With reference to Aoun et al. (2021), in order for VC to outperform MB, there is a need to find a KPI that provides the same value of safety to both signalling alternatives. This goal can therefore be achieved by considering the number of braking applications as the KPI for safety that takes into account the corresponding failure rates for each market segment.

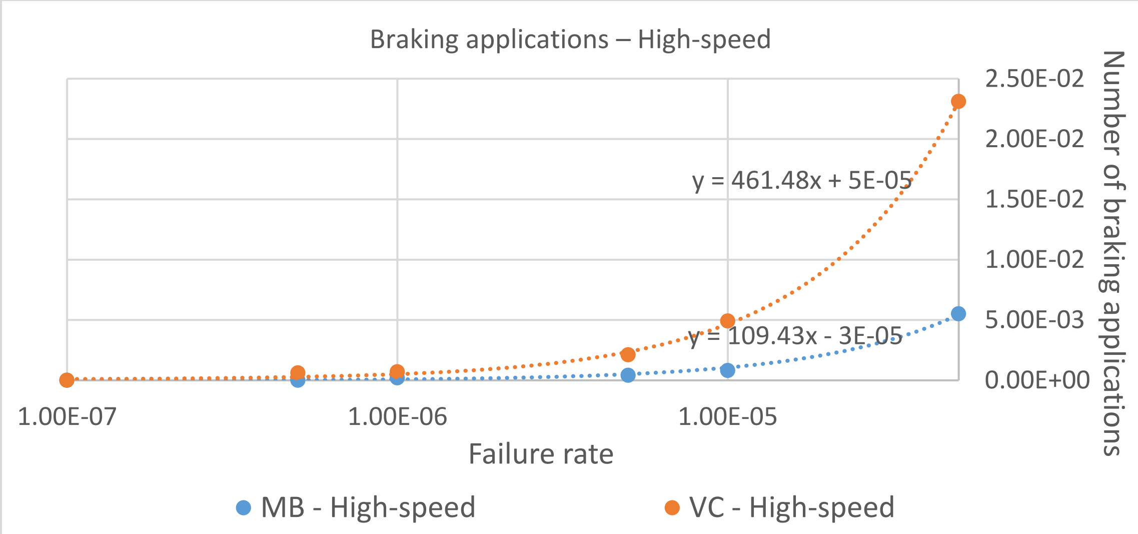

Figure 5.11: Braking applications for high-speed in the case of MB and VC

5.6 Conclusions

This chapter proposed a novel approach combining FTA and SAN to quantitatively analyse the effectiveness of next-generation signalling in safely supervising train movements under nominal and/or degraded conditions involving signalling equipment failures. An FTA model has been built for both MB and VC which describes the functional relationships among trackside, onboard and radio communication signalling components and mutual cause-effect dependencies which might lead to unsafe train movements. An apportionment of failure rates has been made possible among the different signalling components considering a Safety Integrity Level 4. The component failure rates were then used as input to the SAN model to assess the effectiveness of MB and VC signalling in supervising safe train movements under nominal conflict-free conditions as well as in the scenario that a TPR error occurs. Experiments have been conducted over five different rail market segments by analysing the impact that different failure rates of the TPR can have on the number of braking applications. Specifically, the KPI used for safety and effectiveness relates to the number of braking applications that would be triggered in case a TPR error occurs under MB and VC operations.

Results indicated that the FTA-SAN method can capture the stochastic behaviour of a system in normal and degraded operational conditions, and could be used for representing concurrent systems such as the V2V communication in VC. In addition, FTA-SAN evaluates the complexities and challenges imposed by new technologies in real-world conditions. The proposed approach can also deal with the aspects of the RAMS analysis, namely reliability, availability, maintainability and safety. The study investigated the effectiveness of MB and VC in safely supervising train movements for several market segments in scenarios involving different types of degraded conditions and failure rates of signalling components and design variables, where an example has been applied on the TPR. The results show that the overall approach can support infrastructure managers, railway undertakings, maintenance service providers and data analysts to assess a given configuration of MB and VC signalling components in terms of the effectiveness in supervising and guaranteeing safe train movements. Therefore, the methodology and the models developed so far are promising and have high potential.

