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Executive Summary

The present document constitutes Deliverable D4.2 "Cost-Effectiveness Analysis for Virtual Coupling" in the framework of TD2.8 of IP2 according to the Shift2Rail Multi-Annual Action plan (MAAP). This deliverable introduces a Multi-Criteria Analysis framework for assessing impacts of train-centric signalling in the operational, technological and business domains. Specifically, Virtual Coupling (VC) and Moving Block (MB) signalling are compared in terms of eight key criteria and benchmarked with respect to the current state of practice for the different rail market segments identified by the S2R MAAP (i.e. high-speed, main-line, regional, urban and freight). Quantitative criteria include total costs, infrastructure capacity, system stability, travel demand, and energy consumption. In addition, qualitative criteria include public acceptance, regulatory approval, and safety. Consolidated mathematical techniques and engineering methods have been used to assess each of the quantitative criteria while a Delphi approach has gathered values for the qualitative criteria based on extensive Subject Matter Expert (SME) interviews and workshops.

A Multi-Criteria Analysis (MCA) has been setup by implementing a hybrid Delphi-Analytic Hierarchic Process (AHP) technique to weight and combine the different criteria in final performance scores of MB and VC signalling. The adopted Delphi-AHP technique has been proven to enhance collaboration among experts in selecting and weighting the criteria by means of an iterative feedback loop ending when consistent weights of relative criteria importance were achieved.

The individual analyses of single criteria show that VC outperforms MB for all market segments in terms of infrastructure capacity, system stability, energy consumption and travel demand. VC enables trains to follow each other at a distance shorter than an absolute braking distance, which can reduce headways significantly, especially if trains can move cooperatively in virtually coupled platoons. This is also reflected in terms of system stability and energy given that the advantage of running at a shorter safe separation while continuously being informed about the speed of adjacent trains improves the capability of mitigating delay propagation and enhancing energy efficiency. An increased modal shift to railways is observed for VC, especially for the regional and freight markets where a more flexible train service would better satisfy customer needs currently poorly addressed on those segments. Deployment of VC will be slightly more expensive than MB mostly due to the need of installing ATO and V2V communication while operational costs for the two systems will be comparable. Issues and priorities identified for regulatory approval and public acceptance were judged by SMEs to be very similar for MB and VC. In terms of safety, VC scores lower than MB given the different technological maturity level and the larger number of vital issues yet to be solved.

The SMEs assigned a very high importance weight to the safety criterion, which therefore affects greatly the final result of the MCA. The MCA score is hence in favour of MB for all market segments, despite the better performance of VC for single criteria like capacity, stability, energy consumption and travel demand. A fairer comparison can be obtained when assuming the same maturity level of MB and VC in a future point in time. In that case, VC clearly outperforms MB for all market segments and for freight and regional in particular, given that the provided train service flexibility would facilitate larger modal shifts of the customer demand.

Abbreviations and Acronyms

Abbreviation/Acronyms	**Description**
3-Aspect	Three-Aspect fixed block signalling
AHP	Analytic Hierarchy Process
ANP	Analytic Network Process
ATC	Automatic Train Control
ATO	Automatic Train Operation
CAPEX	Capital Expenditure
CBTC	Communication-Based Train Control
CCS	Control, Command and Signalling
CEA	Cost-Effectiveness Analysis
CI	Consistency Index
comm	communication
CR	Consistency Ratio
d_b	braking distance
DM	Decision Maker
ELCTRE	ELimination Et Choix Traduisant la REalité
ER	Evidential Reasoning
ETCS L2	European Train Control System Level 2
ETCS L3	European Train Control System Level 3
EVC	European Vital Computer
IM	Infrastructure Manager
Infra	Infrastructure
k	Thousand
M	Million
MA	Movement Authority
MAAP	Multi-Annual Action Plan
MADM	Multi-Attribute Decision Making
MB	Moving Block
MCA	Multi-Criteria Analysis
MCDM	Multi-Criteria Decision Making
MS	Market Segment
MU	Multiple Unit
N/A	Not Applicable
No.	Number
OLS	Overhead Line System
OPEX	Operational Expenditure
RBC	Radio Block Centre
RBD	Relative braking distance
RI	Random Index
RS	Rolling Stock

Abbreviation/Acronyms	Description
RU	Railway Undertaking
SEU	Signal Equivalent Unit
SM	Safety Margin
SME	Subject Matter Expert
TIM	Train Integrity Monitoring
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
V2V	Vehicle-to-Vehicle
VC	Virtual Coupling
VOBC	Vehicle On-Board Controller
ΔT	System reaction time
↗	Increase
$\nearrow^{+}$	Further increase
↘	Decrease
$\searrow_{-}$	Further reduce

1. Introduction

1.1. Background

The MOVINGRAIL project aims at identifying and analysing operational, technological and business changes that plain Moving Block signalling and Virtual Coupling will bring about in the railways. The main objective of the project is to quantify overall impacts of next-generation train-centric signalling systems and provide recommendations and strategies enabling effective and cost-efficient migration from current railway systems. The main purpose of this deliverable is to perform a multi-criteria impact analysis of the Virtual Coupling concept in order to understand practical advantages and/or limitations versus current fixed-block and plain Moving Block train operations. The work carried out in this deliverable builds on operational scenarios, technical judgement and stated travel demand preferences extended from the previous deliverable D4.1 “Market potential and operational scenarios for Virtual Coupling”, published in July 2019.

Deliverable 4.1 of the MOVINGRAIL project aimed at investigating the benefits and limitations of Virtual Coupling from the technical, technological and business perspectives, as well as its attractiveness to customers. Five market segments are defined by the Shift2Rail Master Plan (high-speed, main line, regional, urban/suburban and freight) and a case study has been defined for each market segment. Those case studies include:

- For the high-speed, the Italian corridor Rome-Bologna;
- For the main line, the UK route between London Waterloo and Southampton on the South West Main Line (SWML);
- For the regional segment, the UK stretch between Leicester and Peterborough on the Birmingham-Peterborough line;
- For the urban segment, the UK route London Lancaster-London Liverpool Street on the London Central Line;
- For the freight segment, the Rotterdam-Hamburg corridor between the Netherlands and Germany.

A survey was conducted with a focus on railway experts to identify technical and operational challenges of Virtual Coupling. Preliminary operational scenarios have been set up by means of workshops and brainstorming sessions with railway experts across Europe. A SWOT analysis has ultimately been performed to assess main Strengths, Weaknesses, Opportunities and Threats by collecting expert opinions of key stakeholders relative to technical/business effects of Virtual Coupling train operations for the different market segments defined by the Shift2Rail MAAP. Table 1 shows the SWOT analysis reporting elements which are common to all market segments, while Table 2 details the SWOT for each distinct rail market segment.

Table 1 – SWOT Analysis of Virtual Coupling to all Market Segments

Strengths	Weaknesses
• Line capacity ↗ • Delay propagation ↘ • Latency in comm with RBC in MB ↘ • Service flexibility ↗ • OPEX ↘ • Potential accidents impact ↘	• Full ABD at diverging junctions • Safety risks for heterogeneous braking rates • Investments needed to install the V2V • Infra upgrades to the OLS, platforms and possibly switch technologies • Potential ticket fees ↗
Opportunities	**Threats**
• Railway customers ↗ • Potential profit ↗ of IMs and RUs • Deregulation of the railway market with opening to smaller transport operators • Restructuring of railway market from a competitive to a more cost-effective cooperative consortium model • Migration of current CCS to more future-proof and efficient digital railway architectures • Capacity ↗+ and maintenance costs ↘- by installing advanced switch technologies.	• Ticket costs ↗ for railway customers • Possible train control complexity ↗ with respect to MB • Costs of stakeholders ↗+ to address safety issues due to RBD • Policies, processes and engineering rules.

Table 2 – Additional Strengths, Weaknesses, Opportunities and Threats of Virtual Coupling to each Market Segment

Market Segment	Strengths	Weaknesses
High Speed	• Significant headway ↘ • Platooning efficiency ↗ • Coupling/Decoupling feasible on-the-run	• High safety risks in case of V2V signal loss • Substantial stress of overhead catenary
Main Line	• Capacity ↗+ • Potential amount of level crossing closures ↘ • Coupling/Decoupling feasible on-the-run	• High complexity and uncertainty in managing heterogeneous rolling stock in one convoy
Regional	• Potential amount of level crossing closures ↘	• Potential longer closure of level crossing to road users • Coupling/Decoupling only allowed at standstill
Urban	• Platooning efficiency ↗	• Only marginal capacity improvements
Freight	• Flexibility ↗+ and capacity ↗+ of freight delivery • Handling operations at marshalling yards ↘ • Coupling/Decoupling feasible on-the-run	• Complexity in platoon sequencing due to different rolling stock characteristics

Market Segment	Opportunities	Threats
High Speed	• None additional to Table 1	• None additional to Table 1
Main Line	• Migration to advanced systems for ATC	• None additional to Table 1
Regional	• Customers ↗+	• None additional to Table 1
Urban	• None additional to Table 1	• Investments for VC deployment might not be compensated by a sufficient customer increase
Freight	• Attracting relevant market share from other modes • Shorter trains with fixed composition overcome limitations of TIM while reducing brake build-up times • Collection and distribution of goods over the last mile can be optimized and automated.	• Legislative rules in terms of weight and length platooning.

This Deliverable 4.2 consists of pursuing the four steps of Deliverable 4.1 (see Figure 1) towards a Multi-Criteria Analysis (MCA) which will be exhaustively explained in the following sections.

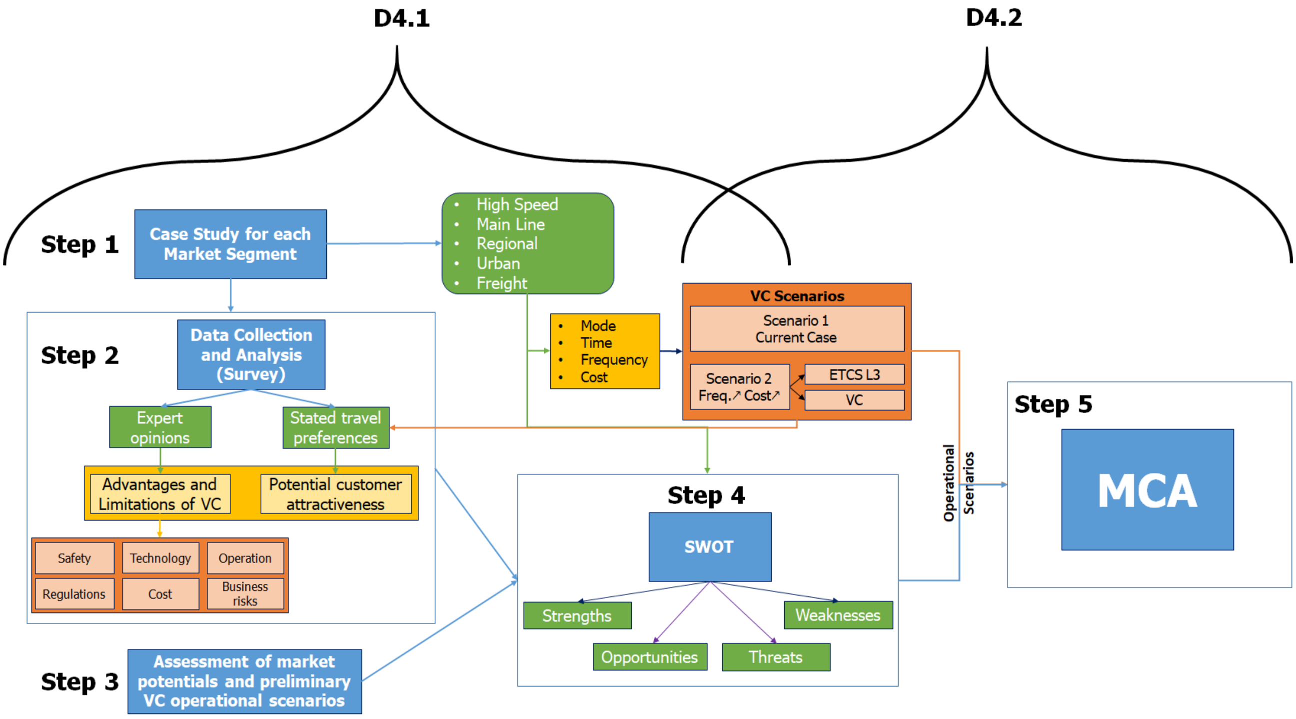

Figure 1 – Current Process of Work Package 4

According to the MOVINGRAIL framework illustrated in Figure 2, impacts of train-centric signalling technologies are estimated based on a comparative analysis versus current state-of-practice respectively for the operational, technological and business dimensions. Such an integrated framework allows capturing interdependencies that impacts in one dimension (e.g. operational) will have on another dimension of the railway service (e.g. business). To a comprehensive evaluation of both dimension-specific and inter-dimensional impacts of train-centric signalling, a multi-criteria impact assessment analysis is performed. In delivering such analysis we applied a multi-criteria decision-making technique, which combines the advantages of the Analytic Hierarchical Process (AHP) and the Delphi methods in a hybrid approach. This Delphi-AHP hybrid Multi-Criteria Analysis (MCA) method enables a more effective combination of expert and end-user surveys, analytical railway capacity models, simulation techniques and cost prediction methods to the identification of both qualitative and quantitative parameters in the operational, technological and business dimensions.

This report provides an extensive description of the proposed hybrid MCA technique and its application for assessing multi-criteria impacts of train-centric signalling for the different market segments.

