

Capacity benefits of Virtual Coupling over ETCS L3 Moving block in a realistic operational environment

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Capacity benefits of Virtual Coupling over ETCS L3 Moving Block in a realistic operational environment

by

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Preface

This thesis is my last requirement for obtaining the MSc degree in Civil Engineering, with a specialization in Transport and Planning. As we are going through the first months of the European year of Rail 2021, I am happy to be sharing the results of this research, which focuses on next generation signalling concepts. This thesis would not have been completed without the contribution of several people.

First, I want to express my gratitude to my daily supervisor Egidio Quaglietta, for inspiring me with the topic and his continuous support and patience along the whole process. Thank you Egidio for sharing your knowledge on railway signalling systems but most of all, for making me like railways more. Next, I would like to thank my head supervisor, Professor Rob Goverde for his insightful and constructive feedback, especially in the last steps of this thesis. I am also grateful to Meng Wang for his detailed comments. To Paul van Koningsbruggen and his colleagues from Technolution, I appreciated all the meetings we had and the useful feedback you always provided to me. Of course, I also want to thank Rafael Borges from the DRT lab of TU Delft for his interest in my project and the time he devoted to help me with the simulation software.

Completing this master's program would not be possible without the priceless support of my family. I would like to thank to my parents, my sister Iliana and my brother Alexandros for believing in me.

Working on a thesis during a pandemic is not the best experience someone can have. However, there are people in my life that made days brighter and pushed me in a nice way to achieve my goals. Special thanks to my fiends Dimitris, Roxani, Pantelis, Alexandra, Panos for listening to all my concerns about my thesis and all the beautiful moments we had the last year. Caro, thank you for your kind support, love and patience. I also want to thank my friends Paula, Sena, Vinicius, David, Shubham, Vasilina, Vaso and Stathis for all the nice memories in Delft. And finally, big thanks to my friends from Greece for being there for me all these years!

I wish you a pleasant reading!

Delft, February 2021
Panagiotis Spartalis

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Summary

Introduction

As the demand for transport of goods and passengers increases, the capacity of railway networks is becoming more and more saturated. Railway infrastructure managers aim to increase the rail network capacity with the minimum possible investments in infrastructure. Applying innovative railway signalling solutions is one way for increasing rail line capacity. European Rail Traffic Management System (ERTMS) is a cab signalling system which aims to replace the existing national block signalling and Automatic Train Protection (ATP) systems, providing safety and interoperability. Next generation signalling systems such as ETCS L3 Moving Block (MB) and Virtual Coupling (VC) are expected to bring significant capacity benefits to railway corridors. In moving block, the minimum line headways are highly reduced as the End of Authority (EoA) shifts to a moving point (i.e., the rear end of the front train) assuming a reliable Train Integrity Monitoring (TIM), compared to the fixed points that are considered to determine the EoA in traditional fixed block signalling. Minimum train headways can further be reduced under Virtual Coupling, where the concept of relative braking distance is followed, similar to road traffic. Under VC, a second End of Authority for VC (EoA_{VC}) is issued to the following train, based on the kinematic data of the leading train. The relative braking distance implies that the following train adjust its kinematic behavior according to the speed of the leading train, assuming that the predecessor cannot come to a standstill instantly. While car-following and enabling technologies have been widely studied and tested, train-following models are still in early stages of research. Safety distance car-following models (i.e., Gipp's, 1981) or even more advanced strategy-based models such as the Intelligent driver model (IDM) or the Microscopic model for simulation of intelligent cruise control (MIXIC) are models that can be adapted to the railway sector. Objective of this study is to investigate potential capacity benefits of VC over ETCS L3 MB in a realistic operational setup, where trains with different acceleration and braking capabilities, varied V2V update delays, train control delay times and positioning errors exist. Therefore, the main research question is formulated as:

What are the potential capacity gains of Virtual Coupling over ETCS L3 Moving block in a realistic operational environment where different rolling stock characteristics, operational speeds, driving behavior and uncertain traffic information exist, by adapting driving technologies from the automotive sector?

Model development

The selected model for analyzing VC operations is the multi-state train-following developed in Quaglietta et al. (2020), since it includes non-linear train dynamics, traction power limitations, motion and track resistances, but also provides an analytical flow between different states when two trains are running under VC. In this model, trains are separated by a relative braking distance plus a constant safety margin. For various rolling stock characteristics, V2V communication delay, train control delay times and positioning errors, VC operations may increase the safety risk, especially in case the leading train applies emergency braking. Influenced by safety distance car-following models, the multi-state train following model is enhanced by a dynamic term in this thesis, the dynamic safety margin (DSM), which substitutes the constant safety margin

already incorporated in the multi-state train-following model. The conceptual framework of model adapted by Quaglietta et al. (2020), includes five consecutive states as depicted in Figure 1. By default, trains run under ETCS L3 MB. By the time a V2V connection is established between a leading and a following train, the European Vital Computer (EVC) computes a dynamic safety margin based on the kinematic information sent by the leading train. If conditions allow it, the following train switches to the coupling state, trying to reach the speed of the leader, without violating the dynamic safety margin. Then, if the leading train speed is reached, the following train switches to coupled running state where trains run in a convoy with similar speeds and a relative short separation distance. In case the following train is outdistanced more than a space threshold from the leader, then the following train unintentionally decouples from the leading train and continues to run according to its own speed profile without considering the kinematic behavior of the predecessor. If conditions allow it again, the following train can switch again to the coupling or the coupled running state. If a coupled train convoy approaches a diverging junction, then the following trains decoupled from the leader and switches back to ETCS L3 running considering also an additional safety distance required to move and lock the switching point.

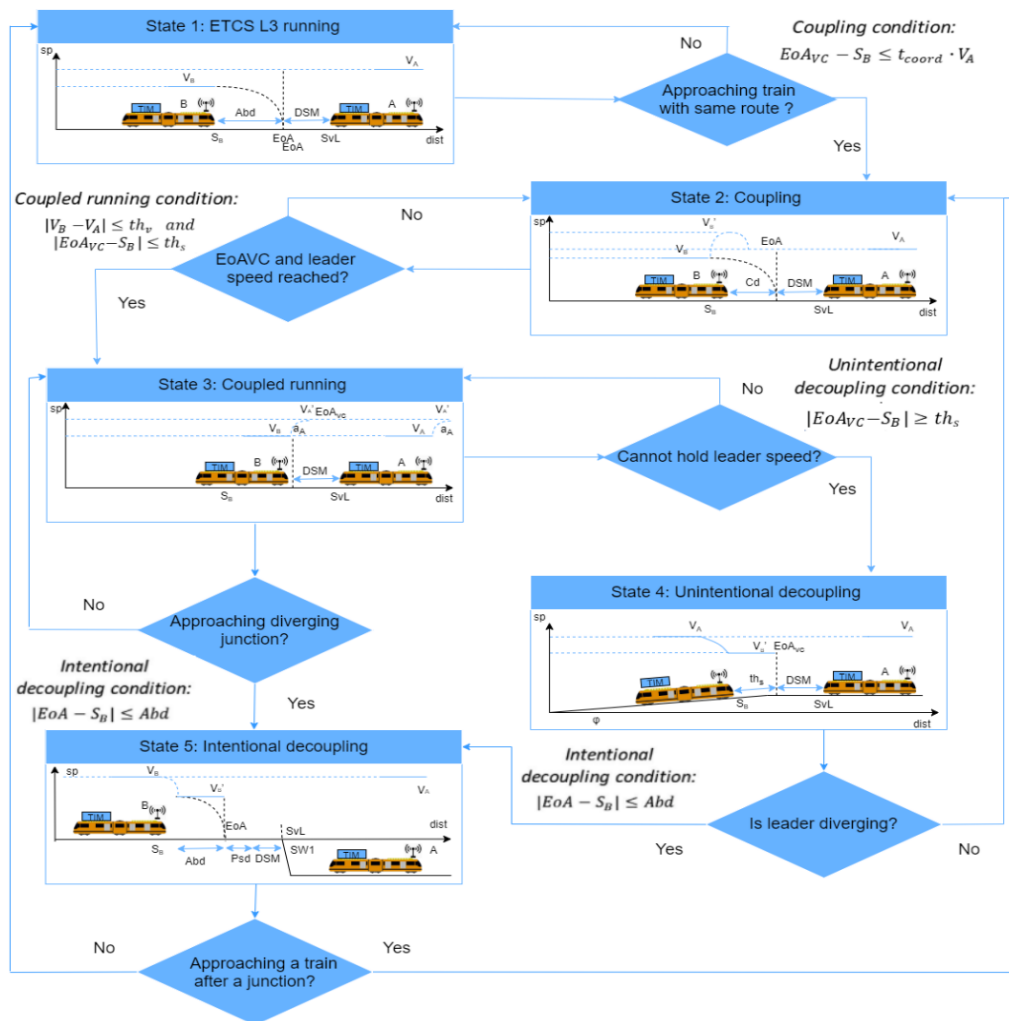


Figure 1 Multi-state train-following model with a DSM (adapted by Quaglietta et al.2020)

The DSM depicted in Figure 2, consists of several safety distances as shown in (1) which account for: a nominal safety distance SM_0 (50 m), the positioning errors of trains, computed by (2) for each train, an additional safety distance in case the service braking distance of the following train is higher than the emergency braking distance of the leading train, given by (3). In addition, a safety distance is added if the following train runs at a higher speed than the leading train, to account for the V2V update delay in (4). Finally, to consider different control delay time of trains, a safety distance is computed in (5) based on the speeds and the control delays of both trains.

$$SM = SM_0 + SM_{odometry} + SM_{delay} + SM_{control} + SM_{braking} \quad (1)$$

$$SM_{odometry,t} = 5 + \beta * d_{balise,k}, \text{ with } \beta = \frac{0.05 * d_{balise,k}}{L_{balise,k}} \quad (2)$$

$$SM_{braking,k} = \max\left(0, \frac{u_{n,k}^2}{2b_{n,max}} - \frac{u_{n-1,k-\tau_{delay}}^2}{2b_{emerg}}\right) \quad (3)$$

$$SM_{delay,k} = \max\left(0, \tau_{delay} * u_{n,k} - \tau_{delay} * u_{n-1,k-\tau_{delay}}\right) \quad (4)$$

$$SM_{control,k} = \max\left(0, \tau_{c,n} * u_{n,k} - \tau_{c,n-1} * u_{n-1,k-\tau_{delay}}\right) \quad (5)$$

, where $d_{balise,k}$ is the distance from the last balise the train has passed at time instant k , and L_{balise} the distance between two balises, $b_{n,max}$ and b_{emerg} the deceleration rate of following train and the emergency braking rate of the leading train, τ_{delay} the V2V update delay, $u_{n-1,k-\tau_{delay}}$ is the speed of the leading vehicle at time instant k minus the τ_{delay} and $u_{n,k}$ the speed of the following train at time instant k , $\tau_{c,n-1}$ and $\tau_{r,n}$ the control delay time of the leading and the following vehicle, respectively.

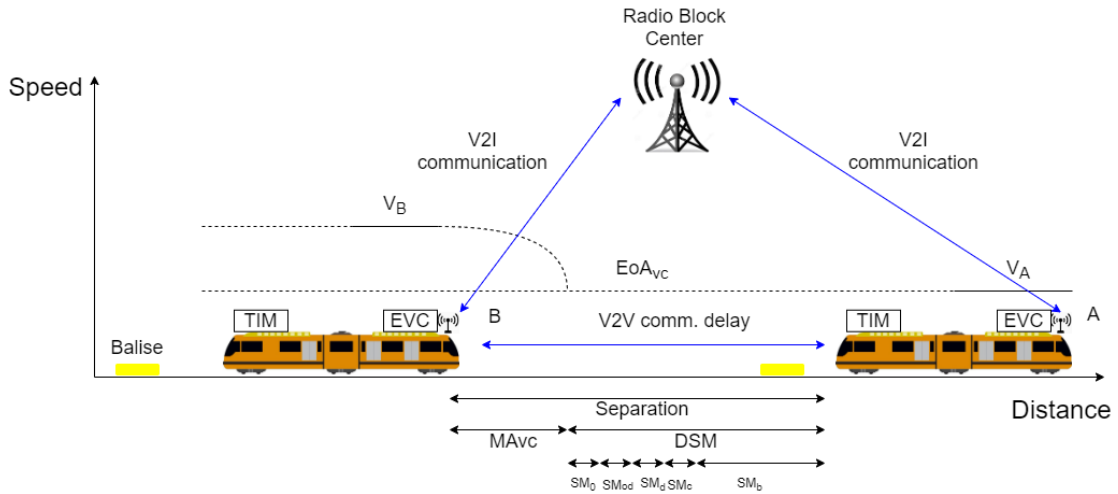


Figure 2 Dynamic safety margin

Sensitivity analysis

Several model parameters are assumed to influence the rail line capacity. These parameters concern the space and speed thresholds (th_s and th_v), the V2V communication update delay, the train control delay time and the service braking rate of the following train. An One-at-a-time (OAT) sensitivity analysis of the enhanced multis-state train-following model is performed to investigate the impact of the above

mentioned parameters on rail line capacity. For increased V2V communication update delay, the train headways between trains under VC increase, limiting the rail line capacity. When trains have equal train control delays, no change in corridor capacity is anticipated. Headways increase where trains running in following mode with different speeds, have different train control delay times. Furthermore, varied gradients have a negative impact on VC, as the coupled running state duration is lower compared to the case when trains form a convoy on a hypothetical track with 0% gradient. Among the selected parameters, the braking rate of the following is proved to have a great impact on rail line capacity, since small changes in the braking rate lead to relatively high changes in the time headways.

Operational scenarios

Several operational scenarios have been simulated in EGTRAIN simulation environment. The scenarios concern train convoy formations on the South West Main Line (SWML) corridor in the UK on a 20 km route stretch, between Waterloo and Surbiton, with and without intermediate stops. Three different train types are considered, being the British Class 455 (suburban), the British Class 450 (regional) and the British Class 220 (intercity), from the slowest to the fastest. The model results are evaluated through a comparative capacity analysis with the ETCS L3 MB and the former VC model developed in Quaglietta et al. (2020) without considering a DSM. Regarding services without stops, homogeneous convoys of trains with improved acceleration and braking behavior promise higher capacity benefits. For heterogenous train combinations, the headways are reduced when faster trains follow slower ones. For homogeneous train convoys of slower trains and for slower trains following faster trains, no additional benefits over ETCS L3 MB are identified.

Table 1 Capacity benefits of VC with a DSM over ETCS L3 MB for different train combinations on the route Wtl-Sbn without stops

Leader-Follower		Surbiton
Sub-Sub		0%
Re-Re		23%
Ic-Ic		35%
Re-Sub		5%
Sub-Re		22%
Re-Ic		41%
Ic-Re		6%

The analysis shows that for services with stops, the proposed model brings capacity benefits for all rolling stock combinations. The most significant benefits are observed at stations Raynes Park and Surbiton. The highest headway reductions under the proposed model compared to ETCS L3 MB, are identified for heterogenous train convoys, as it is observed in Table 2. Headways can be reduced to the minimum when faster trains follow slower trains.

Table 2 Capacity benefits of VC with a DSM over ETCS L3 MB for different train combinations on the route Wtl-Sbn with stops

Leader - Follower	ClaphamJn	Wimbledon	Raynes Park	Surbiton
Sub-Sub	32%	15%	38%	60%
Re-Re	43%	14%	40%	59%
Ic-Ic	42%	42%	60%	31%
Re-Sub	34%	24%	76%	84%
Sub-Re	29%	35%	46%	67%
Re-Ic	55%	30%	62%	65%
Ic-Re	35%	52%	71%	56%

With the proposed model, multiple train convoy formations are possible based on a predecessor-follower communication topology, where the EVC of each train computes A DSM and adjust its kinematic behavior based on the kinematic data of the leading train. An example of a four-train convoy comprised of different rolling stock types (Sub-Re-Ic-Re) is simulated for the same route with one stop at Surbiton station. The first two trains stop at the first platform and the next two trains diverge at Berryland junction and arrive at the second platform of the station. As seen in Figure 3, trains run with a safety distance in between which is reduced compared to ETCS L3 MB, resulting in lower headways at Berryland junction.

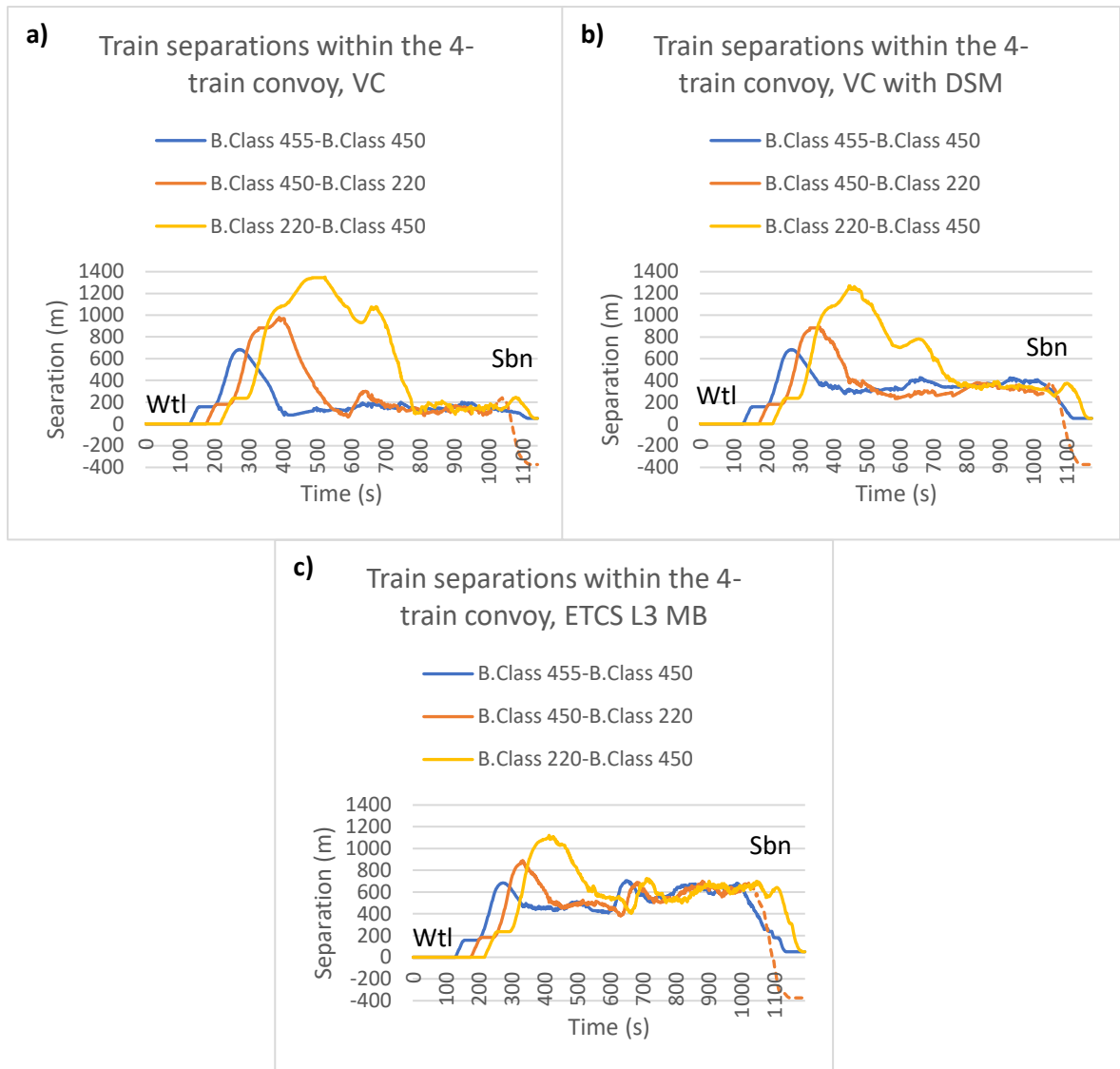


Figure 3 Train separation between trains of the four-train convoy for a) VC, b) VC with a DSM and c) ETCS L3 MB

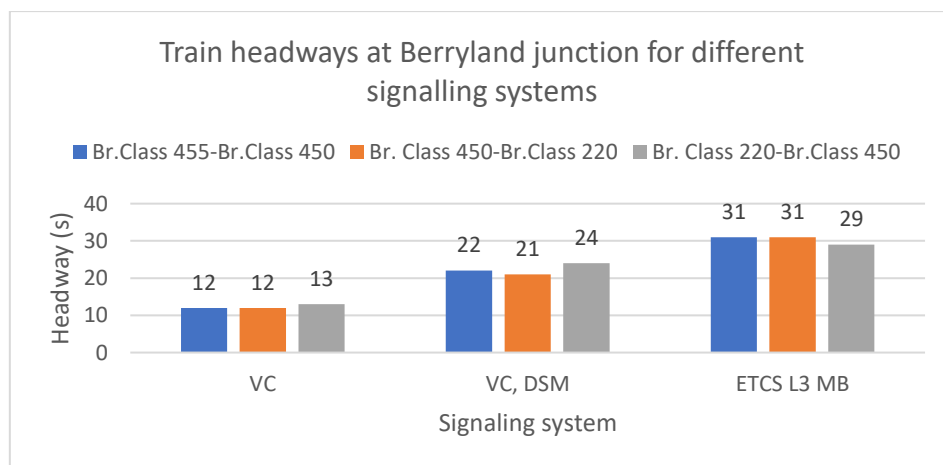


Figure 4 Train headways at Berryland junction for different signalling systems

Conclusions & Recommendations

In this research, a safety distance model for VC operations has been developed, considering varied acceleration and braking capabilities of trains, V2V update delays, train control delay times and varied positioning errors of the odometry system. Through an OAT sensitivity analysis, it is found that the braking rate of the following trains has a significant impact on rail line capacity. The model is applied on the South West Main Line in the UK between Waterloo station and Surbiton station. For trains services without stops, the proposed model promises the highest benefits for trains with improved acceleration and braking characteristics, either for homogeneous or heterogeneous train convoys. Significant capacity benefits of the proposed model are identified for services with stops for all train convoy formations that are investigated, while heterogeneous train convoys are shown to have the highest capacity benefits compared to ETCS L3 MB. Although VC considering a DSM shows promising benefits over ETCS L3 MB, if different infrastructure and rolling stock are used, results may be varied. Further research considering different infrastructure characteristics, more rolling stock types, the ETCS emergency braking curve, different V2V communication topologies, control algorithms, additional safety, and energy efficiency aspects, is required to support the research on railway virtual coupling.

Abbreviations

Abd	Absolute braking distance
ATO	Automatic Train Operation
ATP	Automatic Train Protection
CACC	Cooperative Adaptive Cruise Control
CAM	Cooperative Awareness Message
CBTC	Communications-Based Train Control
C-ITS	Cooperative Intelligent Transport Systems
DSM	Dynamic Safety Margin
EGTRAIN	Environment for the desiGn and simulaTion of RAllway Networks
EoA	End of Authority
EoA _{vc}	End of Authority Virtual Coupling
ERTMS	European Rail Traffic Management System
ETCS	European Train Control System
EU	European Union
EVC	European Vital Computer
FRMCS	Future Railway Mobile Communication System
GoA	Grade of Automation
GNSS	Global Navigation Satellite System
GSM-R	Global System for Mobile Radio Communications
IDM	Intelligent Driver Model
L1	Level 1
L2	Level 2
L3	Level 3
MA	Movement Authority
MA _{vc}	Movement Authority Virtual Coupling
MB	Moving Block
MIXIC	Microscopic model for simulation of intelligent cruise control
MSTF	Multi-state train-following model
PTC	Positive Train Control
RBC	Radio Block Centre
Rbd	Relative braking distance
SvL	Supervised Location
TIM	Train Integrity Monitoring
TMS	Traffic Management System
UIC	International Union of Railways
VC	Virtual Coupling
V2V	Vehicle-to-Vehicle

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1 Introduction

Friday January 1st, 2021 was marked as the inauguration of the European year of Rail 2021, an initiative from the European Commission that highlights the benefits of rail as a sustainable, safe, and innovative transport mode (European Commission, 2020). In the context of the European Green Deal, the European Commission encourages both individuals and businesses to support the rail sector.

In the meantime, as the demand for passenger and freight rail transport constantly increases, the capacity of railway networks around the world is getting saturated, especially in peak hours, where trains run every few minutes in busy railway corridors. To serve the future demand, countries around the world are trying to find ways to increase the railway network capacity, with the minimum possible investments in infrastructure. Under this goal, the Shift2Rail Joint Undertaking, initiated by the European Commission, aims to increase the capacity, reliability, punctuality of railway networks, while simultaneously reducing the life-cycle cost of rail transport within the European Union. Next generation signalling systems such as ETCS L3 Moving block (MB) and Virtual Coupling (VC) are included among several areas of research of IP2 of Shift2Rail, being safe train positioning systems (i.e., based on GNSS), next generation communication systems, automatic train operation, train integrity monitoring (Figure 1.1).

Applying innovative signalling technologies is one of the main ways of increasing rail network capacity. ETCS L3 Moving block and Virtual Coupling are next generation signalling systems that have a potential to increase capacity significantly, compared to legacy signalling systems.

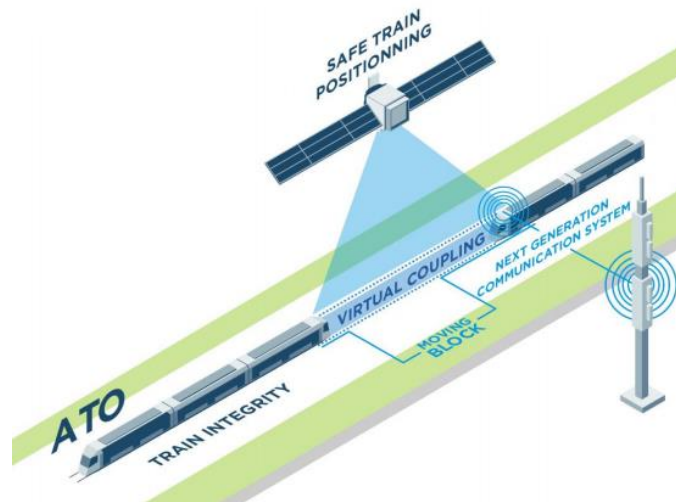


Figure 1.1 Technologies under research in IP2, Shift2Rail (Travaini, 2020)

In ETCS L3 Moving Block headways between successive trains are significantly reduced as movement authorities are issued based on a dynamic moving block that moves along with the train. In Moving block, successive trains are separated by the absolute braking distance which ensures that a following train can come to standstill anytime, supposing the position of the front train is known. Under Virtual coupling, rail capacity can be increased even more, as trains are separated by a relative braking distance, which is observed in road traffic. VC enables the formation of train convoys, in which trains communicate their kinematic parameters to following and leading trains by means of Vehicle-to-Vehicle (V2V) communication, while keeping a safety distance between each other.

1.1 Problem Statement and research questions

Virtual coupling is a promising concept for tackling capacity limits of railway networks. Even though much research has been conducted in car-following models and vehicle platooning in road traffic, train-following models and Virtual Coupling are still in early stages of research due to several challenges, such as:

Principles and technology requirements of virtual coupling related to safety have not been clearly defined and formalized. These concern mainly safety separation distances between trains accounting for dangerous situations. For instance, at diverging junctions, switches need be moved fast for consecutive trains that are virtually coupled. A safe separation distance between consecutive trains should always be provided in safety critical scenarios, i.e., the leading train applies emergency braking while considering heterogeneous characteristics of trains.

Moreover, required technologies that should be utilized to allow safe VC of train sets is not proven or developed enough, mainly concerning the V2V communication layer which is of crucial importance for the transmission of information between trains in a convoy. Factors such as the communication range and the reliability the communication layer, are crucial for fast and reliable kinematic data exchange between trains.

The real capacity gains of Virtual coupling over the existing signalling systems, including stochastics in operations of the railway systems, are not fully analyzed yet. These stochastics refer to heterogeneous train operation, having varied attributes such as acceleration and braking characteristics, lengths, weights, etc.

Considering the high braking distances in rail operation, especially when train run at high speeds, ETCS L3 MB and VC are considered as safety-critical signalling concepts as the train separation distance is reduced significantly. The realization of VC requires reliable Automatic Train Operation (ATO) and V2V communication technologies, where varied communication latencies, system and driving reaction times may have a significant impact on capacity gains, especially under degradation scenarios.

1.1.1 Research objective

The objective of this study is to develop train-following model from a safety perspective by adapting technologies and car-following models to the rail operation and estimate potential capacity gains of Virtual Coupling over ETCS L3 Moving block considering a realistic operational setup. The parameters of the realistic operational setup concern different rolling stock characteristics and uncertain factors such as train control delay times, delays in traffic updates and train positioning errors.

1.1.2 Research questions

In order to reach the objective of this research, the main research question has been formulated as follows:

What are the potential capacity gains of Virtual Coupling over ETCS L3 Moving block in a realistic operational environment where different rolling stock characteristics, operational speeds, driving behavior and uncertain traffic information exist, by adapting driving technologies from the automotive sector?

To answer the main research question, several sub-questions are proposed as follows:

- 1) *To what extent can car-following concepts and technologies in the automotive sector be transferred to the concept of train-following models and Virtual Coupling?*
- 2) *Which rail operation parameters are assumed to have an impact on train-following models?*
- 3) *How can realistic rail operation parameters be integrated in train-following models, ensuring a safety distance between trains?*
- 4) *What is the impact of realistic rail operation parameters on train separation distance?*
- 5) *What is the effect of a V2V communication or ATO degradation in the train separation distance under ETCS L3 MB and VC?*
- 6) *What is the effect of homogenous and heterogeneous trains on the railway corridor capacity under ETCS L3 and MB?*

1.2 Research Scope

The goal of this thesis is to develop of a train-following model which can represent realistic and safe rail operations by considering real-time static and dynamic data interaction between trains that are operated under ETCS L3 Moving block and Virtual

Coupling. In addition, this study aims to identify capacity benefits of next generation signalling systems under realistic operational parameters.

First, it is important to point out differences between the concepts of vehicle platooning in road traffic and Moving Block in railway systems. Following, a question that needs to be answered concerns what kind of technologies are proven for cooperative driving of vehicles in road traffic. These technologies may concern technologies used in Cooperative adaptive Cruise Control (CACC), V2V communications layer, control algorithms, incorporation of different vehicle types in platoons and different driving styles, etc. Looking into the specifications and principles of these technologies and considering the principles of Moving Block and Virtual Coupling, migration of technologies to rail operations can be identified. In addition, car-following models that have been extensively studied in literature for many years, can benefit the development of train-following models, where safe and efficient algorithms for train-following need to be produced.

The parameters that are expected to have an impact on the operation of ETCS L3 Moving block and Virtual coupling, are the V2V communication delay, the train control delay time of the EVC embedded in the locomotive and the varied braking factors of different rolling stock types. Furthermore, the track gradient is assumed to influence the virtual coupling operations of trains.

To ensure a safety distance between trains forming convoys on the run, the EVC of the following train should adjust the train's kinematic behavior considering its own acceleration and braking characteristics but also the kinematic parameters of the leading train. Thus, a direct communication link from V2V should exist, so that the following train receives static and dynamic data of the predecessor train. Then, an additional safety distance should be calculated in real time, which extends the gap between the End of Authority (EoA) and the Supervised location (SvL) from the rear end of the preceding train. In advantage of safety the following train updates the EoA so that there is a safety separation distance that allows the following train to come to a standstill applying service braking in case the leading train applies emergency braking.

Since specifications for VC applications have not yet been determined, it is yet unknown what is the impact of varied V2V communication delay, train control delay, track gradients, braking factors in the separation distance which is translated into headways between trains operating as a virtually coupled train set. A sensitivity analysis through microscopic railway simulation (EGTRAIN) can answer to this question.

In realistic railway operation, a degradation of the V2V communication layer between trains of a convoy may happen. Moreover, train control delay time may be significantly increased if the ATO operation degrades to manual driving. By simulating specific scenarios, the impact of the system degradation cases can be investigated through simulation.

The investigation of VC operations for this study is executed through microscopic simulation in the South West Mainline in the UK, on a route stretch between Waterloo station and Surbiton station. Three train types are used in the simulation experiments, suburban trains (British Class 455), regional trains (British Class 450) and intercity trains

(British Class 220), from the slowest to the fastest. Each train composition is characterized by different attributes, i.e., length, weight, braking factor, tractive-effort speed curves, etc. By different combinations of train types for train convoy formation, different capacity benefits may be identified.

1.2.1 Scientific gap

This study enhances the multi-state train-following model developed in Quaglietta et al. (2020) with a dynamic safety parameter that is incorporated in the model. Therefore, it contributes to developing a safety distance train-following model for VC operations, similar to the safety distance models in car following. The results of the simulation study contribute to the railway operation of homogeneous and heterogeneous rolling stock under ETCS L3 Moving Block and Virtual Coupling ensuring a minimum safety separation between trains. Thus, this study aims to providing additional information to whether VC would be beneficial for future investments or better, where, when and under which conditions VC promises to bring significant capacity gains over moving block signalling.

1.2.2 Societal relevance

Next generation signaling systems such as ETCS L3 Moving block and Virtual coupling are considered as technologies that will bring additional capacity benefits to railway networks without the need of additional infrastructure. That said, the future signaling approaches are contributing on the rail infrastructure as less lineside infrastructure elements are needed. Another aspect of this study relevant to the societal benefit is safety. When a new technology is introduced, it must fulfil all safety requirements before it is deployed in testing. This study contributes to strengthening the multi-state train-following model of Quaglietta et al. (2020) by means of safety and efficiency.

Recently, railway VC is also regarded as a technological concept that promises to reduce crowding at stations, implying less risk of infections during pandemics. Except for improved passenger flows at railway stations, infection risk inside railway carriages is also possible, since many more vehicles are expected to operate under VC compared to the current signalling practices (Cao et al., 2020).