One of the ways that we used to further the level of realism in the analysis of failure rates in VC and MB configurations is using a sensitivity analysis. A sensitivity of failure rate estimations to different design variables or parameters can help in understanding how changes in assumptions and data impact the results. In this chapter we focused on the example of a TPR error. In the future, the use of a global sensitivity analysis (e.g., variance-based sensitivity analysis –often referred as the Sobol method) can determine how much of the variability in model output is dependent upon each of the input design variables, which can provide a more realistic evaluation of the failure rates for VC and MB. In future research, we will continue the model development, by increasing the level of detail of all the modelling artifacts, and investigating the application of the FTA-SAN to more specific and more detailed use cases for the safety-performance evaluation of train-centric signalling systems by taking into account the characteristics of the track layouts considered for each case study with merging and diverging junctions. In addition, as the application of emergency braking could trigger injuries (and fatalities), there is a need to conduct a risk analysis where safety is assessed in terms of both probability and severity.

The impact of a collision or derailment in physically coupled trains is usually very high as all cars in the train move as one whole entity. In VC operations instead, given the fact that a follower train continuously receives updates about the position, speed and acceleration of its predecessor and since the trains are virtually connected, the magnitude of a derailment event might be reduced. This is particularly true when an adequate dynamic safety margin is modelled and designed to ensure a sufficient distance in case of emergency braking of the leader train. Therefore, a recommendation for future research would be to do a Risk Assessment according to the Common Safety Method (CSM-RA) to evaluate the potential types of accidents that might occur in the case of VC and better understand whether and how the collision propagation can be restrained to the following trains within the same convoy.

Chapter 6

Conclusions

This thesis is dedicated to provide methods and frameworks for the design, assessment and development of next-generation railway signalling technologies in terms of performance, safety and feasibility for different market segments. Feasibility refers to the technical, financial and regulatory perspectives. Five specific research questions have been posed and investigated in the previous chapters to achieve the main research objective. In this chapter, we draw conclusions and main findings in Section 6.1, followed by recommendations for practice and future research in sections 6.2 and 6.3, respectively.

6.1 Main findings

According to Chapter 1, the main research question of this PhD thesis is: *How can train-centric rail signalling technologies be assessed in terms of performance, safety and feasibility for different market segments?* To answer this main question, we first provide answers to the four defined sub-questions as follows.

RQ1: What are the potentials of Virtual Coupling for different rail market segments? **(Chapter 2)**

Virtual Coupling (VC) has various potentials to five different market segments including high-speed, mainline, regional, urban and freight railways. Chapter 2 highlighted those potentials by means of a SWOT analysis that aims at capturing the strengths, weaknesses, opportunities and threats of VC to each of the defined market segments. To achieve this aim, the challenges of VC were first presented and data was collected from railway experts and stated travel preferences to understand potential customer attractiveness of VC operations and the main advantages and limitations that VC could have in terms of safety, technology, operation, regulations, costs and business risks. Preliminary operational scenarios for each market segment were also introduced in terms of various operational characteristics that relate to the planned service headways, the train composition, the onboard customer facilities, the train platforming procedures, the crowd management at platforms, the train power supply and the main principles to control train convoys. The SWOT results showed that implementing VC can reduce OPEX and communication latency. In urban and regional railways, the homogenisation of the rolling stock characteristics allows a more efficient platooning. However, weaknesses arise from increased CAPEX and safety at diverging junctions, especially for trains with heterogeneous compositions (mainline market segment). The potential increase in ticket fees introduces some threats to the VC implementation. Other threats arise from the higher complexity of V2V communication, safety issues of relative braking distance operations and the market deregulation. Nevertheless, VC would open opportunities to both IMs and RUs given the reduced operation costs and the increased profits. For instance, the collection and distribution of goods in freight railways over the last mile can be automated and optimized. In addition, VC engenders a deregulated and more competitive railway market and a potential for cooperative consortia of railway operators leading to higher Benefit/Cost ratios.

RQ2: How to assess the overall impact of train-centric rail signalling systems? **(Chapter 3)**

Applying a hybrid Delphi-AHP MCA can provide an overall assessment to the impacts of railway signalling innovations using a framework encompassing multiple interdisciplinary methods for evaluating operational, technological and business domains. This framework was applied to two train-centric signalling system alternatives, i.e., MB and VC, and eight criteria, namely infrastructure capacity, system stability, lifecycle costs, energy consumption, travel demand, safety, public acceptance and regulatory approval. The results of the MCA showed that VC would be more beneficial to railway customers and the industry when considering the same level of technological maturity, represented by the safety criterion, with MB. The provided general evaluation of VC effects proved to be effective to support the railway industry in strategic investment and development plans for VC.