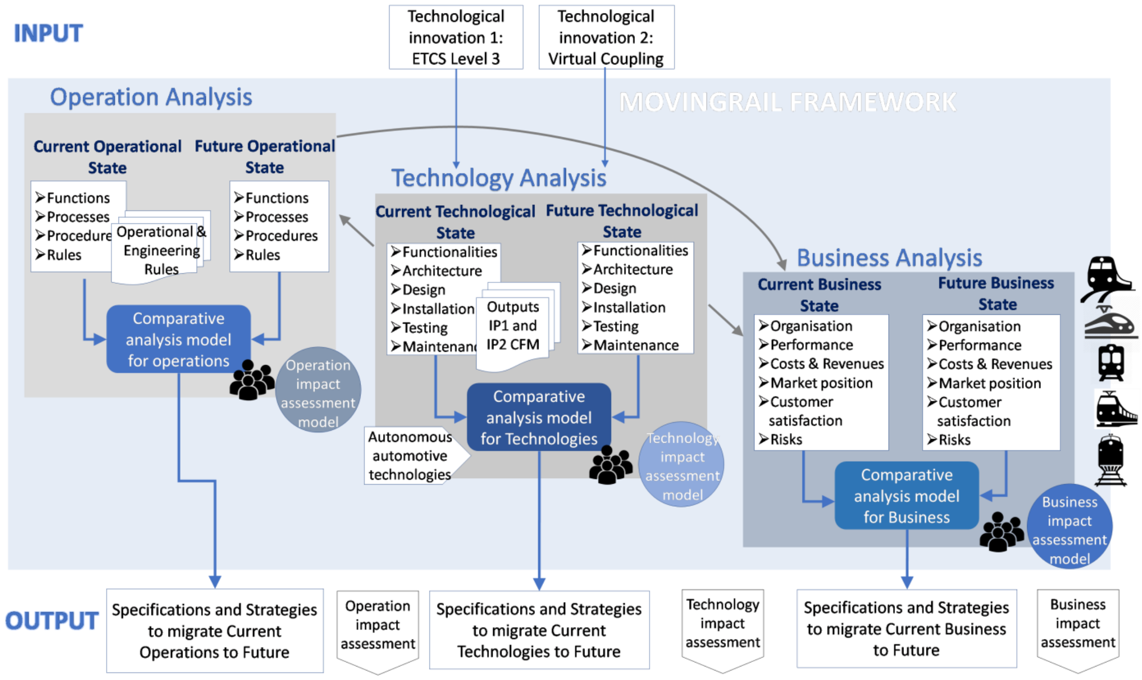

Figure 2 – MOVINGRAIL multidimensional analysis framework with the introduction of two technological innovations: ETCS Level 3 and Virtual Coupling.

1.2. Methodology

The evaluation of dimension-specific and inter-dimensional impacts of train-centric signalling systems is here performed by means of a hybrid Multi-Criteria Analysis technique which combines advantages of the state-of-the-art approaches such as the AHP and the Delphi method. The proposed MCA technique has been applied to all the rail market segments defined by the Shift2Rail MAAP to assess multidimensional impacts of train-centric signalling like Moving Block and Virtual Coupling in terms of costs, capacity, stability, energy consumptions, safety, public acceptance and regulatory approval. For each market segment, overall impacts are estimated by considering segment-specific operational scenarios (including those defined in Deliverable D4.1 “Market potential and operational scenarios for Virtual Coupling”) and deployment costs.

Quantitative criteria such as costs, capacity and energy have been determined by means of analytical and simulation models. Specifically defined stated preference surveys have been distributed online to a statistically significant group of potential railway end-users to characterise future travel demand choices quantitatively, as well as qualitative criteria such as public acceptance of train-centric train operations. Other qualitative criteria like regulatory approval and system safety have been collected by means of expert surveys on technical and business-related impacts of Virtual coupling and Moving Block signalling. A comparative analysis is then performed to identify benefits and limitations of Virtual Coupling versus ETCS Level 3 Moving Block as well as current fixed-block signalling systems.

1.3. Outline

In Chapter 2, the objectives of this deliverable are further stated. Chapter 3 provides a detailed literature review on state-of-the-art multi-criteria methods. Chapter 4 reports on the methodology applied to deliver the MCA, while Chapter 5 gives the results of the defined MCA for

each market segment. Chapter 6 provides conclusions about the findings of our research as well as general recommendations for the scientific community and the railway industry.

2. Objectives

The work in this deliverable represents a Cost-Effectiveness Analysis (CEA) for the implementation of Virtual Coupling for each of five market segment, building on the operational scenarios defined in MOVINGRAIL Deliverable 4.1. The analysis performed also allows to compare impacts of Virtual Coupling to those relative to Moving Block and traditional fixed-block signalling. A CEA is often integrated in a Multi-Criteria Analysis (MCA) which is applied in this deliverable to allow for a combination of different quantitative and qualitative decision criteria for various signalling alternatives, including costs and performance impacts, as well as the safety and feasibility from the public and regulatory perspectives. The final objective is to evaluate the most appropriate signalling system alternative to each of the market segments.

3. Literature review on Multi-Criteria Analysis (MCA)

3.1. Literature review

A Cost-Effectiveness Analysis compares the relative costs and effects of different alternatives. A Multi-Criteria Analysis (MCA) is similar in many aspects to a CEA but involves multiple indicators of effectiveness [1]. It is a scientific method to support practitioners in making the effective decisions with respect to several conflicting criteria [2][3]. Multi-Criteria Decision Making (MCDM) started by the mid of last century [4] and is still dynamically developing to provide the Decision Maker (DM) with some tools, which enable him/her to solve a complex problem where different points of view are taken into account [5].

According to Xu and Yang (2011) [6], two distinctive types of MCDM problems can be defined. The first type is the Multi-Objective Optimization Problems that consist of an infinite number of solutions, whereas the second type deals with a finite number of solutions called Multi-Attribute Decision Making (MADM) analysis [3]. Multi-objective decision-making regards conflicting goals that cannot be achieved simultaneously and can be solved by means of mathematical programming techniques. The MADM analysis aims at choosing the optimum alternative which has the highest degree of satisfaction for all relevant attributes from a set of alternatives. MADM is considered as a qualitative approach due to the existence of criteria subjectivity, where the DM can rank the attributes in terms of weights (i.e. importance) [7].

Hwang and Yoon [8] distinguished between two types of MCDM methods; one is compensatory and the other is non-compensatory. The non-compensatory methods do not permit trade-offs between attributes. These techniques are simple and reasonable in their application domains. However, they may not be helpful for general decision-making. Some examples of non-compensatory methods include the dominance method, maximin/maximax methods, conjunctive/disjunctive constraint methods, etc. [6]. Compensatory methods consider instead trade-offs between attributes; if one attribute is slightly declined, it can be compensated by some enhancement in one or more other attributes. Compensatory methods are classified into three main subgroups as follows:

i) Scoring methods: the alternative is selected according to its score or utility, e.g. simple additive weighting [6], Analytic Hierarchy Process (AHP) [9].

ii) Compromising methods: the alternative is selected based on the closest to the ideal solution, e.g. Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) [8].

iii) Concordance methods: the alternative is generated by a preference ranking which best satisfies a given concordance measure, e.g. the linear assignment method [6].

The Evidential Reasoning (ER) approach is the latest development in the MCDM area [10] capable of handling MCDM problems with uncertainties and hybrid natures [6]. ER uses an extended decision matrix in which each attribute of an alternative is described by a distributed assessment using a belief structure. Many MCDM have been used in almost all decision making-related problems. The most effective methods which have mostly been known in the literature are described below.

The Analytic Hierarchical Process (AHP) is a system engineering method that transforms qualitative

analysis into quantitative analysis [9]. Weighing of quantitative and qualitative criteria by means of the AHP can effectively avoid difficulties [11]. The AHP method is widely used for determining weights by means of the relative importance based on multiple criteria while keeping the consistency of the judging process. The AHP method was originally developed by Thomas Saaty in the 1970s-1980s to solve socio-economic decision-making problems. The AHP is an American-based compensatory scoring method which eliminates incomparability between variants and builds on a utility function of aggregated criteria [9]. The AHP has been considered as the most appropriate MCDM technique for solving complex cases [12].

The Analytic Network Process (ANP) brings all the decision objectives, criteria, alternatives and actors into a single framework by facilitating feedback and interaction capabilities among the different cited elements within and between groups. In other words, ANP allows for inner and outer dependence [13]. ANP is suitable for studying complex networked decision problems with various intangible criteria [14].

The ELECTRE method is used to choose the best actions from a given set of actions. This method has been applied to three main problems: choosing, ranking and sorting. The two main ELECTRE applications are related to outranking relations and recommendations, depending on the addressed problem. However, calculated thresholds in ELECTRE are highly translated into subjectivity, which might lead to unreliable results [15].

The TOPSIS technique was developed by Hwang and Yoon [16]. TOPSIS is based on selecting the shortest distance from the positive ideal solution (i.e. best possible combination of criteria) and the longest distance from the negative ideal solution (i.e. worst criterion values). Each measure in this method is either assumed to be a monotone increasing or decreasing one-way benefit. TOPSIS is an easy deterministic method which does not consider uncertainty in weightings [15].

3.2. The AHP multi-criteria analysis method

The extensive literature review provided above has supported us in choosing the MCA technique as the suitable means to evaluate impacts of futuristic railway technologies like Virtual Coupling. The result of this analysis has indicated that the Analytic Hierarchy Process (AHP) or Analytic Network Process (ANP) methods are the most appropriate to our needs. This finding is also in line with Feretti and Degioanni [18], who identify AHP and ANP as quantitative multi-criteria decision techniques particularly appropriate to solve problems related to railway management.

Based on Santana [19], the AHP method assures the consistency analysis of the judgements and is more robust than ELECTRE and TOPSIS. Results showed that TOPSIS is considered as the simplest of the studied methods. Zak [20] demonstrated that AHP and ELECTRE are the most reliable and users' friendly MCDM methods. Salomon [21] suggested the use of the AHP as results can provide an excellent optimum solution, especially if there are no more than nine alternatives and if the criteria and alternatives are total independent [11].

3.3. AHP applications

The AHP has been used to solve a wide range of decision-making problems [2]. Macharis and Bernardini [22] provided an overview of the MCDM methods for transport project appraisal, where the use of AHP/ANP covered 33% from 1985 until 2012. Barić and Starčević [23] showed that 18%

of railway-related papers included the application of the AHP method.

AHP has been used considerably in socio-economic fields to solve network-based or hierarchical decision problems [2]. Li et al. [24] used AHP to get a comprehensive ranking index of road sections in Jiangsu Province network level pavement maintenance decision-making. AHP has also been widely used to solve decision-making problems with complicated structures (i.e. big amount of criteria, factors difficult to quantify). By applying the AHP, Kumru [2] showed that railway transportation is a suitable alternative in Turkey. An et al. [25] developed a risk assessment system by means of fuzzy AHP to evaluate both quantitative and qualitative risk data related to the safety management of railway systems. Gercek et al. [26] applied AHP to evaluate different railway transit projects for the European side of Istanbul.

4. Methodology: A hybrid Delphi-AHP Multi-Criteria Analysis method

The work performed in this deliverable advances the state-of-the-art of Multi-Criteria Decision Making (MCDM) by developing a hybrid Delphi-AHP method, which consists in defining and assessing criteria in rounds with respect to the goal by means of pairwise comparison matrices for all the involved stakeholders. To better understand the proposed hybrid MCA method, a more detailed explanation of the pure Delphi and AHP methods are given below.

4.1. The Delphi technique

The Delphi technique was developed during the 1950s by the RAND Corporation while involved on a sponsored project for the U.S. Air Force [27]. Delphi consists of combining points of view and opinions from a group of individuals by means of iterative questionnaires with controlled feedback. The process enables cohesion among individuals with different points of view [28]. Four key features are regarded as necessary to define a 'Delphi' procedure: anonymity, iteration, controlled feedback and statistical aggregation of group responses [29]. However, the requirements of iteration and controlled feedback make the Delphi technique more challenging than other techniques [35].

The Delphi technique has been used in various research and projects including forecasting, planning and curriculum development [28]. Morgan [41] recognised the Delphi approach as "the most detailed scientific study" at that time. A remarkable planning example was undertaken by the Graduate Medical Education National Advisory Committee (GMENAC) in 1976 where the number of needed doctors in the foreseeable future has been estimated.

In most of the literature, the Delphi method aims at shortlisting and identifying the prominent variables (e.g. criteria). For instance, in the maritime transport sector, Da Cruz et al. [59] used the Delphi technique to determine the most important factors out of twelve factors identified in the literature review, which resulted in five considered criteria for the AHP pairwise comparison. The Delphi technique could also be used for consistency checking. If the result derived from one specialist does not meet the consistency requirements, then the expert needs to re-evaluate his/her input until consistency is achieved [2],[36].

Linstone [37] suggests "a suitable minimum panel size of seven". However, the decision about panel size is considered empirical and pragmatic, depending on different factors such as expenses and time [38]. Powell [39] showed that the representation of the panel size is assessed by the qualities of the expert panel rather than numbers. Therefore, a main advantage of the Delphi technique is that there is no requirement for a minimum number of participants. However, at the end of the process, an acceptable solution is drawn from an adequate number of respondents. Another advantage of the Delphi technique is that it is suitable for geographically dispersed experts [35]. Walker and Selfe [40] claim that "repeated rounds may lead to fatigue by respondents", and most studies use two or three rounds [35]. In this study, the number of rounds has been limited to three.

4.2. The Analytic Hierarchy Process (AHP)

The AHP has been originally developed by Saaty in the 1970s [11]. AHP is applicable to decision-making problems with complex hierarchies and multiple criteria/indices. The AHP method is considered as practical, systematic and terse [24].

Qualitative criteria usually rely on subjective evaluations which do not allow an accurate reflection on the actual situation and result in "distorted" results. AHP determines the weighting values of each decision-making influence factor.

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

1) Building the hierarchical model
2) Constructing the pairwise comparison judgment matrix
3) Consistency check.

Step 1: Building the hierarchical model
The hierarchical model consists of three main layers. The top layer represents the overall goal for determining the ranking of importance. The middle level displays the criteria which influence the goal. Those criteria are used for evaluating the alternatives which consist the bottom level of the hierarchical model [42]. In other words, each alternative has its own values of criteria associated with it. Figure 3 shows the Analytic Hierarchical Process model where the goal layer is denoted as A, the n criteria level denoted as C_1, C_2, …, C_n and the m alternatives level denoted by S_1, S_2, …, S_m.

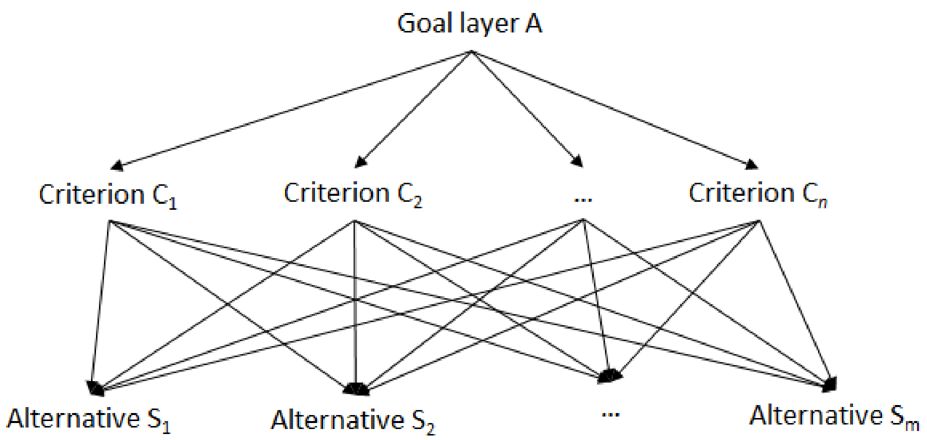

Figure 3 – Analytic Hierarchical Process model

Step 2: Constructing the pairwise comparison judgement matrix
The judgement matrix for criteria weighing is constructed by pairwise comparing two elements [11],[43]. The pairwise comparisons are used to determine the relative importance of each element of one layer to the element of the above layer. In this deliverable, we consider one level of pairwise comparison which consists of determining the relative importance of each criterion with respect to the goal. The decision-maker has to express his/her opinion about the value of one single pairwise comparison at a time based on the scale of relative importance shown in Table 3. The number of comparisons within the level is based on the equation: $n(n-1)/2$ where n is the number of comparable elements (i.e. in this case the number of criteria).