1.3 Thesis outline

The methodology of the research is depicted in Figure 1.2 In Chapter 2 a literature review on car following models and enabling technologies from the automotive domain is conducted. Next, background information on railway signalling and literature relevant to railway Virtual coupling are presented in Chapter 3. Influenced by the automotive sector, while respecting the principles of railway operation, a safety distance train-following model is developed in Chapter 4 based on the multi-state train-following model developed in Quaglietta et al. (2020). In Chapter 5 an One-at-a-time (OAT) sensitivity analysis is conducted through microscopic simulation in the EGTRAIN tool to assess the impact of the varied model parameters on the model output, being the train separation distance, which is then translated in time headways between trains. Afterwards, a comparative capacity analysis for ETCS L3 Moving Block, Virtual coupling and the proposed model incorporating a dynamic safety margin is conducted in Chapter 6. Specific operational scenarios are simulated, concerning homogeneous and

heterogeneous train convoy formations, degraded operations, a multiple heterogeneous train convoy formation as well as an example of incorporating a coasting phase in the speed profile of trains. Based on the simulations results, conclusions for next generation signalling systems are drawn in Chapter 7, which are followed by recommendations for the research community and the rail industry.

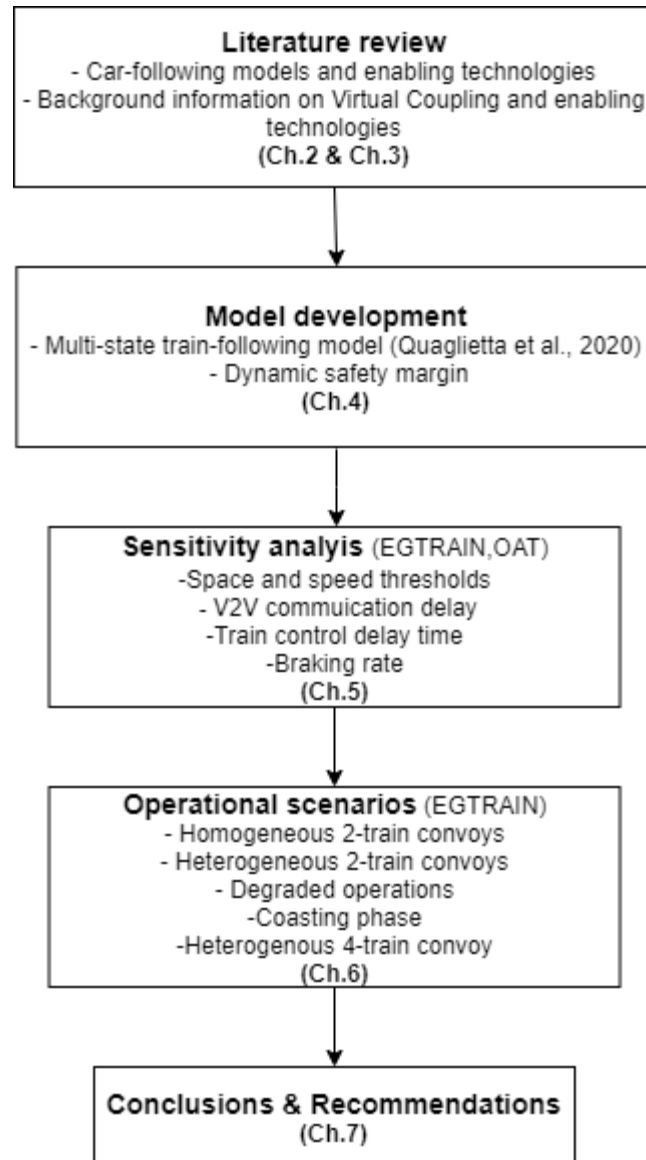


Figure 1.2 Thesis outline

2 Car-following models and enabling technologies

Since the adaptation from the automotive sector for developing new concepts for train-following and next-generation technologies is considered crucial, this chapter presents the results of a literature review on car-following models and enabling technologies.

2.1 Car-following models

Since the 1950's, several car following models have been developed for road traffic, which can be classified in three categories, being the stimulus-response models, the safety-distance or collision avoidance models and the psycho-physical models.

- **Stimulus response models** are based on the principle that there is a basic relationship between a leading and a following vehicle, which is a stimulus-response type of function. An example of these models is the Gazis-Herman-Rothery (GHR) model which states that the follower's acceleration is proportional to the speed of the follower, the speed difference between the follower and the leader, and the space headway (Gazis et al., 1961). More stimulus-response models concern the Helly's model, stating that the acceleration of a vehicle maintains a linear relationship with the deviation from a desired headway and the deviation from the speed of the leader (Helly, 1959). In Optimal Velocity Models (Bando et al., 1995), drivers select their velocity based on the relative velocity with the leading vehicle.
- **Safety-distance models** are developed based on the principle that the follower always keeps a safe distance from the leader to avoid a possible collision (Olstam et al., 2004). One of the mostly used safety-distance car following model is the Gipp's model

(Gipps, 1981), which assumes that the driver of the following vehicle selects a certain speed so that he could stop even if the leader vehicle suddenly comes to a halt avoiding collision. Gipp's model is an extensively used safety distance car-following model where the acceleration of the following vehicle depends on the speed and position of the vehicle itself and the front vehicle, the driving reaction time and estimation of the front vehicle's deceleration rate. In this model, the separation distance between the vehicles is constrained by a safety margin, which consists of the vehicle length plus a margin that the following vehicle is not allowed to violate, even in standstill conditions.

- **Psycho-physical models**, like the one developed by Wiedemann and Reiter (1992) and Fritzsche (1994), use thresholds according to which drivers change their behavior and react to changes in spacing or relative speed (Olstam et al., 2004).

Except for those three basic categories, there are more advanced **strategy-based models** such as the Intelligent Driver Model (Treiber et al., 2000), where drivers choose the acceleration or braking strategy according to the headways with the leading vehicle. Car-following models have also been developed to model traffic for **intelligent vehicles**. These models can optimize the vehicle's own behavior or the behavior of a whole group of connected vehicles. For car following models of intelligent vehicles such as CACC and CAV's the most widely used models are the IDM and its extensions and other models such as the Microscopic model for simulation of intelligent cruise control (MIXIC) developed by van Arem et al. (2006). The difference between the IDM and the MIXIC model is that the MIXIC assumes V2V communication which enables the exchange of acceleration, speed and differences in braking capabilities between vehicles for the safety separation distance determination.

2.1.1 Vehicle characteristics in car-following models

Different vehicles can have different attributes such as braking or acceleration capabilities. This difference has been incorporated in car following models for the development of CACC systems. In van Arem et al. (2006), the difference of vehicle braking factors is considered for the calculation of the safety separation distance between vehicles. Amoozadeh et al. (2015) developed a platoon management protocol based on Vehicular Ad-hoc network (VANET) and vehicles with CACC, where the CACC car following models is based on one vehicle look ahead communication. Wang et al. (2017) developed a consensus-based algorithm for CACC, based on predecessor follower strategy to describe the forming, merging, and splitting of vehicles in a platoon. Aiming to produce a realistic model, the algorithm is tested for a platoon of four different vehicles, which have different attributes such as braking characteristics, lengths, etc. In Naus et al. (2010), four different vehicles (2 sedans, 1 SUV and 1 truck) with different parameters such as speeds, braking factors, antenna placements are utilized in different scenarios to investigate the convergence of the CACC system. The vehicles drive on the same lane while at some time point, they switch to platooning mode. Aiming to measure the consensus of vehicle's absolute positions, the weighted desired intervehicle distances are used instead of time gaps, where the weighted desired intervehicle distances are calculated by multiplying the braking factor with the desired intervehicle distance being the same for all types of predecessor-follower pair.

2.1.2 V2V communication in car-following models

Vehicular communications are a highly complex issue which by itself comprises a wide research area and it can be extensively analyzed. Since the efficiency and reliability of cooperative driving systems depend on messages broadcasting between vehicles, car-following models include the impact of these delays in the mathematical equations of the vehicles' kinematic data, being the position, speed, and the acceleration. Aiming to assess the impact of V2V communication latencies, several studies use different approaches, either assuming the communication delay as a fixed value (i.e., the mean value of a distribution), or as a stochastic variable that is changed within a known range. Generally, in V2X communications, there is a transmission delay in the range of 0.1 s - 0.4 s due to intermittencies and packet drops (Song et al., 2019). In Chen et al. (2018), a Min-Max model predictive control algorithm is developed, considering fixed feedback delay and stochastic actuator lag. The feedback delay, which generally lies between 0.1 s and 0.3 s is considered as 0.2 s, while the actuator lag is varied stochastically between a design range (0.2 s - 0.8 s) but also between an out-of-design range performance (0.8 s - 0.9 s).

2.1.3 Incorporating human factors in car-following models

The incorporation of human factors in car-following models has been extensively studied in the literature (Saifuzzaman et al., 2014). Mathematically, the human factors can be included in car-following models according to (2.1) (Van Lint et al., 2018):

$$a_i(t + \tau_i(t)) = f(S_i(t), \theta_i(t), \omega_i(t)) \quad (2.1)$$

, where $a_i(t)$ denotes the acceleration, $\tau_i(t)$ the reaction time, $S_i(t)$ a set of stimuli such as speeds, speed differences, distance gaps, $\theta_i(t)$ driver preferences and $\omega_i(t)$ a set of characteristics of the environment for driver i and t denotes time.

Generally, there are two approaches for incorporating human factors (perception and response) in car-following models, the exogenous approach, and the endogenous approach. In the exogenous approach, the human factors as deterministic parameters, which have fixed or mean values or drawn from a known distribution. Hoogendoorn & Bovy, (2001) indicate that the delay from the occurrence of an unexpected event to a remedial action lies in the range of 0.6 s - 1.5 s, according to field studies. In endogenous approaches, human factors are modelled by functions or algorithms that explain dynamics in reaction time, response parameters and inter-driver differences. In addition, to consider, the driving performance, driving task demand and capacity are used. That said, when there is a driving task saturation, the performance of drivers can deteriorate leading to higher reaction times and larger perception errors. Saifuzzaman et al. (2015) incorporate human factors in car-following models by introducing the Task Capability Interface model, where there is a dynamic interaction between the task demand and the task capacity of each drivers. The model is applied to two popular CF models, namely the Gipp's and the IDM.

2.2 Enabling technologies for C-ITS

Railway Virtual Coupling can be considered as strictly related to cooperative driving, since trains running in a convoy, share information with their predecessor and follower trains but also with the infrastructure (Felez et al., 2019). Since the current study focuses both on train-following models and the applicability of road driving technologies to the

railway moving block and virtual coupling, it is important to focus on the Cooperative Intelligent Traffic Systems (C-ITS). C-ITS refers to “transport systems, where the cooperation between two or more ITS sub-systems (personal, vehicle, roadside and central) enable and provides an ITS service that offers better quality and an enhanced service level, compared to the same ITS service provided by only one of the ITS sub-systems” (Car-2-Car consortium, 2020). Three main use case services are offered by the C-ITS, being the following:

- Awareness driving
- Sensing driving
- Cooperative driving

Awareness driving services includes several warnings that the drivers cannot see or foresee such as intersection collision warning, emergency vehicle warning, dangerous situation warning, stationary vehicle warning, traffic jam warning, pre/post cast warning. In the same logic, sensing driving services filter information from sensors and offer warnings or other protective services for situations that the drivers are not able to perceive. Sensing driving encompass services like overtaking warning, extended intersections collision warning, vulnerable road user warning, cooperative adaptive cruise control (CACC), etc. Regarding cooperative driving, cooperative road users are interacting in complex traffic situations, so that services such as platooning, cooperative merging, lane changing, and overtaking are possible. Among these three main sub-categories that concern C-ITS, sensing and cooperative driving and more specifically **CACC**, **cooperative merging** and **platooning** are assumed to be able to provide railways with insights related to virtual coupling scenarios. CACC is an evolution of cruise control (CC) technology. Cruise control, which aims at maintaining the driver's desired speed, is a proven technology embedded in the automotive for many years now. Adaptive cruise control (ACC), the evolution of CC, adjusts the vehicle's acceleration based on the separation distance and the speed difference with the preceding vehicle. Under ACC, the following vehicle uses sensors to detect the motion characteristics of the leading vehicle. The Cooperative Cruise Control (CACC), extends the ACC technology by adding a V2V communication layer between vehicles, which allow them to exchange their kinematic characteristics such as the acceleration, deceleration, the braking capability, etc. Under CACC, the required minimum safety distance which is used in ACC is no longer required, thus the headways can be further reduced. It could be argued that ACC is based on safety distance car-following models while more advanced technologies such as CACC and CAV are based on more intelligent, strategy-based models such as the IDM or extensions of it.

CACC system architectures

CACC systems have been tested in real traffic situations (Milanes et al., 2013). A typical CACC system architecture is depicted in Figure 2.1, which comprises of five subsystem modules, being the communication, the planning, the perception, the control, and the localization module. Each module of the CACC system, utilizes specific hardware and software (Wang Z. et al., 2019).

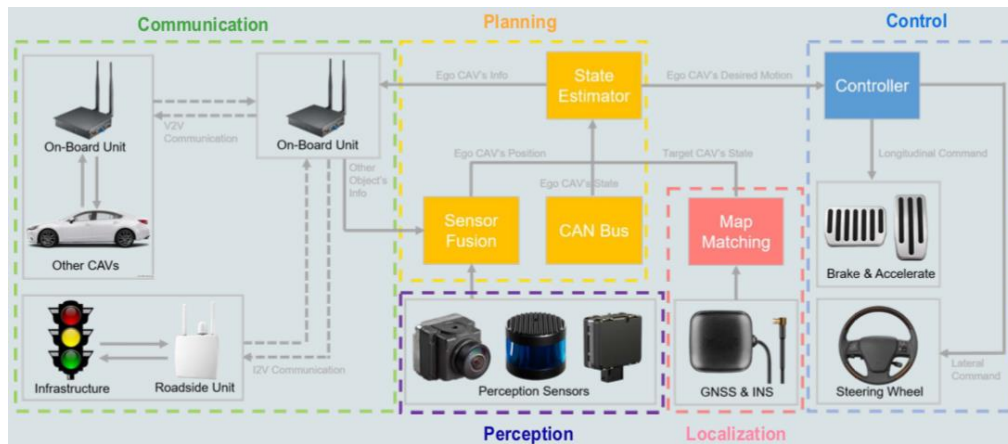


Figure 2.1 CACC system architecture (Wang Z. et al., 2019)

Control strategy

A longitudinal vehicle control strategy is necessary for vehicles to achieve and maintain the same speed with the rest vehicles in CACC systems, while maintaining a constant longitudinal inter-vehicle distance or time headway. Based on the available literature, the most common control strategies are the model predictive control (MPC), the consensus control, the optimal control and the string stability. Model predictive control refers to a group of control algorithms that use a process to predict the future state of a system. Usually, model predictive controls are structured on a basis of linear discrete time models. Optimal control is usually based on an optimization problem which tries to minimize energy consumption or the travel time. String stability strategy is considered as of high importance for the safety of CACC systems and its objective is to reduce the position, speed, and acceleration errors (Wang Z. et al., 2018). Regarding the considering inter-vehicle distance within platoons, there are two basic strategies used in the literature, namely the *constant time gap policy* and the *constant spacing policy*. In control algorithms, car-following models are used to mimic the following behavior vehicles. In typical CACC systems, each vehicle includes a two-layer controller, where the upper controller calculates the desired acceleration to maintain the string stability, while the lower controller is responsible for the actuation of the throttle and braking input to satisfy the desired acceleration (Nardini et al., 2018).

2.2.1 Enabling technologies for V2V in connected vehicles

In V2V communications the basic key feature is the cooperative awareness message (CAM), by which vehicles broadcast their kinematic data and attributes to their neighbor vehicles. CAM's are generated in a high frequency of 1-10 Hz. Moreover, the V2V communication is based on an information flow topology, which describes the information transmission exchange among the several vehicles in the CACC system. Some of the most common topologies developed in the literature are presented in Figure 2.2, being the predecessor-following, predecessor-leader following, two predecessor-following, two-predecessor-leader following and bidirectional.

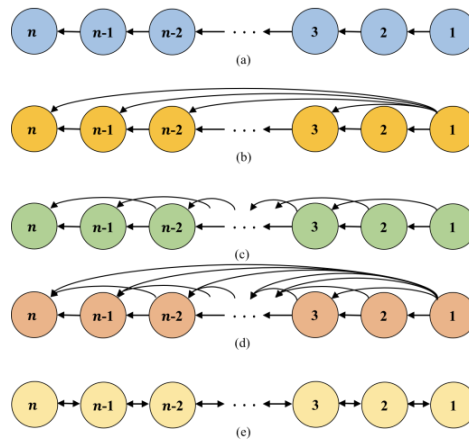


Figure 2.2 Typical information flow topologies: (a) predecessor-following, (b) predecessor-leader following, (c) two predecessor-following, (d) two predecessor-leader following, and (e) bidirectional (Wang Z. et al. 2018)

V2V communication technologies

Currently there are two main technologies developed for V2V communications, being systems based on the IEEE 802.11p and the cellular V2V technologies. Except for these, there are a few more, such as visible light communication (VLC) or the Millimeter Wave that could also be implemented or have a complementary role to the two basic technologies.

IEEE 802.11p

The IEEE 802.11p is a mature and reliable communication technology which was standardized by the IEEE in 2009 and it is widely used in platooning experiments. It is based on a fully distributed medium access protocol and its 70MHz band is divided in 7 channels of 10MHz each, where one channel is the control channel, and the rest are used as service channels. Fast V2V communication is enabled by the medium access control level (MAC), while the IEEE 802.11p also includes collision avoidance services. However, the reliability is affected in heavy traffic conditions due to increased channel use, causing collisions. Wang Z. et al. (2019) identify the dedicated short-range communications (DSRC) as the most promising technology for V2V communications are, which is the enabling technology for the USA based on the IEEE 802.11p standard, operating in the frequency band of 5.9GHz (75MHz of the spectrum). The corresponding technology for Europe is called ITS-G5 operating in the spectrum of 30MHz of the 5.9 GHz frequency band.

Long Term Evolution (LTE)/ 4G

LTE was standardized in 2017 and allows direct communication between devices when in proximity. LTE-Direct was the first step, being supported by the 3GPP LTE advanced release 12, which allowed for the first time in history direct communication between peers, using the cellular network. With the 3GPP release 14, short range V2V communication was added to the LTE. Due to its high diffusion and low latency LTE-V2V can supplement the mature DSRC/ ITS-G5 for safety applications and traffic management, while also pave the way towards the next generation technologies, such as 5G (Masini et al., 2017).

Next Generation (NG)/ 5G

The successor technology of LTE, the 5G, is expected to reduce end-to-end delay to 1 ms and increase packet delivery ratio to 99.999%, while providing 100 times higher capacity and data rates than the 4G (Rashdan et al., 2016). According to the 5GPP METIS project, 5G general requirements for safe applications include end-to-end latency of 5 ms, beacon periodicity of 10Hz, reliability of 99.9999%, communication range up to 1km and position accuracy of less than 0.5 m. Masini et al. (2017) indicate that the future standard of vehicular communications will consist of a combination of ITS-G5 and 5G, where the first technology would allow wireless access signaling and the second data transmission and service provisioning.

2.2.2 Positioning technologies and perception sensors

For vehicle positioning in road traffic, the most common technology for determining the absolute position of the vehicle is the GNSS systems (i.e., GPS, Galileo, GLONAS) or advanced GNSS systems that provide higher accuracy such as the Differential GPS or the Real-Time Kinematic GPS. Except for GNSS, mobile positioning systems, artificial landmarks and maps are utilized for absolute vehicle positioning. Regarding the relative positioning methods, vehicles use dead reckoning methods (i.e., wheel odometry, inertial navigation or Doppler radar) and visual-based methods (i.e., visual odometry).

Several sensors are used in the automotive for sensing the surrounding environment of the vehicle such as RADARs, LiDARs and several types of visual cameras (i.e., monocular cameras, stereo cameras, omnidirectional, infrared cameras, etc.). Since each sensor shows different benefits and drawbacks, data fusion by multiple technologies is used to result in accurate and reliable outcomes. For instance, aiming to define the accurate position of vehicles, GNSS systems are exploited, in cooperation with dead reckoning methods and visual based methods (ASTRail, 2019).

3

Railway signalling and literature review on virtual coupling

In railway operations, the movement of vehicles is stricter compared to the automotive, since there is a standard or seasonal timetable, and the traffic management lies in the responsibility of the infrastructure manager. Based on the strategy that the rail traffic is operated today, where the route, the departure time are known advance, it is assumed that the track sections where train convoy formation could be applied could be more easily predefined compared to the stochastic platoon formation of vehicles in road traffic. Recently, research on the automotive sector has been inspiring for the railway sector, since researchers are adapting car-following models, control algorithms for VC operations and even traffic flow theory to analyze rail operation.

Since there are big differences in traffic management between the road traffic sector and the railway sector, basic principles of the signalling, systems, the train control, the braking behavior, the railway communication systems are presented in this chapter. Table 3.1 shows the main differences identified between car following on highways and mainline railway operations, which are categorized based on the vehicles' characteristics, human and operational characteristics.

Table 3.1 Differences between car following on highways and train-following for mainline railway operations

Vehicle characteristics	Car following (highways)	Train following (mainline)
Heterogeneity	High heterogeneity between vehicles	Lower heterogeneity compared to road traffic
Braking distances	Relatively low braking distances due to high friction, usually lower than the sight distance (normal braking rate ca. -4 m/s^2 , emergency braking rate ca. -10 m/s^2)	Significantly higher braking distances due to low friction between rail and wheel especially for high speeds, can be higher than the sight distance (normal braking rate ca. $0.5\text{--}1.0 \text{ m/s}^2$, emergency braking rate ca. -1.2 to -1.5 m/s^2)
Acceleration behavior	Tractive-effort speed curve (maximum acceleration 3 m/s^2)	Tractive-effort speed curve (consisted of more parabolas than in the automotive, maximum acceleration ca. 1.0 m/s^2)
Mechanical delay (for braking/acceleration actions)	Low actuation delays (ca. 0.5 s)	Higher actuation delays (up to 3.5 s for emergency braking application)
Vehicle size	Relatively short lengths, varying per vehicle type (i.e., car, trucks, up to ca 20 m), relatively small weight and mass	Relatively long lengths (i.e., up to ca 700 m for freight trains), large weight and mass
Infrastructure characteristics		
Infrastructure size	Multiple lanes on highways, vehicles can change lanes freely by steering	Vehicle motion on dedicated track (no steering) switches need to be moved before trains can change tracks
Track gradient and curvature	Relatively high gradient and curvature, impact of sags on capacity especially for heavy vehicles	Relatively low track gradient and curvature, high impact of track gradient and curvature on train motion
Human factors		
Human interactions	Humans only as drivers, or intervene in case of special situations (disruptions)	Except for train drivers, humans control the switches and crossings, provide MA's, and manage disruptions
Human driving reaction times	Low reaction times (i.e., 1.2 s)	Higher reaction times (i.e., 3 s on open track)
Operational characteristics		
Movement authority (MA)	No movement authority is provided	MA is important in rail operation, which is provided by the trackside operations center (RBC).
Stopping	Vehicles do not stop on highways; they enter or exit the highway through ramps	Trains need to stop at stations, which impose bottlenecks sometimes depending on the available tracks
Separation distances	Relatively small separation distances, use of relative braking distance	Relatively high separation distances in advantage of safety

3.1 Block signalling

Nowadays, mainline rail operations are realized by fixed block signaling. In traditional fixed block signalling, the railway track is divided into separate physical blocks. The minimum headway between two successive trains (Figure 3.1) is given by the summation of several distances being: the distance over the time to setup the route and clear the signal, the sight distance to approach the signal, the approach distance to the main signal, the block length, the clearing distance over train length and overlap and the distance overtime to release the block (Goverde, 2019).

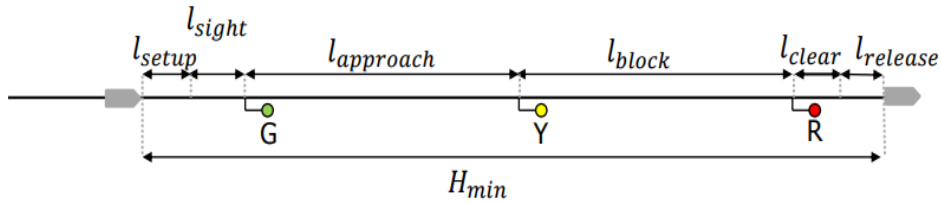


Figure 3.1 Minimum headways under fixed block signalling (Goverde, 2019)

In Moving block signalling the track is not divided in physical blocks, but each train is characterized by its safe zone (moving block) which is defined in real time. Basic requirement for this signalling approach is the knowledge of the exact location and speed of all trains and a continuous and reliable communication between the trains and the trackside signalling center. By moving block, the separation distances between successive trains can be decreased significantly, which leads to lower minimum headways compared to the fixed block signalling. While moving block signalling is widely used in Communications Based Train Control (CBTC), for instance in metro operation, for mainline railway operation moving block signalling is under development as there are still various technological and safety challenges.

In moving block, the minimum line headways are highly reduced as the EoA shifts to a moving point (i.e., the rear end of the front train) assuming a reliable Train Integrity Monitoring (TIM), compared to the fixed points that are considered to determine the EoA in traditional fixed block signalling (X2Rail-3, 2019).

3.2 European Train Control System (ETCS)

The European Railway Traffic Management System (ERTMS) consists of two main subsystems, the European Train Control System (ETCS), which is the signaling and control component of the system, ensuring safe train operation. The second main subsystem is the GSM-R, which is responsible for all the communications between the trains and the infrastructure. The ETCS has three main levels of implementation (Appendix A). In ETCS Level 0, a vehicle equipped with ETCS is moving in an area that is not equipped with trackside ETCS. ETCS L1 is a cab signalling system that can exist over the national signalling systems. In ETCS L1 the trackside signals are necessary and the MA are transmitted to the vehicles via transponders, called balises. After receiving the MA, the EVC can compute the maximum speed as well as the braking curves. Additional to balises a loop infill or a radio infill can be applied to ensure data exchange over longer distances. In ETCS L2, the lineside signaling is redundant and signalling shifts only to cab signalling. ETCS L2 is based on a continuous bidirectional data

exchange between the vehicles and the trackside by Euroradio (GSM-R). Thus, MA transmitted by the RBC is displayed in the driving cabin. In ETCS L3, the track side train detection and the line side signals are replaced by the EVC and the TIM. Trains communicate with the Radio Block center (RBC) by GSM-R to report their position and the RBC transmits the movement authority (MA) to the train, which is located at a safety margin from a supervised location which may be the tail of a front train or another point such as a switch. While ETCS L2 is currently used in several railway corridors in the EU, ETCS L3 is under development. Challenges of ERTMS L3 concern mainly the absence of a reliable TIM system for variable train compositions and train types, the accuracy of the train positioning and safety issues regarding communication losses. For the realization of ETCS L3, four main types of ERTMS L3 that are being developed, namely the ERTMS L3 overlay, the ERTMS L3 hybrid, the ERTMS L3 virtual block and the ERTMS L3 moving block. The ETCS L3 hybrid, being the most advanced one and the lowest risky solution to be applied, supports both trains with and without train integrity monitoring, while train detection is still required (Furness et al., 2017). ETCS L3 MB is the version of ETCS L3 that promises the highest capacity benefit requiring a reliable TIM for all trains while train detection is not vital. For the calculation of minimum headways between successive trains under ETCS L3, the absolute braking distance (Abd) is considered, which is defined as the distance required for the successive train to come to a standstill from its current speed (Theeg & Vlasenko, 2009).

3.2.1 Braking under ETCS

ETCS uses braking curves to assist the train drivers to brake efficiently and in time. The system computes continuously the prediction of the braking distance based on the rolling stock and track characteristics. The main and the most critical braking curve is the emergency braking curve corresponds to the worst case of full brake application so that the trains stop at the movement authority, while more supervision limit points are indicated by the system so that the train driver has enough time to react before the emergency braking is applied (Figure 3.2). These supervision limit points consist of the indication point (I), the permitted speed point (P), the warning limit (W), the service brake intervention point (SBI) and the emergency brake intervention point (EBI), after which the ETCS bypasses the human intervention (European Railway Agency, 2016).

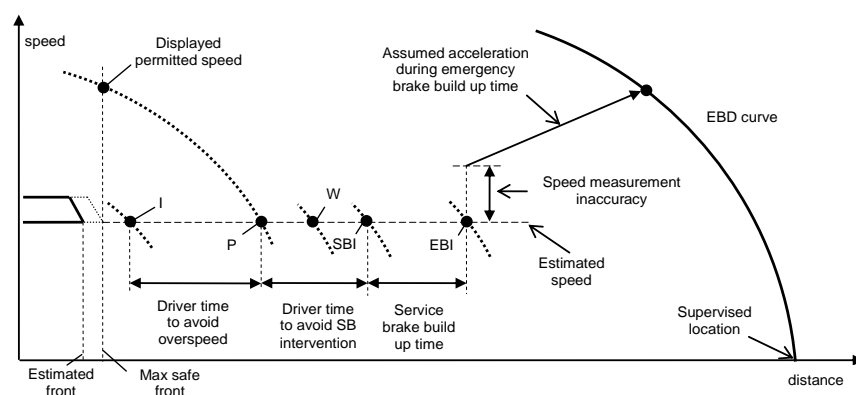


Figure 3.2 Overview of the EBD curve and the relative supervision limits (ERA, 2016)

The EBD curve, which is the most crucial braking curve from a safety perspective is computed based on the deceleration due to the emergency brake system of the rolling stock and the deceleration due to the gradient of the track as in Figure 3.3.

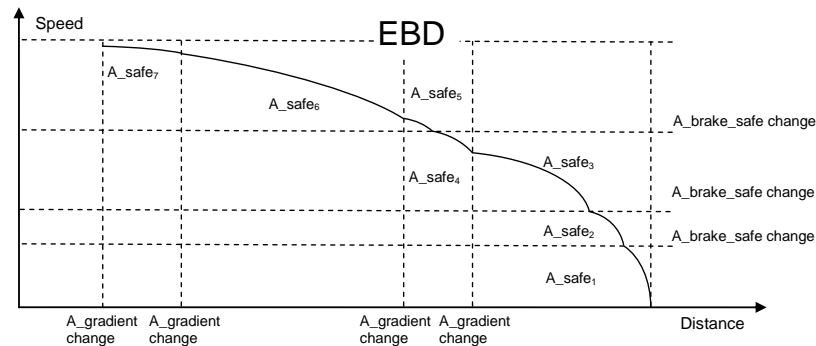






Figure 3.3 EBD computation (ERA,2016)

3.2.2 Automatic Train Operation (ATO) over ETCS

From a safety perspective, Virtual Coupling requires optimized train operation under ATO, since variations in manual driving behavior are assumed to bring critical safe situations since trains are separated by a relative braking distance. ATO replaces several functions that were previously operated by the human drivers. As in automated vehicles, there are different grades of automation (GoA), which vary depending on the tasks that the computer system of the ATO is responsible to undertake. As depicted in Figure 3.4, GoA 1 is related to human driving under Automatic Train Protection (ATP), where the driver is responsible for every operation. In GoA 2 or semi-automated train the movement of the train is controlled by the ATO and the ATP, while the driver is still present for controlling the doors and the train operation in case of disruptions. In GoA 3 or driverless train operation, the driver is substituted by a member of the operations staff, who controls the door closing operation, where in GoA 4 or unattended train operation, all functions are operated by the ATO system and no on-board staff is required. While ATO of GoA 4 is used for many years in several metro systems around the world, ATO in mainline networks is still in testing phase due to complexity in railway operation. Recently, several test of ATO GoA 2 have been successfully conducted by railway undertakings in the Netherlands and in several other countries such as Switzerland and Germany (Nicholson, 2010). Regarding ATO over ETCS L3 Moving block or Virtual coupling, it is assumed that the first trials of these advanced signaling systems will be implemented together with ATO GoA 2, before proceeding to higher automation levels.

Grade of Automation	Type of train operation	Setting train in motion	Stopping train	Door closure	Operation in event of Disruption
GoA 1 	ATP with driver	Driver	Driver	Driver	Driver
GoA 2 	ATP and ATO with driver	Automatic	Automatic	Driver	Driver
GoA 3 	Driverless	Automatic	Automatic	Train attendant	Train attendant
GoA 4 	UTO	Automatic	Automatic	Automatic	Automatic

ATP - Automatic Train Protection ATO - Automatic Train Operation

Figure 3.4 Grades of automation of ATO (Nicholson, 2010)

3.2.3 GSM-R and future communication systems for ERTMS

GSM-R is the communication system of ERTMS which ensures the required data transmission for the ETCS. GSM-R is a cellular communication system, based on the Global system for mobile communication, which was adopted in 1990's as the dedicated technology for railway communications of the ERTMS. GSM-R is a very reliable communication system for speeds up to 500km/h and the GSM-R stations are placed at distances in the range of 7-15 km. Although it has high reliability, GSM-R is characterized by inefficiency, inflexibility and limited transmission capacity which make it obsolete for future railway operations. According to Le et al. (2015), even though the GSM-R has high reliability and communication range due to its distributed stations, latencies of 200-500 ms make it insufficient for time critical applications like dynamic virtual coupling.

Future railway mobile communication system (FRMCS) was initiated by the UIC to set requirements specification for the successor for GSM-R. For the FRMCS there are several candidate communication systems such as the Terrestrial Trunked radio (TETRA), the General packet Radio Service, (GPRS), the Universal Mobile Telecommunication System (UTMS), the Worldwide Interoperability for Microwave Access (WiMAX) based on the 802.16 standard and the Long-Term Evolution (LTE), developed by the Third Generation Partnership project (3GPP). Among the several candidate technologies, LTE is recognized as the most probable to replace GSM-R, since it is an indirect successor of GSM-R, offering high transmission capacity and low latency. In addition, LTE can be gradually deployed while GSM-R is still in use, it can pave the way towards next generation technologies such as 5G.