RQ3: How to identify potential critical step-changes in the development of train-centric rail signalling systems? **(Chapter 4)**

The outcomes of the MCA performed in Chapter 3 were used to delineate a roadmap to the potential deployment of VC for the different railway market segments in Europe, where step-changes are categorized into different themes and domains that relate to operation, business and technology. The chapter focused on the impacts of five prominent factors for the deployment of new transportation technologies, namely demand, CO_2 emissions, capital and operational expenditures, and regulatory approval. In Chapter 4, we proposed a framework to develop scenario-based roadmaps based on a SWOT (Chapter 2), a hybrid Delphi-AHP MCA (Chapter 3) and expert judgement. Outcomes revealed that the proposed approach does not only apply to the VC system but also to other dynamic businesses or systems where step-changes can be explored, mapped and interpreted based on distinct scenarios. Particularly, on one hand, the results of a SWOT analysis are adapted to highlight the enablers for the implementation of a certain project and to generate ideas on how gaps can be closed through a list of step-changes. On the other hand, the results of a hybrid Delphi-AHP MCA are used to define the priorities of the step-changes and quantitatively explore optimistic and pessimistic scenarios. Lastly, expert judgement provides a recognized and skilled opinion of individuals with specialized knowledge on the investigated specific area of expertise. The outcomes of the VC case study showed that both optimistic and pessimistic scenarios fulfil the target of deploying VC by 2050 except for the pessimistic scenario of mainline railways where VC could only be deployed by 2054. The main bottleneck was shown to be the development of integrated cooperative train operation, traffic management and interlocking for train convoys.

RQ4: How can the safety and performance of train-centric rail signalling systems be analysed? **(Chapter 5)**

In this chapter, we propose a new approach to evaluate the safety and performance of next-generation train-centric signalling systems based on the outcomes in Chapter 3 and Chapter 4. As the results in Chapter 3 showed that the crucial factor of safety for VC requires further investigation, we looked into different quantitative safety methods to identify the potential critical functionalities of the components of each investigated signalling system. In Chapter 4, we identified the critical step-changes that might prevent or limit the actual deployment of the VC technology. These included actions related to the longitudinal motion control systems in convoys, the operational procedures, and the integrated traffic management and train control. To achieve those steps, safety is a foremost step as there must be a guarantee of safe distance between the trains before being able to achieve following step-changes. To this end, we applied an overall FTA to both MB and VC. The aim of this FTA was to understand the criticalities of the system functionality in protecting against the boundary failures that lead to the core/root hazard. Results showed that the main causes that lead to an unsafe train movement relate to communication, trackside or onboard faults. From the communication perspective, the critical functionalities of the signalling components of both the MB and VC systems relate to an MA broadcasting time delay from the RBC to the train, and the TPR broadcasting time delay from the train to the RBC. Additional critical functions for VC relate to the V2V communication potential faults like a loss of this communication, or a V2V frequency coverage error, or a V2V limited broadcasting capacity. As there are no written specifications or requirements for VC, we considered in our study that the trackside and onboard faults are common to both MB and VC except for the EoA_{VC} update anomaly which depends on delayed or not received information from the V2V. The quantitative FTA was based on an apportionment of the failure rates based on requirements for SIL 4.

Based on the outcomes of the FTA, the interactions of the essential system components for MB and VC were investigated in a system safety and performance analysis by applying an FTA-SAN approach. The aim of this proposed method is to find a design configuration that enables a safe and effective VC deployment according to the principles of the MB system. Experiments were conducted for the five different rail market segments defined in Chapter 2 by using as KPI the number of triggered braking applications in case a TPR error occurs under MB and VC operations. This KPI was set to analyse the impact that different failure rates can have on the number of times that the trains brake according to a permitted braking curve. Results obtained from the different case studies indicate that the proposed FTA-SAN approach can capture effects of both nominal and degraded operational conditions with stochastic failure events on train service performances. In addition, FTA-SAN evaluates the complexities and challenges imposed by new technologies in real-world conditions. The used KPI was also set as input to the MCA developed in Chapter 3.

In response to the main research question, train-centric rail signalling technologies can be assessed in an overall hybrid multi-criteria Delphi-AHP analysis that encompasses multiple cross-disciplinary methods for evaluating several criteria that relate to performance, safety and feasibility from the technical, financial and regulatory perspectives. Different KPIs are proposed to evaluate the impacts of train-centric signalling for five different rail market segments. Feasibility is first investigated by means of a SWOT analysis to understand what the potential strengths, weaknesses, opportunities and threats of VC are and consequently define operational scenarios for the defined market segments. Scenario-based roadmaps are then developed to evaluate the deployment feasibility of VC in accordance to the EU vision towards increasing railway capacity, reducing CO_2 emissions and decreasing lifecycle costs. Results from the MCA and the roadmaps highlighted the importance and criticality of the safety criterion. To this end, a dedicated safety-performance analysis has hence been conducted by means of an FTA-SAN framework whose outcome has been used to feed back the MCA to ensure a fair impact comparison between MB and VC.