Table 3 – AHP Scale of relative importance

Scale of relative importance	
Intensity of relative importance	**Definition**
1	Equal importance
3	Moderate importance
5	Strong importance
7	Demonstrated importance
9	Absolute importance
2, 4, 6, 8	*Intermediate values between two adjacent judgement values*
Reciprocal value	The judgment value of the importance of element *i* with respect to element *j* is r_{ij}, the reciprocal value is $1/r_{ij}$

Step 3: Consistency check

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

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

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

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

The weights are called priority vector (or normalised principle eigenvector) [2]. An eigenvector is computed based on the normalised judgement matrix. However, inconsistencies might arise when many pairwise comparisons are performed (i.e. high number of criteria). For example, if a decision maker evaluates criterion A as more important than criterion B and criterion B more important than criterion C, an inconsistency arises if criterion C is assessed as more important than criterion A. The purpose of matrix consistency is to ensure that the judgement is rational and avoid conflicting results.

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

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

It is known that $\lambda_{max} \geq n$ and $\lambda_{max} - n$ measures the deviation from the judgements from the

consistent approximation. A Consistency Index (CI) is then calculated as

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

Finally, the Consistency Ratio (CR) is obtained by dividing CI by the Random Index (RI) associated with the number of comparable elements n with values as displayed in Table 4 [2], i.e.,

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

Table 4 – The RI Values

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

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

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

Finally, the weighted MCA performance scores are defined as the weighted sum of all criteria values per signalling alternative and market segment.

4.3. The hybrid Delphi-AHP technique

The hybrid Delphi-AHP technique aims at combining the Delphi technique discussed in Section 4.1 with the AHP MCDM described in Section 4.2. This technique has been traced in many research areas such as project management [30], logistics [31], forecasting [32], safety [33], and transportation [34]. However, to the best of our knowledge, it has not been used in the railway sector. Lee et al. [34] used the combined Delphi-AHP technique to examine the competitiveness of international shipping industry. Arof [35] shows that usually the number of participants involved in a Delphi survey is different than those involved in an AHP survey. The number of panellists generally depends on the level of expertise required, the availability of experts and their willingness to participate in the study [35].

In this study, the Delphi technique has been used for a double purpose. First to identify the most relative criteria with respect to the AHP goal, second to evaluate a consistency check in the pairwise comparison matrix of the AHP technique.

The advantages of this hybrid technique include:

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

The contributions of this technique to the state-of-the-art are:

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

The Delphi-AHP framework is illustrated in Figure 4.

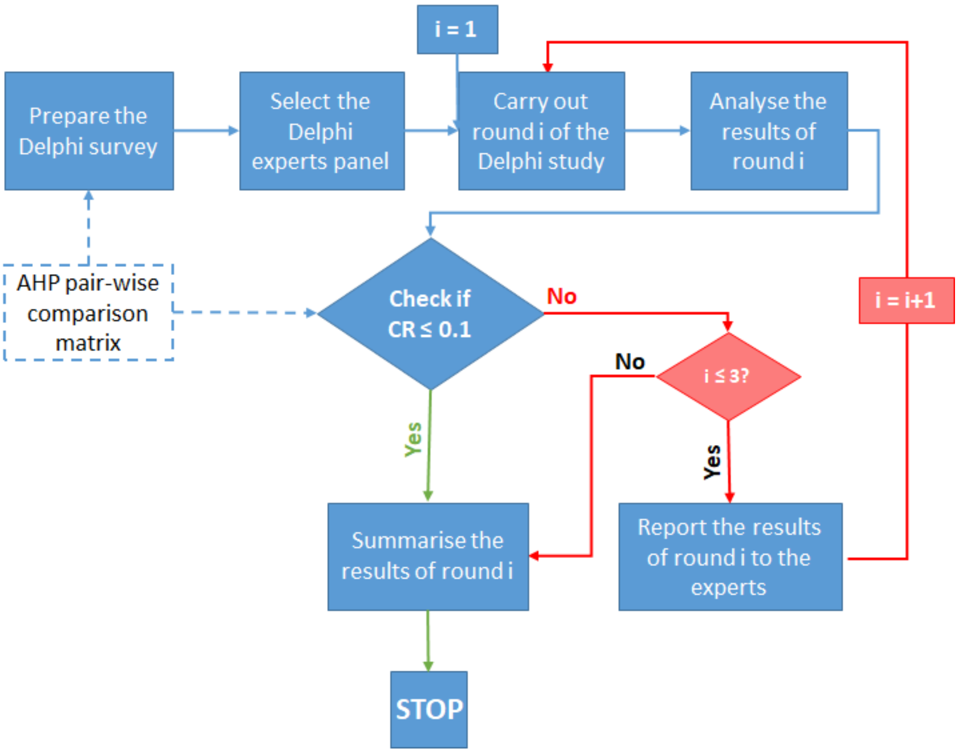

Figure 4 – Delphi-AHP Framework

The framework starts from the preparation of the survey required to address the selected decisional process. Based on the set of expertise required for the survey, a panel of experts is accordingly selected. After that a round of the Delphi survey is performed, and survey results are analysed in terms of consistency of the AHP pairwise comparison matrix. In case the consistency ratio of the relative criteria assessment is above the threshold of 0.1 (i.e. 10%), all of the respondents providing inconsistent matrices are required to re-do the survey so to give consistent responses (i.e. $CR \leq 0.1$). After each round of the AHP pairwise comparison matrix, the survey results are distributed to the interviewed panel for further feedback until final consistent results are returned.

4.4. MCA Framework

The MCA builds on two main elements: alternatives (derived from options) and criteria (derived from objectives). An alternative is a choice defined between two or more possibilities (i.e. options).

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

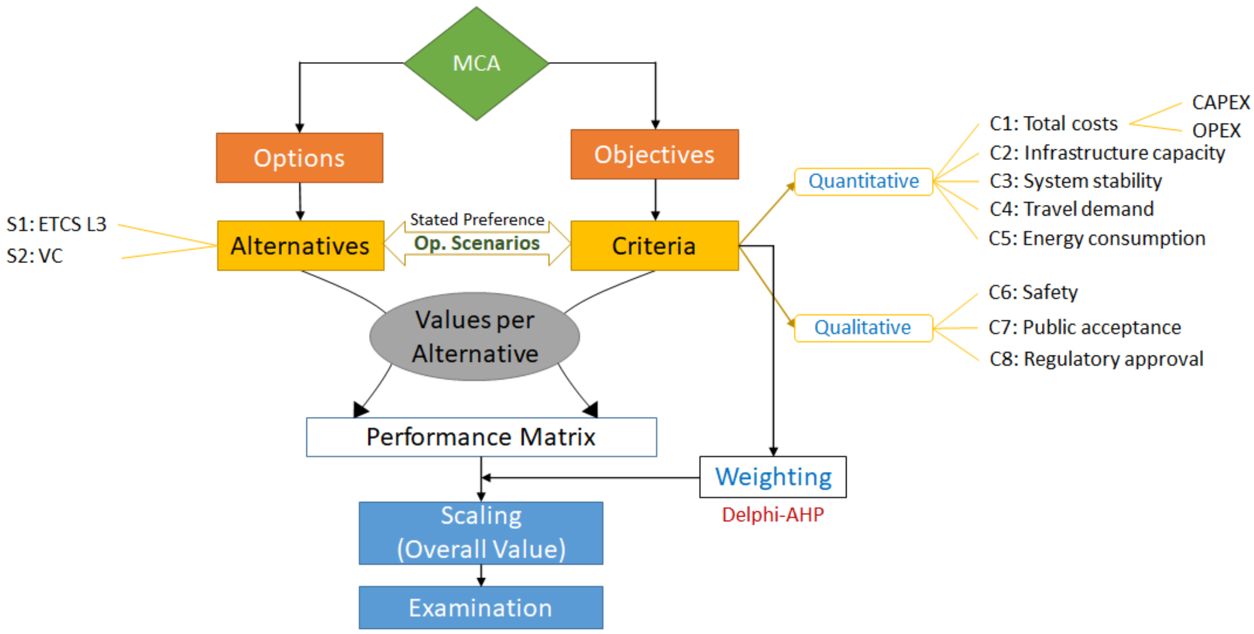

Figure 5 – MCA Framework

In this deliverable, the interactions between alternatives and criteria depend on different operational scenarios detailed in Section 4.6. Stated preference surveys are involved to assess travel demand distribution, and stakeholders' judgement is used for safety, public acceptance and regulatory approval. After combining the different combinations of criteria values per alternative, a performance matrix is constructed. Criteria are weighted by means of the explained hybrid Delphi-AHP method (Section 3.2). Then, decision matrices are normalized and weighted to ultimately provide an overall value for each alternative. In this methodology, the examination process consists of enabling cohesion among the different points of view of the involved SMEs and evaluating consistency to reach a final reasonable consensus matrix. Finally, results are examined and shared with the respondents. A summary of the described MCA framework is illustrated in Figure 5.

4.5. Decision alternatives

The Multi-Criteria Analysis is performed by comparing overall impacts of different decision alternatives for the railway signalling system. Two main signalling alternatives are considered in this work, namely:

- **ETCS Level 3** Moving Block, here defined as **alternative S1**. For this alternative, we assume that for a given rail market segment a direct migration from the currently installed signalling system to ETCS Level 3 will be carried out.
- **Virtual Coupling**, defined as **alternative S2**. Similar to the previous alternative, we assume here that for a certain market segment a straight migration from the currently equipped signalling system to Virtual Coupling will take place.

These two decision alternatives are then benchmarked versus the **baseline**, here indicated as **alternative S0**, which represents the signalling system currently installed on a railway network for a specific market segment. A fixed-block three-aspect signalling system (**alternative S01**) is considered as the baseline for all market segments but the high-speed market segment where the baseline is instead ETCS Level 2 (**alternative S02**).

4.6. Definition of Operational Scenarios

Operational scenarios have been defined based on different combinations between manoeuvres and signalling system configurations. A manoeuvre is defined as a movement of a train over a plain track or an interlocking area. The type of movement that the train will perform in a manoeuvre will very much depend on the layout of the track and/or junction as well as on the interaction with other trains that might move in the same direction.

A system configuration is defined as a specific set of values of design variables of the signalling system. Specific design variables of Virtual Coupling signalling would for instance be the frequency and latency of the Vehicle-to-Vehicle communication layer, the communication delay between the train and the RBC to exchange the position report and the Movement Authority (MA), and the safety margin between two trains in a convoy. More details about the combinations of manoeuvres and system configurations defined in this deliverable are provided in the following sections.

4.6.1. Manoeuvres

As illustrated in Figure 6, three manoeuvres have been identified as relevant for understanding benefits and limitations of Virtual Coupling operations with respect to Moving Block and fixed-block signalling for the different rail market segments. The three manoeuvres relate to trains following each other in the same direction. Manoeuvre M1 refers to the case of a plain line, Manoeuvre M2 considers trains merging at a junction and Manoeuvre M3 relates to trains diverging at a junction. Two cases have been identified; the first is in the case of trains running continuously without stopping whereas the second considers stopping patterns as illustrated in Figure 6.

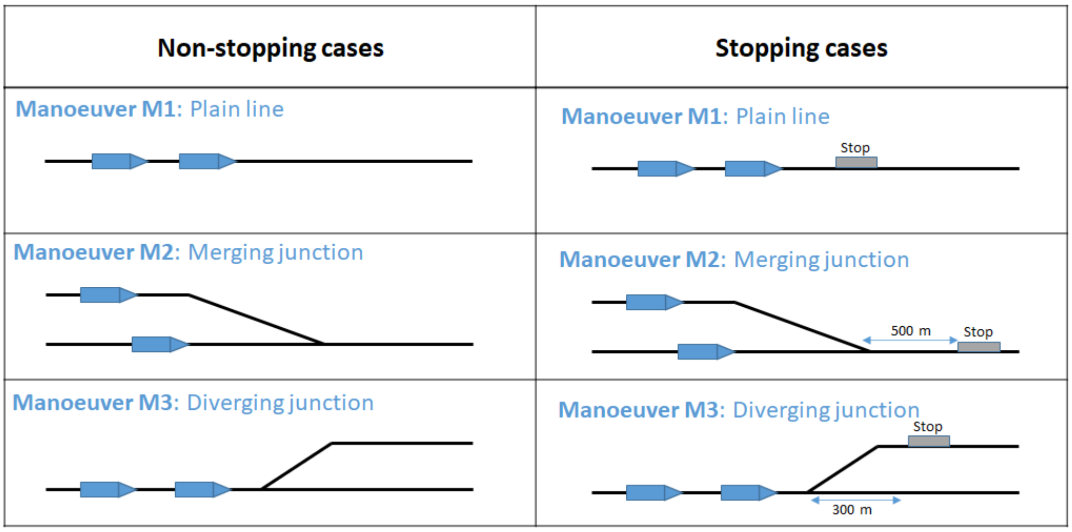

Figure 6 – Manoeuvres for investigating ETCS L3 Moving Block and Virtual Coupling

In the stopping case of M1 (plain line), both trains stop at the station. In the case of M2 (merging junction), the station is assumed to be located 500 meters from the switching point where both trains stop. In the case of M3 (diverging junction), the leading train (i.e. train in front) stops at the station -located 300 meters from the switching point- and the follower carries on over the other track overtaking the leader while this latter is dwelling at the station.

4.6.2. System configurations

Three system configurations are considered in this deliverable. All the configurations are based on a combination of three main design variables that vary based on the adopted signalling system and/or the market segment (MS). The main design variables defining a system configuration are here considered to be:

- The safety margin, *SM*, defined as the minimum distance that protects the back of a train when operating under moving-block and virtual coupling signalling. A train following another will therefore always be able to safely stop before this safety margin from the tail of the train ahead. The absolute (when in ETCS Level 3 moving block) or the relative (if in virtual coupling) braking curve of a train shall hence be computed with respect to the safety margin from the tail of the preceding train when computing the minimum train separation. Different safety margins are considered for the different market segments depending on typical maximum operational speeds and in line with the operational scenarios defined in MOVINGRAIL D4.1. At a platform the virtually coupled trains in a convoy will be able to stop as close as possible to the preceding train to fully occupy the platform. Hence, the safety margin between virtually-coupled trains at standstill must be minimal and indeed can also be smaller than between running trains. Note that the relative braking reduces to the absolute braking when a preceding train is at standstill.
- The system update delay or system reaction time, *ΔT*, which is the time for the signalling system to update its status, e.g. to update the train position report (if in ETCS Level 3) or the occupation state of track vacancy detection sections (if in conventional signalling).