3.2.4 Train positioning and perception technologies for ERTMS

In ERTMS, the main components for train positioning system are the onboard odometer system, and the balises that act as fixed geographical reference points for the re-calibration of the vehicle's position (Quaglietta et al., 2020). Unlike the automotive sector, GNSS are not utilized in the ERTMS, however GNSS is used in the Positive train control (PTC) signaling system but also in other applications such as train collision avoidance systems (RCAS). Generally, much research is undergoing regarding the utilization of GNSS in the railway sector.

With respect to ATO functions requirements, a weighted sum model method is developed by the project ASTRail, 2019 to assess the migration of technologies from

the automotive to the railway field. The most suitable technology for vehicle positioning for ATO would be based on artificial landmarks, for providing the absolute train position but also for calibrating the odometry. GNSS systems could provide an accurate positioning solution, but the fact that there is an uncertainty of a few meters, this causes problems in the determination of the track that the train is running on. Also, in low visibility areas such as station or tunnels, train positioning cannot be provided accurately. For fixed obstacle detection, the technology that is already mature and used in the automotive and other transport sectors, is the RADAR, which can operate in long ranges. However, a specific RADAR for the railway systems should be developed in order to satisfy the corresponding railway requirement (i.e., range). LiDAR is another technology that is considered to play a role in obstacle detection since it has a very high accuracy. However, it is yet not as mature as the RADAR while high cost and requires much maintenance. In general, RADAR may be used for long range detection, LiDAR for mid-range detection, supported by stereo and omnidirectional cameras for more specific recognition (ASTRail, 2019).

3.3 V2V communication technologies for railway operations

Among the available technologies on V2V communications, the most prominent for ETCS L3 moving block and VC applications are the TETRA, the IEEE 802.11p, the cellular technologies (LTE-4G/ NR-5G) and the Millimeter Wavelength (Parise et al., 2019).

Terrestrial Trunked Radio (TETRA)

The Terrestrial Trunked radio is a European standard for radio communications in several domains such as the railway operation, military, emergency services, etc. TETRA is characterized by good performance at high relative speeds and multipath environments, while its communication range is also high, being 3 km for urban and 20 km for rural areas. However, the relatively large communication delay (4-12 s), makes it insufficient for time-critical operation like virtual coupling and moving block. Nevertheless, it could still be used for non-time-critical train operation, for instance to manage different train convoys separated by long distances, to achieve higher line capacity.

Technologies based on IEEE 802.11p

The potential usage of ITS-G5 in railway environments is slightly studied in the literature. Unterhuber et al. (2017) test and evaluate the use of ITS-G5 for V2V communication between high-speed railway vehicles in a railway high speed line between Naples and Rome. According to the measurements, ITS-G5 is suitable for medium range communication for electronic coupling applications, where medium range is considered as up to 2 km's distance between the vehicles. However, the performance of the technology for short range communications up to several hundred meters was not evaluated. The ITS-G5, as discussed in the previous chapter on vehicular communication technologies in the automotive sector, is a strong candidate technology for V2V communications in railway operation since it can ensure very low end-to-end delays. Le et al. (2015) identify the main challenge of the use of the ITS-G5 technology for communication in virtual coupling applications, as the fact that the channel should be shared between car-to-car communications and train-to-train communications.

Therefore, the performance of the communication technology would be dependent on the vehicle density on the road parallel to the railway track. To improve the performance of the communication layer between trains, the authors propose an increase on the train-to-train transmission power, a reduction on the packet length and the use of directional antennas that can reduce the interference from the road systems and increase the received signal power at the train receivers. Through a simulation study where several scenarios are tested, the effect of the transmit power and the antenna type is investigated. Based on the results, the higher the transmit power for train-to-train communications and the use of directional antennas leads to lower end-to-end delays.

Cellular technologies (LTE, NR-5G)

Cellular technologies can bring lower delays of up to 20 ms compared to the GSM-R, which is higher than the ITS-G5. Moreover, LTE might perform worse in terms of update delay in congested situations, where the ITS-G5 achieves lower correlation errors at distances higher than 100 m, important for moving block and virtual coupling operations. However, this technology could be effectively utilized at stations and rail yards.

Millimeter Wavelength

Millimeter Wavelength technology shows lower communication range than ITS-G5, but it could achieve fast data transmission in low distances, functioning as an additional communication technology (Parise et al., 2019).

3.4 Human driving factors in railway operations

In fixed block signaling systems, blocking time theory considers sight and reaction time before the signal approach (Goverde et al., 2013). In next generation signaling, physical blocks are absent, along with lineside signals. The driving task is limited in the driving cabin, where the train driver interacts with the DMI. The driving reaction time under degraded operations can be subject to several factors such as the familiarity of the route, the fatigue level, the driver's expertise, etc. The mean driving reaction time varies between 4 and 8 seconds for different driving block sections under automatic speed control. Under manually driven operation, the corresponding driving reaction time lies between 3 and 4 seconds (Brandenburger & Jipp, 2017). In Moving block and Virtual coupling operations under ATO GoA 2, the utility of train driver switches from active to passive, since the task of the driver is to observe and intervene if needed. Brandenburger et al. (2019) highlight that the fatigue levels may be increased with driving time under GoA 2, thus limited capacity gains and human factor related challenges may shift the favorability of ATO grade towards GoA 3, where no train driver is present.

3.5 Virtual Coupling

Under reliable V2V communications, accurate and reliable train positioning and smart perception sensors, railway **Virtual Coupling** (VC) is an emerging signalling concept that promises significant capacity gains in railway capacity, but also benefits in flexibility and robustness (X2RAIL-3, 2020). VC has been studied by several researchers and it has been also mentioned as "*ERTMS L4*", "*hit soft wall*" or "*closer running*". Park et al. (2020) define VC as a system that enables multiple trains to merge to a single train on the move

or a single train to be separated into multiple smaller trains, with the separation distance between the consists being smaller than those allowed by fixed block signaling. Virtual coupling is a concept in which two successive trains are separated by a relative braking distance, like the one that is used in road traffic (Quaglietta, 2019). According to Ling et al. (2019), VC is a new train operation control mode, which can realize cooperative operation of multiple trains at extremely small intervals through wireless communication without physical connection.

Train separation under VC is based on the so-called relative braking distance (Rbd). Ning, 1998 defines the relative braking distance as the distance required considering the speed, position, and braking capacity of the front train. Thus, the absolute braking distance is a case of the relative braking distance, in which the speed of the front train is 0. The author also indicates the case when the front train applies emergency braking (Figure 3.5), under which the following train is separated by a distance ($P'-P_0'$), being the summation of a safe protection distance (in case the following train applies service braking) and an additional margin to account for the speed fluctuations of the leading train.

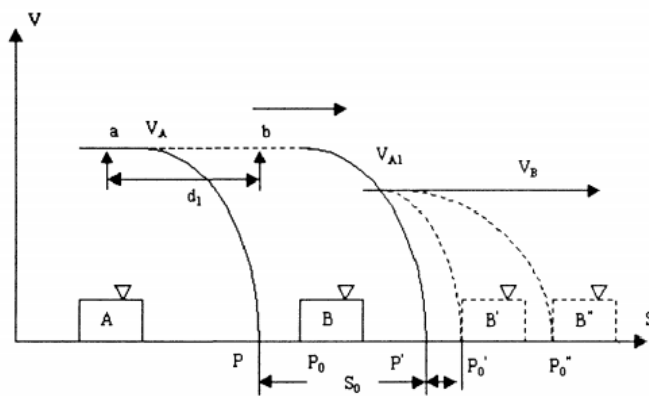


Figure 3.5 Relative braking distance (Ning,1998)

The relative braking distance is described by Aoun et al. (2020) as the distance required by a train to come to a standstill by considering the braking characteristics of the train ahead. In Quaglietta (2019) the RBD is described as the braking distance required by the following train to slow down to the speed of the leading train. In Yan et al. (2012) a distinction is defined between two moving block operation modes, the “hit hard wall”, which considers the absolute braking distance for the following train and the “hit soft wall” mode, where the braking distance of the front train is considered as the emergency braking distance, while the following train applies service braking.

3.5.1 Modelling train-following under Virtual Coupling

Virtual Coupling was introduced by Bock (1999) for freight rail operations. Since then, several researchers have studied the modelling of VC based on various methodologies. To model moving block operations in urban rail systems based on cellular automata, Yan et al. (2012) introduce the “hit soft wall” concept, where the minimum separation distance depends on the service braking effort of the following train and the emergency

braking effort of the leading train. However, the study is limited since the impact of the communication delay and the reaction time is neglected. Pan et al. (2014) develop a dynamic control of high-speed train operation where the safety separation distance is changed dynamically based on the velocities of the preceding and the following train. In contrast to the movement authority that ensures safe train operation under the ERTMS, in this model the real-time safety distance is calculated, aiming to improve the safety and efficiency of the following train movement. Shi-Gen et al. (2015) developed a cooperative adaptive bidirectional control for train platoon formation under CBCT signaling systems. In this model, the trains are separated by a distance that consists of the braking distance, a redundant safe distance, and an additional distance accounting for positioning errors. Despite its ability of the model to provide a string stable train platoon based on the constant spacing policy, the impact of communication delays is not included in this study. Zhao et al. (2016) develop cellular automata (CA) model to describe train convoy signalling. A comparative analysis with fixed block signalling and moving block signalling shows that the proposed model promises higher capacity benefits and higher robustness to disturbances. After simulating several scenarios, Schumann (2016) identifies potential capacity increase of Shinkansen highspeed line if VC is used, with a partial extension of infrastructure. However, in this study the train following model is not described in detail, in terms of coupling or decoupling maneuvers. Felez et al. (2019) develop a decentralized model predictive control framework for virtual coupling application and test different strategies through simulations. In one scenario, where two trains form a convoy, the leading train has higher maximum deceleration than the follower train, whose maximum deceleration rate is varied. For higher deceleration rate difference, the separation distance is increased in every strategy that is modelled. In this study, the collision avoidance is ensured by a constraint according to which trains should be always outdistanced by a safety distance equal to a minimum safety distance plus the positioning errors. Although this study offers interesting results on the capacity gains of virtual coupling, uncertainties regarding the track gradient profile, communication delays and train heterogeneity are not included. Based on Virtually coupled train sets concept, Ling et al. (2019) develop a novel model for improving the capacity of station capacity. Their case study on the Nanjing South High-speed railway station showed that under VC, the arrival and departure capacity can be increased by 128 % and 143% respectively, compared to the current capacity. Di Meo et al. (2019) related VC to platooning from the automotive sector and propose enrichments of ETCS L3 MB with VC instead of defining a completely new signalling system. In their study, a leader-predecessor-follower communication topology (LPF) is adopted, while V2V communication delay is varied. The model is said to provide safe separation between vehicles even under emergency braking. However, rolling stock heterogeneity is not considered in the study. In Park et al. (2020) a robust SMC (Sliding model control)-based gap control model is proposed including a position error correction scheme. However, the study is limited to the convoy formation of two trains, while the rolling stock attributes are obtained from metro lines. Moreover, the speed limit of trains is considered as 80 km/h. Duan et al. (2020) proposed a combination of moving block and the relative braking distance to achieve reduced headways. According to their study, capacity benefits can increase by 59% by this approach.

3.6 Conclusions

Influenced by the automotive sector, where car following and platooning scenarios have been widely researched and tested in real experiments, the main technologies that are probable to migrate into the ETCS L3 MB and VC operations in railway systems are listed in Table 3.2. Regarding V2V communications, it is expected that technologies based on the IEEE 802.11p standard, such as ITS-G5 will be utilized in cooperation with LTE, which is the main candidate for replacing the obsolete GSM-R and it is also able to pave the way for 5G. As in CACC, sensor fusion is considered to play an important role in virtual coupling application since more perception technologies are expected to be used such as RADARs, LiDARs, cameras, maps, etc. Regarding positioning, GNSS could be utilized if its limitations can be mitigated, together with odometry systems and the use of artificial landmarks.

Table 3.2 Current and emerging technologies for the automotive and the rail industry

Technologies	Automotive (highways)		Rail (mainline)	
	<i>In practice</i>	<i>Emerging</i>	<i>In practice</i>	<i>Emerging</i>
V2V communication	WiFi	LTE,5G	-	WiFi,LTE, 5G,TETRA
Vehicle positioning	GNSS, Dead reckoning methods Digital maps	Visual-based methods Data fusion	Trackside detection Odometry sensors, Balises, GNSS	GNSS-based Technology fusion (GNSS, odometry,etc.)
Perception	Radar, Cameras	LiDAR, Data fusion	-	Radar, LiDAR, Cameras
Automatic vehicle control	SAE level 2	SAE level 3 and higher	ATP	ATO

Studying the relevant literature on car-following models, CACC applications, train-following models and railway virtual coupling, the main papers that are considered relevant for the model development of a VC model in a realistic operational environment are summarized in Table 3.3. The consideration of dynamic vehicle characteristics, the V2V communication delay, train control delay times, positioning errors are parameters that dominate in the relevant literature and should be integrated in train-following modelling for ETCS L3-MB and VC operations.

According to the literature findings on MB and VC modelling, in most of the common studies, the heterogeneity of vehicle characteristics is not investigated. In addition, the impact of V2V communication delay and the train control delay time is not extensively studied. Few studies also discuss safety-critical situations based on emergency braking application.

3. Railway signalling and literature review on virtual coupling

Table 3.3 Literature review findings on railway VC modelling

Authors	Title	Year	Methodology	Characteristics	Railway type	Main results	Limitations
Yan, X., Cheng-Xun, C., Ming-Hua, L., & Jin-Long, L.	Modeling and simulation for urban rail traffic problem based on cellular automata	2012	Cellular automata model (CA)	Virtual coupling applied as "hit soft wall" MB Emergency braking Different train lengths Delay analysis	Urban	Impact of train length on urban traffic flow	Train homogeneity, Ignorance of communication and train control delay, speed limit 100 km/h
Shi-Gen, G., Hai-Rong, D., Bin, N., Clive, R., Lei, C., & Xu-Bin, S.	Cooperative adaptive bidirectional control of a train platoon for efficient utility and string stability.	2015	Cooperative adaptive control	Bidirectional communication topology String stability	Generic	Model capable of online estimation of system parameters and train platoon string stability	Message transmission delay Channel bandwidth
Di Meo, C., Di Vaio, M., Flammini, F., Nardone, R., Santini, S., & Vittorini, V.	Ertms/etcs virtual coupling: Proof of concept and numerical analysis.	2019	Decentralized Control strategy from automotive cooperative driving	Leader predecessor follower comm. Topology Time-varying V2V comm. Delays Emergency braking	Mainline	High capacity gains of VC Safety ensured even in degraded scenarios	Train homogeneity More safety related scenarios need to be modelled
Felez, J., Kim, Y., & Borrelli, F.	A Model Predictive Control Approach for Virtual Coupling in Railways	2019	Model predictive control based on a train longitudinal dynamics model	Optimal control of trains, Incorporation of positioning errors	Urban	MPC based short prediction strategy allows shorter distances VC outperforms MB	Train homogeneity Uncertainties in kinematic data and transmission delays
Quaglietta, E., Wang, M., & Goverde, R. M.	A multi-state train-following model for the analysis of virtual coupling railway operations	2020	Car following based model incorporating realistic train dynamics	Non-linear vehicle dynamics V2V Communication delay ATO reaction time	Mainline	Promising results of VC, especially for services with stops and trains having different routes	Emergency braking, Train homogeneity, Speed limit 144 km/h, Two-train convoys
Xun, J., Chen, M., Liu, Y., & Liu, F.	An Overspeed Protection Mechanism for Virtual Coupling in Railway	2020	Limit speed difference (LSD) and collision mitigation minimizing the relative kinetic energy	Homogenous and heterogenous emergency braking Multiple train convoy Different control strategies	Highspeed	MPC outperforms ACC and DBC	Maximum braking rate of first train
Park, J., Lee, B. H., & Eun, Y.	Virtual Coupling of Railway Vehicles: Gap Reference for Merge and Separation, Robust Control, and Position Measurement.	2020	SMC-based gap controller, Position error correctio scheme	Nonlinear train model including uncertainties	Urban	Gap control perturbations are minimized	Train homogeneity Speed limit 80 km/h

4 Model development

This chapter elaborates on the train-following model that is used in this study to analyze ETCS L3 Moving block and Virtual Coupling operations which is the multi-state train-following model developed by Quaglietta et al. (2020). The selection of the model is justified on the fact that this model defines analytically the different states in VC and the transitions between them, while simultaneously incorporates non-linear vehicle dynamics and realistic motion and track resistances. Afterwards, a safety issue of the current model is identified considering that the leading train may apply emergency braking at any time. The train-following model is enhanced by a dynamic parameter, the safety margin, which aims to lead us to the development of a safety-distance train-following model. Finally, an implementation example of the proposed model is presented.

The model is deployed in a time-driven microscopic railway simulation software, EGTRAIN. EGTRAIN tool is an object-oriented model developed in C++, which incorporates all the elements of a railway network and rail operations, such as the infrastructure (tracks, signals, switches, etc.), the rolling stock, the signaling and interlocking system, and the timetable. The kinematics of trains are calculated at each timestep based on the Newton's motion formulas, which are used afterwards to update the status of the signaling system (Quaglietta, 2019). EGTRAIN is considered as the ideal tool compared to other commercial tools (i.e., OpenTrack, RailSys, HERMES etc.) for the development of the proposed model since it offers an open-source API which enables the customization of functions and alternations of the model parameters.

4.1 The multi-state train-following model

In Quaglietta et al. (2020), a multi-state train following model is developed, which introduces principles, along with operational states and transitions of virtually coupled train movements. Under V2V communication, a new movement authority for virtual coupling is generated, containing data of the leading which are sent to the following train.

The operational states and the transitions between the different states are described as follows:

State 1: ETCS L3 running

In ETCS L3 the train separation is governed by an absolute braking distance (Abd). The train motion is modelled using a finite-difference integration of Newton's motion formula with timestep $\Delta t = t_k - t_{k-1}$, where the current time is t_k and t_{k-1} the previous time instant. At each timestep the speed and the position of each train are calculated by mathematical equations that represent the acceleration phase, the braking phase and the cruising phase of the train speed profile.

Acceleration phase

A train accelerates if at the previous time instant t_{k-1} its speed v_{k-1} is lower than the indicated max ceiling speed v_{lim} and its front position s_{k-1} has not yet reached the braking Indication Point IP , which is given by (4.1).

$$IP(v_0) = s_{target} - \int_{v_0}^{v_{target}} \frac{\rho M v}{\rho M b - R(v, \varphi, r)} dv \quad (4.1)$$

, where s_{target} is the EoA or the start of a section with a reduced speed limit, v_0 the current train speed, M the train mass, ρ the rotating mass factor, $b < 0$ the braking rate, $R(v, \varphi, r)$ is the motion resistance depending on the speed v , the track gradient φ and curvature radius r . For $s_{k-1} < IP$ and $v_{k-1} < v_{lim}$, the current speed v_k and the position s_k of the train that is in the acceleration phase are computed from the previous time instant as in (4.2):

$$\begin{cases} v_k = v_{k-1} + \frac{T(v_{k-1}) - R(v_{k-1}, \varphi, r)}{\rho M} \cdot \Delta t \\ s_k = s_{k-1} + \frac{\rho M}{T(v_{k-1}) - R(v_{k-1}, \varphi, r)} \cdot v_{k-1} (v_k - v_{k-1}) \end{cases} \quad (4.2)$$

, where $T(v_{k-1})$ is the tractive effort of the train for the speed v_{k-1} .

Braking phase

In case that in the previous time instant the train speed has passed the given speed limit, or the front position of the train has passed the point IP , then the train brakes until the target speed is reached before the EoA. Thus, for $s_{k-1} \geq IP$ or $v_{k-1} > v_{lim}$, the speed and position of the train is computed as (4.3):

$$\begin{cases} v_k = v_{k-1} + \frac{\rho M b - R(v_{k-1}, \varphi, r)}{\rho M} \cdot \Delta t \\ s_k = s_{k-1} + \frac{\rho M}{\rho M b - R(v_{k-1}, \varphi, r)} \cdot v_{k-1} \cdot (v_k - v_{k-1}) \end{cases} \quad (4.3)$$

with $b < 0$ the service braking rate.

Cruising phase

If at the previous time step the train has already reached the target speed before reaching the IP , then the train enters the cruising phase with a constant speed v_{target} ,

where the tractive effort is equal to the motion resistance. , for $s_{k-1} < IP$ and $v_{k-1} = v_{target}$ the train speed and position are computed as in (4.4):

$$\begin{cases} v_k = v_{k-1} \\ s_k = s_{k-1} + v_{k-1} \cdot \Delta t. \end{cases} \quad (4.4)$$

State 2: Coupling

If a train approaches another one, the RBC or the EVC of the following train checks if the trains have common routes. In case they do, the following train tries to reach the speed of the leading train after a coordination time, during which the train accelerates or brakes analogously to its initial speed and the speed of the leader. The following train starts coupling with the leading train if the distance between its front and the EoA_{VC} is lower than the distance travelled by the leading train during the coordination time which is expressed mathematically as $|EoA_{VC} - s_{k-1}| \leq t_{coord} \cdot v_{lead}$. The coordination time t_{coord} is the time needed by the follower train to coordinate its speed with the leading train, and it is computed as in (4.5):

$$\begin{cases} \int_{v_{k-1}}^{v_{Bf}} \frac{\rho M}{T(v) - R(v, \varphi, r)} dv + \int_{v_{Bf}}^{v_{lead}} \frac{\rho M}{\rho M b - R(v, \varphi, r)} dv & \text{if } v_{k-1} \leq v_{lead} \\ \int_{v_{k-1}}^{v_{lead}} \frac{\rho M}{\rho M b - R(v, \varphi, r)} dv & \text{if } v_{k-1} > v_{lead} \end{cases} \quad (4.5)$$

The following train receives an enhanced MA_{VC} containing the EoA_{VC} which is located at a fixed safety margin from the rear end of the leading train. The point where the trains are expected to start coupling is defined by the summation of the EoA_{VC} and the distance the leading train has covered during the coordination time, as shown in (4.6).

$$P_{coupling} = EoA_{VC} + t_{coord} \cdot v_{lead}; \quad \text{with } EoA_{VC} = Tail_{lead} - sm, \quad (4.6)$$

The safety margin sm is considered to account for calculation errors and exogenous factors such as weather conditions.

State 3: Coupled running

After the following train has reached the leading train speed and the predicted EoA_{VC} the train steps into the coupled running mode where the following train motion is supervised by the EVC based on the actual kinematic parameters of the leading train. In addition, the EVC is responsible so that the safety margin from the leading train is not violated. The speed, position and acceleration of the following train are computed as:

$$\begin{cases} v_k = v_{k-1} + a_{k-1} \Delta t \\ s_k = s_{k-1} + v_{k-1} \Delta t \end{cases} \quad (4.7)$$

$$a_{k-1} = \begin{cases} a_{k-1}^{max}, & \text{if } a_{lead} > a_{k-1}^{max} = \frac{T(v_{k-1}) - R(v_{k-1}, \varphi, r)}{\rho M} \\ a_{k-1}^{min}, & \text{if } a_{lead} < a_{k-1}^{min} = \frac{\rho M b_{max} - R(v_{k-1}, \varphi, r)}{\rho M} \\ a_{lead}, & \text{otherwise.} \end{cases} \quad (4.8)$$

State 4: Unintentional decoupling

Due to traction power limitations or high motion resistances, the following train cannot continue running at the same speed with the leading train, implying that the separation distance between the trains becomes greater than the space threshold. Thus, if $|s_{k-1} - EoA_{VC}| > th_s$, the following train decouples from the leading train and continues running independently under ETCS L3, where its speed and position are computed as in equations (4.1) - (4.4). Based on the traction power and the motion resistances, the following train switch again to coupling state.

State 5: Intentional decoupling

While in coupled running mode, the trains can also decouple intentionally under safety-critical situations when for example approaching a switch or when the leading train diverges. In this case, the trains are separated by an Abd instead of an Rbd and continue running under ETCS L3. An IP decoupling point is estimated by the EVC, located at least at a safety margin sm from the SvL plus the distance needed to move and lock the point (Psd), as:

$$IP_{decoupling} = SvL - sm - Psd - \int_{v_{k-1}}^0 \frac{\rho M v}{\rho M b - R(v, \varphi, r)} dv \quad (4.9)$$

4.2 Safety issue of the multi-state train-following model

In the multi-state train-following model (Quaglietta et al., 2020), the EoA is always located at a safety margin (sm) from the supervised location SvL (i.e., the potential danger point). The safety margin is needed to prevent that potential train location errors might cause the train to overshoot the SvL and cause derailments or train collisions. The safety margin is also considered when computing braking curves in any of the Virtual Coupling operational states identified in the model. In Quaglietta et al. (2020) the safety margin is set to a fixed value of 50 m (Figure 4.1).

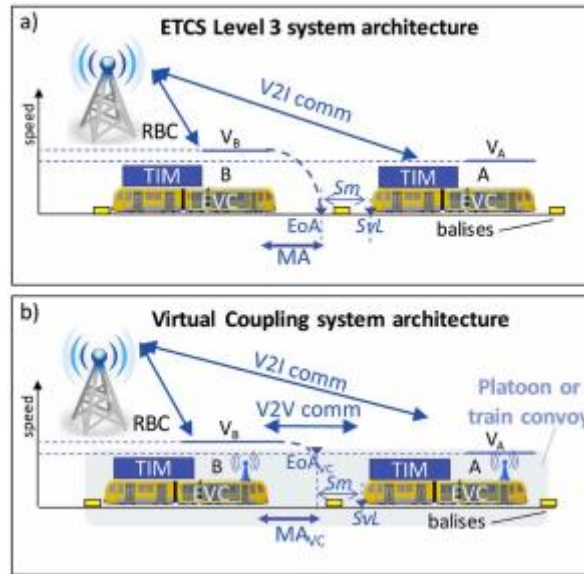


Figure 4.1 Schematic system architecture of ETCS L3 and Virtual Coupling (Quaglietta et al., 2020)

When a safety margin of 50 m is incorporated in the model, trains come in proximity, while afterwards, the separation distance varies based on the infrastructure and train characteristics. Since the train separation becomes very small according to this model, a safety issue is identified of using the relative braking distance. That said, supposing two trains couple along the run, in case the predecessor train applies emergency braking, the successor train might not be able to stop in time before reaching the tail of its predecessor. Figure 4.2 presents the separation between two British Class 450 on the route Waterloo station- Surbiton station considering a fixed safety margin of 50m. In the same graph, the minimum required separation distance is plotted, which is computed at each time instant as the difference between the service braking distance of the following train and the emergency braking distance of the leading train as in (15).

$$\text{Required safety distance}_k = \frac{u_{n,k}^2}{2b_{n,max}} - \frac{u_{n-1,k}^2}{2b_{emerg}} \quad (4.10)$$

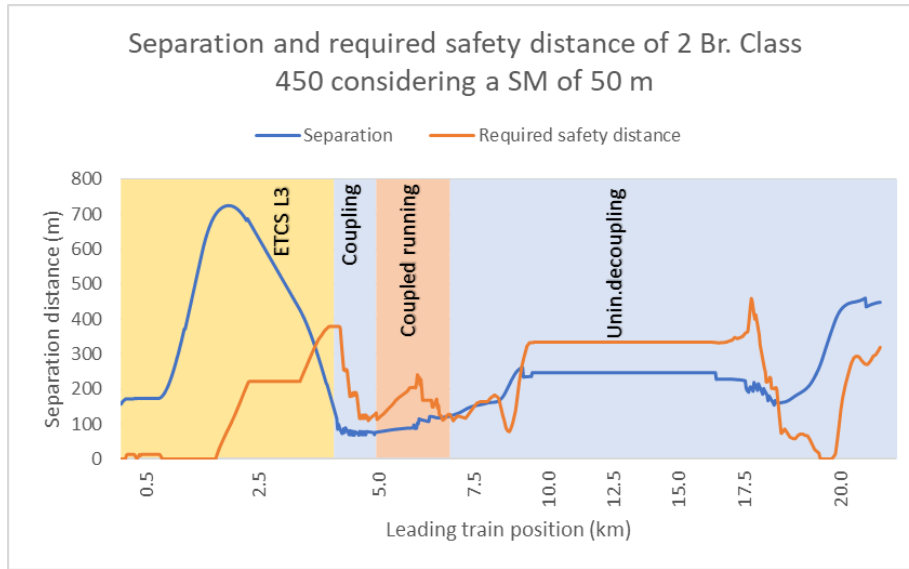


Figure 4.2 Train separation and required safety distance, WTL-SBM with stops (a) and without stops (b)

In case the leading train applies emergency braking at any moment, there is not available separation distance between the trains so that the following train can come to a standstill before reaching the leading one and by applying service braking. Thus, the following train would have to apply emergency braking to avoid a collision with the leading train.

4.3 Model enhancement by a dynamic safety margin

The model that is used in this study is the multi-state train-following model adapted from Quaglietta et al. (2020). The only difference is that the fixed safety margin considered from the rear end of the train, is replaced by a dynamic parameter called the dynamic safety margin (DSM). Since no diverging routes are investigated in this study, the state of Intentional Coupling is not considered. Figure 4.3 shows the states and the transitions between states of the model that is used in this study. The dynamic parameter that enhances the current train-following model practically limits the EoA_{VC} by adding an additional safety distance between the EoA_{VC} and the SvL from the preceding train. The DSM depicted in Figure 4.3 ensures that the following train which

is coupling or already coupled to another one will come to a standstill applying service braking even in case the leading train applies emergency braking. Moreover, the DSM accounts for additional safety distances which are required in case varied train control delay times, V2V communication delays and positioning errors are present in realistic rail operation. All safety distances that comprise the DSM are elaborated below.

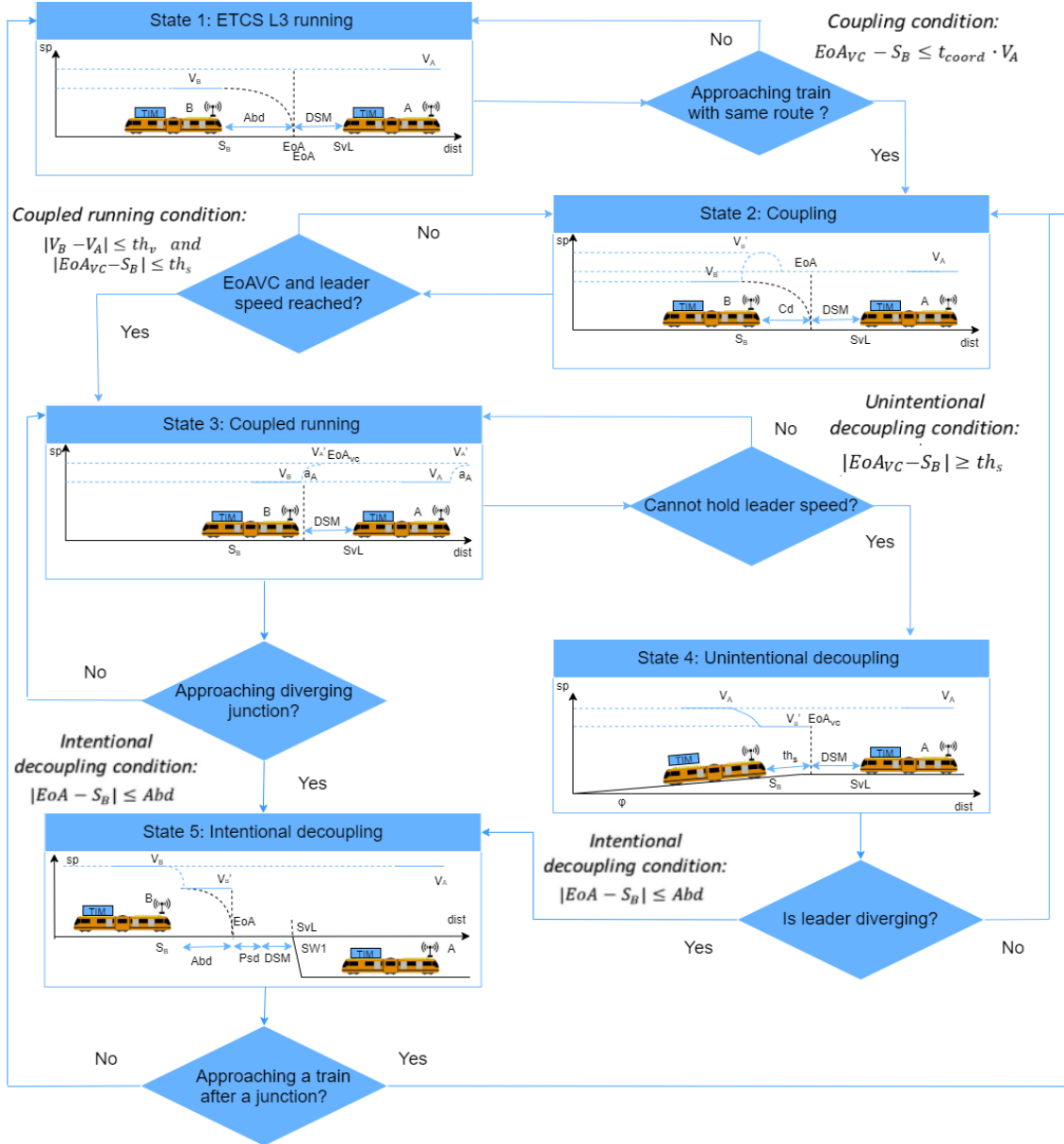


Figure 4.3 Multi-state train-following model considering a DSM (adapted by Quaglietta et al., 2020)

The dynamic safety margin, depicted in Figure 4.4 consists of the summation of five parameters, as seen in (4.11).

$$SM = SM_0 + SM_{odometry} + SM_{delay} + SM_{control} + SM_{braking} \quad (4.11)$$

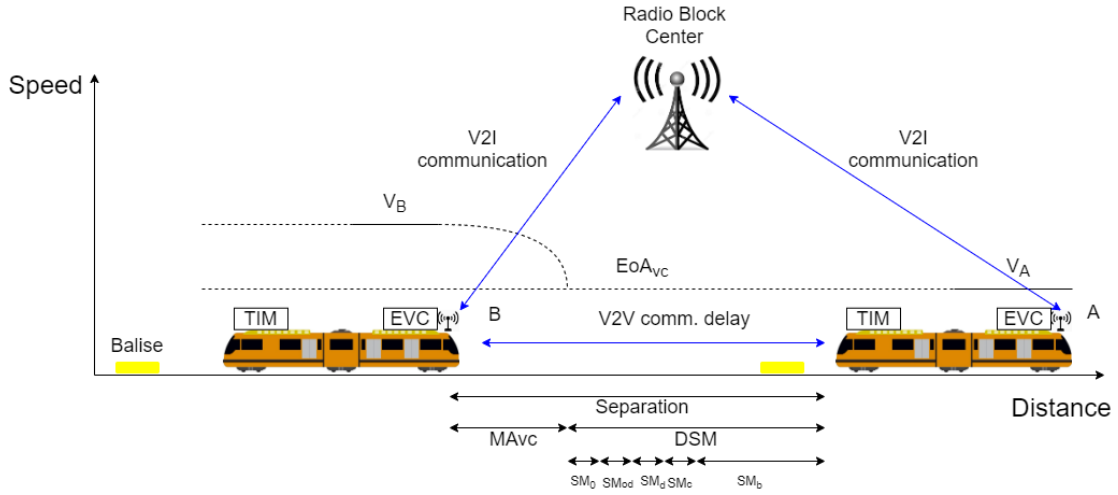


Figure 4.4 Dynamic safety margin

The first parameter, SM_o is a nominal safety distance that accounts for exogenous parameters e.g., weather conditions and is considered as 50 m.