6.2 Recommendations for practice

The following extensions are made from a practical perspective.

The preliminary operational scenarios defined in Chapter 2 include different operational characteristics that are relevant to the implementation of real railway projects. The developed scenario-based roadmaps in Chapter 4 can be tailor-made to these operational characteristics for each market segment in a way that helps operators to better manage strategies in advance. For instance, when considering the crowd management at platforms, there is a possibility of allocating more cars to potentially congested trains within a convoy or suggesting some passengers to board into uncrowded trains that go to the same destination (within the same convoy). To significantly improve management at platforms, decisions are made upon the investigated market segment, where roadmaps would include the possibility of either segregating the platforms into sections delimited by boards or by physical barriers and platform doors (e.g., to high-speed and mainline railways).

The investigated hybrid Delphi-AHP MCA in Chapter 3 can help decision-makers to foresee the impact of decisions on passengers and goods so that the different requirements for the investigated criteria and alternatives can be adjusted in a more reliable way. The obtained results in Chapter 3 (and 4) can be used to identify potential critical criteria (and step-changes) that need to be given more attention in the railway industry, based on which infrastructure managers, operators and decision-makers can take some actions in advance.

The operational scenarios defined in Chapter 3 cover the operation of two consecutive trains in plain line, merging junctions and diverging junctions with specific input for the stopping pattern. Given the flexibility of the VC technology due to coupling and decoupling operations on the run, having additional stops or skipping scheduled stops can be optimized based on the actual or predicted travel demand. Consequently, alternative train services help to shorten passengers' travel times particularly during overcrowding, disturbances or disruptions.

As mentioned in Chapter 3, VC can facilitate the implementation of on-demand train services which could possibly revolutionize the entire idea of timetabling. Therefore, an accurate information provision system is recommended to help passengers in planning their journeys with real-time data based on various choices.

The roadmapping framework developed in Chapter 4 can help stakeholders to identify and solve potential criticalities to the deployment of VC and to setup investment and development plans. As different market segments have been exploited, it is essential to determine the durations and the level of priority of each step-change based on the investigated scenarios and the particular characteristics that relate to each market segment. For instance, in the case of a pessimistic scenario where longer durations are required to complete a certain step-change due to certain unpredicted circumstances, a re-ordering or re-classification of the priorities of the defined actions could provide a more optimal path towards the deployment of the investigated technology.

Analysing performances of train-centric signalling systems in effectively providing safe train movements is a complex task especially if involved technological components have not yet been implemented in real life. Therefore the proposed FTA-SAN approach in Chapter 5 provides a better understanding of the impact of failures on safety and performance while effectively dealing with system's complexities and behaviour. The obtained results can support infrastructure managers, railway undertakings, maintenance service providers and data analysts in identifying the most critical system components based on their defined functions and the developed fault trees. The proposed approach also provides an efficient capability of dealing with the core problems of reliability and safety analysis methods.

6.3 Recommendations for future research

We recommend in this section several directions for future research as follows.

As VC can provide more flexible train services in line with passengers' demand, further research can be conducted on the impact of the demand variation on the rolling stock composition during on-peak and off-peak hours under VC operations. Another direction for future research is the optimized composition of VC convoys. In addition, swarming trains could help alleviating congestion, particularly in crowded urban areas, and be a potential consequence of the Mobility as a Service (MaaS) vision with a fully customised dial-a-ride type of service that aims to maximize the flexibility of public transport modes.

The application of the FTA-SAN approach can be further expanded to a higher level of all modelling artifacts as well as more specific and detailed use cases for the safety-performance evaluation of railway or other transportation systems by taking into account additional properties of the topology and braking behaviour of the investigated system. Moreover, additional tests with more practical conditions that relate to onboard/trackside errors or lags in vehicle dynamics can provide a more robust and effective analysis of the VCTS controllers.

Information flow and communication technologies are essential in the implementation of cooperative systems. In this thesis, no detailed measures or investigations were considered about the V2I and V2V communications. There are also no standardized requirements of the V2V communication within train convoys. Therefore, bridging these gaps allows the inclusion of more technological features and implementation issues that can foster the level of detail of the developed roadmaps towards the deployment of VC for the five defined market segments.

Further research directions include the design of the rolling stock composition of virtually coupled trains during on-peak and off-peak hours based on specific demand patterns. Another direction for future research is to evaluate the extent to which VC can provide flexibility to passenger and freight railways. In addition, future studies can include a deeper study of the information architecture and information flow of cooperative systems that can lead to a higher performance of VC operation.