- The switching time, t_s , that is the time to set, move and lock a switch in an interlocking area.

Train lengths are considered to be in line with typical train compositions in each of the market segments. Train compositions will hence be reported for each of the case studies analysed for a specific market segment.

The baseline system configuration S0 is the conventional signalling system currently installed for a given market segment. For the main-line, regional, urban and freight markets we mainly refer to a three-aspect fixed-bock signalling (i.e., S01). For the high-speed segment instead the baseline signalling is ETCS Level 2 (i.e., S02).

The alternative system configuration S1 refers to the ETCS L3 Moving Block signalling while the alternative configuration S2 corresponds to the Virtual Coupling signalling system.

Table 5 – System configurations

System Config	Signalling System	Parameters		
		Safety margin (m)	System reaction time (s)	Switching time (s)
S01	Multi-aspect*	N/A	$\Delta T_{(S01,MS)}$	$t_{s(MS)}$
S02	ETCS L2**	N/A	$\Delta T_{(S02,MS)}$	$t_{s(MS)}$
S1	ETCS L3	$SM_{(S1,MS)}$	$\Delta T_{(S1,MS)}$	$t_{s(MS)}$
S2	VC	$SM_{(S2,MS)}$	$\Delta T_{(S2,MS)}$	$t_{s(MS)}$

*: Multi-aspect signalling is considered for main line, regional, urban and freight trains.
**: ETCS L2 is considered for high-speed trains.

The safety margin, the signalling system delay times, the switching times at junctions, maximum operational speeds and train length are all essential for the computation of minimum headways between train movements for each of the signalling alternatives and market segments. Train headways have been computed by using the timetable compression method for each of the manoeuvres illustrated in Figure 6 as a localized version of the UIC Code 406 [47].

Maximum operational speeds $Vmax_{(MS)}$ adopted for each of the MS are reported as follows:

- $Vmax_{(S02,Highspeed)}$ = 300 km/h
- $Vmax_{(S01,Mainline)}$ = 140 km/h
- $Vmax_{(S01,Regional)}$ = 120 km/h
- $Vmax_{(S01,Urbanl)}$ = 80 km/h
- $Vmax_{(S01,Freight)}$ = 100 km/h

The approaching time component of the blocking time is therefore computed referring to those operational speeds for each MS. In the case of the three-aspect signalling, the approaching time equals the time for a train to cross the previous block section. For ETCS Level 2 instead the approaching time is the time needed by the train to cross the absolute braking distance in rear of the marker-board protecting the block section. For ETCS Level 3 moving block, the approaching time is instead defined as the time for crossing the absolute braking distance to a safety margin in

rear of the tail of the preceding train. For virtual coupling the approaching time is instead referred to as a speed coordination time, that is, the time needed for a train to coordinate its speed with the one of the train ahead, while always keeping at least a safety margin separation. This means that if a train is running faster than the preceding train, the approaching time would equal the time to cross a relative braking curve to a safety margin behind the tail of the train ahead.

Block section lengths $BL_{(MS)}$ used for baseline signalling systems (i.e. three-aspect and ETCS Level 2 for high-speed) and safety margins adopted for moving block and virtual coupling are reported as follows for each of the MS:

Block sections for Baseline signalling (S0)	*Safety Margin for MB (S1) and VC (S2)*
$BL_{(S02,Highspeed)}$ = 1200 m	$SM_{(S2,Highspeed)}$ = 200 m
$BL_{(S01,Mainline)}$ = 850 m	$SM_{(S2,mainline)}$ = 120 m
$BL_{(S01,Regional)}$ = 700 m	$SM_{(S2,regional)}$ = 100 m
$BL_{(S01,Urbanl)}$ = 400 m	$SM_{(S2,urban)}$ = 80 m
$BL_{(S01,Freight)}$ = 1,000 m	$SM_{(S2,Freight)}$ = 100 m

Block section running times for baseline signalling systems (i.e. three-aspect and ETCS Level 2) are considered as the time needed by the train to cross the block section, while such a component exists only for switch sections when considering moving block and virtual coupling. Occupation of switches under moving block operations is indeed considered to be working as for ordinary block sections in fixed-block signalling. Values of the switching times have been differentiated accordingly by market segment as reported below:

- $t_{s(Highspeed)}$ = 9 s
- $t_{s(mainline)}$ = 8 s
- $t_{s(regional)}$ = 7 s
- $t_{s(urban)}$ = 5 s
- $t_{s(freight)}$ = 7 s.

Sight and reaction times are considered 6 s for all the signalling systems and for all the market segments but virtual coupling where the reaction time is set to 1 s to take into account Automatic Train Operation. The release time component of the blocking time has been set equal to the system update delay previously described as *ΔT,* which assumes the following values for the different signalling alternatives that are considered equal for all the market segments:

- $\Delta T_{(S01,MS)}$ = 4 s (System reaction delay)
- $\Delta T_{(S02,MS)} = \Delta T_{(S1,MS)}$ = 2 s (Communication to/from RBC)
- $\Delta T_{(S2,MS)}$ = 2 s (Communication to/from RBC) + 0.02 s (V2V communication latency) = 2.02 s.

4.6.3. Operational scenarios

Based on the SWOT analysis derived in the MOVINGRAIL Deliverable 4.1, different challenges and threats for the implementation of Virtual Coupling have been identified. Therefore, the SWOT results gave rise to the identification of different operational scenarios based on the typical characteristics of each market segment.

An operational scenario is defined as the combination of manoeuvres and system configurations,

either with or without stopping train operations. For a given market segment, we mainly investigate manoeuvres which are typical to be observed in that specific market as explained in the following paragraphs.

For urban railway lines, only three operational scenarios with stopping trains are defined. They consist of all the system configurations S0, S1 and S2 defined in Section 4.6.2 for manoeuvre M1 (Section 4.6.1). This means that the first operational scenario consists of the combination of manoeuvre M1 with stopping trains under three-aspect signalling (3-Aspect). The second scenario relates to manoeuvre M1 for stopping trains under ETCS L3 whereas the third scenario regards manoeuvre M1 for stopping trains under VC. For the regional market segment, nine operational scenarios are investigated with stopping trains for the three defined manoeuvres M1, M2 and M3 which consider all the system configurations S0, S1 and S2 defined in Section 4.6.2. For the high-speed, main line and freight market segments, all the combinations extracted from the defined manoeuvres in Section 4.6(4.6.1 are considered as they can all be observed for these three market segments. Therefore, each of the mentioned market segments holds eighteen operational scenarios based on the same manner explained above for urban railways. The 18 operational scenarios are displayed in Table 6 for main line (operational scenarios 13 to 30), high-speed (operational scenarios 31 to 48) and freight (operational scenarios 49 to 66).

Table 6 – Definition of operational scenarios for each Market Segment

Operational Scenario	Market Segment	Manoeuvre	Stopping Trains	System Configuration
1	Urban	Plain	Yes	3-Aspect
2				ETCS L3
3				VC
4	Regional	Plain	Yes	3-Aspect
5				ETCS L3
6				VC
7		Merge	Yes	3-Aspect
8				ETCS L3
9				VC
10		Diverge	Yes	3-Aspect
11				ETCS L3
12				VC
13	Main line	Plain	No	3-Aspect
14				ETCS L3
15				VC
16		Plain	Yes	3-Aspect
17				ETCS L3
18				VC
19		Merge	No	3-Aspect
20				ETCS L3
21				VC
22		Merge	Yes	3-Aspect
23				ETCS L3
24				VC
25		Diverge	No	3-Aspect
26				ETCS L3

Operational Scenario	Market Segment	Manoeuvre	Stopping Trains	System Configuration
27				VC
28		Diverge	Yes	3-Aspect
29				ETCS L3
30				VC
31	High-speed	Plain	No	ETCS L2
32				ETCS L3
33				VC
34		Plain	Yes	ETCS L2
35				ETCS L3
36				VC
37		Merge	No	ETCS L2
38				ETCS L3
39				VC
40		Merge	Yes	ETCS L2
41				ETCS L3
42				VC
43		Diverge	No	ETCS L2
44				ETCS L3
45				VC
46		Diverge	Yes	ETCS L2
47				ETCS L3
48				VC
49	Freight	Plain	No	3-Aspect
50				ETCS L3
51				VC
52		Plain	Yes	3-Aspect
53				ETCS L3
54				VC
55		Merge	No	3-Aspect
56				ETCS L3
57				VC
58		Merge	Yes	3-Aspect
59				ETCS L3
60				VC
61		Diverge	No	3-Aspect
62				ETCS L3
63				VC
64		Diverge	Yes	3-Aspect
65				ETCS L3
66				VC

4.7. Criteria

Different types of criteria are defined in the MCA framework to compare the different decision alternatives in terms of key performance indicators, measuring the impact of signalling systems in different dimensions. The defined criteria are both quantitative and qualitative. Quantitative criteria are measured by means of mathematical models, statistical analysis or simulation while the assessment of qualitative criteria relies on expert stakeholder opinions. Structured weighing

methods (i.e. the Delphi and AHP) have been adopted to perform the assessment of both quantitative and qualitative parameters.

Based on the result of two brainstorming sessions with SMEs, a total of eight criteria have been defined for the MCA. Specifically, five of those criteria are quantitative, namely:

1. **Total Costs:** the entire cost to install (CAPEX) and operate (OPEX) a signalling alternative. Detailed items that are considered for the CAPEX are costs to:
   a) Remove track-side signalling equipment
   b) Install Automatic Train Operation (ATO) on the entire fleet
   c) Install Train Integrity Monitoring (TIM) on board of the train fleet
   d) Install the V2V communication layer
   e) Update the software/hardware of the on-board European Vital Computer (EVC)
   f) Update the power supply system
   g) Upgrade the rolling stock.

   The items included for the OPEX are annual costs for:
   h) Track maintenance
   i) Rolling stock maintenance
   j) Energy provision to operate the service
   k) Personnel salary.
2. **Infrastructure capacity**: defined as an index related to the maximum number of trains that can cross a given section of track within a time unit (referred as 1 hour) for a signalling alternative.
3. **System stability**: defined as the capability of a signalling alternative to mitigate delay propagation over the network.
4. **Travel demand**: considered as the spatial-temporal distribution of the travel demand and modal shifts among the different transport modes when a given rail signalling alternative is deployed.
5. **Consumed energy**: which is the total amount of energy consumed by trains to operate under a specific signalling alternative. We also analysed CO_2 equivalent emission, that is, the total amount of CO_2 equivalent emissions necessary to operate the train service under a given signalling alternative for an estimated model shift.

In addition, three qualitative criteria have been considered and are described as follows:

6. **Safety**: The degree by which a signalling alternative can prevent critical incidents that could compromise the health and/or the status of objects and people.
7. **Public acceptance**: Acceptance of a signalling alternative and its operating modes by the general public (collectivity). This is a qualitative criterion referring to measuring the degree by which customers are willing to accept the implementation of a signalling technology and make use of it based on their perception and personal experience of safety, comfort and convenience.
8. **Regulatory approval**: Legal approval licenses, registrations or authorizations of any national, supra-national (e.g. the European Commission), regional governmental entity or regulatory agency, that are necessary for the formal introduction of a signalling alternative in the regulatory jurisdiction.

5. Results of Multi-Criteria Analysis (MCA)

The results of the Multi-Criteria Analysis (MCA) are described in the following sections based on the methodology discussed in Section 4. The analysis of the quantitative and qualitative criteria are reported in Section 5.1 and Section 5.2, respectively. A detailed explanation and interpretation of the MCA results are discussed in Section 5.3.

5.1. Quantitative criteria

The evaluation of the defined quantitative criteria for the different signalling alternatives are reported from Section 5.1.1 to Section 5.1.5. *Infrastructure capacity* has been assessed in terms of a capacity index specifically defined for the MCA which provides for each signalling alternative a minimum train headway that is normalised with respect to the baseline and averaged across all of the considered manoeuvres. As previously mentioned, for a given combination of signalling system and market segment, minimum train headways are computed based on the compression method and an extension of it in order to be applied to Moving Block and Virtual Coupling. *Total costs* have been assessed based on reference unit costs provided by reference documents and field knowledge of Park Signalling Ltd. (partner of the MOVINGRAIL consortium) as well as from official national/international sources and specific literature on unitary expenditures for railway personnel, maintenance and energy. *System stability* is evaluated based on the UIC code 406 recommendations on maximum thresholds of infrastructure occupation to have stable train operations on a given market segment. *Travel demand distribution* is forecasted by means of a statistical analysis based on stated travel preference surveys distributed over a sample of 229 interviewees, to capture potential modal shifts to railways that the introduction of moving block and virtual coupling could lead to. *CO_2 emissions* are assessed based on computed modal shares among railways and the other transport modes (e.g. car, bus, plane). Initial CO_2 emissions have been extracted from consolidated emission models supported by the railway industry which are publicly available online such as EcoPassenger [44], The Green Freight Handbook [45] and the UK government [46]. And finally, *consumed energy* has been computed in terms of mechanical power by means of the microscopic railway traffic simulator EGTRAIN [48] applied to a representative train for each of the market segments running under each of the signalling alternatives.

More details on the methodology and results of the different criteria are provided in the following sections.

5.1.1. Infrastructure capacity

5.1.1.1. Capacity Index

Capacity is here defined as the maximum number of trains that can cross a section of infrastructure during a time period with a given level of service. Capacity depends on several factors relative to the delivered timetable and the railway infrastructure. Timetable-related factors include the stopping pattern of trains, the set of selected train routes (e.g. sequence of track sections and switches from origin to destination of a train service), the mix of train categories (e.g. intercity vs regional), the scheduled time margins (i.e. buffer and running time recovery times). Infrastructure-related factors involve instead signalling and interlocking rules as well as the topological layout of the infrastructure especially in interlocking areas like stations and junctions [47].

With the introduction of Virtual Coupling, the traditional railway operational paradigm is set to

change significantly. This means that changes in both the timetable and the infrastructure will need to happen that will deeply influence railway infrastructure capacity. Capacity impacts of Virtual Coupling have been investigated for each market segment according to the operational scenarios defined in Section 4.6.3. Those operational scenarios include a combination of typical following train manoeuvres (explained in Section 4.6.1) and different stopping patterns analysed for several configurations of the signalling system. For each of the operational scenarios referring to a given market segment, train infrastructure occupation has been estimated in terms of blocking times and the minimum train headway has been then computed by means of the compression method, which has been here extended to consider Virtual Coupling operations. Note that in a usual railway capacity assessment method, such as defined in UIC Code 406, the infrastructure occupation is computed by timetable compression of the blocking time staircases over complete corridors, where the minimum line headways between successive train paths thus include running time differences to the critical blocks on the corridor. Here we compute the local minimum headway times by compressing (local) operational scenarios defined by typical manoeuvres and signalling system configurations, see Section 4.6. Hence, we focus on the bottlenecks to compare the different signalling alternatives.