Odometry errors

The positioning technology for VC is assumed to be based on a combination of different technologies such as GNSS, odometry sensors, IMU, etc. It is assumed that reference points (balises) that are currently being used in railway operation will be used as landmarks for recalibrating the vehicle's position.

$SM_{odometry}$ is an additional safety distance that is needed to incorporate the odometry error, which can reach at maximum $5 \text{ m} \pm 5\%$ of the distance travelled between two reference points (UNISIG, 2015). That said, the percentage of positioning error increases linearly as the train moves far from the previously passed reference point (Figure 4.5). When the leading train that reports continuously its position to the following train, is located at a balise, then the position error of the leader is considered as 5 m, while it reaches a maximum value ($5 \text{ m} + 5\%$ of the balise-to-balise distance) when the leading train is exactly before the next balise.

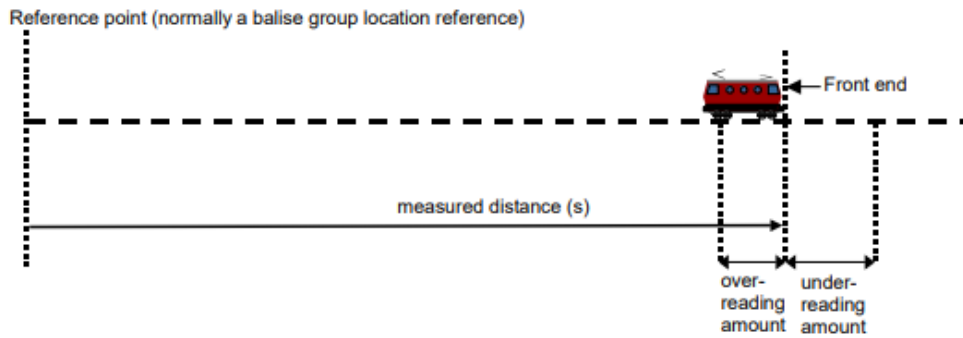


Figure 4.5 Positioning error (UNISIG, 2015)

Thus, the safety margin at time instant due to odometry errors is given by (4.12).

$$SM_{odometry} = SM_{odometry,leader} + SM_{odometry,follower} \quad (4.12)$$

$$SM_{odometry,train} = 5 + \beta * d_{balise,k} \quad (4.13)$$

$$, \text{ with } \beta = \frac{0.05 * d_{balise,k}}{L_{balise,k}} \quad (4.14)$$

, where $d_{balise,k}$ is the distance from the last balise the train has passed at time instant k , and $L_{balise,k}$ the distance between the two reference points (balises). In this study, a balise grid is assumed, where the distance between two balises is considered merely as 250 m. Therefore, the maximum positioning error of a train which approaches a balise is given as:

$$SM_{odometry,train} = 5 + 249.99 * \frac{0.05 * 249.99}{250} = 17.5 \text{ m}$$

V2V update delay

At each time instant t_k , the leading train transmits its kinematic data to the following train which arrives after $t_k + \tau_{delay}$. However, during the communication delay, the leading train has moved forward $S_{n-1,tdelay} = u_{n-1,k} + 0.5 * a_{n-1,k} * t_{delay}^2$, while the following train has moved forward $S_{n,tdelay} = u_{n,k} + 0.5 * a_{n,k} * t_{delay}^2$. In case the leading train is running with a higher speed than the following train, then no additional safety distance is required since $S_{n-1,tdelay}$ is always higher than $S_{n,tdelay}$. However, in case the leading train applies braking or in case the following train approaches the leading train with a higher speed, then an additional safety distance is required to account for the difference between $S_{n-1,tdelay}$ and $S_{n,tdelay}$. Therefore, additional safety margin due to the communication delay is given by (4.15).

$$SM_{delay,k} = \max(0, \tau_{delay} * u_{n,k} - \tau_{delay} * u_{n-1,k-\tau_{delay}}) \quad (4.15)$$

, where $u_{n,k}$ is the speed of the following vehicle at time instant k and $u_{n-1,k-\tau_{delay}}$ the speed of the leading train sent by the leading to the following after a delay of τ_{delay} seconds.

In Quaglietta et al. (2020) the V2V communication delay, incorporated in the Newton's motion formulas, is regarded as a constant value (1 s). The V2V communication delay in this study is defined as the update delay, which is the time between two successfully received messages from a specific transmitter to a specific receiver. For instance, if the communication delay is considered as 3 s, the leading train is running with 27.77 m/s (100 km/h) and the following with 33.61 m/s (121 km/h), the additional safety distance is $3 * 27.77 - 3 * 33.61 = 17.52 \text{ m}$.

Train control delay time

In the same line of reasoning with the SM_{delay} , an additional safety distance is calculated to account for variations of train control delay time. Train control delay time is defined as the actuation delay from the ATO, which is the time difference between the reception of the kinematic data from the leading train and the application of an action, being acceleration or braking. In case of manual driving, train control delay is the time between the moment the train driver perceives a stimulus until the moment the braking/acceleration action is applied.

In case both trains have equal train control delay time, then no additional safety distance is required, except for the case that the following train is running with a higher speed. If the following train has a higher control delay time, then the $SM_{control}$ increases significantly based on the speed difference between the trains. In case the following train has a higher control delay than the following, it is assumed that no additional safety distance is required. Thus, the additional $SM_{control}$ due to the system reaction time is given in (4.16).

$$SM_{control,k} = \max(0, \tau_{c,n} * u_{n,k} - \tau_{c,n-1} * u_{n-1,k} - \tau_{delay}) \quad (4.16)$$

, $\tau_{c,n-1}$ and $\tau_{c,n}$ the control delay time of the leading and the following vehicle, respectively.

In the multi-state train following model it is assumed that in every case of virtual coupling or ETCS L3 moving block, the trains are driven under ATO. The ATO system reaction time is considered as a fixed value (1 s). However, it is not specified which GoA of ATO will be implemented. If it is assumed that GoA 4 will be utilized, where all operations including train driving in disruptions are executed by the ATO system, then the system reaction time is considered as a fixed value which can be varied to assess its impact on the railway line capacity. For the early stage of Virtual coupling and Moving block deployment under ATO, it is assumed that GoA 2 and GoA 3 will be tested before full automation is applied. That said, it is assumed that human drivers will be present in the driver cabin, so that they can take over the train control in case of disruptions, for instance when the system downgrades from Virtual Coupling to ETCS L3 manual driving or in case they need to intervene due to an unexpected event. Thus, the human driving factor should be incorporated in the model to represent critical-safe operational scenarios.

Rolling stock characteristics

The fifth parameter, ***SM_{braking}*** is inserted to account for different rolling stock characteristics. These rolling stock parameters concern the speed and the braking rate of the trains. Emery (2008) identifies the main safety problem of using relative braking distances in rail operations. That said, there is a possibility of secondary accidents, where the successive train could collide with the rear-end of the leading train in case the last is brought to a sudden standstill due an accident (i.e., collision with an obstacle), or due to a deceleration with an unexpected high braking rate. Indeed, a secondary accident under relative braking distances would lead to catastrophic consequences, including several casualties, injuries. In addition, the emergency brake application of following trains is not favorable since full application of brakes damages the tracks and the train wheels.

The ***SM_{braking}*** is based on the fail-safe scenario that the following train needs to be outdistanced by a distance that is enough for it to come to a standstill even if the leading train applies emergency braking. If the leading train is running with $u_{n-1,k}$, then the braking distance to standstill if emergency braking is applied is computed as

$$S_{emergency} = \frac{u_{n-1,k}^2}{2b_{emerg}}.$$

Similar, the service braking distance of the following train running with $u_{n,k}$ is calculated as $S_{service} = \frac{u_{n,k}^2}{2b_{n,max}}$. Thus, an additional safety distance is added when $S_{service}$ is higher than $S_{emergency}$, as shown in (4.17).

$$SM_{braking,k} = \max\left(0, \frac{u_{n,k}^2}{2b_{n,max}} - \frac{u_{n-1,k-\tau_{delay}}^2}{2b_{emerg}}\right) \quad (4.17)$$

, where $b_{n,max}$ and b_{emerg} the deceleration rate of the following train and the emergency braking rate of the leading train respectively.

How the dynamic safety margin is applied in the model

Suppose a train departs at time k and the second train departs at $k+50$ seconds. It is assumed that leading train can communicate its kinematic information within a specific communication (e.g. 1000 m or higher) to the following train, so that the EVC of the following train can compute continuously the dynamic safety margin, based on the speed and position of the predecessor on the previous timestep. The incorporation of the DSM assumes that the kinematic information has not significantly changed at the time instant the predecessor's kinematic data are transmitted to the EVC of the following train. After the DSM calculation on the EVC of the following train, the MA of the successor train is updated based on the relative braking distance plus the DSM. As soon as the following train approaches its predecessor and the coupling criteria are fulfilled, then the following switches through the different states of the multi-state train following model. When the distance of consecutive trains becomes large enough due to limited traction power or increased track gradient, then the following train decouples unintentionally from its leader and moves under ETCS L3 MB. The DSM is coming up again in case the following train approaches the leading train enough so that a transition to a coupling or coupled running state is allowed. To account for dangerous situations where the so-called safety envelope of the leading trains is violated, a warning braking intervention is incorporated in the model. That said, in case two train operating in VC brake and the following train has poorer braking performance, then a warning braking application (30% higher than the service braking) is applied so that the following train respects the safety envelope of the leading train. In addition, it is assumed that the EVC of the following train supervises the separation distance between trains and in case the DSM exceeds the separation distance, then a service braking action is triggered by the following train to bring the train back to a safe separation distance.

4.4 Dynamic safety margin implementation example

After the integration of the DSM in the multi-state train-following model, the same simulation as in 4.6 is repeated, for 2 British Class 450 trains between Waterloo Station and Surbiton station with a departure headway of 50 s. As depicted in Figure 18, the train separation always respects the dynamic safety margin along the total route length.

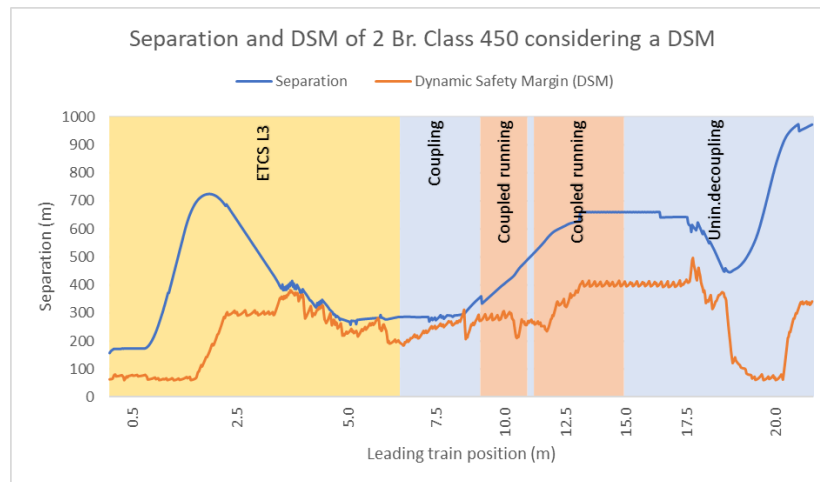


Figure 4.6 Train separation and DSM after the incorporation of the DSM in the multi-state train-following model.

Figure 4.7 depicts the variation of the different parameters of the DSM presented in. The $SM_{braking}$ is the major factor of the DSM while the SM and SM take positive values when the speed of the following train is higher since the V2V update delay is set to 1 s and the trains have equal reaction time set to 1 s as well. The SM accounting for the positioning error of trains shows that the additional safety distance for both trains varies between 10 m and 35 m.

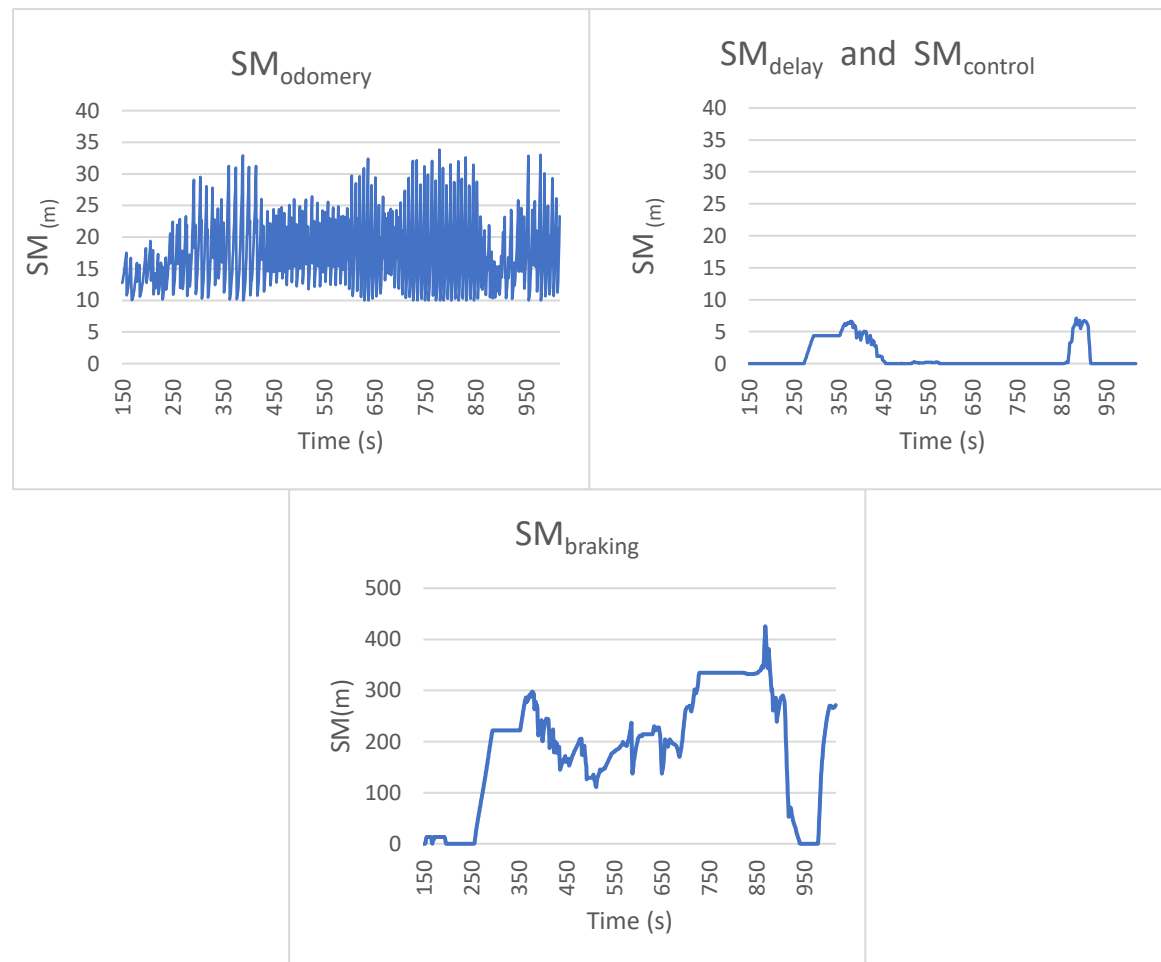


Figure 4.7 Dynamic safety margin parameters for Br. CClass 450- Br.CClass 450, route Wtl-Sbn without stops

5 Sensitivity analysis

In this chapter, a sensitivity analysis is executed for the multi-state train-following model considering a dynamic safety margin proposed in chapter 4. First, background information on sensitivity analyses on car-following modes is provided. The methodology that has been followed for the sensitivity analysis is the one-at-a-time method, where one parameter is alternated at a time to assess its significance in the model output. In the end of the chapter, the sensitivity of each parameter under investigation is evaluated based on partial derivatives.

5.1 Sensitivity analyses in car-following models

Model uncertainty is not an accident of the scientific method, but it is substance (Saltelli et al., 2008). Microscopic traffic simulation, which reproduces traffic over infrastructure networks, models decisions of each individual vehicle both at strategic and tactical level. Models involve several uncertainty sources of different natures, which can be mixed as well. The uncertainty of the model output is related to the inadequacy of the model itself to represent the reality or the uncertainty of the model inputs or both (Punzo et al., 2014). To reduce model uncertainty, scientists can either improve the adequacy of the model in terms of improving the model assumptions, mathematical equations, etc. or improve the model input, which can be observable or unobservable. Figure 5.1 shows the conceptual framework of model uncertainty analysis, including four steps. In step A, the problem is specified including, the input and output definitions, the model specification, and the quantities of measuring the uncertainty of the model outputs. Step B contains the uncertainty modelling, by gathering direct observations, interviews with experts in the field, indirect estimations, etc. and the uncertainty propagation is completed in step C, where usually a Montel Carlo simulation approach is adopted.

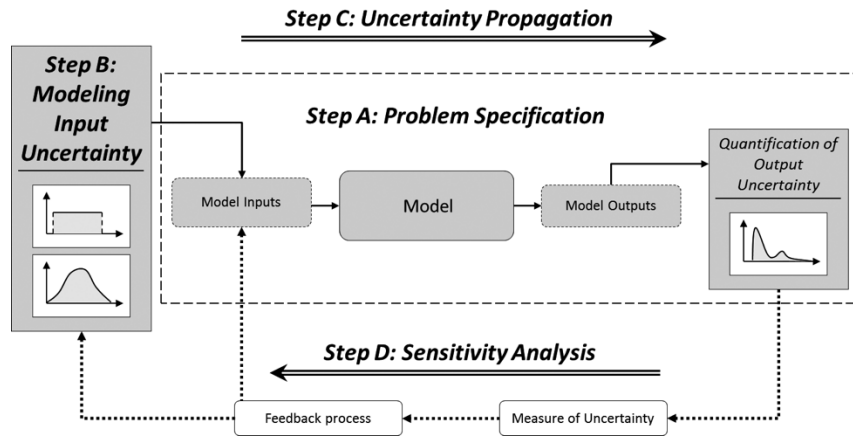


Figure 5.1 Conceptual Framework of model uncertainty analysis (Punzo et al.2014)

Finally, step D contains the sensitivity analysis, a feedback process which helps the analyst understand the relative importance of the uncertain inputs to the desired outputs. Among techniques of sensitivity analysis in traffic models, the most common are the input and output scatter plots, the One-at-Time (OAT), the elementary effect test, the standardized regression coefficient analysis, the metamodeling method, the analysis of variance (ANOVA), sigma-normalized derivatives, the partial correlation coefficient analysis, and the variance-based methods on Sobol decomposition of variance (Punzo et al., 2014). Since OAT sensitivity analysis is widely used in microscopic car-following models in the literature and its ease of implementation, OAT is selected to be used to assess the sensitivity of the selected parameters on the model output.

5.1.1 One-at-Time (OAT) sensitivity analysis

One of the most common approach for sensitivity analysis in traffic models is the One-at-Time method due to its simplicity. In OAT, the variations of the model output are studied, while the input parameters are changed one at a time and the rest model parameters remain fixed at certain values. Lownes and Machemehl (2006) have applied this method in the Vissim model to find the sensitivity of the simulated capacity in the driver behavior parameters. Kesting and Treiber (2008) used OAT sensitivity analysis to get insights of model parameter values after the calibrations of the IDM and the VDIFF (Velocity Difference model). Chatterjee et al. (2009) varied car-following and lane-changing parameters, one at a time, in the VISSIM model to obtain different work zone capacity values. Leclercq et al. (2011) use the OAT sensitivity analysis approach to estimate the sensitivity of the relative capacity drop to the Newell-Daganzo merge model. Habtemichael and Picant-Santos (2013) used OAT sensitivity analysis and the Surrogate Safety Assessment model aiming to find the most influential parameters of the car-following and the lane-change model that are incorporated in the VISSIM model. Despite its ease of implementation, drawback of the OAT based sensitivity analysis is that it is a local approach, and it does consider possible interactions between the input parameters, which may lead to unreliable results (Saltelli et al., 2006).

The sensitivity analysis has been conducted through simulation in the EGTRAIN tool, developed in C++. A two train-convoy is simulated at each simulation run on the South West Mainline in the UK, between Waterloo London station and Surbiton station, while the rolling stock type is set as the British Class 455 (suburban) for both trains. The selected parameters that are varied are the space and speed thresholds, the V2V update

delay, the train control delay of the following train and the braking factor of the following train. The speed and space thresholds are the responsible parameters for trains switching between the different states of the virtual coupling model, thus they influence the train separation and consequently the corridor capacity. Regarding the braking factors, only the braking factor of the following train of the convoy is considered, since the calculation of the dynamic safety margin assumes that the predecessor train applies emergency braking ($b=1.2$ m/s). Thus, alternating the predecessor braking factor does not have an impact on the safety margin calculation and then in the model output.

To evaluate the impact of the varying model input on the model output, the separation distance between trains is plotted, which is then translated in headways at Surbiton station. Moreover, the track gradient profile is assumed that influences the states of virtual coupling model, thus all results are given assuming a track with 0% gradient and a track with the actual gradient profile, depicted in Figure 5.2. To enable trains couple and decouple on the run, a speed restriction of 18 m/s is imposed to the first train for the first 430 seconds of the simulation. Table 5.1 summarizes the model parameters under investigations as well as the min and maximum values that are assumed.

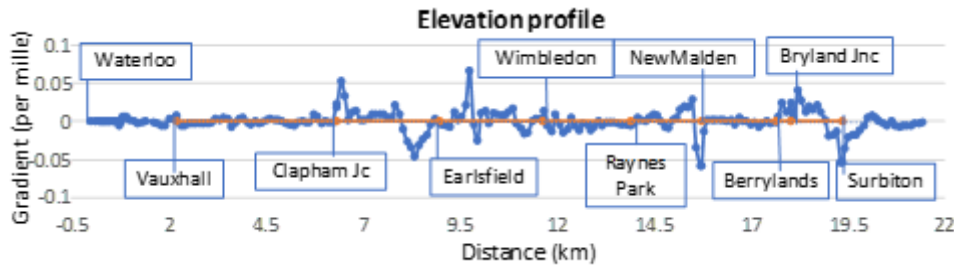


Figure 5.2 Track gradient profile between Waterloo and Surbiton (Quaglietta et al. 2020)

Table 5.1 Parameters investigated through the sensitivity analysis

Parameter	Value range
Speed threshold th_v (km/h)	1-5
Space threshold th_s (m)	50-500
V2V update delay (s)	1-8
Following train control delay (s)	1-8
Following train braking rate (m/s ²)	0.4-0.9

The importance of the selected parameters on the model output being the train headways at Surbiton, is evaluated based on the partial derivatives, which show how much the model output has changed, relative to the change in the input parameter, as in (5.1).

$$d_i(X) = \frac{\partial Y}{\partial X_i} \quad (5.1)$$

, where Y is the model output (headway at Surbiton) and X_i the input parameter.

To rank the parameters under investigation, two metrics are computed similar to the elementary effects method. The mean of the absolute partial derivatives and the standard deviation of the partial derivatives are computed for each parameter by (5.2) and (5.3) respectively.

$$\mu_i^* = \frac{1}{r} \sum_{j=1}^r |d_i(X^{(j)})| \quad (5.2)$$

$$\sigma_i = \sqrt{\frac{1}{(r-1)} \sum_{j=1}^r (d_i(X^{(j)}) - \mu_i)^2} \quad (5.3)$$

, where μ_i is the mean of partial derivatives and r the sampling space of the input parameters.

5.2 Speed and space thresholds

In Quaglietta et al. (2020), the space and speed thresholds are set to 30 m and 0.278 m/s (1km/h) respectively, when a constant safety margin of 50 m is considered. After the inclusion of the dynamic safety margin and keeping the said parameter values, it was observed that trains stay in the coupled running state for only a few seconds, which means that the second train is in following mode with the predecessor, without coordinating itself characteristics according to its predecessor train. Thus, several values have been tested for the coupling criteria (space and speed thresholds), which are evaluated based on headways at Surbiton station (19.5 km). The sensitivity of the parameters is evaluated in terms of coupled running state duration and train headways at the selected locations. Moreover, the train separation graphs are included in Appendix B. For the reference scenario, the space scenario is set as 50 m and the speed threshold as 1 km/h.

5.2.1 Flat track

First, the space threshold is alternated between 50 and 500 m at each simulation run on the route considering a flat track with 0% gradient, while the speed threshold is set to 1 km/h.

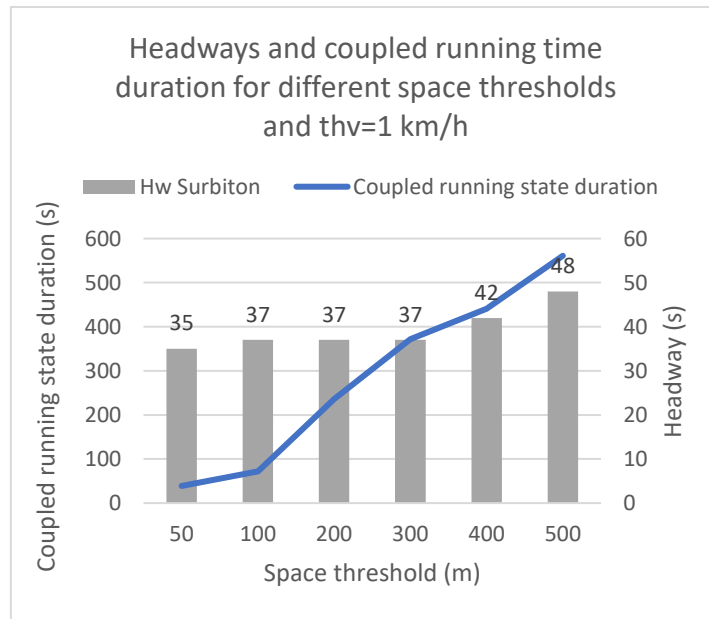


Figure 5.3 Headways and coupled running time duration for different space thresholds, flat track

There is obviously an increasing trend between the coupled running state duration and the space threshold as depicted in Figure 5.3. However, the headways are also increased, which is not beneficial for the corridor capacity. A possible cause to this is explained as follows: forcing trains to be in a convoy for a large part of the route length, means that the following train may have to apply normal braking or even warning braking for more times, compared the case where the successor train is in following mode, but it does not coordinate its characteristic according to the predecessor.

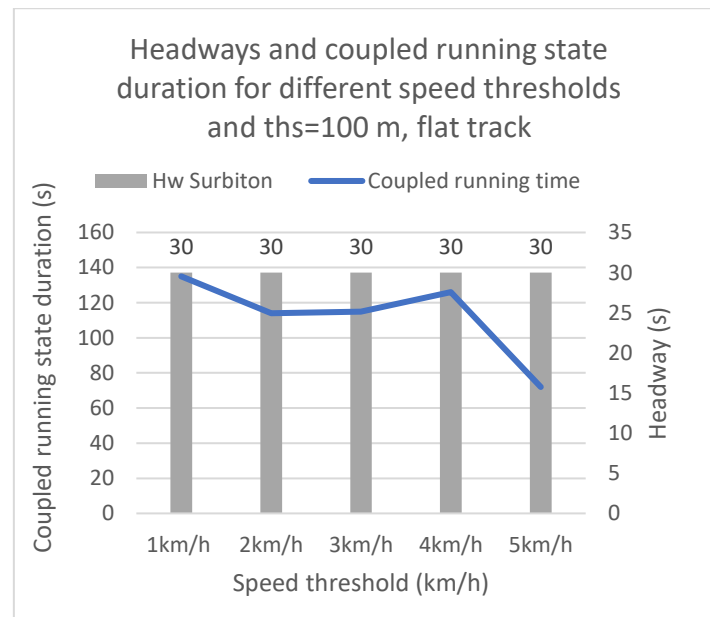


Figure 5.4 Headways and coupled running state duration for different speed thresholds, flat track

By increasing the speed threshold (th_v), the coupled running time duration is decreased. However, no significant changes are observed in the headways (Figure 5.4).

5.2.2 Track considering the real gradient profile

Repeating the same simulation runs as in 5.2.1, but considering the real track gradient profile, the coupled running state duration is increased, however, no significant changes are observed for headways for space threshold values up to 300m (Figure 5.5).

For varied speed thresholds considering the realistic track gradient profile, the coupled running state duration slightly increases if trains are allowed to couple earlier considering a higher speed threshold. However, the headways are not significantly changed (Figure 5.6).

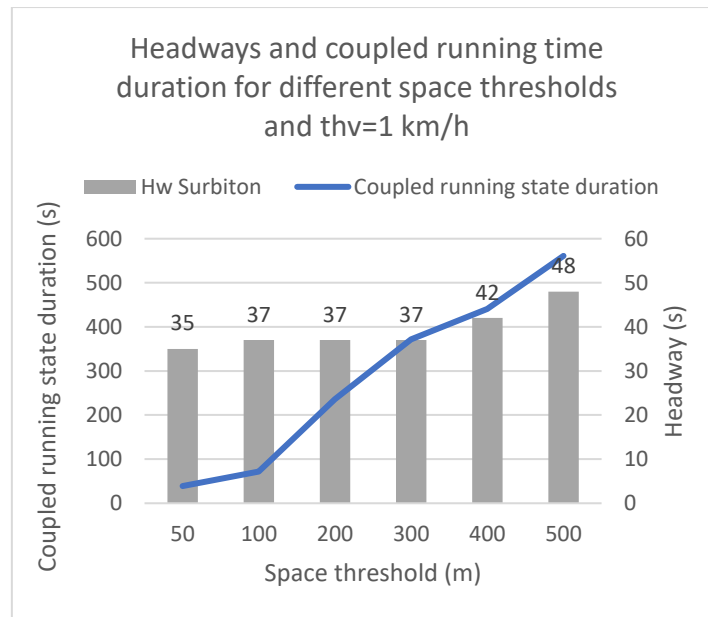


Figure 5.5 Headways and coupled running time duration for different space thresholds, real track gradient profile

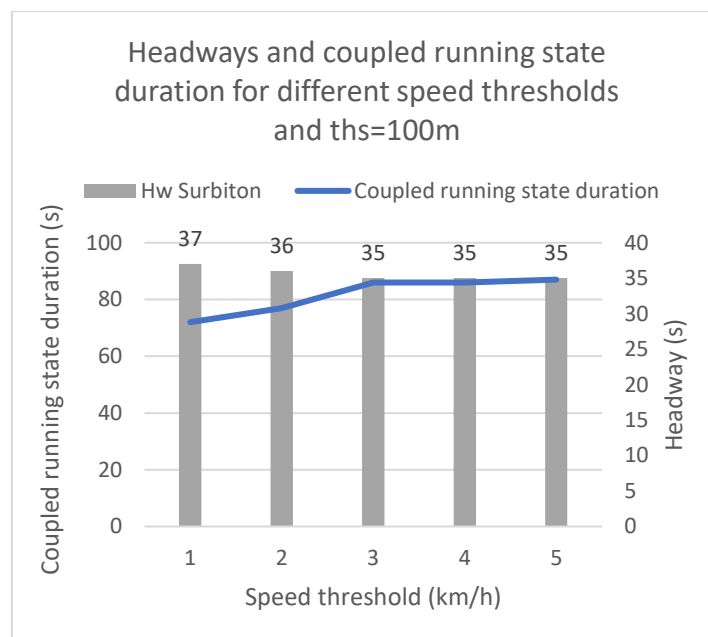


Figure 5.6 Headways and coupled running state duration for different speed thresholds, real track gradient profile

For the rest model parameters that are investigated in this sensitivity analysis, the space and speed thresholds are set to 100 m and 1 km/h respectively, so that the trains are virtually coupled (coupled running state) for a considerable amount of time, but at the same time they can shift to unintentional decoupling, especially before stopping at stations or when the motion and track resistances are high.