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Summary

As the deployment of new railway technologies requires official approval from local authorities and governmental agencies, a well-specified strategy can foster investment decisions for technological developments and the overall system migration process. Therefore, it is crucial to guarantee that the proposed railway technologies can enhance operational efficiency and ensure safety to passengers and freight transport. Next-generation train-centric signalling systems can provide substantial capacity benefits to railway undertakings. Moving Block (MB) or the European Rail Traffic Management System / European Train Control System Level 3 (ERTMS/ETCS L3) is a radio-based system without any trackside equipment. A Radio Block Centre (RBC) receives positions of each train continuously and computes a Movement Authority (MA) to each of them. In this signalling system, the track is not partitioned into fixed blocks as is the case in conventional railways but the trains operate under "moving blocks" with a safe distance in front determined by the absolute braking distances. As there is no available trackside equipment, it is vital that trains guarantee their integrity by means of a Train Integrity Monitoring (TIM) system. Virtual Coupling (VC) is one of the most advanced train-centric signalling concepts that drastically reduces train headways and allows trains to move synchronously together in platoons using Vehicle-to-Vehicle (V2V) communication. However, several uncertainties arise in the safety validation and feasibility (from the technical, financial and regulatory perspectives) of the VC technology, particularly when compared to MB.

This thesis aims at developing methodological frameworks to support science and the industry in analysing, assessing and developing new complex systems and next-generation rail technologies. The proposed frameworks use interdisciplinary approaches to address complex decision-making processes such as market potential analysis, impact assessment and roadmapping. In addition, a novel methodological framework is proposed to evaluate the safety and performance of technologies and complex systems.

We first investigate the market potentials and operational scenarios of VC for different segments of the railway market: high-speed, mainline, regional, urban, and freight trains. The research builds on the Delphi method, with an extensive survey to collect expert opinions about benefits and challenges of VC as well as stated travel preferences in futuristic VC applications. Survey outcomes show that VC train operations can be very attractive to customers of the high-speed, mainline, and regional market segments, with benefits that are especially relevant for freight railways. In particular, customers of regional and freight railways are observed to be unsatisfied with current train services and willing to pay higher fares to avail of a more frequent and flexible service enabled by VC. Operational scenarios for VC are then defined by setting market-attractive service headways and defining characteristics of the rolling stock, infrastructure, and traffic management. A SWOT analysis of strengths and weaknesses of this

concept together with business opportunities and threats is carried out. The defined VC future scenario is set to induce a sustainable shift of customers from other travel modes to the railways.

Second, we examine the overall impact of next-generation train-centric signalling systems to identify development strategies to face the forecasted railway demand growth. To this aim, an innovative Multi-Criteria Analysis (MCA) framework is introduced to analyse and compare VC and MB in terms of relevant criteria including quantitative (e.g., costs, capacity, stability, energy) and qualitative ones (e.g., safety, regulatory approval). We use a hybrid Delphi-Analytic Hierarchic Process (Delphi-AHP) technique to objectively select, combine and weight the different criteria to more reliable MCA outcomes. The analysis has been performed for different rail market segments including high-speed, mainline, regional, urban and freight corridors. The results show that there is a highly different technological maturity level between MB and VC given the larger number of vital issues not yet solved for VC. The MCA also indicates that VC could outperform MB for all market segments if it reaches a comparable maturity and safety level. The provided analysis can effectively support the railway industry in strategic investment planning of VC.

Third, developments in the railway industry are continuously evolving and long-term transition strategies can enable an efficient implementation of signalling technologies that provide a significant increase in network capacity and operation efficiency. VC advances MB signalling by further reducing train separation to less than an absolute braking distance using V2V communication and cooperative train control within a Virtually Coupled Train Set (VCTS). This chapter proposes a method to develop scenario-based roadmaps based on the SWOT and hybrid Delphi-AHP MCA. Step-changes are identified and initially assessed in a Swimlane based on priorities and time order collected from stakeholders through a survey and further developed in a workshop. Optimistic and pessimistic scenarios are assessed regarding various factors and timelines. The step-changes are then enriched with the optimistic and pessimistic scenarios, and associated durations are estimated for each of the step-changes, which finally result into scenario-based roadmaps that can be used as an efficient tool for stakeholders to identify and solve potential criticalities/risks to the deployment of VC as well as to setup investment and development plans. The approach is applied to deliver implementation roadmaps of VC for different market segments with particular focus on mainline railways.