The computation of blocking times relies on a preliminary calculation of train distance-time diagrams which consider the following train movement stages:

- Acceleration from standstill to the permitted speed,
- Cruising at constant speed,
- Braking to standstill.

Note that we do not consider coasting as we focus on local manoeuvres. Distance and time of a train service have been computed by means of a finite difference integration of the kinematic equations. Train distance d_{n+1} and time t_{n+1} at calculation step $n+1$ for each of the movement stages hence depend on kinematic parameters of the train at the previous calculation step n, as reported in Table 7.

Table 7 – Standard motion equations for train movement stages

	Distance	Time
Acceleration	$d_{n+1} = \frac{\lvert v_{n+1}^2 - v_n^2 \rvert}{2\,a(v_n)}$	$t_{n+1} = \frac{\lvert v_{n+1} - v_n \rvert}{a(v_n)}$
Constant speed	$d_{n+1} = v_n \cdot (t_{n+1} - t_n)$	$t_{n+1} = \frac{(d_{n+1} - d_n)}{v_n}$
Braking	$d_{n+1} = \frac{\lvert v_n^2 - v_{n+1}^2 \rvert}{2b}$	$t_{n+1} = \frac{\lvert v_n - v_{n+1} \rvert}{b}$

Here v_n, $a(v_n)$ and b indicate the train speed, acceleration rate and braking rate at step n, respectively. While the braking rate b can be modelled as a constant parameter with good approximation, the train acceleration is instead a function of the train speed since after a given speed, the maximum tractive effort of the train engine becomes a hyperbolic function of speed. That means that the maximum tractive-effort and hence the maximum train acceleration are decreasing nonlinear functions of speed.

The kinematic equations in Table 7 have been integrated by using the timetabling design software FBS [52] which also includes real maximum acceleration-speed relations $a(v)$ for existing train engines. The FBS tool is however based on traditional railway operating procedures and conventional fixed block-signalling system, so some adaptations have been necessary to map capacity impacts under Moving Block and Virtual Coupling signalling. In particular, we used the FBS software to derive the acceleration-speed curves for given rolling stock and then approximated this nonlinear acceleration curve by a model using three fitted parameters. The method implemented to adapt the software to moving-block and Virtual Coupling is explained as follows.

Step 1.	**Define types of train for each market segment** Rolling stock and train engines were selected from the FBS data archive to match the train characteristics operating on each of the case studies identified for the different market segments.
Step 2.	**Determine dynamic data of the train types using available timetable program** Kinematic equations were integrated over the speed by using a speed interval of 1 km/h in FBS. For each interval, acceleration, time and travelled distance have been computed as reported above.
Step 3.	**Mathematical formulation of the acceleration-speed relation** The relation between the acceleration and speed of a train at a given calculation step n is approximated as $$a(v_n) = a_{v_0} - (a_{v_0} - a_{v_{max}}) \cdot \left(\frac{v_n}{v_{max}}\right)^{c_1},$$ where v_n and $a(v_n)$ are speed and acceleration at step n, $v_0 = 0$, and v_{max} is the maximum train engine speed, while a_{v_0} and $a_{v_{max}}$ are the accelerations of the train engine when starting from standstill (i.e. speed is $v_0 = 0$) and at maximum speed, which are parameters deriving from the tractive-effort speed curve of the traction unit. The factor c_1 is calibrated to adjust to a specific type of train. The values for the factor c_1 are usually in the range between 0.85 and 2.20. For trains with a very high acceleration capacity, such as urban trains, the factor can be up to 5.5.
Step 4.	**Integration of the kinematic equations in Excel** The kinematic equations were integrated by means of a finite difference integration process over the speed with a selected integration interval of 1 km/h. The computation of the average acceleration for two consecutive calculation steps v_n to v_{n+1}, is obtained by means of the relation: $$\bar{a}_n = a(v_n) \cdot (1 - c_2) + a(v_{n+1}) \cdot c_2$$ where the constant factor c_2 is determined from the FBS data archive depending on the type of train. Typical values for c_2 range between 0.55 and 0.85. For trains with a very high acceleration capacity, such as urban trains, the factor can be around 0.4. While the average acceleration value is well suited for calculating the required distance, it leads to large deviations when calculating the time. A third factor c_3 was therefore used for a more accurate computation of the time, as

	$$t_{n+1} = \frac{\lvert v_n - v_{n+1} \rvert}{\bar{a}_n \cdot c_3}$$ The factor c_3 is also a specific fixed value for each type of train fitted from the FBS data. The values for the factor c_3 are usually in the range between 1.01 and 1.3.
Step 5.	**Verification of integrated time-distance diagrams with real vehicle dynamics derived from the FBS tool** The integrated values of distance and time for a given train service were verified by comparison with running time calculations performed in the FBS tool. For this purpose, test tracks were built in FBS to compute running times for the different case studies. With calibrated parameter values for c_1, c_2 and c_3 a maximal deviation of 10 percent is observed to distance and time for the set of train types considered in the capacity analysis for the different market segments. In the pairwise comparisons these errors cancel out, so we assumed the fitted acceleration-speed diagrams in the calculations of all operational scenarios.
Step 6.	**Computation of blocking times for each of the manoeuvres** Based on the computed distance-time diagrams, the infrastructure occupations were computed in terms of blocking times for each of the manoeuvres as well as the stopping patterns considered for a given market segment. All the 66 operational scenarios reported in Section 4.6.3 were considered.
Step 7.	**Minimum train headway computation for each operational scenario** The blocking times computed for each operational scenario were compressed to estimate the minimum headway between two trains for a specific manoeuvre and stopping pattern. This minimum headway then has been used to evaluate an average capacity index for a certain signalling alternative as detailed below.

The validation of train running times integrated by means of a finite difference integration in Excel has been made considering real rolling stock characteristics provided by the FBS tool data archive. Details of the rolling stock characteristics used for the running time verification is given in Table 8 for each of the market segments.

Table 8 – Example trains used for calculations

Market Segment	High Speed (I)	Main Line	Regional	Urban	Freight
Name	ETR 500 (I)	Railjet (A)	Flirt (D)	S-Bahn (D)	Container
Series	ETR 500	ÖBB 1216	BR 428	BR 430	Es64F
$\mathbf{V_{max}}$ [km/h]	300	180	120	80	100
$\mathbf{a(V_0)}$ [m/s^2]	0.537	0.586	1.062	0.980	0.138
$\mathbf{a(V_{max})}$ [m/s^2]	0.069	0.139	0.450	0.697	0.060
$\mathbf{c_1}$	0.850	1.700	2.200	5.500	2.100
$\mathbf{c_2}$	0.82	0.73	0.65	0.30	0.55
$\mathbf{c_3}$	1.303	1.227	1.141	1.010	1.100
$\mathbf{b}$ [m/s^2]	1.000	1.000	1.000	1.000	0.386
Service braking [%]	65%	65%	65%	65%	65%
Emergency braking [%]	90%	90%	90%	90%	90%
Length [m]	328	205	75	137	495
Mass [t]	600	458	142	133	1752
Turnout speed [km/h]	130	80	60	80	60

Table 9 – Parameter values to compute blocking times for the market segments

	High speed	Main line	Regional	Urban	Freight
Switching time [s]	9	8	7	5	7
Safety margin for VC [m]	200	120	100	80	100
Max. speed [km/h]	300	160	120	80	100
Turnout speed [km/h]	130	80	60	80	60
Turnout length [m]	140	76	63	76	63
Block length baseline [m]	1500	1000	700	400	1000
Dwell time [s]	240	60	60	30	120
Gradient	0	0	0	0	0

For the computation of blocking times at Step 6, different values have been set for the switching time, safety margin, operational speeds and dwell times depending on the market segment according to typical values for those rail segments. These values are given in Table 9.

The minimum time headways resulting from the analysis are reported in Table 10, Table 11 and Table 12 for all of the operational scenarios defined for the different market segments (see Section 4.6.3). Specifically, Table 10 refers to the baseline signalling while Table 11 and Table 12 relate to the moving block and virtual coupling signalling alternatives respectively. The minimum headways represented in those tables are the minimum signal headway and therefore do not include timetable buffer time. The stopping scenarios on plain track assumed that the train lengths do not allow two trains at a platform, so these minimum headway times correspond to the time between two successive arrivals including the dwell time at the platform and the time between the departure from the first train and the arrival of the next train at the same stop position.

Figure 7 illustrates the minimum headway calculation for a merging movement, where the critical of the two minimum headway times was used, i.e., here train 1 is the one braking for a restricted speed at the switch and accelerating again after release of the switch section and the second train is running with full speed over the straight switch. Figure 8 illustrates the case of a divergent movement with a stop after the branch for the first train while the second train passes the straight switch at full speed.

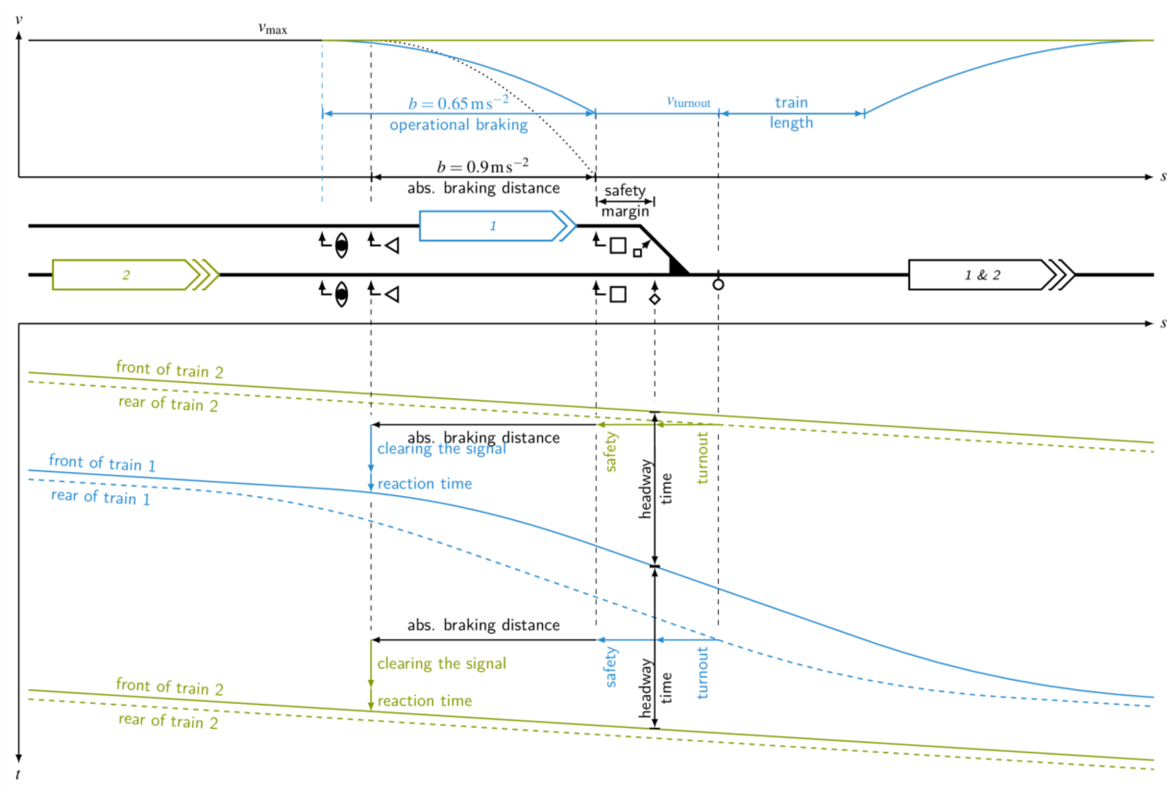

Figure 7 – Illustration minimum headway calculation merging movement

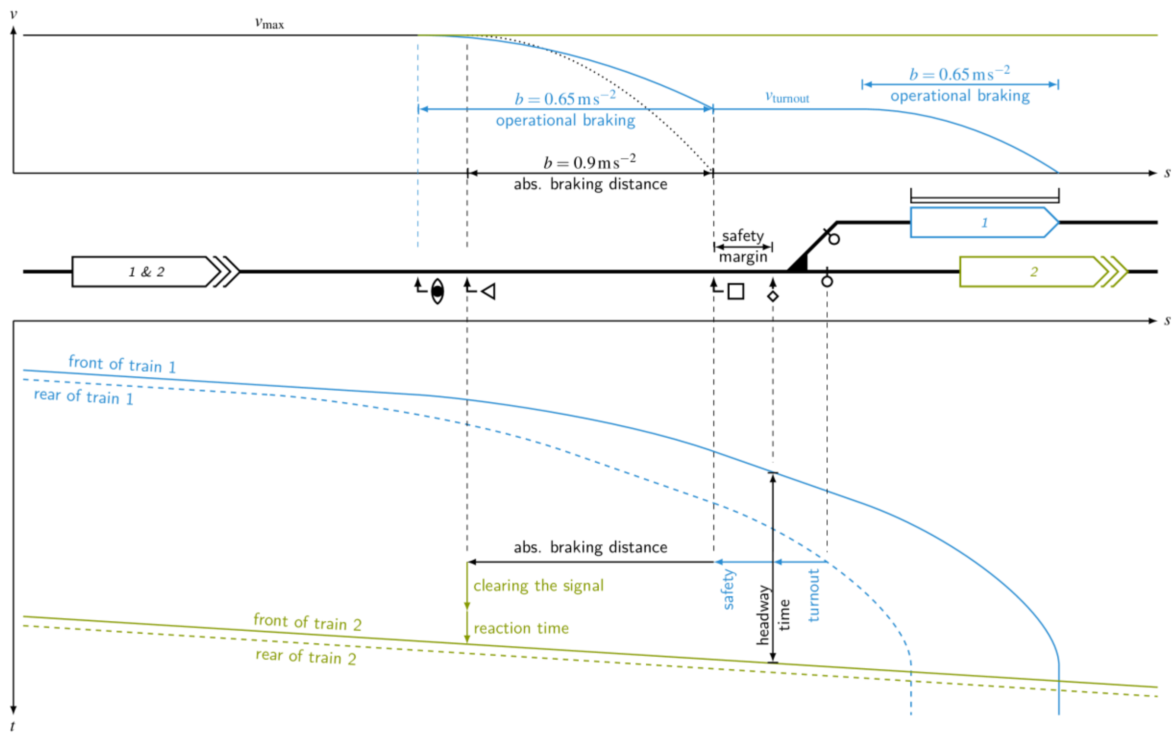

Figure 8 - Illustration minimum headway calculation diverging movement

Recall that these minimum headway times are only representative for a specific manoeuvre for a limited portion of track and do not consider operational dependencies with manoeuvres relative to upstream or downstream interlocking areas. This means that the evaluation of the capacity effects of a given signalling alternative must not compare one manoeuvre per time but an averaged impact over all manoeuvres, since different types of manoeuvres indeed occur across a real railway corridor. To this end, a capacity index $I_{cap}(S_k)$ has been defined to compare capacity effects of the signalling alternatives S_k (for k=1,2) versus the baseline S_0. The capacity index represents the reciprocal of the ratio between the minimum headway H_i of operational scenario i for signalling alternative S_k and baseline S_0, averaged over the total number of operational scenarios N_k applicable to S_k, i.e.,

$$I_{cap}(S_k) = N_k \left(\sum_{i=1}^{N_k} \frac{H_i(S_k)}{H_i(S_o)} \right)^{-1}$$

for $k \in \{1,2\}$. This means that the higher $I_{cap}(S_k)$ the larger is the capacity improvement that a signalling alternative S_k can provide. Of course, a value of the capacity index higher than 1 means that a given signalling alternative provides capacity improvements over the baseline.