5.3 V2V update delay

In the literature relative to CACC including V2V communication between vehicles, the communication range is usually considered as 300 m. For various technologies and conditions, the V2V communications range may vary. For instance, the theoretical range of WiFi is considered as 1000 m. For next generation signaling rail operations, if a dynamic safety margin is applied, it is assumed the leading and the following train will need to connect and start exchanging kinematic information data at a longer range for safety reasons. Depending on the vehicle's capabilities, the communication range of a convoy consisting of two trains might be as high as 1 km or even more if the trains need to start exchanging kinematic data separated even under an absolute braking distance. For the formation of train convoys consisting of multiple trains, the communication range may be varied depending on the communication topology. That said, if, a multiple predecessor-follower topology is inherited, then a train convoy consisting of 5 trains with 150 m length, the required communication range should be higher than 1 km including the required safety separation distances.

Several studies have indicated that, depending on the technology that is being used (Cellular, Wifi, etc.), the update delay, which is the time between two successful message receptions, is increased when the communication range is increased (Cecchini et al., 2017, Seliem et al., 2019). Moreover, the delay might be increased due to network saturated conditions, for instance around train stations or when the communication infrastructure is shared with other transport systems. For example, when trains move parallel highways that utilize V2V communication networks, an increase of communication delay may be experienced. Thus, the railway corridor capacity might be affected by the selected V2V communication technology for next generation signaling approaches. Figure 5.7 shows the impact of the increased V2V update delay in train separation distance which is translated to time headways. In the base scenario, the update delay is set to 1 s, which is then varied between 1 s and 8 s. The influence of this parameter is evaluated in terms of train separation distance and headways at Surbiton (Figure 5.8).

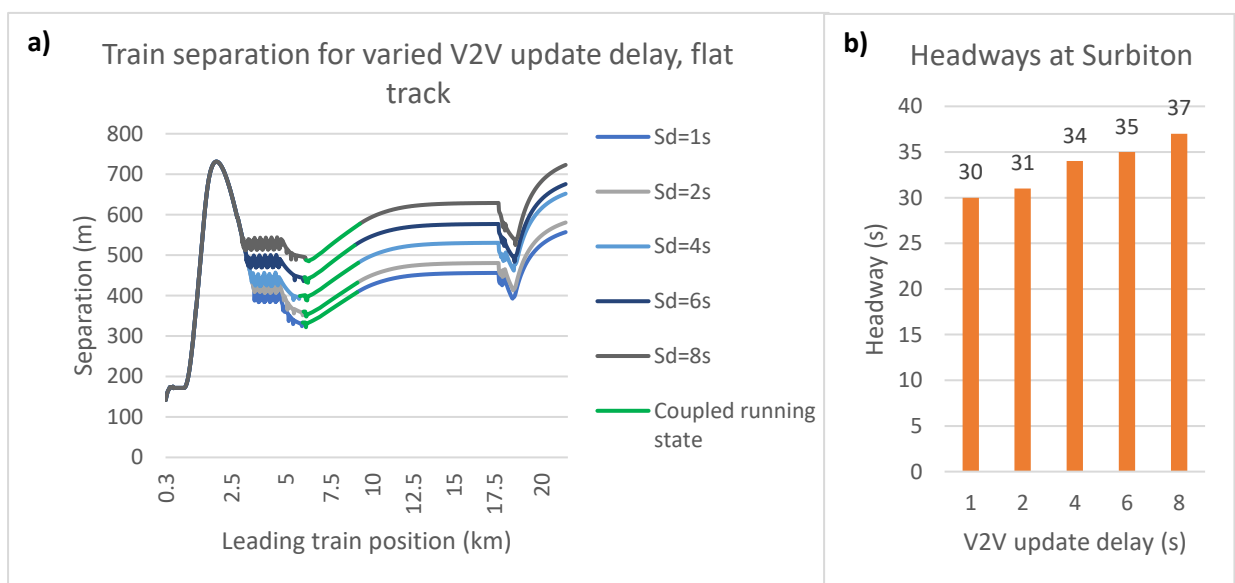


Figure 5.7 Train separation (a) and headways (b) for varied V2V update delay, flat track

In both Figure 5.7 and 5.8, there is an increasing trend of the time headways, when the update delay from the predecessor to the follower is increased.

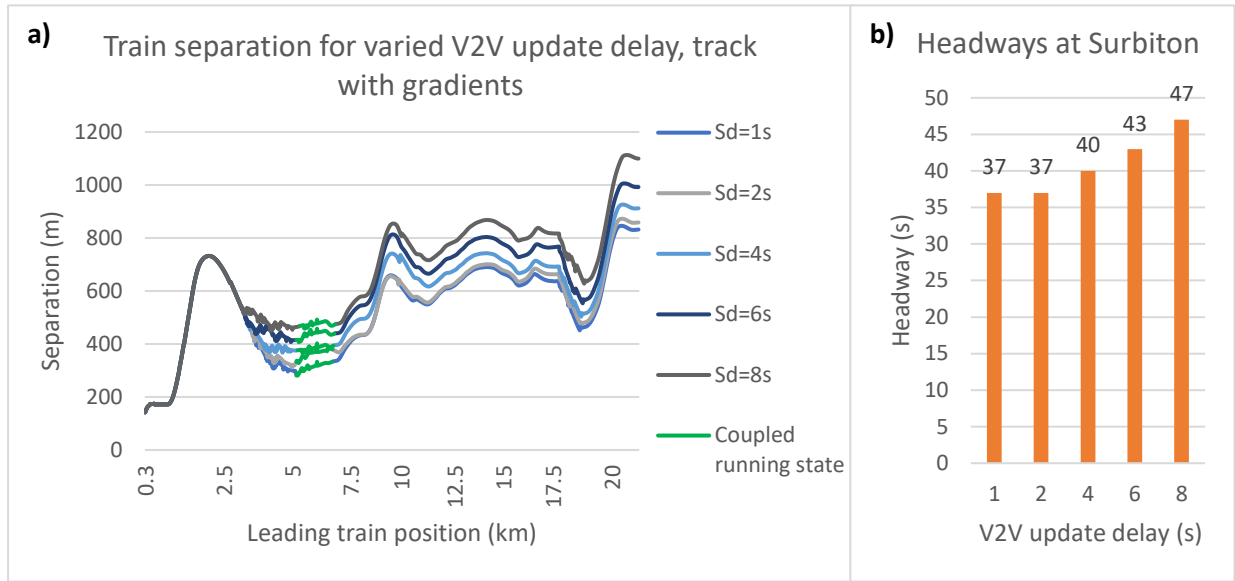


Figure 5.8 Train separation (a) and headways (b) for varied V2V comm. Delay, track with realistic gradient profile

5.4 Train control delay time

Different trains may have different system reaction times. As explained in Chapter 3, the system reaction time is defined as the additional time that is required for the EVC to calculate the dynamic safety margin and update the MA of the train and adjust its speed. Future EVC equipped with ATO are expected to have a very small system reaction time. By default, the train control delay of trains is set to 1 s. In realistic railway operation under Virtual coupling, different trains may have varied system reaction time, or a system degradation might occur, where the system reaction time may be increased. Bearing in mind also that trains will be equipped by GoA 2 during the early stages of Virtual coupling operations, a system degradation might occur, where the train driver might have to take over and continue with the driving tasks. In this subsection, the impact of system reaction time on train headways is investigated. The reaction time is varied between 1 s and 8 s, while the results are presented for both track with 0 gradient and track with the real gradient profile.

As seen in Figure 5.9, considering a flat track, the headway between trains is increased the same as the increase in the control delay time of the following train compared to the base scenario.

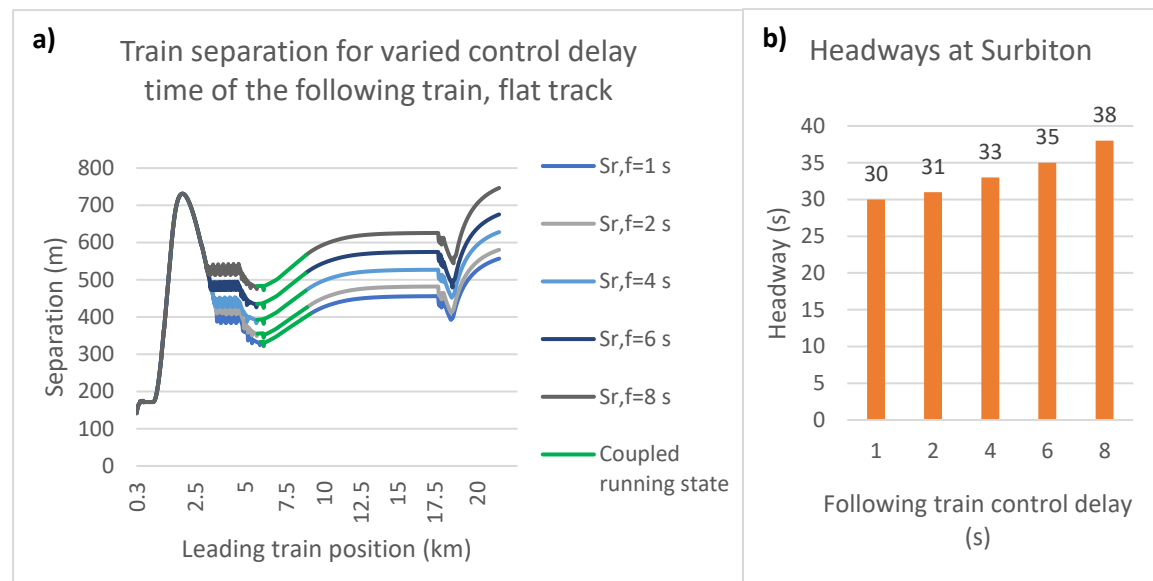


Figure 5.9 Train separation (a) and headways (b) for varied train control delay time of the following train, flat track

Considering the track gradient profile, similar results to Figure 5.9 are obtained in Figure 5.10, since headways are increased along the route. However, considering the realistic track gradient profile, some changes in headways are quite higher than in the case of flat track. For instance, when the update delay is increased from 1 to 2 s, the headway at Surbiton is increased by 2 s.

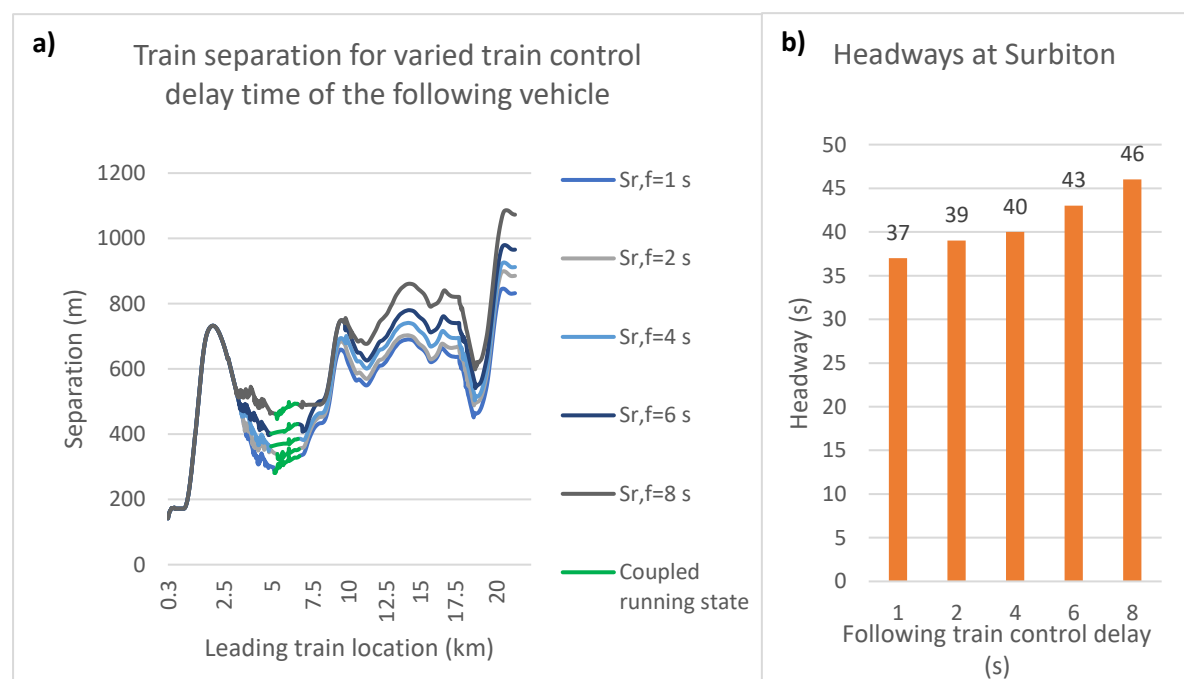


Figure 5.10 Train separation (a) and headways (b) for varied train control delay time of the following train, realistic track gradient profile

5.5 Braking rate

This analysis is based on the critical-safe scenario where the leading train might apply emergency braking at any point along the run due to a possible failure or emergency. Thus, the separation distance that is calculated in real-time by the successor train depends on its own braking performance. Figure 5.11 and Figure 5.12 depict the impact of varied braking factor in the actual train separation, for a track with 0% gradient and the track considering the real gradient profile. As the following train braking factor is increased, the separation distance and consequently the time headways are decreased, bringing additional capacity benefits.

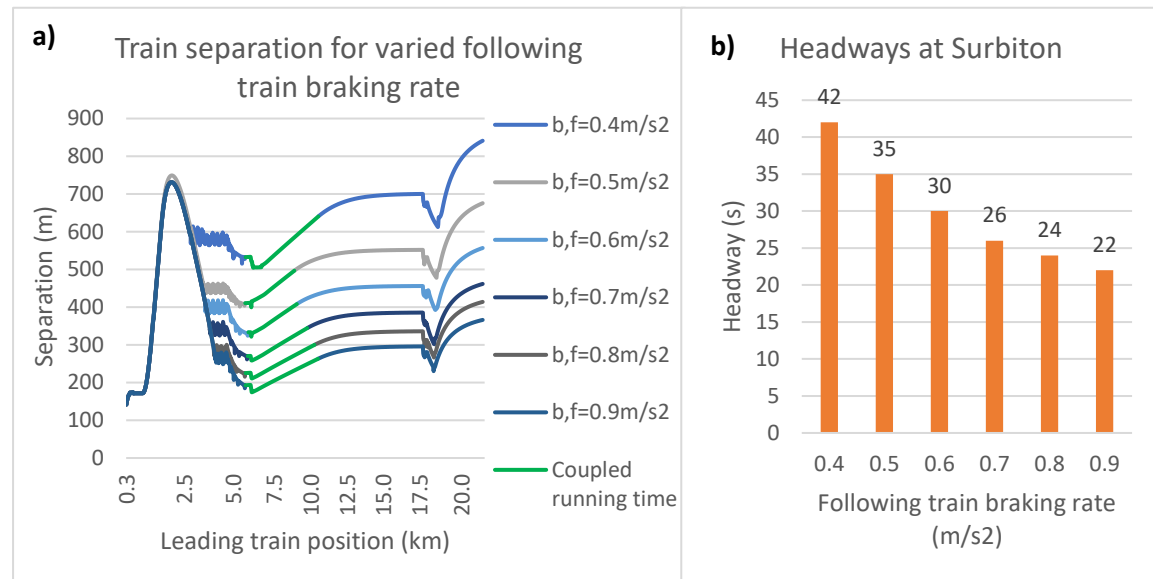


Figure 5.11 Train separation (a) and headways (b) for varied braking rate of the following train, flat track

In both cases, the train headways are decreased as the braking rate of the following train is increased.

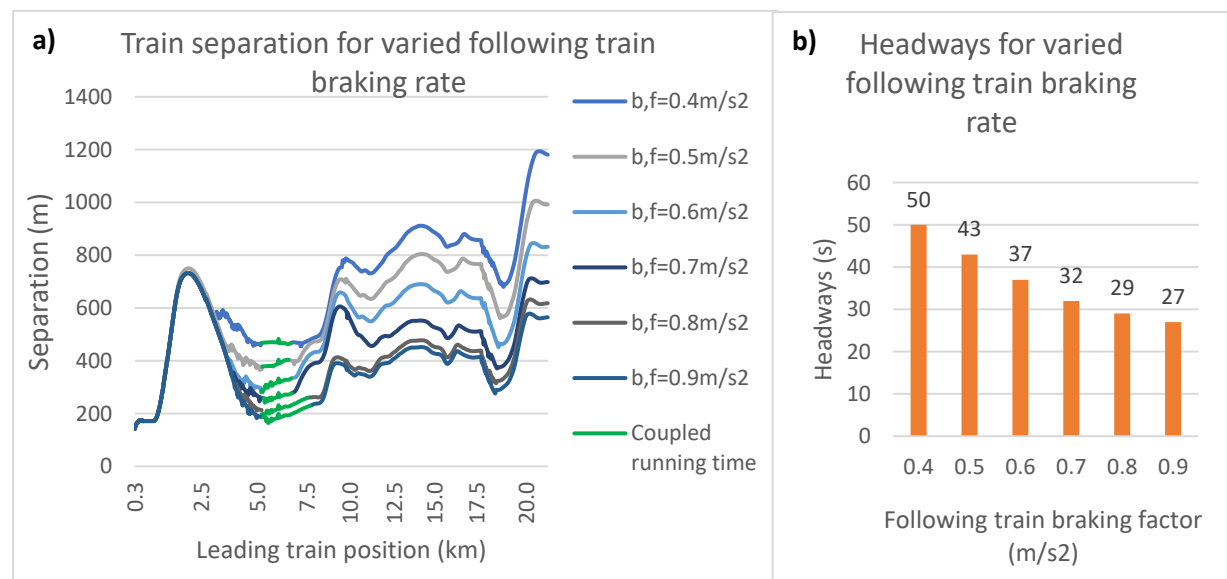


Figure 5.12 Train separation (a) and headways (b) for varied braking rate of the following train, realistic track gradient profile

5.6 Conclusions

This chapter investigated the impact of selected parameters of the multi-state train-following model considering a dynamic safety margin, on the model output, being the train separation and headways at Surbiton station. The determination of coupling criteria, space threshold th_s and speed threshold th_v , influence the coupling and decoupling states of the model. The space threshold impacts a lot the coupled running duration and train headways, while the speed threshold has less significant impact. The values that are selected in this study for these two parameters, both for conducting the sensitivity analysis of the rest selected parameters and the case studies in Chapter 5 are 100 m for the space threshold and 1 km/h for the speed threshold. Increased V2V update delay and train control delay time of the following train lead to an increased safety margin between the trains of the convoy which decreases the corridor capacity. However, the change in headways is proportional to the change in the input change. For trains with equal train control delay times, no changes are anticipated in headways. However, if trains with different reaction times are combined for train convoys formation or in cases where a degradation of the ATO system might happen, capacity benefits might be reduced and should be incorporated in the EVC algorithms. Table 5.2 presents the sensitivity results of the all the parameters that were considered in the sensitivity analysis, while the detailed results of the sensitivity analysis can be found in Appendix B. The significant of its parameter is evaluated based on the mean of the absolute partial derivatives, μ^* and the standard deviation σ , of each parameter variation scenario.

A model parameter with the clearest and highest impact on Virtual coupling operations is the braking factor of the follower train, with the μ^* being around 50. On the contrary, the rest parameters have a lower impact on the model output, as the same metric varies between 0.02 and 1.037. When the braking factor of the following train is increased, then the train headways are lower, since the dynamic safety margin is smaller. In the next chapter emphasis is placed on the formation of convoys by trains with different braking and accelerating capabilities, using data from trains that are currently used on the studied corridor.

Table 5.2 Sensitivity analysis results

Parameter	Flat track		Track with gradients	
	μ_i^*	σ_i	μ_i^*	σ_i
Space threshold (m)	0.02	0.00	0.02	0.01
Speed threshold (km/h)	0.00	0.00	0.79	0.25
V2V update delay (s)	1.08	0.17	0.91	0.63
Following Train control delay (s)	1.04	0.07	1.37	0.44
Following train braking factor (m/s²)	29.80	13.86	49.67	13.25

6 Operational Scenarios

From the sensitivity analysis in Chapter 5, it is shown that the service braking rate of the following train affects the rail line capacity significantly compared to the rest model parameters that were investigated. In this chapter, specific scenarios are simulated to assess the impact of the proposed model in railway capacity. By default, the V2V communication delay is set to 1s and the train control delay time of trains to 1 s as well.

At first, the corridor Waterloo – Surbiton is used to simulate two-train convoy formation using homogeneous and heterogeneous rolling stock, including three train types (suburban, regional and intercity). The selected scenarios validate the strength of VC relative to capacity benefits for Mainline and regional rail, but they also answer to the possible weakness of VC identified by Aoun et al. (2020) regarding the safety risks for combing trainsets with heterogeneous braking capabilities in a train convoy. It is assumed that all these train types can run on the same infrastructure. Simulations are executed for the route considering intermediate stops and plain running without stops. The scenarios are evaluated in terms of train separation, which is then translated to arrival headways at stations in case of the scenarios with stops and to time headways in case no stops are used. For scenarios with stops, three in-between stops are considered between Waterloo and Surbiton, being ClaphamJn, Wimbledon and Raynes Park. Following, the results are compared to the same scenarios under ETCS L3-MB and Virtual coupling considering a constant safety margin of 50 m.

Afterwards, two scenarios of degraded operations are executed on the same route (Waterloo-Surbiton) with one stop at Surbiton. The first scenario of degraded operations investigates the impact of an increase of V2V communication delay after a predefined timestep, while the second scenario represents a driving degradation from ATO GoA 2 to manual driving which implies an increase to the train control delay time of the following train. Furthermore, a first attempt to include a coasting phase in the speed profiles of trains running in a convoy is executed in subsection 6.4.

In the end of the chapter, a scenario of a four-train convoy using heterogenous train types is simulated for the route Waterloo-Surbiton with one stop at Surbiton. The scenario is evaluated in terms of arrival headways between the trains and the train convoy length compared to ETCS L3-MB and Virtual Coupling considering a constant safety margin of 50 m, positioning errors, communication update delay of 1 s and ATO reaction time of 1 s. The rolling stock types that are used in these scenarios are depicted in Figure 6.1, while Table 6.1 contains their attributes. British Class 455 is used as a suburban train, while a British Class 450 as a regional and a British class 220 as an intercity train. Intercity train is having higher acceleration and braking characteristics than the other two train types and the regional has improved characteristics over the commuter trains. That said, the maximum speed of the selected rolling stocks is 33.61 m/s, 44.72 m/s and 55.81 m/s for Br. Class 455, Br. Class 450 and Br. Class 220 respectively.

For the simulation runs under VC with a DSM, the speed and space thresholds are set to 1 km/h and 100 m respectively. In addition, a speed restriction is applied to the leading trains for the first 430 seconds. It is also assumed that trains can already communicate their characteristics prior the coupling commands at distances so that the safety margin is calculated before they are coupled. That said, in the beginning of the route trains run on the corridor under ETCS L3 MB considering a DSM.



Figure 6.1 a) British Class 455 (commuter train), b) British Class 450 (regional train), c) British class 220 (intercity train)

Each vehicle has different attributes, being the mass of the traction unit, m_T (kg), the mass of a single wagon $m_{w,i}$ (kg), number of wagons n_w , maximum speed of the traction unit v_{max} (m/s), service deceleration rate b_s (m/s²), the cross sectional area of vehicles

A_f (m²), the southoff formulae coefficient c_b , the jerk rate J (m/s³) and the total length of the vehicle L (m). All attributes for the three selected train types are listed in Table 6.1.

Table 6.1 Attributes of various rolling stock types

Train type	m_T (kg)	$m_{w,i}$ (kg)	n_w	v_{max} (m/s)	b_s (m/s ²)	A_f (m ²)	c_b	J (m/s ³)	L (m)
Br. Class 455	33988	33988	3	33.61111	0.6	1.45	0.004	0.75	161.84
Br. Class 450	42500	42500	3	44.72222	0.7	1.45	0.004	0.75	163.2
Br. Class 220	46400	46400	3	55.83333	0.8	1.45	0.004	0.75	93.34

Except for the aforementioned attributes, each locomotive is characterized by its own acceleration capability, which is described by tractive effort-speed curves as shown in Figure 6.2. These tractive effort-speed curves are consisted of several parabolas and are mathematically expressed by equation (6.1):

$$F_{Ti}(v) = C_{0,k} + C_{1,k} * v + C_{2,k} * v^2, \quad v_k < v \leq v_{k+1} \quad (6.1)$$

The coefficient describing the parabolas of the tractive effort-speed curve of each locomotive are given in Appendix C.

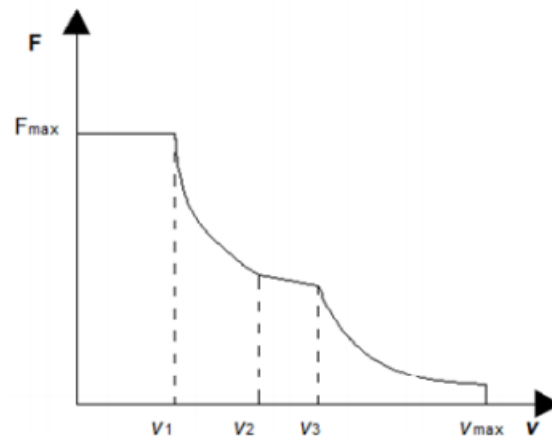


Figure 6.2 Tractive effort-speed curve of a DC unit as a set of parabolas (Quaglietta 2011)

6.1 Homogeneous two-train convoys

In this subchapter, three homogeneous 2-train convoys are simulated on the route Wtl – Sbn with stops and without stops. In each scenario a speed restriction of 18 m/s is applied on the leading train so that the successor can catch up and couple to the leading one.

6.1.1 Suburban trains

Simulating a convoy of a two suburban trains on the route Wtl-Sbn without intermediate stops shows interesting results concerning corridor capacity. In Figure 6.2, it is clearly seen that separation of trains under VC with a DSM approaches the train separation under ETCS L3-MB. More specifically, trains are virtually coupled 30 seconds after the

speed restriction is terminated and stay in coupled running state until ClaphamJn, where they start to decouple unintentionally due to the increased gradient. In terms of headways, VC considering a DSM results to equal headways as ETCS L3 MB, in the end of the route (Surbiton). Under VC without a DSM, capacity benefits can increase up to 57%.



Figure 6.3 Train separation (a), speed difference (b) and headways (c) for Suburban-Suburban, WTL-SBN without stops

When intermediate stops are considered in Figure 6.4, significant benefits are revealed for VC with DSM over ETCS L3 especially at Surbiton and New Raynes Park, where headways are reduced by **60% and 38%** respectively. On the other hand, at Wimbledon, the headway benefit is reduced by 15% compared to ETCS L3 MB. This is justified by the fact that trains reach higher speeds when the distance between stops is relatively high. Between Clapham junction and Wimbledon, the dynamic safety margin is increased compared to route segments with smaller distance. For instance, between Wimbledon and Raynes Park, the train separation is similar to the one observed when the VC model without a DSM is applied.



Figure 6.4 Train separation (a), speed difference (b) and headways (c) for Suburban-Suburban, WTL-SBN with stops

6.1.2 Regional trains

In the previous section it is proved that forming a 2-train convoy of suburban trains (Br. Class 455) on main line without stops does not bring benefits compared to ETCS L3 MB. When, train types with improved characteristics are simulated between Wtl and Sbn without stops, the proposed model seems to outperform the capacity benefits under an ETCS L3 MB, as it is depicted in Figure 6.5. Under VC without a DSM, headways are significantly decreased along the route by **67%** compared to VC with a DSM.

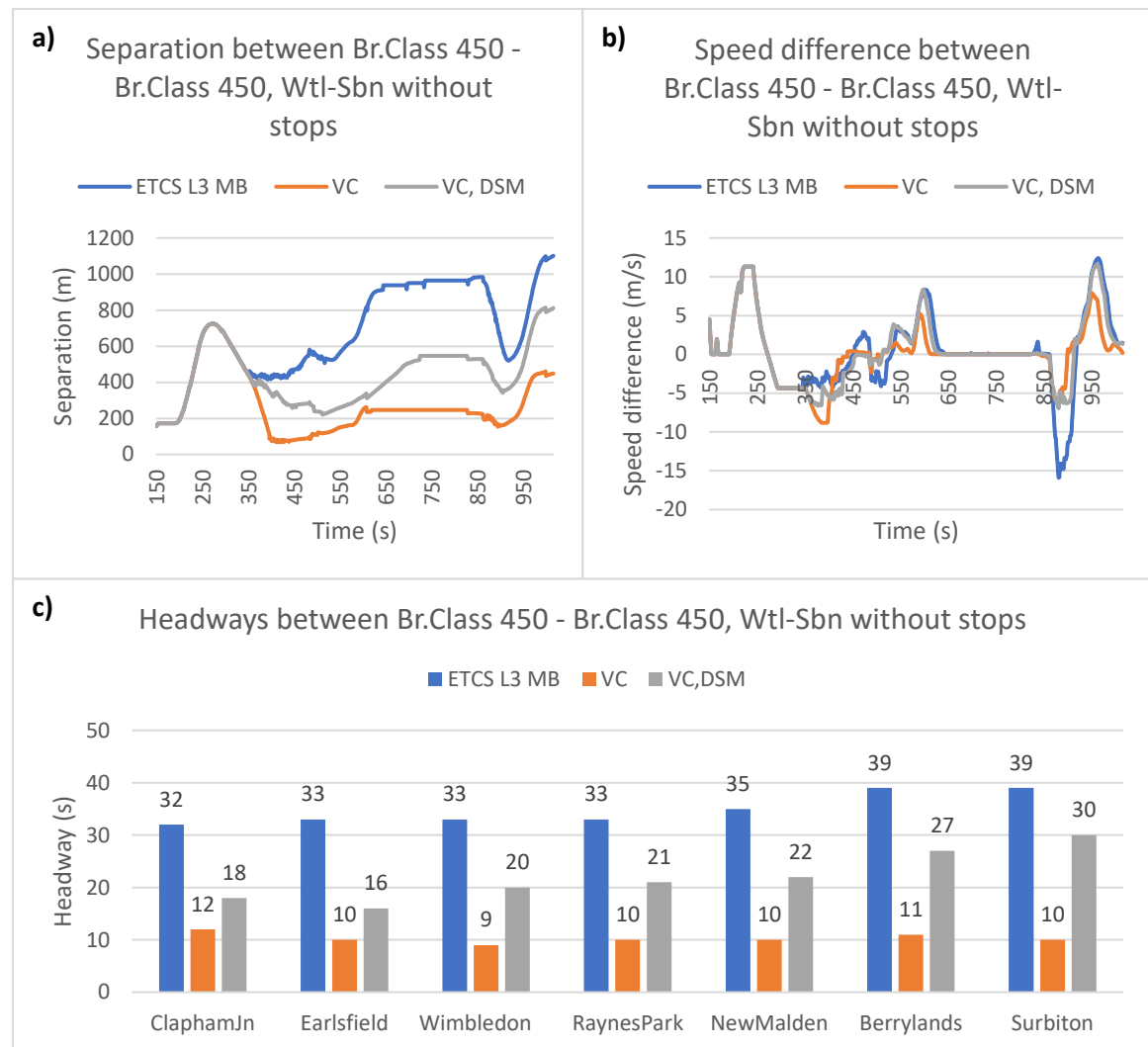


Figure 6.5 Train separation (a), speed difference (b) and headways (c) for Regional-Regional, WTL-SBN without stops

Regarding the same route with stops (Figure 6.6), the convoy formation of two regional trains, shows varied capacity benefits at various locations, with the highest being at Raynes Park (**40%**), Clapham Junction (**43%**) and then Surbiton where the headway is reduced by **59%**. Moreover, VC with DSM approaches the capacity benefits of VC without a DSM for the route segment between Wimbledon and Raynes Park, where trains do not maintain high speeds for a long time. However, until Wimbledon station, not significant benefits of the proposed model are identified compared to ETCS L3 MB.