Fourth, although MB and VC rail signalling will change the current train operation paradigm by migrating vital equipment from trackside to onboard to reduce train separation and maintenance costs, their actual deployment is constrained by the need for methods to identify configurations which can effectively guarantee safe train movements even under degraded operational conditions. In this thesis, we analyse the effectivity of MB and VC in safely supervising train separation under nominal and degraded conditions by using an innovative approach which combines Fault Tree Analysis (FTA) and Stochastic Activity Network (SAN). An FTA model of unsafe train movement is defined for both MB and VC capturing functional interactions and cause-effect relations among the different signalling components. The FTA is then used as a basis to apportion signalling component failure rates needed to feed the SAN model. Effective MB and VC train supervision is analysed by means of SAN-based simulations in the specific scenario of an error in the Train Position Report (TPR) for five rail market segments featuring different traffic characteristics, namely high-speed, mainline, regional, urban and freight. Results show that the overall approach can support infrastructure managers, railway undertakings, and rail system suppliers in investigating the effectiveness of MB and

VC in safely supervising train movements in scenarios involving different types of degraded conditions and failure events. The proposed method can hence support the railway industry in identifying effective and safe design configurations of next-generation rail signalling systems.

In summary, this thesis provides multiple scientific contributions to train-centric rail signalling technologies by developing several methodological frameworks to support decision-making towards the development of complex railway systems. With a rapid growth of the railway demand, this thesis serves as a guidance for practitioners to develop more advanced transportation systems while ensuring an improved evaluation of safety and performance.

Samenvatting

Aangezien de inzet van nieuwe spoorwegtechnologieën officiële goedkeuring van lokale autoriteiten en overheidsinstanties vereist, kan een goed gespecificeerde strategie investeringsbeslissingen bevorderen voor technologische ontwikkelingen en het algemene systeemmigratieproces. Daarom is het cruciaal om te garanderen dat de voorgestelde spoorwegtechnologieën de operationele efficiëntie kunnen verbeteren en de veiligheid voor passagiers en vrachtvervoer kunnen waarborgen. Treingerichte beveiligingssystemen van de volgende generatie kunnen capaciteitsvoordelen bieden voor spoorwegondernemingen. Moving Block (MB) of het Europese Rail Traffic Management System / European Train Control System Level 3 (ERTMS / ETCS L3) is een radio-gebaseerd systeem zonder baangebonden apparatuur. Een radioblokcentrum (RBC) ontvangt continu de posities van elke trein en berekent een rijtoestemming (MA) over een veilige afstand . In dit treinbeveiligingssysteem wordt de spoorbaan niet opgedeeld in vaste blokken, zoals het geval is bij conventionele spoorwegen, maar opgesplitst in "bewegende blokken" met een veilige afstand voor de trein bepaalt door de absolute remweg. Omdat er geen beschikbare baanapparatuur is, is het van vitaal belang dat treinen hun integriteit garanderen door middel van een Train Integrity Monitoring (TIM) systeem. Virtuele koppeling (VC) is een van de meest geavanceerde treingerichte seinconcepten die opvolgtijden drastisch vermindert en treinen in staat stellen synchroon samen te bewegen in platoons gebruikmakend van voertuig-tot-voertuig (V2V) communicatie. Er zijn echter verschillende onzekerheden in de validatie van veiligheid en de haalbaarheid (vanuit technische, financiële en regelgevende perspectieven) van de VC - technologie, met name in vergelijking met MB.

Dit proefschrift is gericht op het ontwikkelen van methodologische kaders om de wetenschap en de industrie te ondersteunen bij het analyseren, beoordelen en ontwikkelen van nieuwe complexe systemen en de volgende generatie spoorwegtechnologieën. De voorgestelde kaders gebruiken een interdisciplinaire aanpak om complexe besluitvormingsprocessen aan te pakken, zoals marktpotentie analyse, impactbeoordeling en roadmapping. Bovendien wordt een nieuw methodologisch kader voorgesteld om de veiligheid en prestaties van technologieën en complexe systemen te evalueren.