Capacity indices obtained for the signalling alternative S_1 (ETCS Level 3) and S_2 (Virtual Coupling) are displayed in Table 11 and Table 12, respectively.

Table 10 – Baseline operational scenarios per market segment

Market Segment	Manoeuvre	Stopping pattern	Minimum headway time (s)
High-Speed (ETCS L2)	Plain	Stopping	481.2
		Non-Stopping	134.9
	Merge	Stopping	418.4
		Non-Stopping	99.5
	Diverge	Stopping	205.9
		Non-Stopping	80.7
Main-line (3-Aspect)	Plain	Stopping	182.5
		Non-Stopping	62.3
	Merge	Stopping	191
		Non-Stopping	72.4
	Diverge	Stopping	56.1
		Non-Stopping	55.8
Regional (3-Aspect)	Plain	Stopping	156
	Merge	Stopping	163.1
	Diverge	Stopping	64.3
Urban (3-Aspect)	Plain	Stopping	114.4
Freight (3-Aspect)	Plain	Stopping	350.1
		Non-Stopping	103.4
	Merge	Stopping	357.4
		Non-Stopping	114.9
	Diverge	Stopping	212.4
		Non-Stopping	90.1

Table 11 – Capacity index for the ETCS L3 operational scenarios per market segment

Market Segment	Manoeuvre	Stopping pattern	Minimum headway time (s)	Normalised ratios relative to Base	$I_{cap}(S_1)$
High-Speed (ETCS L3)	Plain	Stopping	334.1	0.694305902	1.229953
		Non-Stopping	74	0.548554485	
	Merge	Stopping	332.2	0.793977055	
		Non-Stopping	92.3	0.927638191	
	Diverge	Stopping	200.9	0.975716367	
		Non-Stopping	75.7	0.938042131	
Main-line (ETCS L3)	Plain	Stopping	133.2	0.729863014	1.246666
		Non-Stopping	46.5	0.746388443	
	Merge	Stopping	125.8	0.658638743	
		Non-Stopping	56.2	0.776243094	
	Diverge	Stopping	53.3	0.950089127	
		Non-Stopping	53.1	0.951612903	
Regional (ETCS L3)	Plain	Stopping	112.5	0.721153846	1.334347
	Merge	Stopping	105	0.643776824	
	Diverge	Stopping	56.8	0.883359253	
Urban (CBTC)	Plain	Stopping	84.2	0.736013986	1.3586698
Freight (ETCS L3)	Plain	Stopping	284.4	0.812339332	1.177951
		Non-Stopping	81.8	0.791102515	
	Merge	Stopping	270.1	0.75573587	
		Non-Stopping	86.2	0.750217581	
	Diverge	Stopping	211.4	0.995291902	
		Non-Stopping	89.1	0.988901221	

Table 12 – Capacity index for the VC operational scenarios per market segment

Market Segment	Manoeuvres	Stopping pattern	Minimum headway time (s)	Normalised ratios relative to Base	$I_{cap}(S_2)$
High-Speed (VC)	Plain	Stopping	329.8	0.685369909	1.366534
		Non-Stopping	11.4	0.084507042	
	Merge	Stopping	326.1	0.779397706	
		Non-Stopping	92.3	0.927638191	
	Diverge	Stopping	200.9	0.975716367	
		Non-Stopping	75.7	0.938042131	
Main-line (VC)	Plain	Stopping	130.2	0.713424658	1.422611
		Non-Stopping	12.3	0.197431782	
	Merge	Stopping	120.1	0.628795812	
		Non-Stopping	56.2	0.776243094	
	Diverge	Stopping	53.3	0.950089127	
		Non-Stopping	53.1	0.951612903	
Regional (VC)	Plain	Stopping	110.7	0.709615385	1.358359
	Merge	Stopping	100.4	0.615573268	
	Diverge	Stopping	56.8	0.883359253	

Market Segment	Manoeuvres	Stopping pattern	Minimum headway time (s)	Normalised ratios relative to Base	$I_{cap}(S_2)$
Urban (VC)	Plain	Stopping	79.6	0.695804196	1.437186
Freight (VC)	Plain	Stopping	276.9	0.790916881	1.330134
		Non-Stopping	27.2	0.263056093	
	Merge	Stopping	258.2	0.722439843	
		Non-Stopping	86.2	0.750217581	
	Diverge	Stopping	211.4	0.995291902	
		Non-Stopping	89.1	0.988901221	

Figure 9 compares the capacity indexes of moving block (MB) and virtual coupling (VC) per market segment. VC provides relevant capacity improvements over moving block for main-line railways (+14%), freight lines (+13%) and high-speed (+11%). Over main-line railways characterised by heterogeneous traffic patterns and complex interlocking areas, VC would have a positive homogenising effect due to the possibility for trains to follow each other in synchronised platoons. Also, letting trains of different types running close to each other (at a relative braking distance or even platooning at a constant distance from each other) can have a particularly beneficial impact on reducing headway at bottlenecks (e.g. stations, junctions), where capacity-consuming manoeuvres of different train categories merging/diverging from/to other branches usually occur on main-lines. For high-speed railways, absolute braking distances supervised by moving block signalling can be quite long (up to 4-5 km) given the high operational speeds (around 300 km/h), hence VC can provide significant capacity benefits for following train movements. However, headway reductions due to VC are only marginal (in the order of 10 s) with respect to MB, if stopping high-speed trains are separated by a relative braking distance. This can be seen by the headway values obtained for VC (Table 11) and MB (Table 10) concerning manoeuvre M1 with stopping trains. Significant headway reductions (up to 1 min) are instead observed when high-speed trains can move synchronously at a quasi-constant separation in a coupled platoon, as the headway comparison between VC and MB shows for manoeuvre M1 with non-stopping trains.

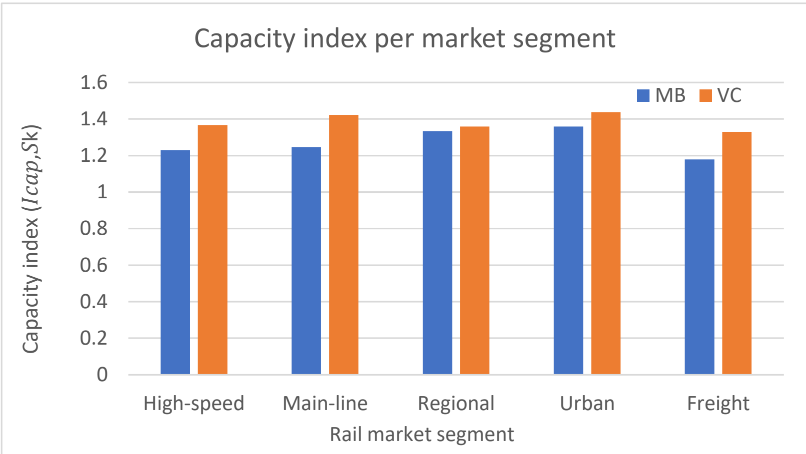

Figure 9 – Capacity index of MB and VC per market segment

The capacity index values that will be used in the MCA analysis (Section 5.3) for each of the market segments and signalling alternative are displayed in Table 13.

Table 13 – Capacity index of ETCS L3 MB and VC per market segment

Capacity Index I_{cap}		
Market Segment	**ETCS L3**	**VC**
High-speed	1.230	1.367
Main line	1.247	1.423
Regional	1.334	1.358
Urban	1.359	1.437
Freight	1.178	1.330

Similarly, the possibility of train platooning can be particularly beneficial for freight trains which usually have non-stopping operations which fit particularly well to the concept of VC, despite the relatively low running speeds. At low speeds indeed the difference between relative and absolute braking distance becomes negligible. For rail market segments having low operational speeds VC can still provide capacity gains over MB thanks to platooning where trains can keep synchronous stable movements over long distances with relative braking distances.

For the regional and the urban segments, VC only shows a little capacity improvement of 1.8% for the former and 5.8% for the latter. This is mainly due to the type of operations on those segments which are mainly characterised by frequent stopping and low operational speeds where a relative braking distance separation would not significantly reduce headways with respect to an absolute braking one. For these two markets, VC could still be beneficial over MB by allowing trains to form platoons and thus enable stable cooperative operation. Composition/decomposition of platoons would however need to occur when trains are at a standstill at stations given the short interstation distances and the frequent stopping patterns of these railway segments which prevent coupling/decoupling operations "on-the-run". This also entails that the first deployment of VC could be made on these two market segments since they do not require additional algorithms for controlling trains when shifting between absolute and relative braking distance under VC signalling. Besides a reliable V2V communication layer, algorithms for synchronous train movements would be sufficient for these market segments since composition/decomposition of platoons could be performed at standstill at stations with the only difference to the current practice of physical coupling that virtual coupling would be made via radio communication rather than by physical couplers.

5.1.1.2. Simulation-based infrastructure capacity assessment and verification

Besides the analytical capacity investigation presented in the previous section for the different manoeuvres, an in-depth analysis has been performed by means of microscopic railway traffic simulation. The main reason for a detailed simulation-based infrastructure capacity analysis is to better understand actual capacity gains that VC could offer over corridors rather than specific manoeuvres in relation to traffic dynamics, data communication processes and train supervision modes taking place during VC operations. Such a corridor simulation study has also allowed verifying the analytical headway computation made in section 5.1.1 for some of the most representative manoeuvres on plain lines, diverging and merging junctions, respectively. The simulation study builds on the Virtual Coupling operational principles defined in MOVINGRAIL deliverable D4.1. Those operational principles have been mathematically translated into a multi-state train-following model that captured different state transitions and supervision modes of trains operating under VC. A detailed explanation of the mathematical background of this model

can be found in Quaglietta et al. [49]. The developed multi-state train-following model has been embedded in the microscopic railway traffic simulator EGTRAIN [48] and applied to the portion between London Waterloo and Surbiton of the South West Main-Line case study (Figure 10).

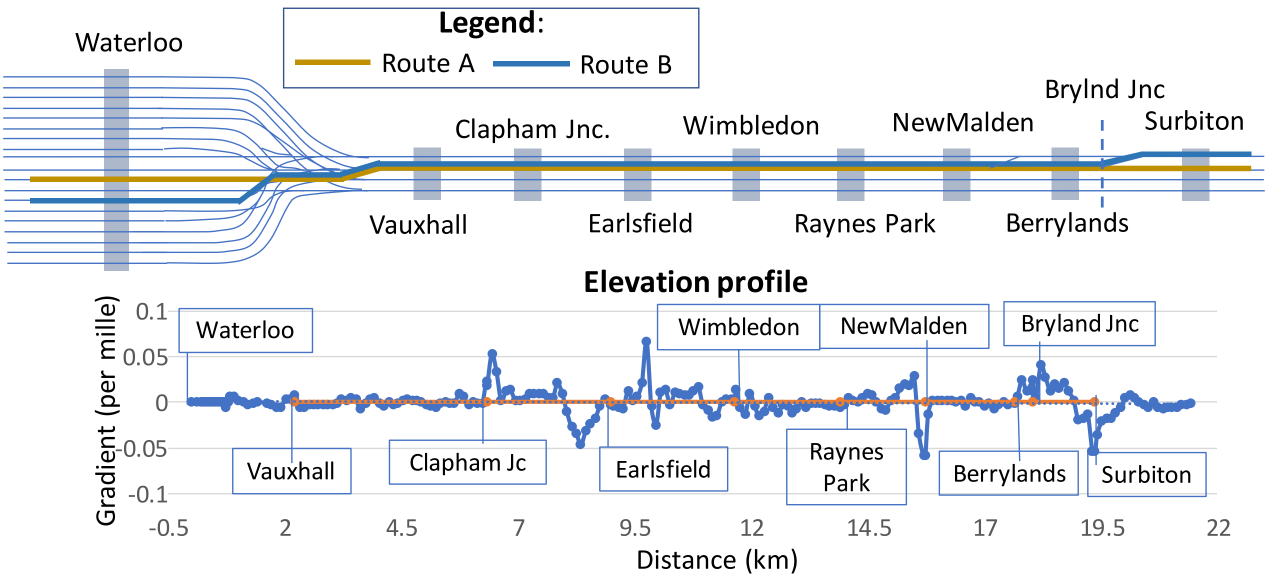

Figure 10 – Portion on the South West Main-Line corridor (UK) used for the simulation-based evaluation of VC train operations

The objective of the simulation experiments was to assess the train behaviour during coupling/decoupling phases over a network in different scenarios of stopping and non-stopping trains for trains having the same or a different route. Experiments have been performed by considering two trains in order to have a clear overview on the state transition of a train when interacting with another one under VC. A temporary speed restriction of 65 km/h has been imposed to the first train so that this latter could slow down and give a chance to the succeeding train to get closer and initiate virtual coupling procedures. Specifically, the first scenario considers only non-stop train services while the second scenario assumes that trains perform four service stops at Clapham Junction (*CpJ*), Wimbledon (*Wbn*), Raynes Park (*RnP*), and Surbiton (*Sbn*), respectively. All trains depart from Waterloo (*Wtl*) passing by timetabling locations such as Vauxhall (*Vxl*), Earlsfield (*Eld*), New Malden (*NMn*) and Berryland (*Bld*). For each scenario the case in which trains have the same route (*Route A*) is compared versus the case in which trains operate on different routes (*Route A* and *B*) that are only partially shared and diverge at Berrylands Junction (*BlJ*).