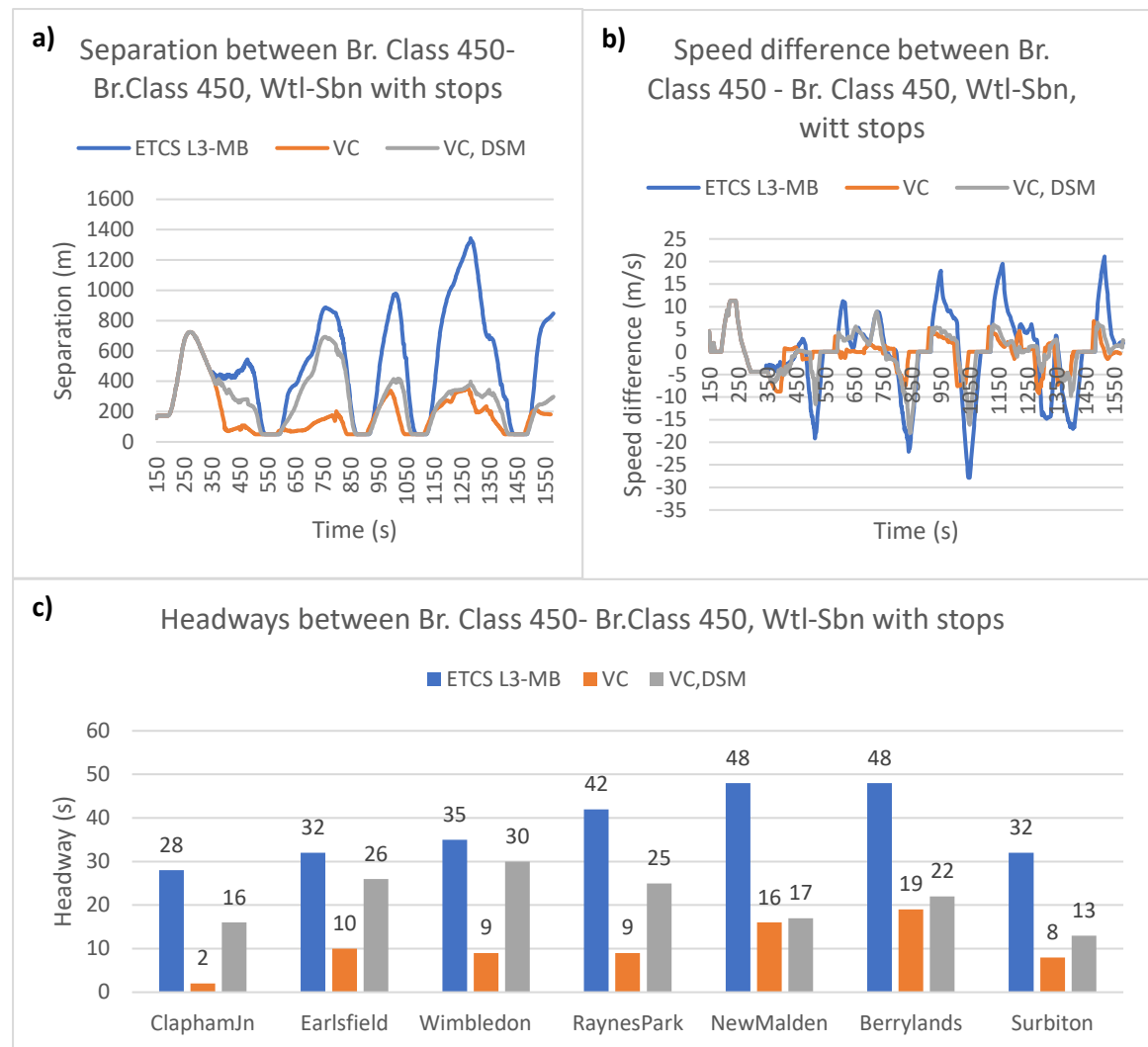


Figure 6.6 Train separation (a), speed difference (b) and headways (c) for Regional-Regional, WTL-SBN with stops

6.1.3 Intercity trains

Figure 6.7 shows the capacity benefits of intercity trains without stops. At Surbiton, the arrival headway of intercity trains running under VC considering a DSM is reduced by **35%** compared to ETCS L3 MB. Using the initial VC train-following model, headways can even be reduced by **68 %** more than the VC approach considering a DSM.

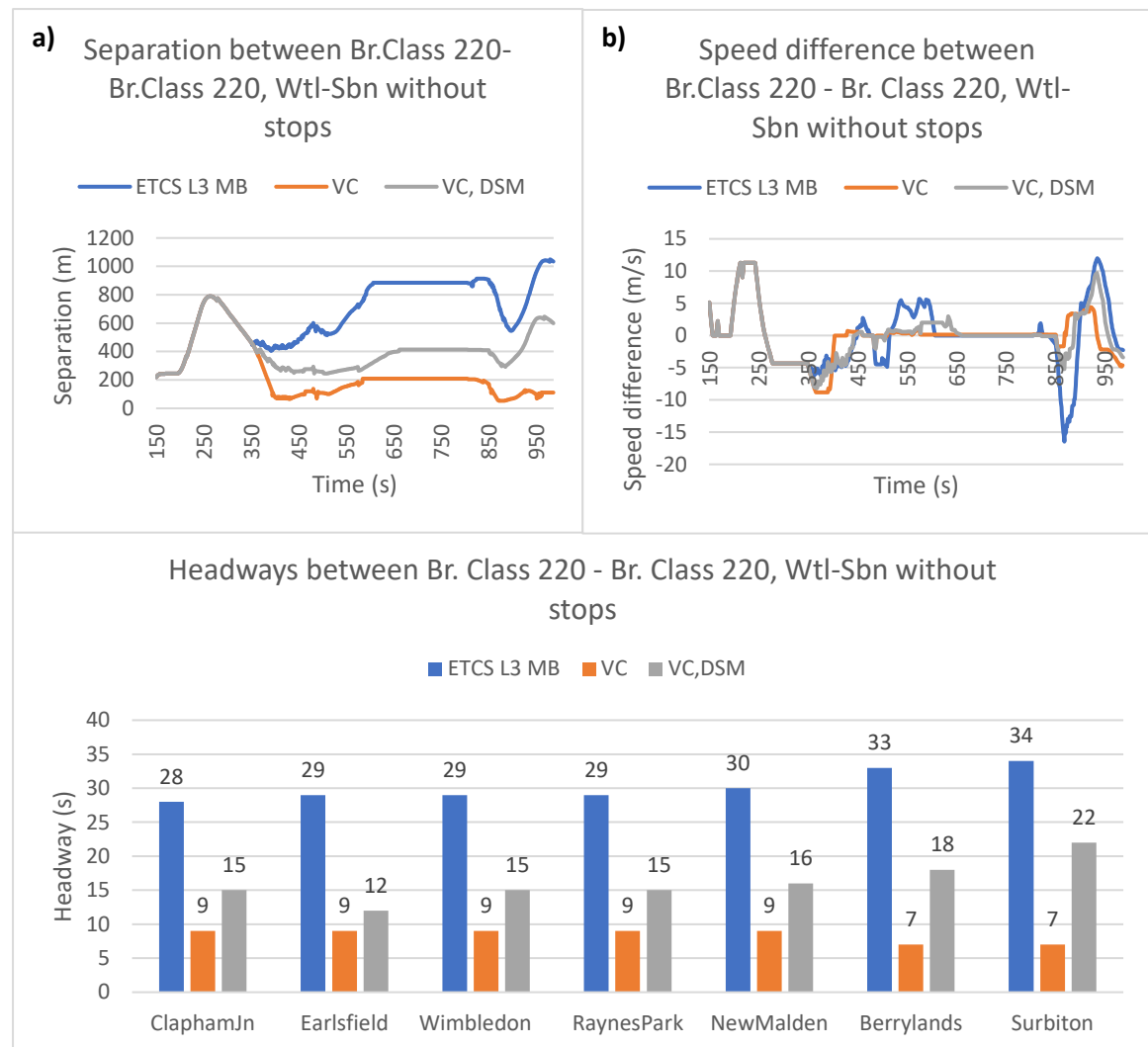


Figure 6.7 Train separation (a), speed difference (b) and headways (c) for Intercity-Intercity, WTL-SBN without stops

Considering the route of Wbn-Sbn with stops, even higher capacity benefits are identified by using intercity trains that are characterized by improved acceleration and braking characteristics. As seen in Figure 6.8, the highest capacity gain is observed at New Malden and Raynes Park, where headway is reduced by **60%** compared to ETCS L3 MB, while it can be reduced by up to **90%** (Wimbledon) if the VC model without a DSM is applied. The lowest headway benefits are observed at Surbiton station, where the headway is reduced by **31%** compared to ETCS L3 MB. Using VC with a DSM, the i train headways fluctuate between 14 and 22 s, which is safer than the headways considering a VC without a DSM, which fluctuate between 2 and 9 s.

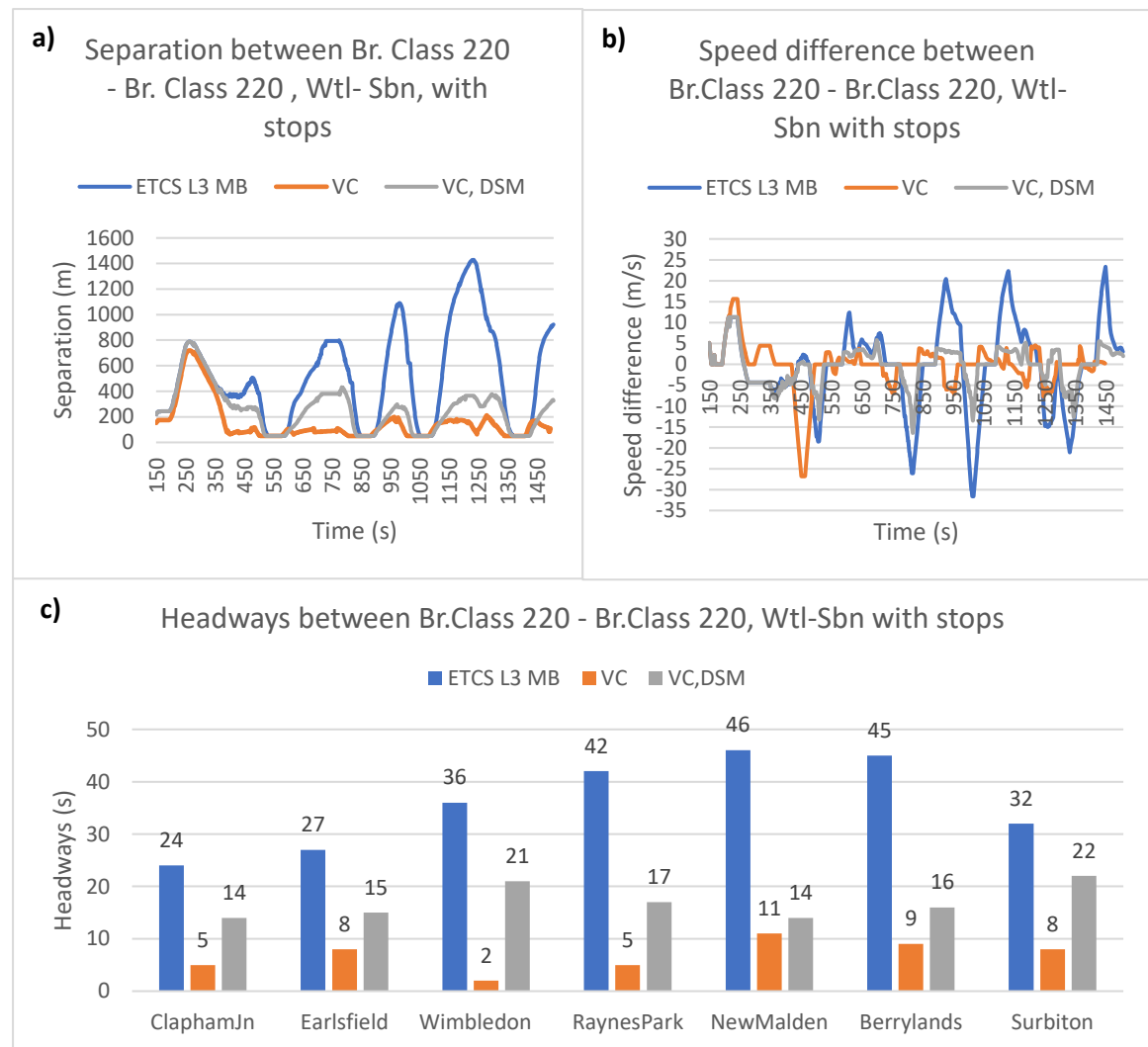


Figure 6.8 Train separation (a), speed difference (b) and headways (c) for Intercity-Intercity, WTL-SBN with stops

6.2 Heterogeneous two-train convoys

By applying a dynamic safety margin, different train types can be used to form a train convoy, while keeping a safety separation distance in-between. This section presents the results of simulations using different rolling stock types to form 2-train convoys. Four train convoy combinations have been simulated, namely:

- Suburban trains following regional trains
- Regional trains following suburban trains
- Intercity trains following regional trains
- Regional trains following intercity trains

6.2.1 Convoy of a suburban train following a regional train

When a suburban train follows a regional train, no additional capacity benefits are identified compared to ETCS L3 MB between Waterloo and Surbiton without stops. As seen in Figure 6.9, the headways at Surbiton are reduced by only **5%**. On the contrary, train headways at Surbiton are highly reduced (**81%**) if the model without a DSM is applied. This is happening since the slower following train is allowed to approach the

faster leading train and run as a convoy with it at a closer distance, which is increased along the route because the leading train has better acceleration capabilities.

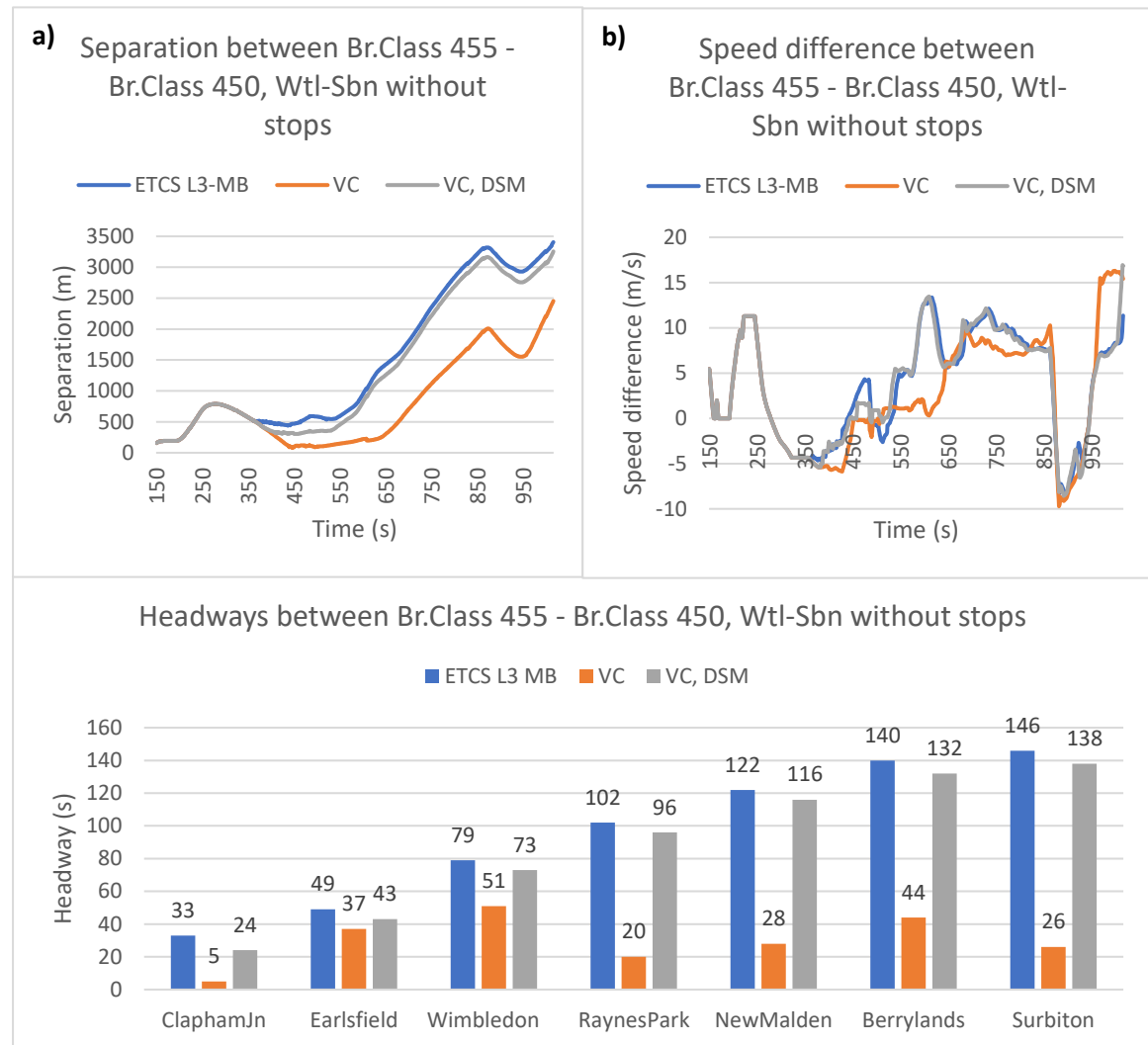


Figure 6.9 Train separation (a), speed difference (b) and headways (c) Regional-Suburban WTL-SBN without stops

Figure 6.10 presents the simulation results of a suburban train following a regional train between Waterloo and Surbiton with intermediate stops. The proposed model leads a headway reduction of **32%** at Clapham junction compared to ETCS L3 MB. The arrival headway at Clapham junction is increased relative to the VC model without a DSM, since the following train is forced to keep a higher safety distance when the VC model with a DSM is used. However, after the Clapham junction and for the rest route length, the train headways of the proposed model are equal to the headways that derive from the VC model without a DSM, proving that the VC model is already safe for this rolling stock combination. This is justified by the fact that the following train cannot catch up with the leading train due to its traction power limitations. Compared to ETCS L3 MB, the proposed model can bring capacity benefits up to **84%** at Surbiton.

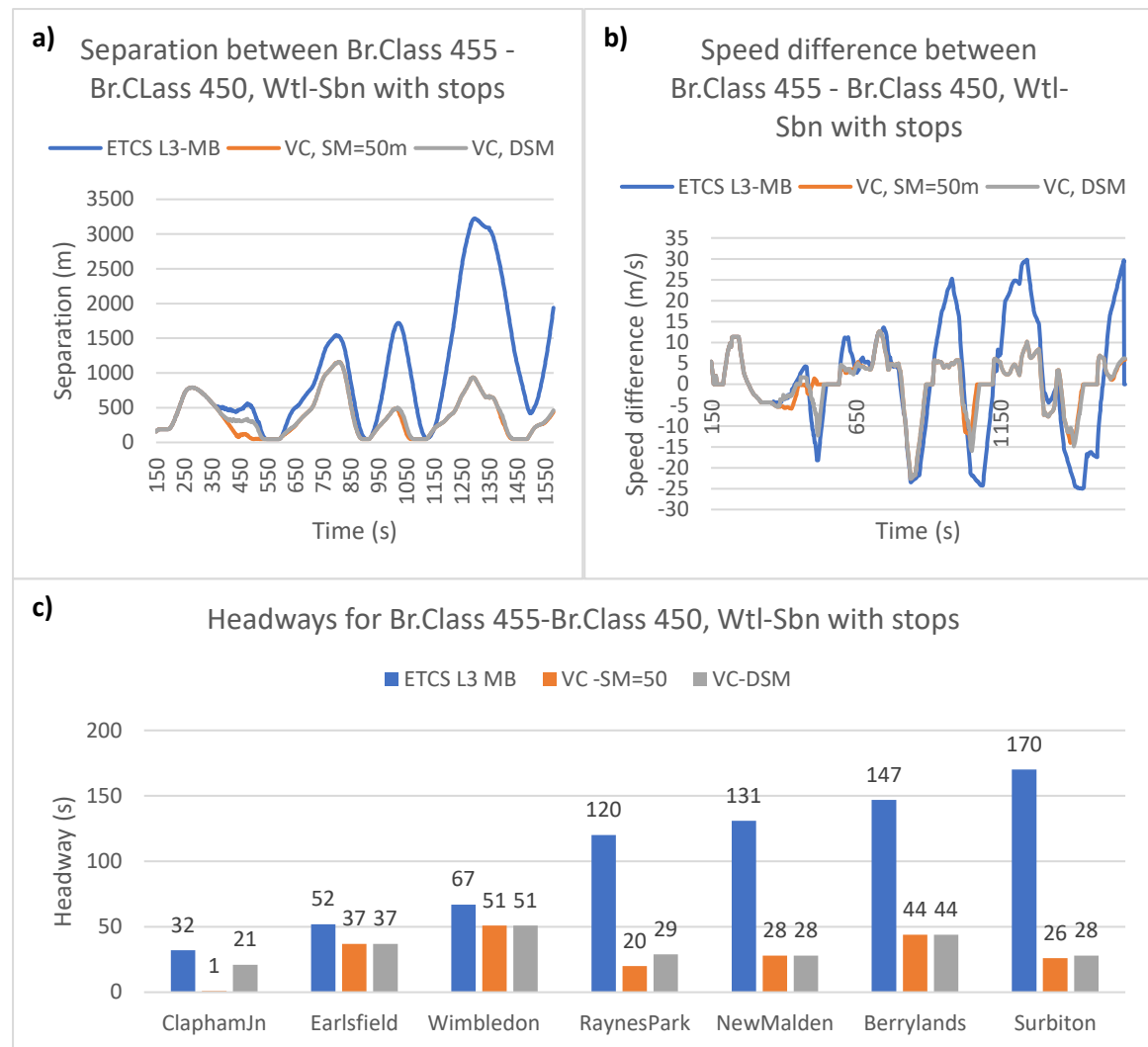


Figure 6.10 Train separation (a), speed difference (b) and headways (c) Regional-Suburban, WTL-SBN with stops

6.2.2 Convoy of a regional train following a suburban train

In this scenario, a regional train is set to follow a suburban train. Due to their different capabilities, the speed difference diagram shows a greater noise compared to the cases of homogeneous train convoys. By using a DSM, headways are increased by 8-14 seconds, ensuring a safety separation distance between trains along the route. Compared to ETCS L3 MB, headway is reduced by **22%** at Surbiton (Figure 6.11), while it can be reduced by **48%** more in case the MTSF is applied.

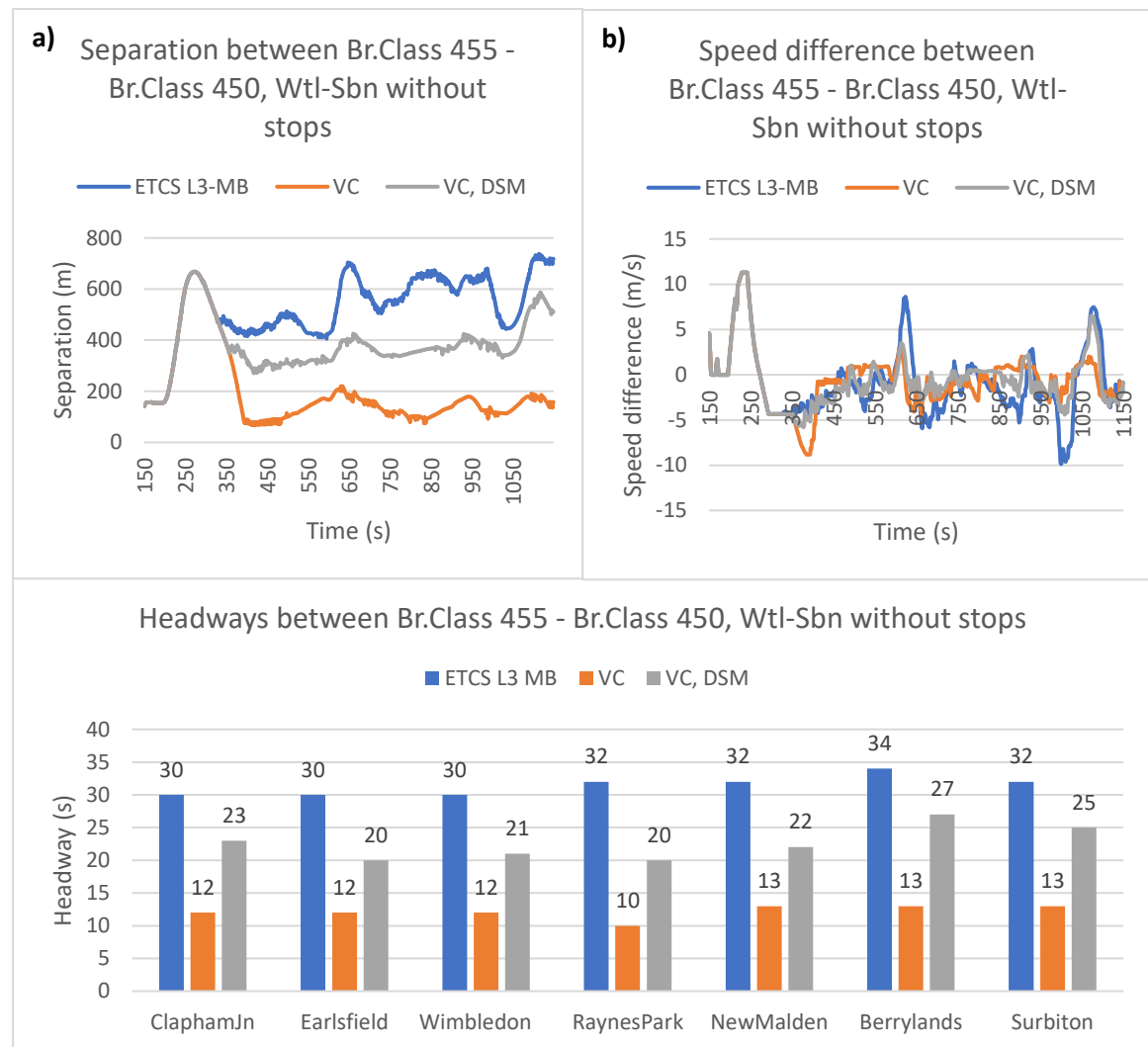


Figure 6.11 Train separation (a), speed difference (b) and headways (c) for Suburban-Regional WTL-SBN without stops

By setting a Br. Class 450 following a Br.Class 455, even higher capacity benefits are observed on the route Wtl-Sbn with stops (Figure 6.12). Since the successor train has better acceleration and braking characteristics, it can follow at a closer proximity its predecessor. The highest benefits are identified at Surbiton (**67%**) while the lowest at Clapham junction (**29%**). On average, the headways are reduced by 44% compared to ETCS L3 MB. If the initial MTSF model is applied headways can be reduced by 77% more in average.



Figure 6.12 Train separation (a), speed difference (b) and headways (c) for Suburban-Regional, WTL-SBN with stops

6.2.3 Convoy of an intercity train following a regional train

Similar to 6.2.1, an intercity train following a regional one can reveal significant capacity benefits, as headways are reduced at Surbiton by **41%** compared to ETCS L3 MB and only increased by 7 seconds compared to VC without a DSM (Figure 6.13).

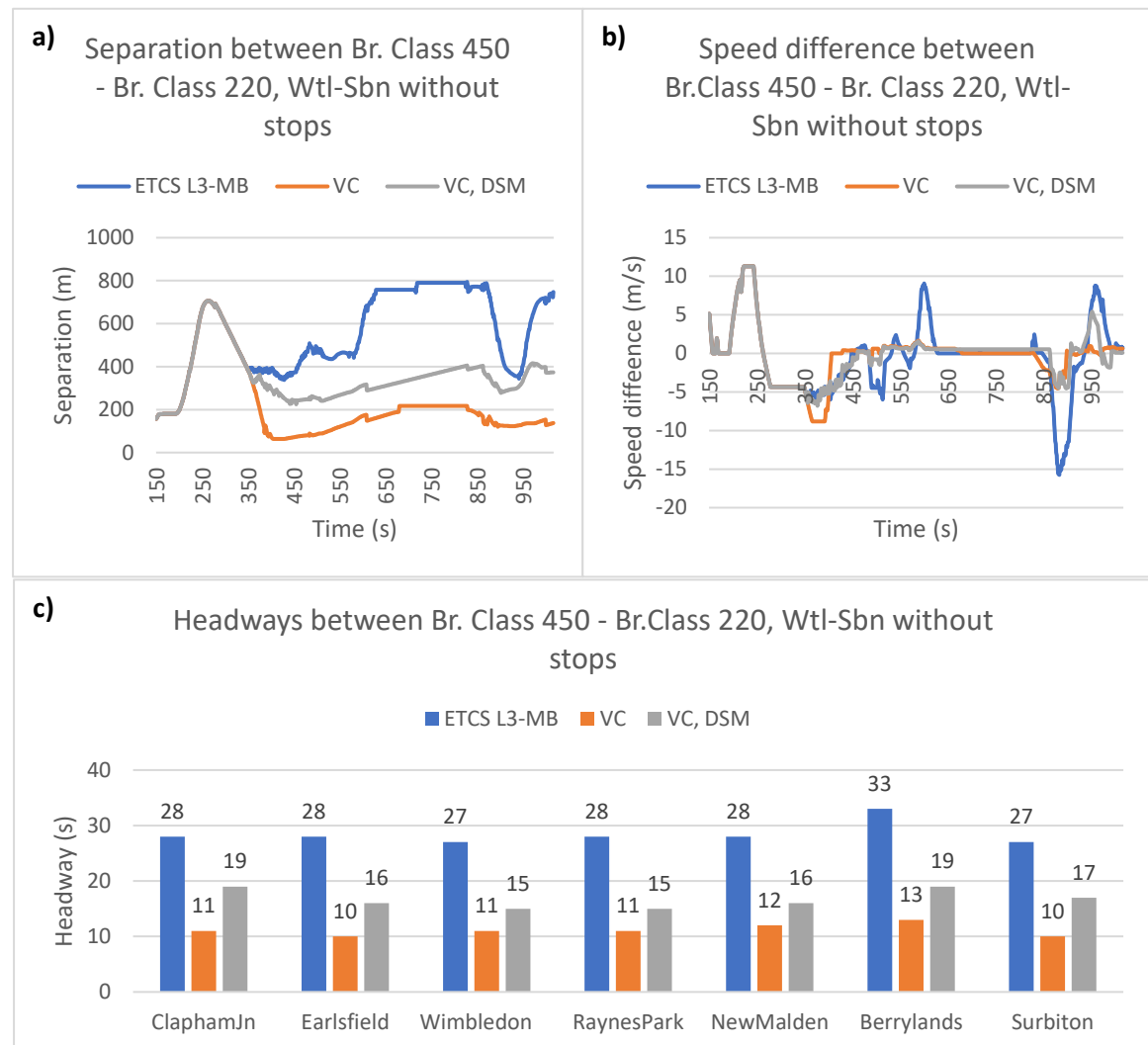


Figure 6.13 Train separation (a), speed difference (b) and headways (c) for Regional-Intercity, WTL-SBN without stops

Regarding the service with stops, the highest headway benefits are identified at Surbiton (**65%**) and Raynes Park (**62%**) while the lowest at Wimbledon (30%) compared to ETCS L3 MB, as seen in Figure 6.14. The VC model without a DSM promises benefits up to 78% at Wimbledon and Surbiton compared to the results of VC considering a DSM.

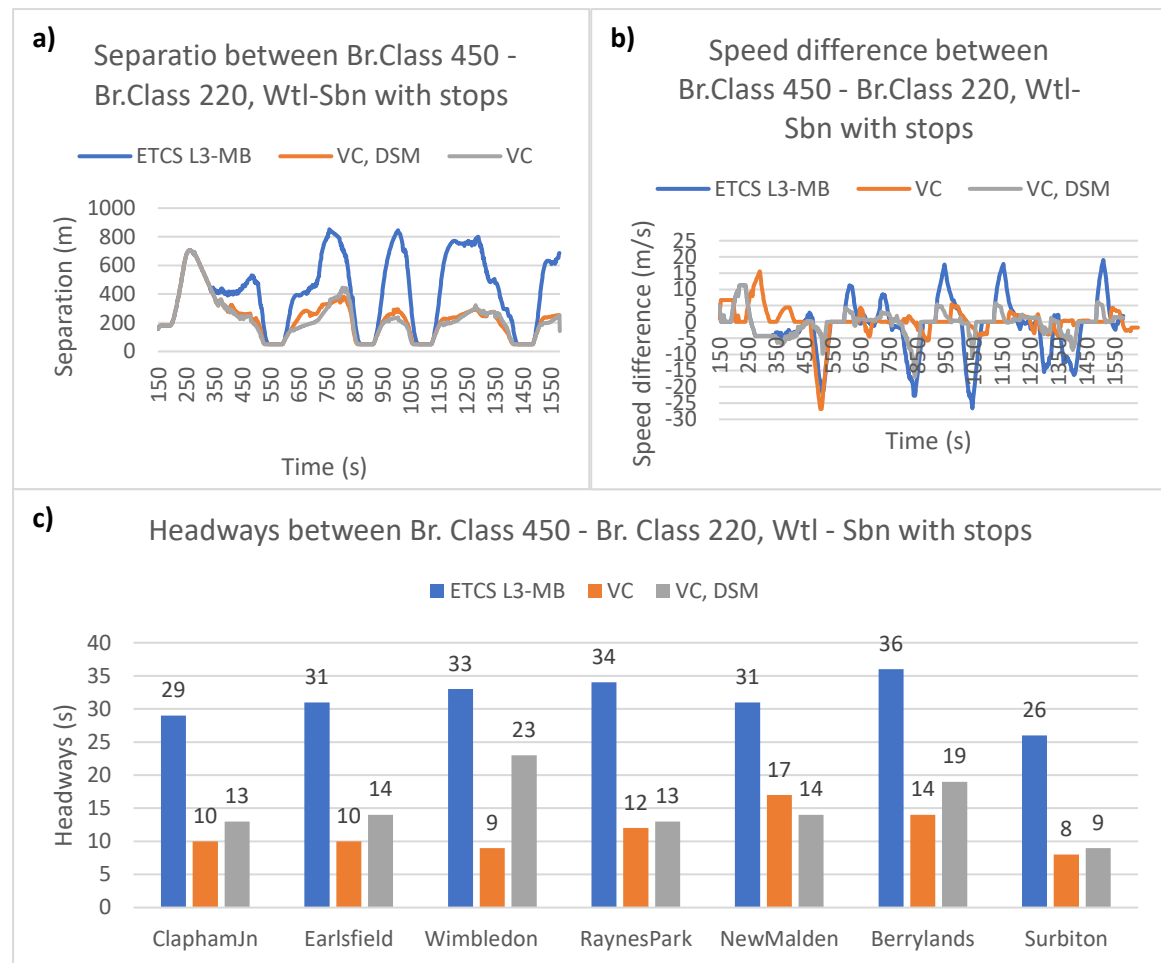


Figure 6.14 Train separation (a), speed difference (b) and headways (c) for Regional-Intercity, WTL-SBN with stops

6.2.4 Convoy of a regional train following an intercity train

The integration of the DSM has significant impact on the corridor capacity since the train separation approaches the train separation when ETCS L3 MB is applied. As seen in Figure 6.15, arrival headways are slightly reduced along the route, while in the end of the route a capacity benefit of only 6% is recorded. This is justified on the fact that the DSM is high since the braking factor of the regional train is lower than the leading intercity, while, both trains have similar acceleration characteristics.