We onderzoeken eerst de marktpotentie en operationele scenario's van VC voor verschillende segmenten van de spoorwegmarkt: hogesnelheidslijnen, hoofdspoor, regionaal spoor, stedelijk spoor en goederentreinen. Het onderzoek bouwt voort op de Delphi -methode, met een uitgebreide enquête om deskundige meningen te verzamelen over voordelen en uitdagingen van VC en aangegeven reisvoorkeuren in futuristische VC toepassingen. De resultaten van de

enquête tonen aan dat VC treinactiviteiten zeer aantrekkelijk kunnen zijn voor klanten van de hogesnelheid, hoofd en regionale marktsegmenten, met voordelen die vooral relevant zijn voor goederenvervoer. In het bijzonder is waargenomen dat klanten van regionaal- en goederenspoor niet tevreden zijn met de huidige treindiensten en bereid zijn om hogere tarieven te betalen om gebruik te maken van een frequentere en flexibele service die door VC mogelijk wordt gemaakt. Operationele scenario's voor VC worden vervolgens gedefinieerd met marktaantrekkelijke frequenties en kenmerken van de rollend materieel, infrastructuur en verkeersmanagement. Een analyse van sterke en zwakke punten van een dergelijk concept samen met zakelijke kansen en bedreigingen wordt uitgevoerd. Het VC toekomstscenario is opgezet om een duurzame verschuiving van andere vervoermodaliteiten naar de spoorwegen te veroorzaken.

Ten tweede onderzoeken we de algemene effecten van de volgende-generatie treingerichte beveiligingssystemen om ontwikkelingsstrategieën te identificeren die de voorspelde groei van de spoorvervoervraag kunnen ondervangen. Hiertoe wordt een innovatief multi-criteria-analyse (MCA) raamwerk geïntroduceerd om VC en MB te analyseren en te vergelijken op relevante criteria, waaronder kwantitatieve (kosten, capaciteit, stabiliteit, energie) en kwalitatieve (veiligheid, regelgeving). We gebruiken een hybride Delphi-analytisch hiërarchisch proces (Delphi-AHP) om de verschillende criteria voor betrouwbare MCA-resultaten objectief te selecteren, te combineren en te wegen. De analyse is uitgevoerd voor verschillende segmenten van de spoorwegmarkt, waaronder hogesnelheid, hoofd, regionaal, stedelijk en goederen. De resultaten laten zien dat de technologische volwassenheid tussen MB en VC erg verschilt, aangezien een groot aantal essentiële problemen nog niet zijn opgelost voor VC. De MCA geeft ook aan dat VC voor alle marktsegmenten MB kan overtreffen als het een vergelijkbaar volwassenheid en veiligheidsniveau heeft bereikt. De analyse kan de spoorwegindustrie effectief ondersteunen bij strategische investeringsplanning van VC.

Ten derde evolueren de ontwikkelingen in de spoorwegindustrie zich voortdurend en kunnen overgangsstrategieën op de lange termijn een efficiënte implementatie van treinbeveiligingstechnologieën mogelijk maken die een aanzienlijke toename van de netwerkcapaciteit en de bedrijfsefficiëntie bieden. VC geeft een verbetering ten opzichte van MB door de opvolgafstand tussen treinen te verminderen tot minder dan een absolute remafstand met behulp van V2V communicatie en coöperatieve treinbesturing binnen een virtueel gekoppelde treinsamenstelling (VCTS). Dit hoofdstuk stelt een methode voor om scenario-gebaseerde stappenplannen te ontwikkelen op basis van de SWOT en hybride Delphi-AHP MCA. Veranderstappen worden geïdentificeerd en initieel beoordeeld in een swimlane diagram op basis van prioriteiten en tijdvolgorde verkregen van belanghebbenden via een enquête en verder ontwikkeld in een workshop. Optimistische en pessimistische scenario's worden beoordeeld met betrekking tot verschillende factoren en tijdlijnen. De veranderstappen worden vervolgens verrijkt met de optimistische en pessimistische scenario's, en de bijbehorende tijdsduren voor elk van de veranderstappen leiden uiteindelijk tot scenario-gebaseerde roadmaps die kunnen worden gebruikt als een efficiënt hulpmiddel voor belanghebbenden om potentiële knelpunten en risico's voor de invoer van VC te identificeren en op te lossen om investerings- en ontwikkelingsplannen op te stellen. De aanpak wordt toegepast om implementatie roadmaps van VC op te stellen voor verschillende marktsegmenten met bijzondere focus op hoofdspoor.