The two train services (respectively named *A3-Wtl-Surbiton-1* and *A3-Wtl-Surbiton-2*) use the same rolling stock, namely a 161.8 m long eight-car British Rail Class 455. In the experiments we assume that the follower train enters the network as soon as the signalling system allows it. The communication time between trains and the RBC for the broadcast of the MA and the position report is set to 1s. Also, the latency of the V2V communication layer in VC is considered to be 1 s. Trains travelling in a virtually coupled platoon are assumed to keep a safe separation margin of at least 50 m. A space tolerance (th_s) of 30 m and a speed tolerance (th_v) of 0.278 m/s (i.e. 1 km/h) have been adopted in the train-following model to identify whether a follower train is coupled/unintentionally decoupled to/from the train ahead. This means that a train is considered

as virtually coupled to a train ahead if it achieves a speed of ±0.278 m/s within a range of 30 m from the safety margin of 50 m (i.e. a range of 80 m in total) from the tail of the train ahead. In case the separation between the two train exceeds such a range then they are no longer considered to travel synchronously in a platoon although they still form a convoy operating under VC.

In ETCS Level 3 and Virtual Coupling, trains are automatically driven by ATO with a reaction time of 0.5 s. In addition, for these signalling systems we allow the two trains to enter a station area together and line up at the same platform to perform their stop. Such an assumption has been made to estimate capacity gains when using the entire potential of moving-block operations. For ETCS Level 2 and TPWS a human driver is instead considered with a sight and reaction time of 2.5 s. For these fixed-block signalling systems state-of-practice rules have been used for modelling stopping operations where a train cannot enter a platform if it is already occupied by another train.

The interaction between the two simulated trains when running under VC is illustrated in Figure 11 for the scenario of non-stopping trains and in Figure 12 for stopping trains.

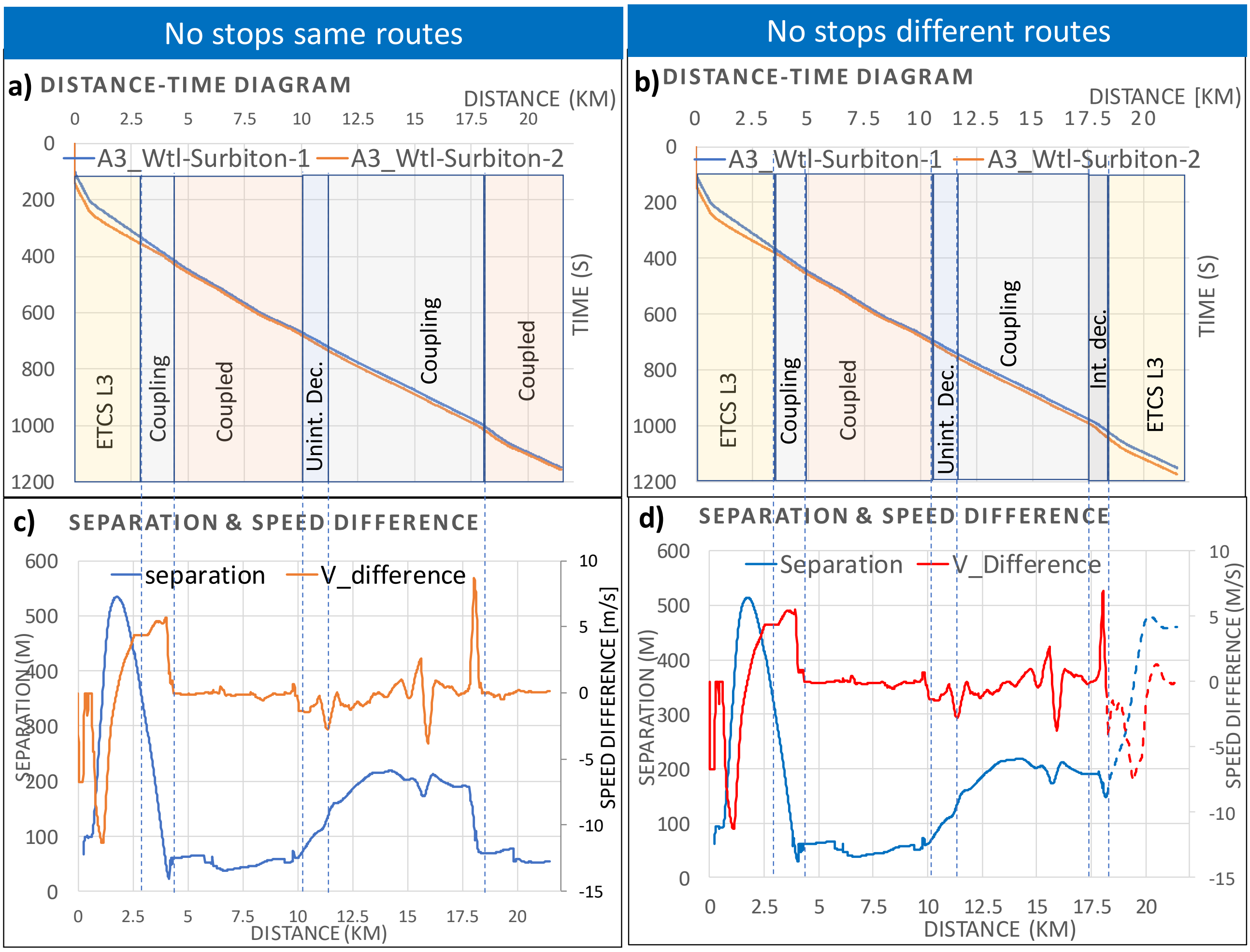

Figure 11 – Distance-time diagram (top), separation and speed differentials (bottom) between leader and follower for non-stopping trains with the same (left) or a different route (right)

Simulated time-distance diagrams of the two trains and the sequence of operational states of the follower (plots (a) and (b) at the top) are illustrated, together with the speed difference and the separation between the trains over their route (plots (c) and (d) at the bottom). The diagrams on the left-side refer to the case in which trains have the same route (*route A*), while those on the right-side relate to the case of different train routes where the leader runs over *route A* and the follower on *route B*.

The diagrams show that the developed train-following model captures the different operational states of a train when running under Virtual Coupling. The sequence of operational states always starts with the follower train running under ETCS Level 3, switching to a "coupling" state as soon as it approaches the train ahead. When the conditions for coupling are satisfied, the train enters a state of "coupled running" assuming the same accelerations and speed of the leader.

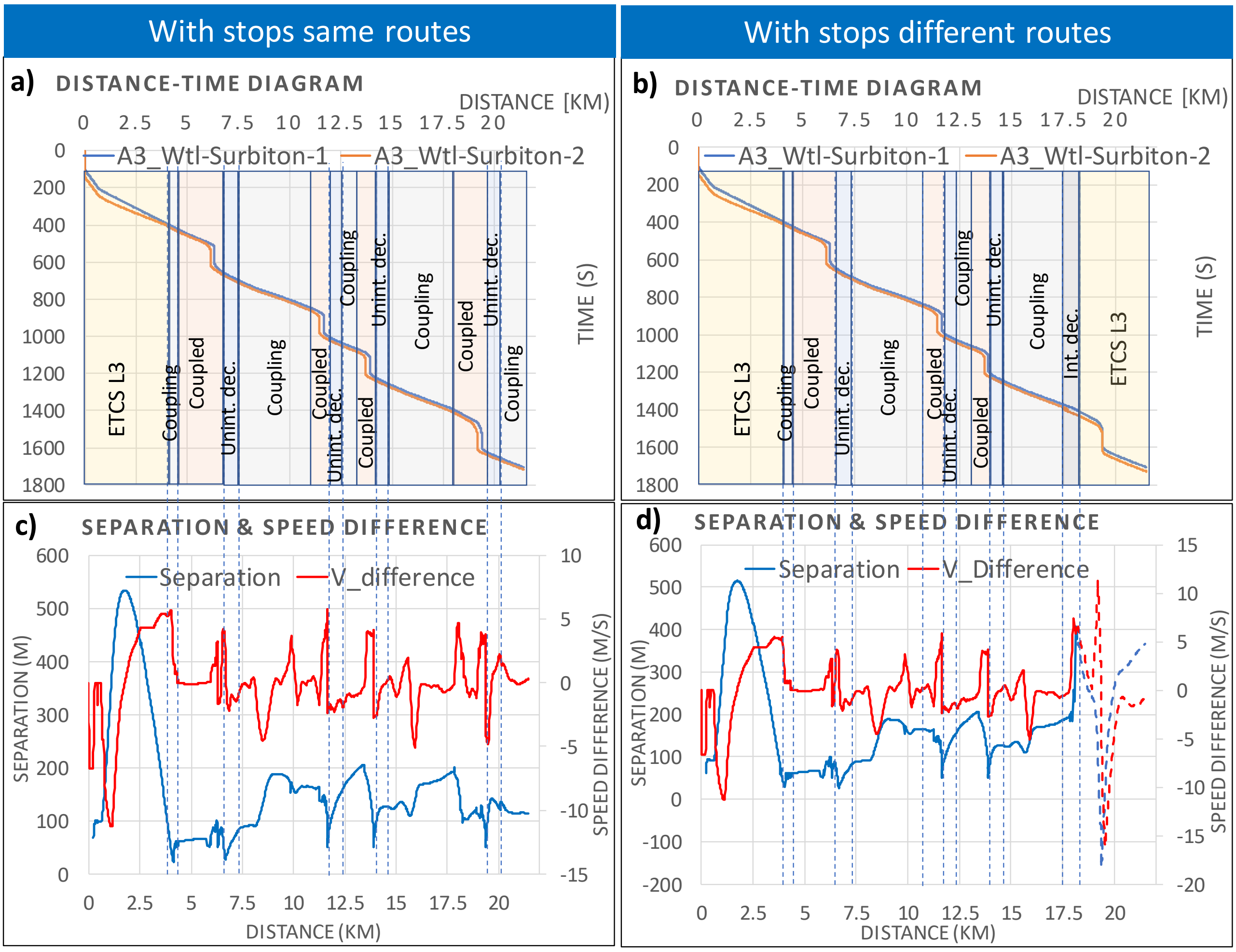

Figure 12 – Distance-time diagram (top), separation and speed differentials (bottom) between leader and follower for stopping trains with the same (left) or a different route (right)

Speed difference diagrams (red line) reported in plots (c) and (d) of Figure 11 and Figure 12, clearly illustrate that speed differentials between leader and follower oscillate around zero while in coupled running. The trains run virtually coupled in a convoy until motion resistances increase at the point that the follower can no longer maintain the leader's speed, resulting in an increasing train separation. A state of unintentional decoupling is hence obtained, that for this railway

corridor is due to a very hilly elevation profile which makes it hard for the follower on a steep uphill to catch up with the leader running ahead on a flatter ground or even downhill. As shown by the separation diagrams (blue line) in plots (c) and (d) of Figure 11 and Figure 12, the unintentional separation between the two trains keeps however below 215 m (considering a platooning reference safety margin of 50 m and a range of 30 m) at an average train speed of 22 m/s (≈ 80 km/h), which is anyway a much shorter separation when compared to existing fixed-block signalling systems and ETCS Level 3 (which would at least require 405 m for the same braking rate of 0.6 m/s^2). For the sake of clarity, a state of unintentional decoupling here means that the two trains are still travelling under Virtual Coupling, however they are no longer running synchronously in a platoon. After having been unintentionally decoupled, the follower train switches again to a coupling state driving at maximum power in the attempt to catch up and couple with the leader. In the scenario of non-stopping trains (Figure 11) the follower will steadily stay in a "coupling" state until track and vehicle conditions allow the train to couple again with the leader (if they have the same route) or to intentionally decouple from it before the diverging junction in Berryland (when using different routes). The transition to the state of "intentional decoupling" is immediately visible in Figure 11(d) where separation and speed difference between the two trains reach a peak before the diverging junction. Dashed lines represent the separation and speed differential after the two trains have decoupled and run over different routes again under the supervision of ETCS Level 3.

In the scenario of stopping trains (Figure 12), the follower unintentionally decouples from the leader every time they leave a stopping station. From a state of "unintentional decoupling" the follower then switches to a "coupling" state, until it catches up with the leader as this latter reduces its speed to approach the next stop. The two trains manage to couple just before any stopping station, meaning that they approach, cross and leave any of those stations as virtually-coupled trains in a convoy. When performing a stop, our model allows the two trains lining up at the same platform, as well as leaving the station together as if they were physically coupled. However, the alternative transitions between coupling and intentional decoupling when the trains approach and leave a station highlight the necessity of a train control system that can optimally supervise the formation of convoys when trains run under VC. Of course, in the case of trains having different routes, the follower train transitions to an "intentional decoupling" state before Berryland Junction so to diverge to a different stopping platform in Surbiton. The intentional decoupling can be seen in Figure 12(d) where the diagrams of separation and speed differential have a peak before the trains undertake different routes. From that point on, trains operate on separate routes (dashed lines in the diagram) switching to ETCS Level 3.

Comparative capacity analysis

The simulation-based analysis has been used to evaluate capacity performance of the virtual coupling signalling alternative with respect to moving-block ETCS Level 3, as well as the baseline signalling ETCS Level 2 and the three-aspect fixed-block system with the class B TPWS. Capacity is here evaluated in terms of train separation over the route and time headways (HW) at main interlocking areas, experienced by the trains during simulation experiments. Outcomes from the capacity analysis are depicted in Figure 13 for the scenarios of non-stopping (top) and stopping trains (bottom), and for the cases in which trains have the same (plots (a) and (c)) or a different route (plots (b) and (d)). Train separation over the entire route (distance is given on the x-axis) is represented with solid lines while a histogram is used to report time headways at main interlocking areas. Results for Virtual Coupling are reported in blue, while those for ETCS Level 3, ETCS Level 2

and TPWS are given in orange, grey and gold, respectively. For all scenarios and cases, Virtual Coupling massively reduces train separations and time headways, when compared to the other signalling systems. A fair comparison with ETCS Level 3 shall however exclude the area of Vauxhall (*Vxl*), since when simulating Virtual Coupling the follower crosses that location while still being supervised by ETCS Level 3 and just transitioning to a "coupling" operational state. Given that in such a location Virtual Coupling train separation is still governed by an absolute braking distance, a comparison with ETCS Level 3 does not make much sense, since it would practically mean to compare ETCS Level 3 to itself. For this reason, capacity measures of Virtual Coupling and ETCS Level 3 in *Vxl* are similar. Also, in the case of trains with different routes, it makes sense to compare train separation and time headways only for those locations along common portions of infrastructure. This means for instance that Surbiton (*Sbn*), where routes A and B use different tracks, is excluded when computing the most critical experienced headway for the different signalling systems.

In the case of non-stopping trains having the same route (Figure 13(a)) we observe that the capacity bottleneck (i.e. the location with the maximum experienced time headway) shifts from Vauxhall (*Vxl*) to Berryland Junction (*BlJ*) when passing from fixed-block signalling (TPWS and ETCS Level 2) to moving-block (ETCS Level 3 and Virtual Coupling).