Considering the route with stops, the proposed model shows similar results to the outcome of the VC without a DSM, indicating that the constant safety margin already fulfills the safety requirement for most segments of the route (Figure 6.16). By applying the DSM the arrival headway at the final destination is slightly increased by 7%. The highest capacity gains are identified at Raynes Park (71%) and Surbiton (56%). Although the VC model considering a implies higher headways at most of the selected positions, at New Malden and Berryland junction, the proposed model seems to reduce the headway compared to the initial model without a DSM. This could be happening due to the fact that trains may be coupled for longer time under VC without a DSM, or it could be happening due to errors in the software that can be investigated.

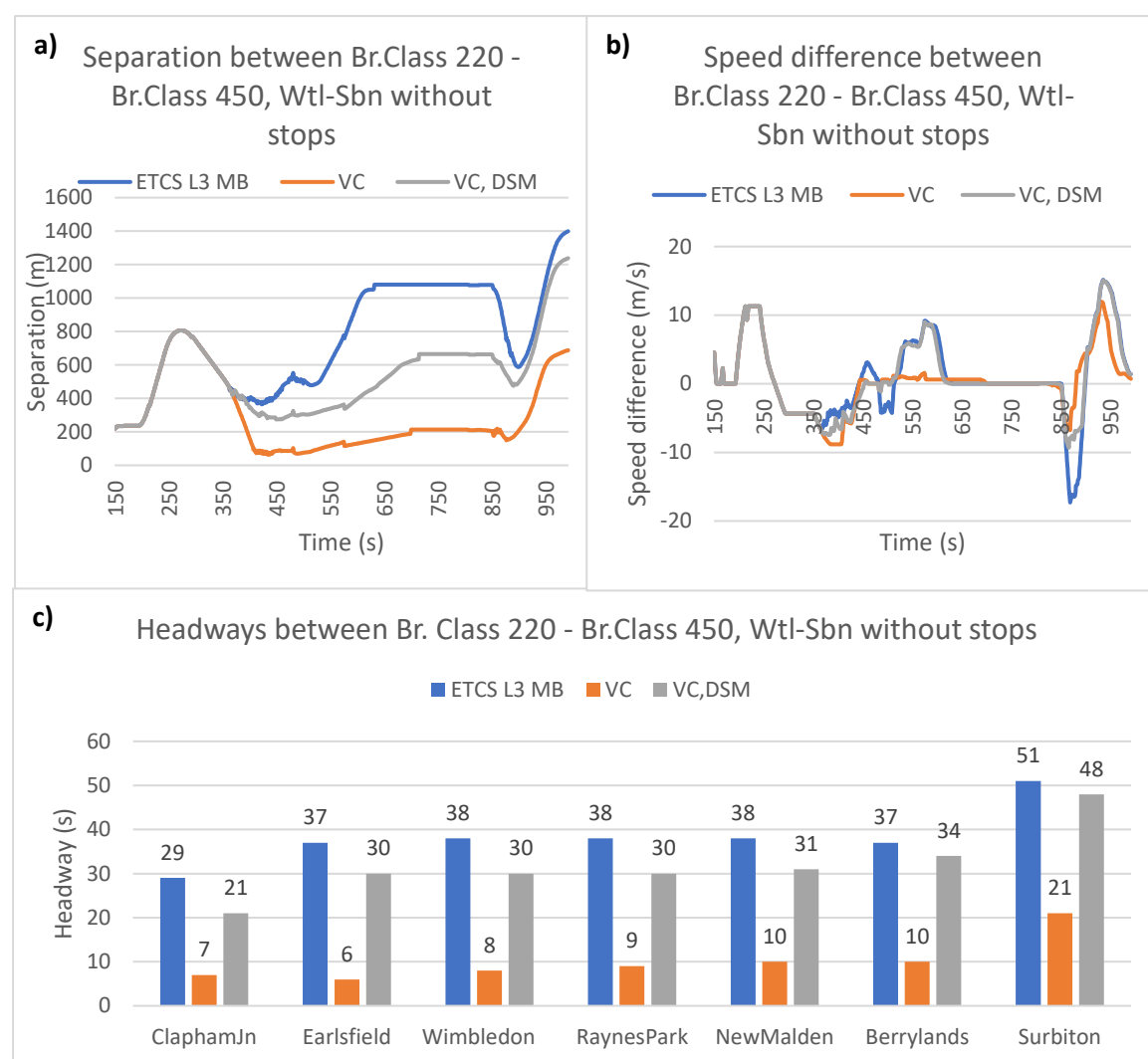


Figure 6.15 Train separation (a), speed difference (b) and headways (c) for Intercity-Regional, WTL-SBN without stops

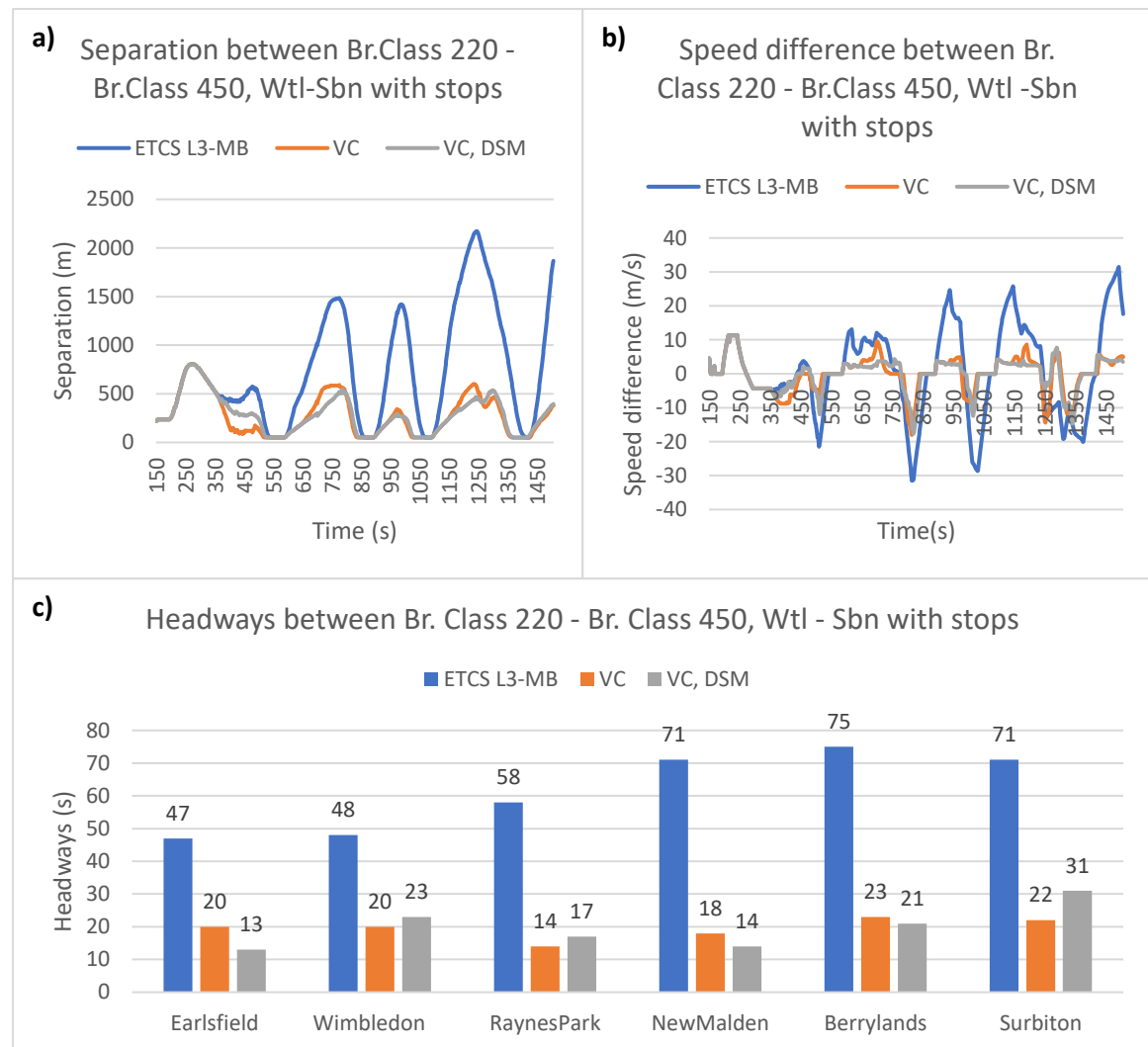


Figure 6.16 Train separation (a), speed difference (b) and headways (c) for Intercity-Regional, WTL-SBN with stops

6.3 Degraded operations scenarios

In this section two system degradation scenarios are simulated. In the first, the V2V communication delay degrades after Wimbledon station, which implies an increase in V2V update delay time from 1 s to 3 s. The second scenario represents a driving degradation scenario, where the train control of the second train switches to manual mode, implying an increase of train control delay time from 1 to 6 s. For both scenarios, a train of Br. Class 220 is set to depart 50 seconds after the departure of a regional train Br. Class 450. The train separation as well as the DSM for each of these two scenarios is depicted in Appendix D.

6.3.1 V2V Communication layer degradation

By default, the V2V communication delay, which is the message transfer delay from the leading train to the following, is set to 1 s. It is assumed that the update delay from the leading to the following train increases from 1 second to 3 seconds between ClaphamJn and Earsfield and remains to 3 s till the end of the route. Figure 6.17 shows the train separation under the base and the degraded operation scenario. By an increase of 2s on the update delay, the arrival headway is increased twice by 4s.

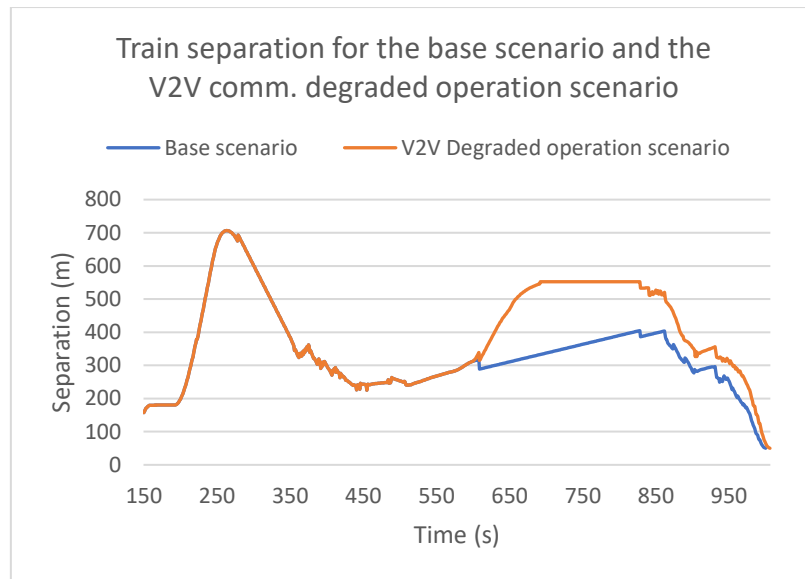


Figure 6.17 Train separation under V2V Communication delay scenario

6.3.2 Train driving degradation scenario

In this scenario, it is assumed that between ClaphamJn and Earsfield, the train driving falls from ATO GoA 2 to manual driving, thus the driver must take over. Due to this degradation, the system reaction time is increased from 1 second to 6 seconds. Thus, the safety margin is increased along with the separation distance between the leading and the following train (Figure 6.18). The transition from ATO to manual driving assumes that the driver will brake as the system degrades in order to bring the separation under the supervised dynamic safety margin. In terms of arrival headways at Surbiton station, the headway in the degradation scenario is increased by 6 seconds, which is equal to the driving reaction time increase of the following train.

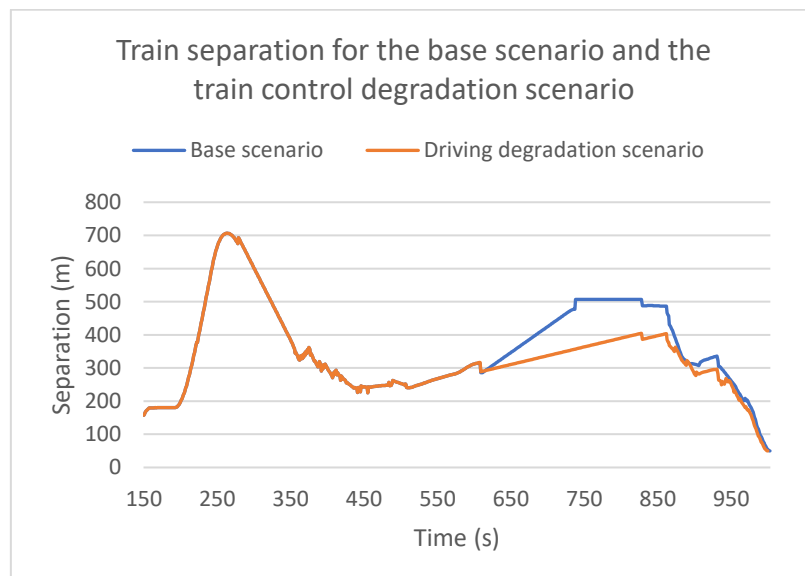


Figure 6.18 Train separation under driving degradation scenario

6.4 Coasting phase

Since ATO is considered as a vital module for next generation signalling concepts such as MB and VC, coasting can bring additional energy savings. In this section, a coasting phase is introduced in the simulation under Virtual coupling considering the DSM. The coasting phase is inserted in the running time model as an acceleration phase, where the tractive effort is set to zero, therefore the train decelerates due to track and motion resistances. A 2-train homogenous convoy of 2 Br. Class 455 (suburban trains) is set to run between Wtl and Sbn with intermediate stops at ClaphamJn, Wimbledon, Raynes Park and Surbiton. Trains are assumed to apply coasting for 1 km before braking to stop at the scheduled stops. Figure shows the separation distance between trains, translated to headways at the scheduled stops, as well as the speed differences for the the model considering a coasting phase and the model with a DSM without coasting. Although the speed profile is not optimized, it is shown that a coasting phase can be integrated in the model, bringing **18%** energy savings. According to Figure 6.19, headways changes are varied for the stops, with the highest headway increase being at Surbiton (7s). It should be noted that this scenario is a first preliminary test of integrating coasting in the developed model. A more holistic and sophisticated approach of coasting should be followed to assess the impact of coasting on VC operations, considering also several rolling stock and track characteristics.

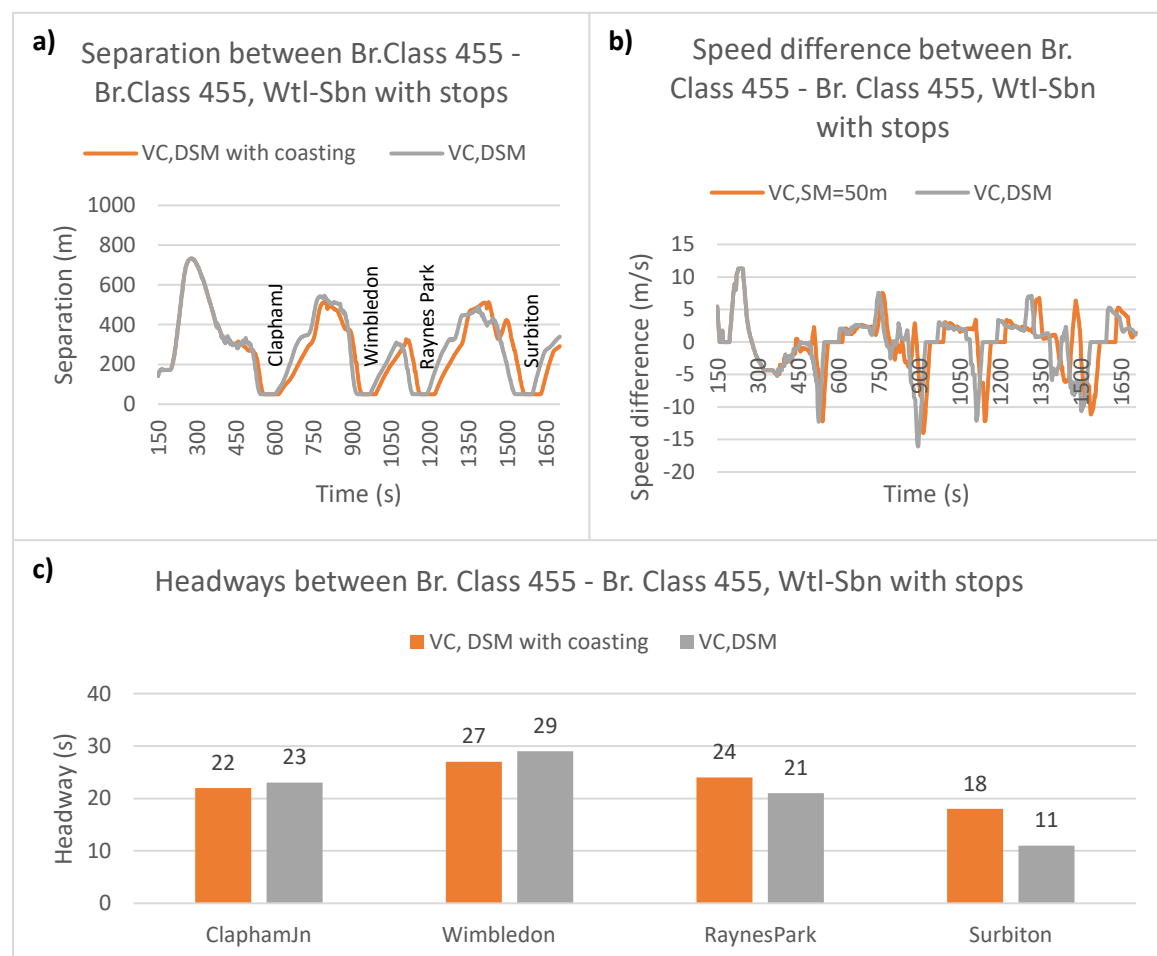


Figure 6.19 Train separation (a), speed difference (b) and headways (c) for Suburban-Suburban, WTL-SBN with stops including coasting

6.5 Heterogeneous four-train convoy formation

In this scenario, a heterogeneous train convoy of four trains is formed. All trains depart from Waterloo station with a departure headway of 50 seconds, with a destination of Surbiton station without intermediate stops. Surbiton station has two platforms of a length about 350 m, thus the first two trains of the convoy use platform 1 and the next two trains the second platform. Therefore, the junction at Berryland is changed after the first two trains have passed, so that the following two trains can change tracks and stop at the second platform. Different rolling stocks are used to form the convoy, with the leading train being a British class 455 (suburban train), the following train a British class 450 (regional train), the third being a British class 220 (intercity train) which is followed by a British class 450 (regional train). In addition, a speed restriction of 64,8 km/h for the first 4,66 km of the route is imposed to the first train, so that the following trains can reach the predecessor trains and form the convoy. At first, the scenario is simulated based on the VC with DSM, which is afterwards repeated under ETCS L3 MB and the former VC model without a DSM. Positioning errors, the communication delay and the control delay time are also considered in the case of ETCS L3 MB and VC without a DSM.

By applying Virtual coupling, each train communicates its parameters to the following, inheriting the predecessor-follower communication topology from platooning in the automotive sector (Figure 6.20). The difference between the two versions of VC is that in the case of DSM, a different safety margin is computed at each timestep between each train couple. Thus, the trains are always outdistanced by a safety distance that is enough for the following train to stop in time applying normal braking, in case the predecessor train applies emergency braking.

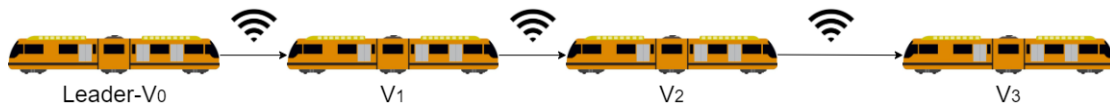


Figure 6.20 Communication topology of the four-train convoy

Figure 6.21 shows the trajectories of the trains of the said convoy under ETCS L3 MB, VC and VC considering a dynamic safety margin, while the DSM between each train couple of the convoy is depicted in Appendix D. In Figure 6.21b, the separation distance between the trains of the convoy is depicted. The smallest separation distance is shown to be kept between the second and the third train of the convoy (B.Class 450 – B. Class 220) which verifies the case in 7.1., stating that the separation distance decreases when trains with better attributes are utilized. In the same line of reasoning, the separation distance is higher for a regional train following an intercity train (B. Class 220 – B.Class 450) . The same is depicted for the same train convoy under ETCS L3 Moving block and VC. It is clear that with the proposed model separation distance are shorter than in the case of ETCS L3 MB, where separation distance are higher and similar between each two trains. Using the VC model without a DSM, the separation distances are kept below 200m indicating a non-safe operation, while with the proposed model, the separation distance are always higher than 200 m.



Figure 6.21 Train trajectories (a,b,c) and train separations between trains (d,e,f) for VC , VC considering a DSM and ETCS L3 MB, WTL-SBN with 1 stop at SBN

Figure 6.22 depicts the train convoy length from the time the fourth train enters the infrastructure. The train trajectories and the separation distances within the 4-train convoy for each signalling approach are presented in Figure 50. The capacity benefits are evaluated in terms of headways at Berryland junction which is the last common point of the route shared by all 4 trains. An indicator for the performance of VC is the train-convoy length, computed as in (25).

$$\text{Train Convoy Length} = S_{\text{leader}} - S_n - L_n \quad (6.2)$$

, where S_{leader} is the front position of the leading train of the convoy, S_n the position of the last train of the convoy and L_n the length of the last train of the convoy.

Figure 6.22 illustrates the total convoy length (leading train head– last train consist tail) from the time instant the tail of the 4th train passes Waterloo station until the moment the head of the 1st train passes the Berryland junction, where the train split to different routes.

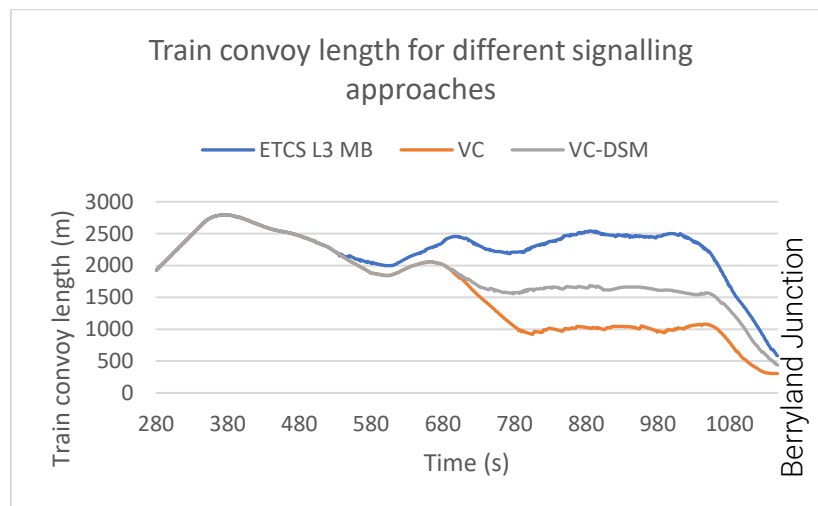


Figure 6.22 Total length of the train convoy for different signaling approaches

Although, the infrastructure occupation of the proposed model does not significantly differ from the occupation under ETCS L3-MB, the same does not hold for arrival headways at Surbiton station.

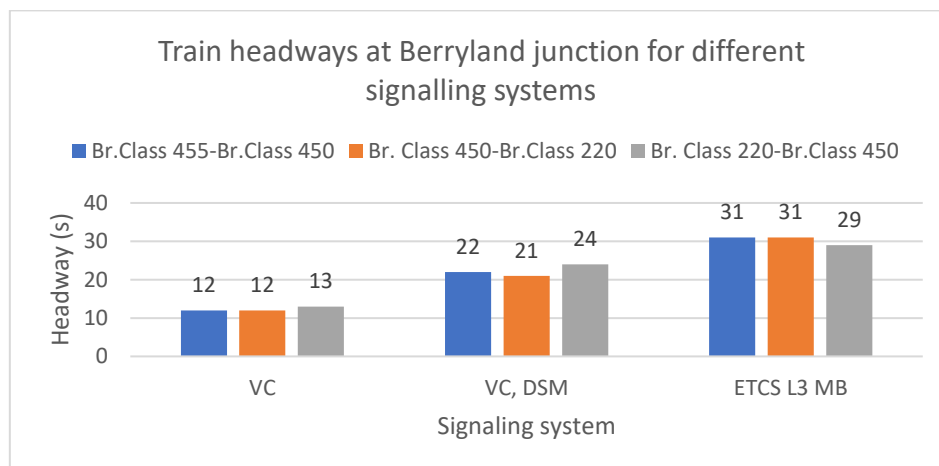


Figure 6.23 Headways for the four-train convoy (Sb-Re-Ic-Re) under different signalling systems, WTL-SBN

As depicted in Figure 6.23, applying a dynamic safety margin, the arrival headways between the different train consists of the convoy at Surbiton are reduced significantly by **29%, 32%, 17%**, compared to the headways under ETCS L3 MB. The arrival headways are considered as the time difference between the arrival of the 1st (leading train) and the n that follows. However, when a constant safety margin of 50 meters is applied, headways can be reduced up to **61%, 61%, 55%** respectively. However, this implies that there is zero possibility for the predecessor vehicle to apply emergency braking. The total travel time of the trains using a DSM is reduced by 47 seconds compared to the ETCS L3 MB.

6.6 Conclusions

Capacity benefits of VC with a dynamic safety margin vary for different rolling stock types. As far as homogenous trains are concerned, the proposed model brings no additional benefits for suburban trains in open track compared to ETCS L3 MB. For route without stops, trains with improved characteristics promise higher capacity benefits, up to 41% compared to ETCS L3 MB (Table 6.2). Capacity benefits can be increased even more, up to 68% (for intercity trains) if the initial VC MSTF model is applied. On the other hand, considering routes with stops, all train combinations for VC are beneficial from a capacity aspect. As far as homogenous train convoys are concerned, on average capacity benefits are higher for trains having better acceleration and braking characteristics. The combination of different rolling stock, especially regional and intercity is proved to be beneficial for VC considering a DSM, as it promises capacity benefits up to 84% for slow trains following faster trains and up to 67% when faster trains follow slower trains (Table 6.3). For the initial VC model considering a fixed safety margin and positioning errors, capacity benefits are higher for regional and intercity trains and for faster trains following slower trains, as seen in Table 6.4.

Table 6.2 Capacity benefits for different train convoy combinations, on the route Wtl-Sbn

Leader-Follower	VC with DSM vs ETCS L3	VC vs VC with DSM
Sub-Sub	0%	57%
Re-Re	23%	67%
Ic-Ic	35%	68%
Re-Sub	5%	81%
Sub-Re	22%	48%
Re-Ic	41%	47%
Ic-Re	6%	15%

Table 6.3 Capacity benefits of VC with a DSM over ETCS L3 MB for different train convoy combinations, on the route Wtl-Sbn with stops

Leader - Follower	ClaphamJn	Wimbledon	Raynes Park	Surbiton
Sub-Sub	32%	15%	38%	60%
Re-Re	43%	14%	40%	59%
Ic-Ic	42%	42%	60%	31%
Re-Sub	34%	24%	76%	84%
Sub-Re	29%	35%	46%	67%
Re-Ic	55%	30%	62%	65%
Ic-Re	35%	52%	71%	56%

Table 6.4 Capacity benefits of VC over VC with a DSM, for different train convoy combinations on the route Wtl-Sbn with stops

Leader - Follower	ClaphamJn	Wimbledon	Raynes Park	Surbiton
Sub-Sub	95%	64%	48%	42%
Re-Re	88%	70%	64%	38%
Ic-Ic	64%	90%	71%	64%
Re-Sub	95%	0%	31%	7%
Sub-Re	90%	75%	79%	67%
Re-Ic	17%	78%	69%	78%
Ic-Re	50%	13%	18%	29%

An example of a heterogenous four-train convoy is presented. With the use of VC considering a DSM, train headways can be reduced by 17% - 32% compared to ETCS L3 MB, while maintaining a safe distance in between. This application might be useful in case of bottlenecks around interlocking areas, where different train types should be virtually coupled to form multiple train convoys.

7 Conclusions

In this chapter the outcome of this research is summarized. First, final conclusions on the proposed model are drawn by answering the research questions formulated in 1.1. Afterwards, the limitations of this study are listed, leading to recommendations for future research and a reflection for the development of enabling technologies for next generation signalling systems.

7.1 Main conclusions

This research adds to the literature on train-following models by enhancing the multi-state train-following model from a safety perspective. The conclusions of this thesis are given as answers to the research questions formulated in 1.1. First, the sub-questions are answered which lead to the outcome of the study answering the main research question.

To what extent can driving technologies in the automotive sector and car-following be transferred to the concept of Virtual coupling train-following models?

Next Generation Signalling systems such as ETCS L3-MB and VC can benefit from the automotive sector where ACC/CACC concepts have been already tested and enabling technologies have been proved. V2V communication technologies such as WiFi, LTE or 5G are candidate technologies for V2V rail communications. Moreover, positioning technologies such as GNSS and perception technologies such as RADAR, LiDAR, cameras and digital maps could support the realization of future railway signalling concepts. Train-following models can be inspired by state-of-practice car-following models. Safety distance models and models used for intelligent vehicle modelling such as the IDM or the MIXIC, which consider the kinematic parameters of the leading vehicle and other attributes such as reaction times and communication delays can be sources of inspiration for developing safety distance train-following models.

Which rail operation parameters are assumed to have an impact on train-following models?

The literature review on railway Virtual coupling and train-following models showed that the vehicle heterogeneity, the V2V communication delays and train control delays are usually neglected in VC or train-following studies. Since braking distances are very long in railway operations, a train-following model should be developed, ensuring a safe separation distance between trains even in the worst-case scenario, when the front train applies emergency braking. Moreover, the V2V communication delay and the reaction or control delay times are important parameters both for car following models but also for railway studies. Finally, positioning error estimation is assumed to have an impact VC operation due to the use of relative braking distance, as well as the track gradient which increases the track resistances significantly.

How can realistic rail operation parameters be integrated in the multi-state train-following model, ensuring a safety distance between trains?

The multi-state train-following model can represent ETCS L3 and VC operations considering a constant safety margin which limits the movement authority provided to the following train. Aiming to ensure safety even in case the following vehicle applies emergency braking at any time, a dynamic safety margin can be estimated to limit the EoA under VC operations. Except for the emergency braking, the dynamic safety margin includes three additional safety distances accounting for the varied V2V update delay, train control delay times and positioning errors.

What is the impact of realistic rail operation parameters on the railway corridor capacity?

The track gradient plays a significant role on rail capacity under train-following concepts as trains stay in the coupling running state for less time compared to the ideal state of a track with 0% gradient. As the V2V update delay is increased, the corridor capacity is reduced since the separation distance between the trains is increased. For train consists having equal train control delay times, no effect in capacity is observed. However, this may differ when combining trains of different types. For increased train control delay time of the following train, headways between trains are increased. Finally, the rail capacity increases as the braking rate of the following train is increased. Among the parameters investigated through the sensitivity analysis, the most influential parameter in the rail line capacity is proved to be the braking rate of the following train. This is justified since the braking rate is incorporated in the computation of the service distance braking of the following train, where the squared of the speed is divided by the braking rate.

What is the effect of a V2V communication or ATO degradation in the rail corridor capacity under VC?

A V2V degradation scenario is simulated where V2V communication delay is increased from 1 s to 3 s after Clapham junction. The arrival headway at Surbiton station increases by 4 seconds. Assuming a predecessor-follower communication topology and under degraded V2V communication conditions, which impose an additional update delay, arrival headways are increased, limiting the corridor capacity. Based on the wanted capacity gains by VC, requirements of the V2V communication technology should be made regarding the update delay, the communication range, etc.

Assuming a degradation of ATO GoA 2 to manual driving (together with an increase of the control delay time from 1 s to 6 s), the arrival headway at the destination is increased

the same as the increase in train control delay time. Therefore, capacity drops, and safety issues are expected in case of degraded ATO scenarios.

What is the effect of homogenous and heterogenous train convoys on the railway corridor capacity?

For trains running on open track, capacity benefits of the proposed VC model over ETCS L3 MB are increased for trains having improved acceleration and braking characteristics (Br. Class 450 and Br. Class 220). For homogenous train convoys of slower trains (suburban trains) and for slower trains following faster trains, no additional capacity benefits of the proposed model are identified.

For services with intermediate stops, the proposed model shows additional capacity benefits for all the train convoy combinations under investigation. The highest capacity benefits are promised by heterogeneous train convoy formations. The train headways can be reduced significantly when faster trains follow slower trains.

Based on the above answers on the sub research questions, the main research questions can be answered:

What are the potential capacity gains of Virtual Coupling over ETCS L3 Moving block in a realistic operational environment where different rolling stock characteristics, operational speeds, driving behavior and uncertain traffic information exist, by adapting driving technologies from the automotive sector?

Based on the literature on car-following models and enabling technologies from the automotive and the railway sector, a dynamic safety margin is integrated in the multi-state train-following model, resulting in a safety distance train-following model for virtual coupling operations. Basic principle of the model is that the following train is capable of stopping at any time applying service braking, even in the worst-case scenario when the leading train applies emergency braking. The dynamic parameter accounts for realistic operational parameters such as different rolling characteristics, V2V communication update delays, train control delay times and positioning errors. For degraded operations of V2V communications or train control, a capacity drop is expected. Capacity benefits for open track vary depending on the train types that are used. Faster trains promise increased capacity benefits over slower trains on open track. For services with stops, the proposed model promises capacity benefits over ETCS L3 MB for all the possible train convoy formations. The most significant capacity gains of the proposed model over ETCS L3 MB are identified for heterogenous train convoys. Train headways can be reduced to the minimum possible if faster trains follow slower trains.

7.2 Limitations

Several limitations are identified in this simulation study which are originated from the assumptions that have be considered.

Case study

This thesis considers only one route on the South West UK Mainline corridor, between Waterloo station and Surbiton station. The speed limits of this route set a considerable

limitation to the study, since trains cannot reach higher speed than the speed limit of each track segment, which limits the model's outcomes.