Ten vierde, hoewel MB en VC treinbeveiliging het huidige treinbedrijf paradigma zal wijzigen door veiligheidskritische apparatuur te migreren van de baan naar de trein om opvolgtijden en onderhoudskosten te verlagen, wordt de daadwerkelijke implementatie beperkt door de behoefte aan methoden om configuraties te identificeren die effectief veilig treinverkeer kunnen garanderen, ook onder gedegradeerde operationele omstandigheden. In dit proefschrift analyseren we de effectiviteit van MB en VC om veilige treinafstanden te garanderen onder nominale en verstoorde omstandigheden met behulp van een innovatieve aanpak die foutenboomanalyse (Fault Tree Analysis, FTA) en Stochastic Activity Network (SAN) combineert. Een FTA-model voor onveilige treinbewegingen wordt gegeven voor zowel MB als VC, dat functionele interacties vastlegt als oorzaak-gevolg relaties tussen de verschillende componenten. De FTA wordt vervolgens gebruikt als basis om faalkansen van de diverse beveiligingscomponenten af te leiden die nodig zijn om het SAN model te voeden. De effectiviteit van de MB en VC treinbeveiliging wordt geanalyseerd door middel van SAN-gebaseerde simulaties in het specifieke scenario van een fout in het treinpositierapport (Train Position Report, TPR) voor de vijf spoormarktsegmenten met verschillende verkeerskenmerken, hogesnelheids-, hoofd-, regionaal, stedelijk en goederenspoor. Resultaten tonen aan dat de aanpak infrastructuurmanagers, spoorwegondernemingen en leveranciers van spoorwegapparatuur kan ondersteunen bij het onderzoeken van de effectiviteit van MB en VC voor treinbeveiliging in scenario's met verschillende soorten verstoorde omstandigheden en faalgebeurtenissen. De voorgestelde methode kan daarmee de spoorwegindustrie ondersteunen bij het identificeren van effectieve en veilige ontwerpconfiguraties voor de volgende generatie treinbeveiligingssystemen.

Samenvattend biedt dit proefschrift meerdere wetenschappelijke bijdragen aan treingerichte beveiligingstechnologieën door verschillende methodologische aanpakken te ontwikkelen ter ondersteuning van de besluitvorming voor de ontwikkeling van complexe spoorwegsystemen. Met een snelle groei van de spoorwegvraag dient dit proefschrift als een ondersteuning van vakmensen om geavanceerde transportsystemen te ontwikkelen en tegelijkertijd een verbeterde evaluatie van veiligheid en prestaties te waarborgen.

About the Author

Joelle Aoun (جويل عون in Arabic) was born on April 27th, 1994 in Antelias, Lebanon. She grew up in her hometown and moved to the Netherlands for her PhD at Delft University of Technology (TU Delft) in 2019. In 2016, Joelle did an internship in Athens (Greece) on the driving dynamics in relation to road safety. Based on the work she performed during this internship, she published her first journal article at the end of her Bachelor, which marked the beginning of her interest in research and traveling.

In 2017, Joelle completed her bachelor in civil engineering at the Holy Spirity University of Kaslik (USEK) in Lebanon. She received her master's degree in civil engineering from the same university in 2018 (1st Grade Hons with a GPA of 93/100). The focus of her masters' programme was on transportation. Joelle got enrolled in several internships related to different civil engineering fields in structure and transportation. She carried out site supervision and design estimation for structural projects in Lebanon. She also develped a feasible public bus transport system with the Keserwan-Ftouh Federation of Municipalities (Lebanon). This project was in collaboration with the University of Versailles-Saint-Quentin-en-Yvelines (UVSQ) in Paris (France). In Greece, she worked at the National Technical University of Athens (NTUA) on a project involving the operational and safety performance investigation of skew superelevation runoff. In 2018, Joelle was the President of the American Society of Civil Engineers (ASCE) at the Holy Spirit University of Kaslik (USEK) in Lebanon, and received a Certificate of Commendation for being awarded to the top 5% of all Student Organizations in the world.

In March 2019, Joelle started her PhD at TU Delft. She worked on the EU H2020 Shift2Rail funded projects MOVINGRAIL and PERFORMINGRAIL which delivered breakthroughs for the deployment of train-centric signalling by defining operational implications, developing testing methods for Moving Block, assessing impacts of Virtual Coupling, and addressing safe operational principles and specifications. From July 2021 to March 2023, Joelle was the representative of the Transport and Planning department at the Civil Engineering and Geosciences PhD Council at TU Delft. She contributed to the PhD community by creating, communicating and implementing improvements that facilitate the support of individual and collective actions to build mutually valued results. She also coordinated with several bodies and support pillars at the university to produce movement and employ constructive changes.

Joelle's main research interests are on multi-criteria impact assessment for market potential and operational scenarios for Virtual Coupling and on developing multiple interdisciplinary methodological frameworks for impact assessment. She also works on analysing and assessing novel operational principles to enable safe train separation, and on defining roadmaps and deployment strategies for technological forecasting and social change.

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Journal articles

Aoun, J., Goverde, R.M.P., Nardone, R., Quaglietta, E., Vittorini, V. (2023). Evaluating the safe and efficient behaviour of rail signalling technologies based on FTA-SAN. Under review.

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