Dynamic safety margin

The safety margin calculation is limited by the fact that the additional safety distance due to the emergency braking of the leading vehicle is based on Newton's kinematic equations. However, the emergency braking curve under ETCS is a more sophisticated procedure which considered more parameters. For the calculation of $SM_{braking}$, the emergency braking rate is considered as 1.2 m/s^2 for all train types. In real railway operations, the emergency braking rates may be varied, which would lead to different safety margins and different train separation among the members of the train convoy. The nominal braking factor of trains, which is included in the input data is considered constant in this study. However, in realistic rail operation, the braking factor may vary in time, impacting the train separation distance.

The calculation of the DSM considers the kinematic characteristics of the leading train at previous timestep of the simulation. However, if the train applies emergency braking, or the communication delay and system reaction time are increased, the error of the transmitted kinematic data may be quite different than those sent to the follower. Thus, a prediction of kinematic characteristics should be estimated by the EVC before the leading train transmits its kinematic data to the following train. In this study, only the positioning error is considered as a factor that impact the dynamic safety margin. However, more kinematic parameters that are transmitted from the leader to the follower, such as the leading train speed may be erroneous. Errors like these should be integrated in the model to increase safety. In addition, the communication delay from the RBC to trains should be also incorporated in the model.

Control strategy

In the proposed mode, the EVC of the successive train adjusts its movement authority for Virtual coupling based on the characteristics of the predecessor and its own characteristics, which means that the successor train does not adjust its braking capability according to the leading train. If another communication topology is applied, different results may be anticipated.

7.3 Recommendations

This study has highlighted capacity benefits of MB and VC operations considering heterogenous rolling stock parameters and degraded communication and ATO scenarios. Several recommendations are listed below both for research and the rail industry.

7.3.1 Recommendations for further model development

Infrastructure and rolling stock

In this study, VC benefits are investigated in only one route segment. The model outcomes may differ if the model is applied on other routes having varied track gradient profiles and curvatures. Thus, several case studies using various track characteristics

should be tested to contribute to formalizing the VC benefits. In addition, more train types, the study can be extended and test scenarios for urban, freight and high-speed rail operations. The impact of track gradient on VC and MB operations should be investigated in detail. That said, if the inclination has a positive effect on corridor capacity, or dangerous situations, for instance when heterogeneous trains are set to coast on downhills, etc. In this study a case of a heterogeneous 4-train convoy is simulated. Convoy formation of multiple trains should be investigated further in longer railway corridors with varied speed limits. Investigation of the impact of multiple train convoys following different routes in capacity benefits.

Investigate the impact of sags, sections of the route where the track gradient changes from downhill to uphill on the capacity and train-following states. The impact of disruptions on railway operation under ETCS L3 and MB and vice versa how next generation signalling systems could be used to mitigate disruptions' effects on the total network capacity. Investigate train convoy splitting before stations, while giving priority to train types to optimize capacity and disruption management.

V2V Communications

It is important to investigate the performance of a V2V communication system for MB and VC operations. Based on the communication network architecture, it should be defined which operational parameters have a serious impact on the message delay, communication range and what are the delay thresholds that should be defined. This VC model is based on a predecessor-successor architecture where the leading train communicates its kinematic characteristics to the following train. Then, the following train adjusts its speed and acceleration based on the predecessor. Suppose a multiple-train convoy scenario, several modeling approaches could be investigated. For instance, if all train communicate their kinematic parameters to all the others trains of the convoy so that a more coordinated motion for all trains is achieved, different outcomes might be expected in terms of capacity and energy efficiency.

EVC and ATO

Regarding the running time model, a constant braking rate is considered. Assuming an optimized ATO module, the braking rate is expected to be precise and constant. In realistic operation the braking force may be varied depending on the rolling stock performance. Thus, a more realistic braking rate function should be integrated in the model, based on historical data. In addition, the dynamic safety margin should integrate the calculation of the Emergency braking curves for ETCS, which is sophisticated method where, acceleration limits and track gradient are influential factors. Also, it should be investigated more, why the VC model considering a DSM outperforms in some cases the VC model with a constant safety margin of 50m, which may be cause by bugs in the simulation software.

Furthermore, an optimized ATO module should be designed to regulate the speed profile of the train consists of the convoy, based on the selected VC system architecture. It is assumed that the leading train runs at its full acceleration capabilities according to the speed limits to minimize its running time. In future scenarios, it should be investigated the case where the leading train may adjust its capabilities to the follower so that a more cooperative control is achieved leading to higher coupled running times, evenly distributed headways, and lower energy consumption. Combine optimal driving strategies including optimized coasting times, regenerative braking and investigate their

impact on train headways and energy consumption. The EVC or the RBC that calculates the dynamic safety margin needs to predict the state of the leading vehicle. For instance, if there is a V2V communication delay of 5 seconds, the following vehicle EVC should predict the kinematic characteristics of the leading (braking/accelerating/cruising) and adapt its own kinematics.

Sensitivity analysis and Model calibration

The method that was applied in this study to evaluate the impact of specific parameter variations in the model output is the OAT method, where each parameter was varied at a time, keeping the rest parameters constant. Although this approach can shed light on the importance of each parameter on the model output, it cannot reveal interactions between the parameters since it is a local sensitivity method and the model that is used non-linear. Thus, a more sophisticated global sensitivity analysis should be applied to reveal more accurate sensitivity indices of the model parameters. Moreover, the sensitivity of more model parameters that are not investigated in this study, such as the train length, weight, etc. should be investigated.

Historical data from the studied corridor might be beneficial for the validation of the speed profiles of the simulation runs and afterwards the calibration of the model parameters.

Safety

More research is required, for defining more safety-critical scenarios of MB and VC operations, such as Hazard and Operability (HAZOP) studies. Furthermore, additional research is needed to investigate the effect of GoA 2 in next generation signaling, especially for the impact of human factor in safety under degraded operations and the capacity consumption. More safety critical application of the EVC should be investigated. For example, regarding a possible degraded operation where ATO level 2 falls back to manual driving, the front train must not apply emergency braking.

7.3.2 Recommendations for infrastructure managers

This study shows that ETCS L3 MB and VC can be implemented to bring additional capacity benefits at saturated railway corridors and interlocking areas, where multiple trains could be coupled and form convoys on a single track. This approach could be used to dissolve bottlenecks and reduce the impacts of failures on the railway network performance, by reducing the secondary delays. Since the specifications and requirements of ETCS L3 MB and Virtual coupling are not yet clearly defined, by the time the technology is mature enough for implementation, it is assumed that VC operations will not be applied everywhere, at least in the first years of operation. Infrastructure managers such as ProRail, Network Rail, etc. should conduct simulation studies and cost-benefit analyses to identify routes and segments, for instance busy corridors and interlocking areas, where ETCS L3 MB or VC operations would provide significant capacity benefits. Finally, VC operations of multiple train convoys should be investigated, so that network-wide capacity benefits can be determined.

7.3.3 Recommendations for the rail industry

Train characteristics such as the braking rate are significant of next generation signaling when trains run at proximity. Thus, attention must be paid on the braking and acceleration performance of vehicles, so that variations and possible failures are diminished. The train manufacturing sector and railway agencies should investigate the smooth transition of rolling stock from traditional fixed block operations to moving block and virtual coupling operations. Thus, technologies such as a reliable TIM, accurate positioning technologies and an improved EVC with an optimized ATO module that supports next generation signaling systems should be developed. V2V communications are vital for safe railway operations under ETCS L3 MB and VC, therefore a reliable communication technology for railway operations, supporting medium-long ranges should be developed. In addition, more research is needed for developing a V2V communication technology for virtual coupling operations, aiming to increase the communication range which is needed to be longer in railways than in road traffic applications. Requirements such as maximum acceptable V2V communication latency and minimum required communication range should be studied, defined, and formalized for VC operations. Fast changeable switches and crossings are also important for VC operations where train will need to change tracks before approaching stations, so that train station capacity utilization is maximized. Also, a communication layer that will allow the switches to be changed by messages transmitted by trains in real time may be beneficial for next generation signaling systems.

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A ETCS levels

The different levels of ETCS are elaborated as follows:

ETCS L1

In ETCS L1 the train movement is continuously supervised, which means that the onboard computer supervises the maximum train speed and calculated the braking curve to the end of the movement authority. In addition, there is a non-continuous communication link between the train and the trackside through Eurobalises. For this level, trackside signals are necessary, and the trackside equipment is responsible for train detection and integrity checks.

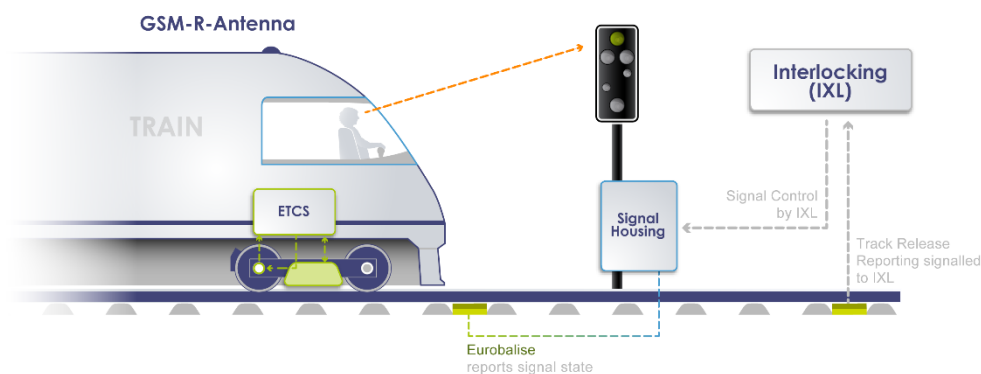


Figure A. 1 ETCS L1 (Thales,2020)

ETCS L2

In ETCS L2, the train movement is supervised continuously by the RBC through continuous communication via GSM-R. The movement authorities are sent to trains and displayed to the train driver through cab signalling, thus trackside signals are not necessary anymore. Eurobalises are used as passive positioning beacons, while train used additional systems such as accelerometer, odometers radar, to refine their position. Train integrity is monitored by the track side equipment.

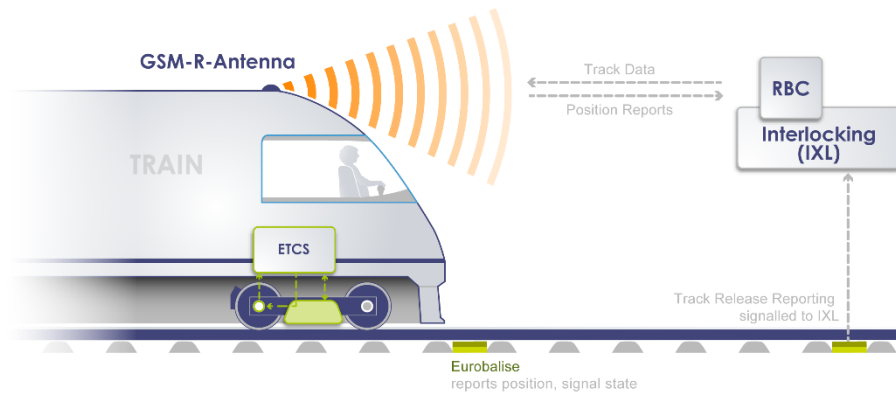


Figure A. 2 ETCS L2 (Thales,2020)

ETCS L3

ETCS L3 is a fully radio-based cab signalling system, where the train movement is supervised continuously by the RBC via the GSM-R. The main difference with ETCS L2, is that the train integrity monitoring (TIM) is supervised by the train itself, thus trackside signals and trackside train detection equipment is not necessary. Eurobalises are still present as a passive positioning system. Therefore, moving block signalling is possible in ETCS L3.

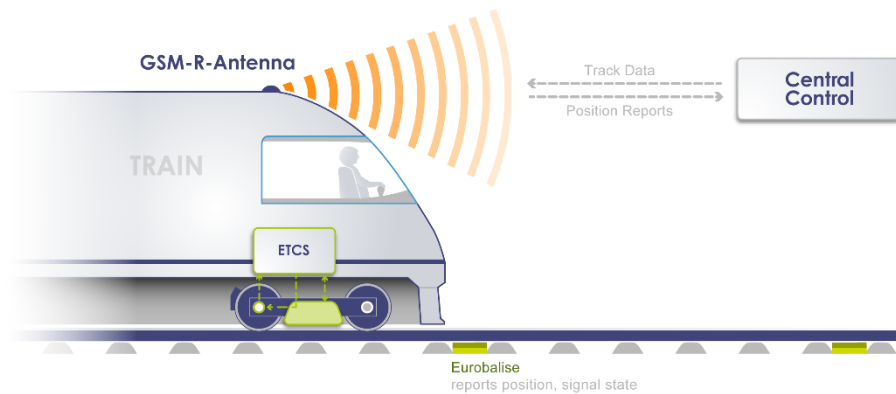


Figure A. 3 ETCS L3 (Thales,2020)

B Sensitivity analysis

B1. Train separation between Class 455 – Class 455 for different speed and space thresholds considering 0% gradient

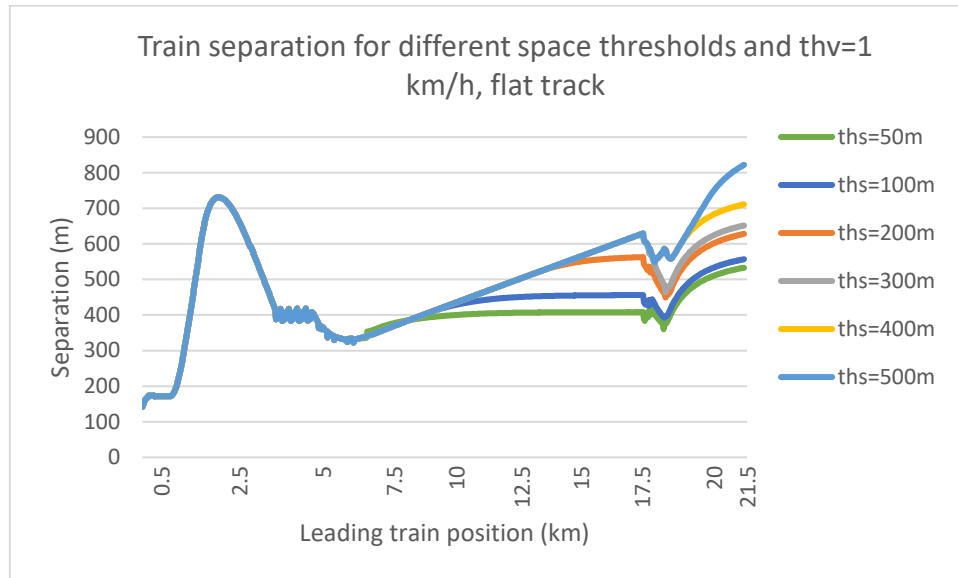


Figure B. 1 Train Separation for different space thresholds, flat track



Figure B.2 Train separation for different speed thresholds, flat track

B2. Train separation between Class 455 – Class 455 for different speed and space thresholds considering the real gradient track profile

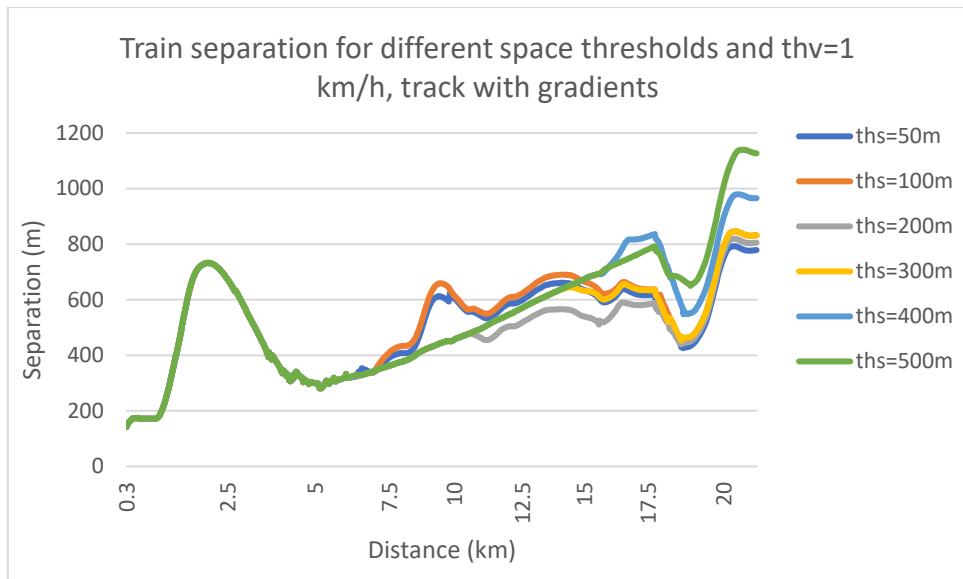


Figure B. 3 Train separation for different space thresholds, track with gradients

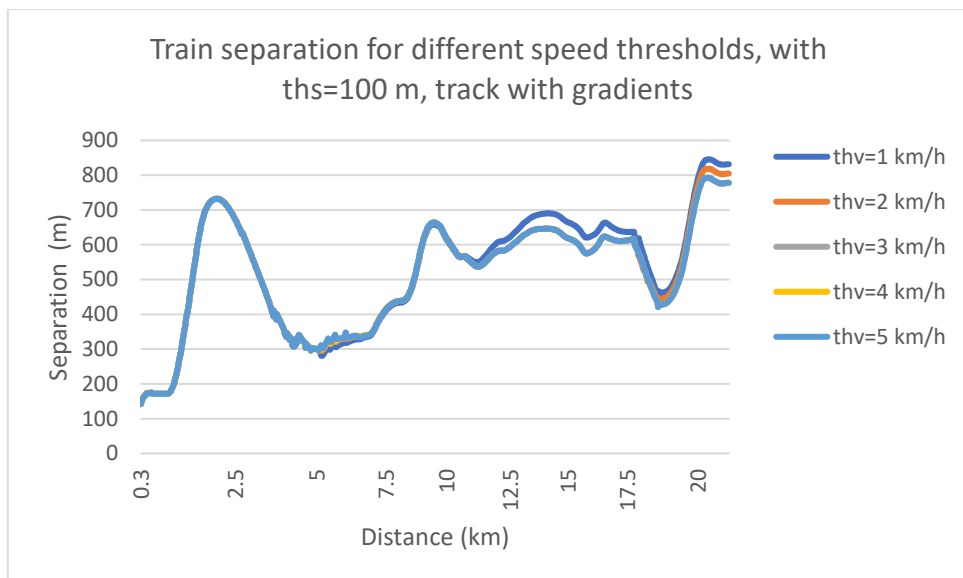


Figure B. 4 Train separation for different speed thresholds, track with gradients

Table B. 1 Sensitivity analysis results

Parameter	Flat track					Track with gradients			
	X_i	Y_i	d_i	μ_i^*	σ_i	Y_i	d_i	μ_i^*	σ_i
Space threshold (m)	50	29	-			35	-		
	100	30	0.02			37	0.04		
	200	33	0.03	0.023	0.003	37	0.01	0.022	0.013
	300	34	0.02			37	0.01		
	400	37	0.02			42	0.02		
	500	40	0.02			48	0.03		
Speed threshold (km/h)	1	30	-			37	-		
	2	30	0.00			36	-1.00		
	3	30	0.00	0.000	0.000	35	-1.00	0.792	0.250
	4	30	0.00			35	-0.67		
	5	30	0.00			35	-0.50		
V2V update delay (s)	1	30	-			37			
	2	31	1.00			37	0.00		
	4	34	1.33	1.083	0.167	40	1.00	0.907	0.630
	6	35	1.00			43	1.20		
	8	37	1.00			47	1.43		
Following Train control delay (s)	1	30	-			37	-		
	2	31	1.00			39	2.00		
	4	33	1.00	1.036	0.071	40	1.00	1.371	0.436
	6	35	1.00			43	1.20		
	8	38	1.14			46	1.29		
Following train braking factor (m/s2)	0.6	30	-			37	-		
	0.4	42	-60.00			50	-65.00		
	0.5	35	-50.00	29.800	13.864	43	-60.00	49.667	13.250
	0.7	26	-40.00			32	-50.00		
	0.8	24	-30.00			29	-40.00		
	0.9	22	-26.67			27	-33.33		

C Rolling stock attributes

C1. Tractive effort – speed curve characteristics of British Class 455 (suburban train)

Table C. 1 Tractive effort-speed curve parabola coefficients for British Class 455

T455	V_k	V_{k+1}	C_{0,k}	C_{1,k}	C_{2,k}
k ₁	0	4.828056	94302	0	0
k ₂	4.828056	5.185556	310572	-44794	0
k ₃	5.185556	11.31	78288	0	0
k ₄	11.31	24.58722	243834	-17894	351.22
k ₅	24.58722	33.61111	75856	-3472.9	42.479

C2. Tractive effort-speed curve parabola coefficients for British Class 450 (regional train)

Table C. 2 Tractive effort – speed curve parabola coefficients for British Class 450

T450	V_k	V_{k+1}	C_{0,k}	C_{1,k}	C_{2,k}
k ₁	0	4.1575	199991	0	0
k ₂	4.1575	8.315	362656	-47502	2153.8
k ₃	8.315	22.21778	187680	-11304	222.94
k ₄	22.21778	44.72222	93739	-2779	26.762

C3. Tractive effort-speed curve parabola coefficients for British Class 220 (intercity train)

Table C. 3 Tractive effort – speed curve parabola coefficients for British Class 220 (intercity train)

T220	V_k	V_{k+1}	C_{0,k}	C_{1,k}	C_{2,k}
k ₁	0	8.627778	160002	0	0
k ₂	8.627778	24.98944	266279	-14943	278.07
k ₃	24.98944	55.83333	121945	-2923	22.651

D Operational scenarios

D1. Duration of the coupled running state for different train convoy combinations.

Except for the train headways, the coupled running duration is summarized for all the scenarios that are investigated, in Figure 46. With the proposed model using a DSM, the highest coupled running state duration, where the following train coordinates its speed according to its predecessor and follows to the minimum possible distance is observed by the combination of an intercity train following a regional train.

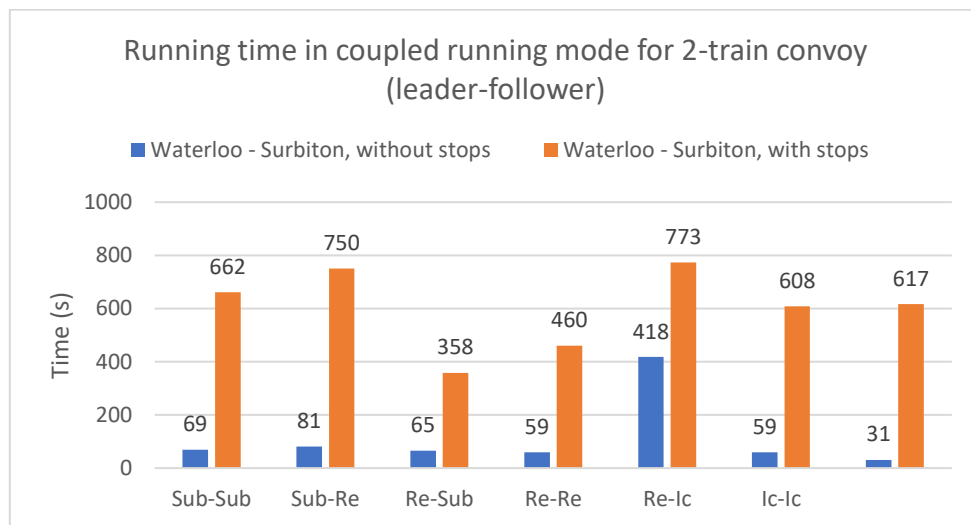


Figure D. 1 Coupled running state duration for different rolling stock combinations, with and without stops

D2. Separation distance and DSM of the degraded operations scenarios

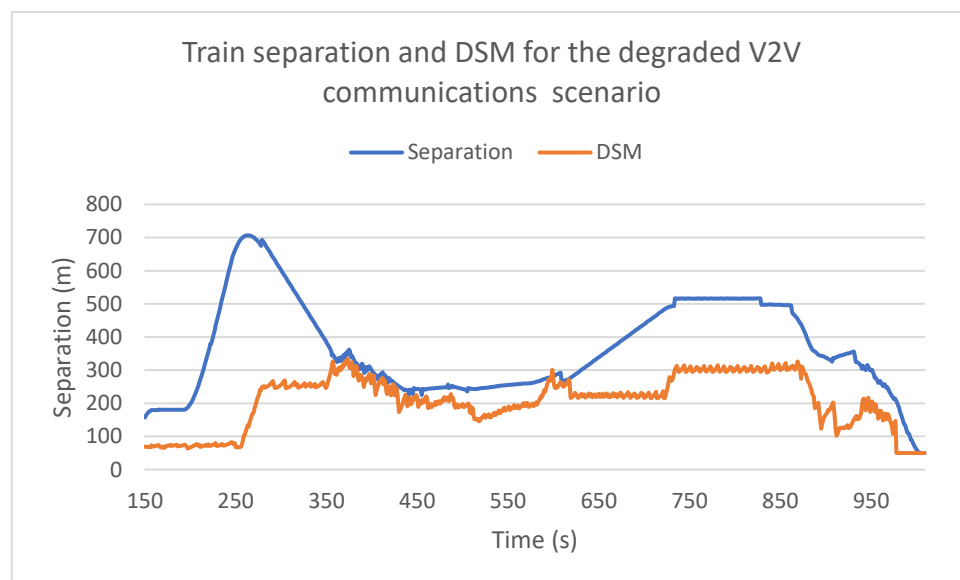


Figure D. 2 Separation distance and DSM for the degraded V2V communications scenario

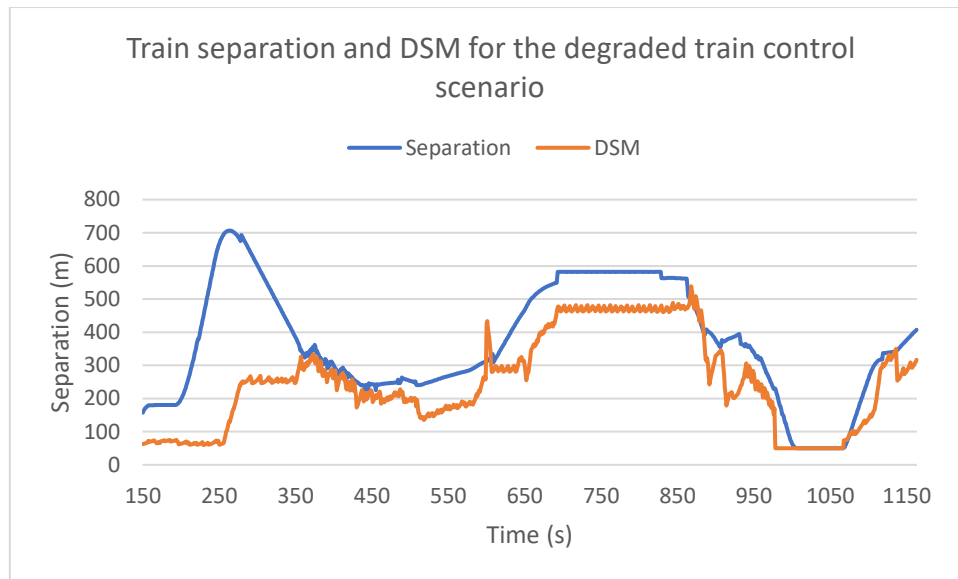


Figure D. 3 Separation distance and DSM for the degraded train control scenario

D3. Speed profiles of two Br. Class 455, with and without a coasting phase

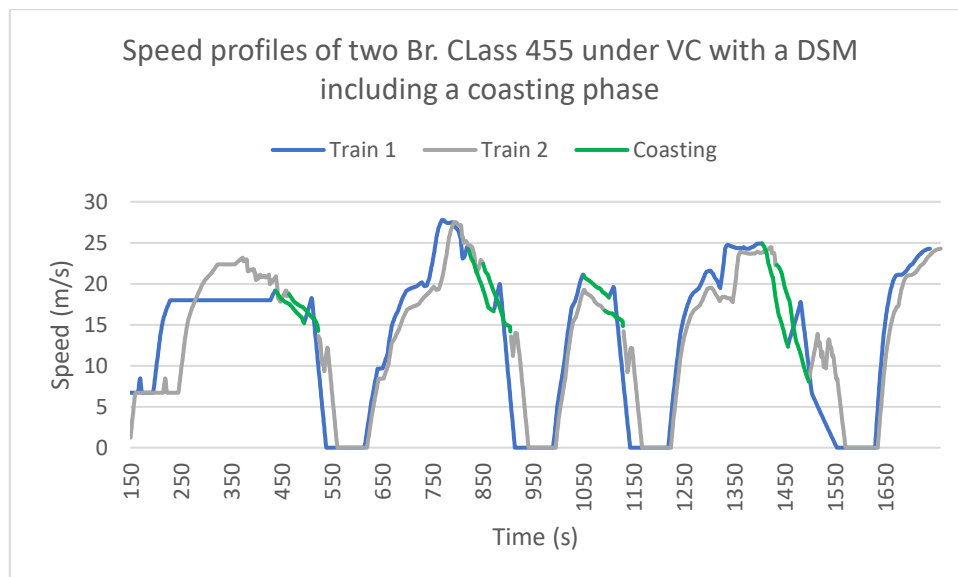


Figure D. 4 Speed profiles of two Br. Class 455 including a coasting phase

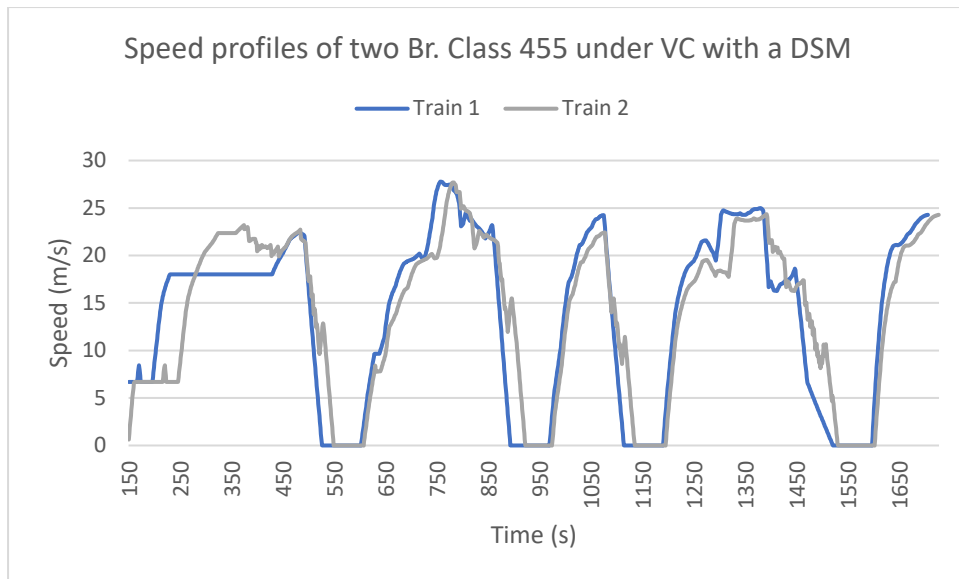


Figure D. 5 Speed profiles of two Br. Class 455 without a coasting phase

D4. Heterogeneous 4-train convoy

Figure D.6 depicts the dynamic safety margins between trains in the 4-train convoy, where DSM1 is the margin between the Br. Class 455 and the Br. Class 450, DSM2 the margin between the Br. Class 450 and the Br. Class 220 and DSM3 the margin between the Br. Class 220 and the Br. Class 450.

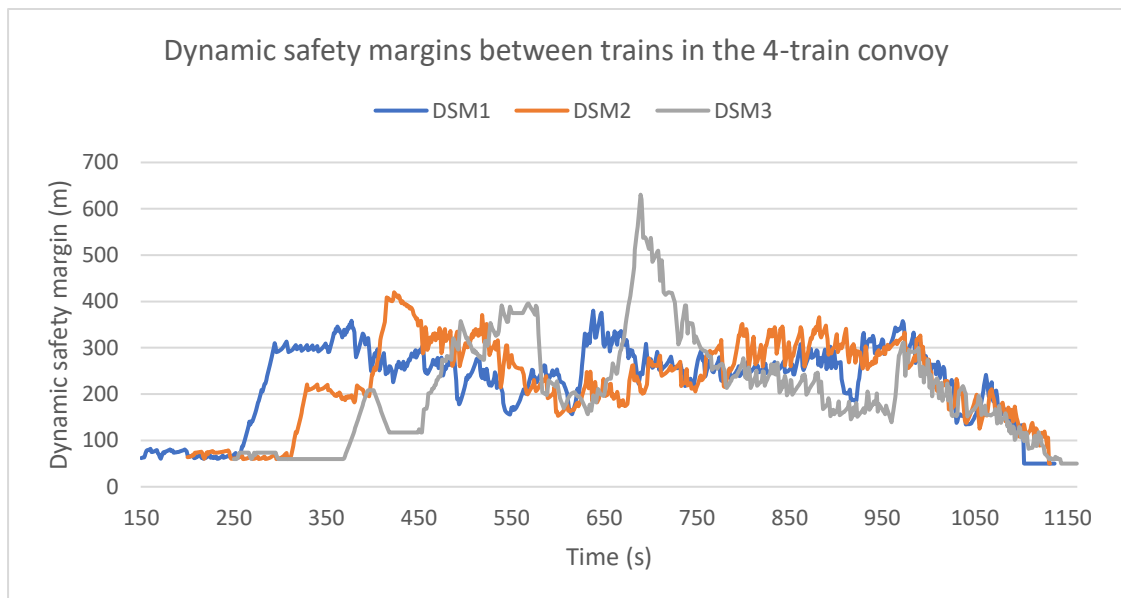


Figure D. 6 Dynamic safety margin between trains in the 4-train convoy