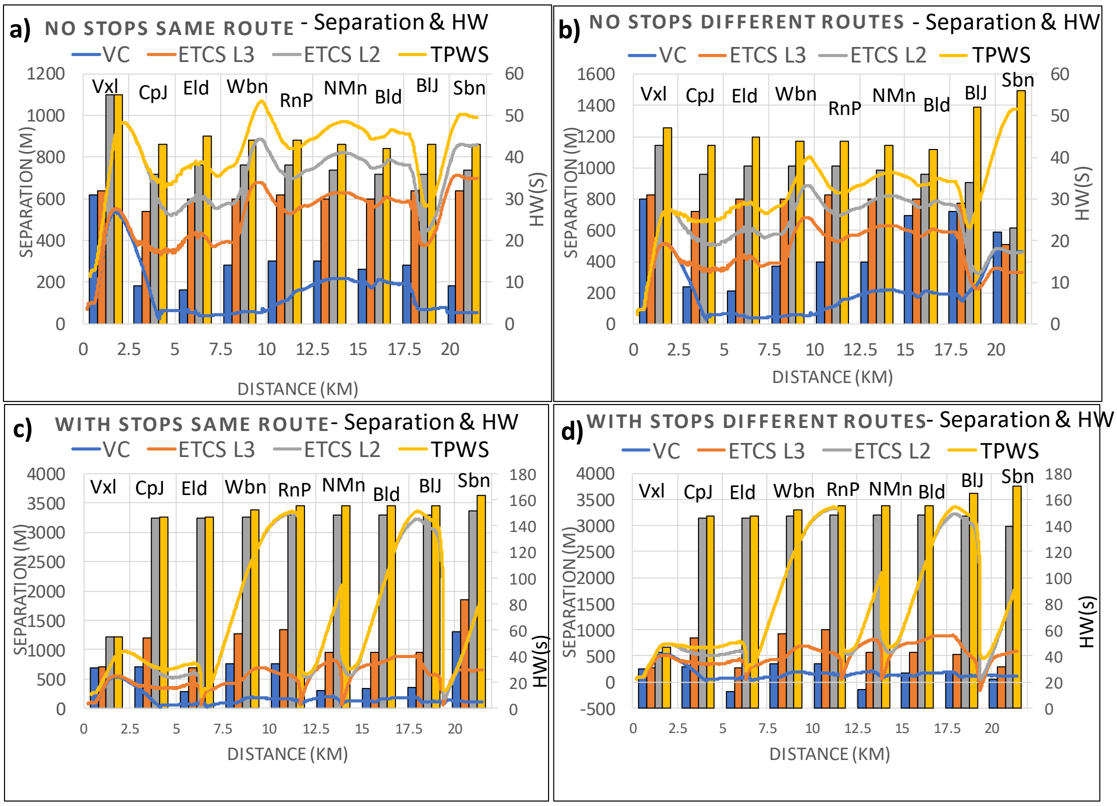

Figure 13 – Train separation and time headway (HW) at main interlocking areas for non-stopping (top) and stopping trains (bottom) using the same (left) or a different route (right)

The maximum headway reduces from 55s for fixed-block signalling to 32 s if ETCS Level 3 is implemented, getting down to only 15 seconds when referring to pure Virtual Coupling operations. Virtual Coupling reduces critical headways by 67%, 61% and 53% when compared with TPWS, ETCS Level 2 and ETCS Level 3, respectively. In terms of maximum train separation, this translates into

a corresponding decrease of 50%, 44% and 25%.

When non-stopping trains have different routes (Figure 13(b)) the location with the most critical headway changes from *BlJ* for TPWS to *Vxl* for ETCS Level 2, and from *RnP* for ETCS Level 3 to again *BlJ* when pure Virtual Coupling operations are considered (so excluding *Vlx* where trains still operate under ETCS Level 3). As already said, in this case *Sbn* is not considered, given that in that location trains use different tracks. A maximum time headway of 21 s is experienced by trains under Virtual Coupling, which means a reduction by 60%, 51%, and 32% versus TPWS (with a max HW of 52s), ETCS Level 2 (max HW = 43s) and ETCS Level 3 (max HW = 31s), respectively. When referring to maximum train separation, it means a respective reduction by 62%, 42% and 24%. Capacity benefits of Virtual Coupling are even more significant for the scenarios of stopping trains. In this scenario we also observe that TPWS and ETCS Level 2 have a very similar performance, especially in terms of train separation, as their separation diagrams are almost entirely overlapping.

In the case that trains have the same route (Figure 13(c)), *Sbn* is the most critical location for all the signalling systems. The time headway in this location decreases from 163 s for TPWS to 151s for ETCS Level 2 and from 83s for ETCS Level 3 to 59 s when considering Virtual Coupling. This latter signalling system hence reduces the maximum headway on the line by 63%, 61% and 28% in reference to TPWS, ETCS Level 2 and Level 3, respectively. This translates into a corresponding decrease in the maximum train separation that equals 85%, 84%, and 40%. When trains have different routes instead (Figure 13(d)), the location with the largest headway moves from *BlJ* in the case of TPWS to *RnP* when considering ETCS Level 2, Level 3 and Virtual Coupling. In such a case, Virtual Coupling has a maximum experienced headway of 34 s, corresponding to a reduction of 79%, 77% and 43% when compared with TPWS (max HW= 165s), ETCS Level 2 (max HW= 148s) and Level 3 (max HW=60s), respectively. Referring to maximum train separations on the line this means a respective decrease by 85%, 64% and 43%.

A further analysis has been carried out to identify advantages of Virtual Coupling over ETCS Level 3 moving-block under disturbances (e.g. a rolling stock malfunctioning) which limit the maximum speed of the leader in the area after Reynes Park. By simulating multiple disturbed scenarios imposing different speed limitations to the leader it is possible to grasp the operational speed below which absolute braking distances are comparable to relative braking distances, resulting in similar performances of Virtual Coupling and ETCS Level 3. Figure 14 illustrates such a comparison in terms of train separation over the entire line, for the case of stopping trains having the same route (so that the follower is forced to stay behind the leader). Train separation under Virtual Coupling (blue line) and ETCS Level 3 (orange line) is reported for undisturbed operations (plot (a) and for each disturbed scenario respectively limiting the leader's speed to 80 km/h (b), 60 km/h (c), 40 km/h (d) and 20 km/h (e). The disturbed area is represented in light yellow. Figure 14(f) provides instead the ratio η between the running time under Virtual Coupling and the running time under ETCS Level 3 of the follower for the undisturbed and the disturbed scenarios.

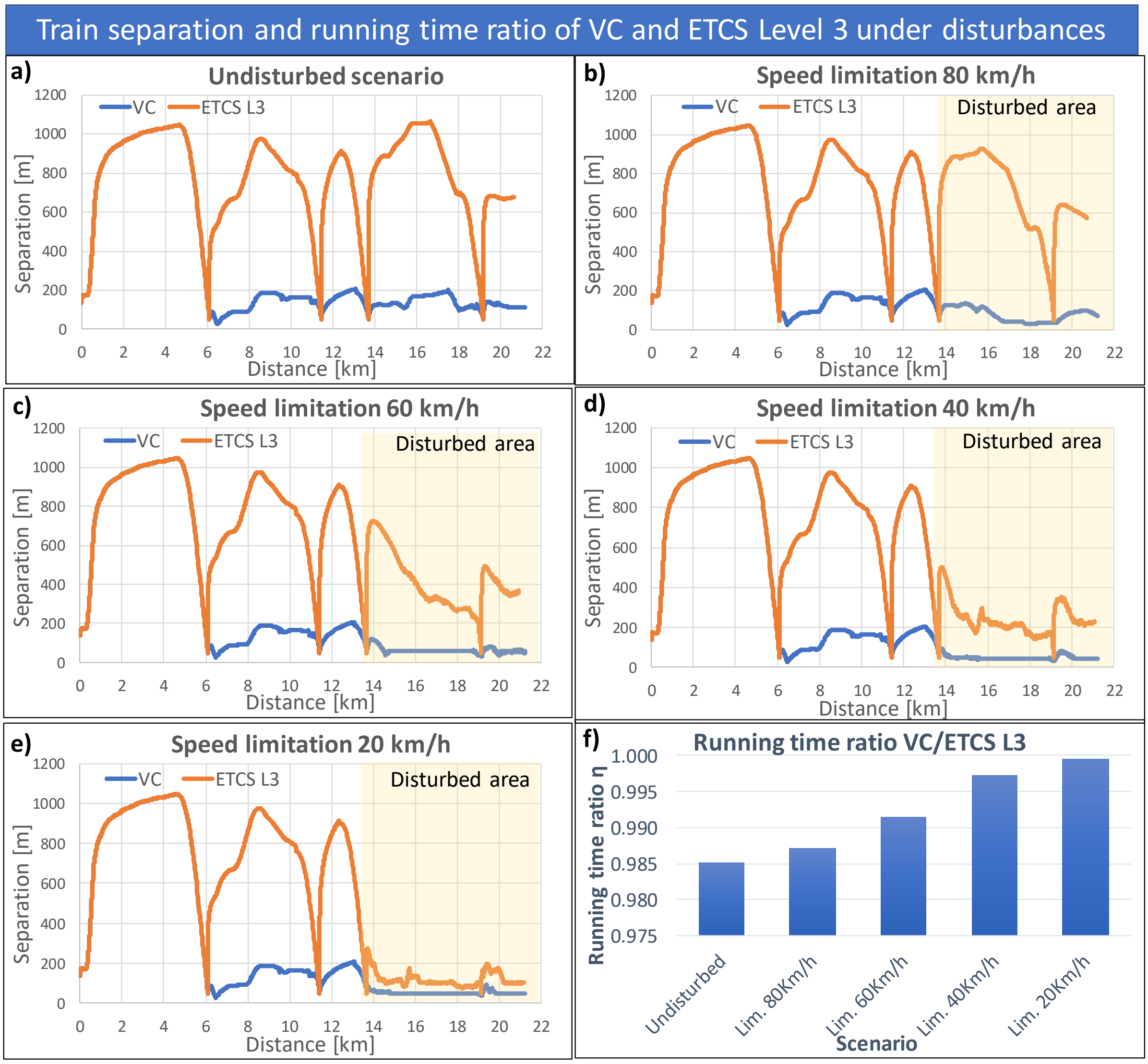

Figure 14 – Comparison of train separation and running time ratio of the follower for Virtual Coupling and ETCS Level 3 under disturbances limiting the speed of the leader

For Virtual Coupling the follower runs under ETCS Level 3 until Clapham Junction (km 6 on the route) where it finally catches the leader and couples to it. This explains why train separation diagrams of the two signalling systems are overlapping until Clapham. In the disturbed area, the difference in train separation between Virtual Coupling and ETCS Level 3 visibly decreases with the imposed speed limitation until it becomes marginal when the limit goes down to 20 km/h. When running at very low speeds the absolute and relative braking distances hence become comparable, making advantages of Virtual Coupling negligible. Such a result is also observed in Figure 14(f) where the running time ratio η of the follower gradually increases when reducing the speed limitation until it reaches a value very close to 1 for a limit of 20 km/h. The performed analysis provides preliminary evidence that the concept of Virtual Coupling might be very beneficial over moving-block on high-speed, conventional and regional lines, while on suburban and rural networks with limited operational speeds, investments might be evaluated case by case.

The operational configurations and the infrastructure layout of the simulated corridor has additionally allowed to verify the analytical headway calculation made for the main-line rail

segment in section 5.1.1 for the set of relevant manoeuvres reported in Table 14.

Table 14. Deviation between analytical and simulated VC headway improvement versus MB for representative manoeuvres

Market segment	Manoeuvre		Analytical ΔH_i [%]	(Simulated) ΔH_i [%]	Deviation [% point]
Main-line	*Infrastructure layout*	*Service type*			
	Plain line	Non-Stopping	-73.5	-73.3	**0.2**
	Merging junction	Non-Stopping	0.0	-3.1	**-3.1**
	Diverging junction	Non-Stopping	0.0	-6.9	**-6.9**

For each manoeuvre i, both the analytical and simulated minimum headway improvement ΔH_i of VC versus MB have been compared and the corresponding deviation computed. The minimum headway improvement ΔH_i of VC versus MB for manoeuvre $i \in \{1, \dots, 3\}$ is calculated as

$$\Delta H_i = \frac{H_i(VC) - H_i(MB)}{H_i(MB)},$$

where $H_i(VC)$ and $H_i(MB)$ represent the minimum headway for manoeuvre i obtained for VC and MB respectively for a specific capacity computation method (i.e. analytical versus simulated). The locations considered on the simulated SWML corridor to compute the percentage VC headway improvement for the different manoeuvres are Earlsfield for the plain line, the exit of Waterloo station for the merging manoeuvre, and Berryland Junction for the diverging manoeuvre.

The comparison shows that the analytical capacity results have a maximum deviation of 6.9% from the microscopic simulation outcomes. This means that the capacity index calculated in section 5.1.1 for the different manoeuvres are approximations of the real capacity results. The maximal deviation is obtained for the case of diverging junctions which could be explained by the detailed dynamics in the simulation model that could not be accounted for in the analytical capacity model. In this case, the analytical capacity model assumes a following train at maximum speed that is separated by the absolute braking distance just when the switch is released by the preceding (diverting) train according to the compression method of conflict-free train paths. Note that here the absolute braking distance is maximal corresponding to the maximum speed. In the microscopic simulation model instead, the two trains were simulated for a longer time before the diverging manoeuvre at the junction. Here, the two trains were running in a convoy which had to be decoupled for the diverging manoeuvre. Hence, not only the leader slowed down for the diverging movement through the switch, but also the follower to guarantee an absolute braking distance to the diverging junction. Then as soon as the switch was released, moved and locked again the follower train could reaccelerate again to the maximum speed. Hence, in this dynamic cooperation the absolute braking distance of the following train is shorter reflecting the lower speed from the decoupling process, and therefore the minimum headway turns out to be shorter, as opposed to a maximum speed of the follower when approaching the junction as assumed in the analytical model.

Still, the simulation results provide conclusions that are very much in line with those obtained from

the capacity index in section 5.1.1. Indeed significant capacity gains are observed for Virtual Coupling over ETCS Level 3 under the condition that cooperative train control algorithms can efficiently coordinate the composition/decomposition of virtually coupled platoons. Note that in the simulation a multi-state train-following model was used that respects the VC operational procedures and as such the simulation demonstrates the capabilities of VC. However, advanced cooperative control algorithms based on optimal control methods could further optimize the performance of VC. Such algorithms are still in development, so the simulation results reported here can be further improved by considering more advanced algorithms in the future.

5.1.2. Total costs

Estimates for investment costs (CAPEX) of ETCS Level 3 and Virtual Coupling have been provided based on field knowledge of Park signalling Ltd. as a signalling system supplier as well as related literature available. Assessments relative to operational costs (OPEX) derive from projections relying on available cost data for Moving Block signalling mainly adopted in urban areas, e.g. Communication-Based Train Control (CBTC), and official reports on unitary costs for track and rolling stock maintenance, as well as personnel salaries. Energy provision expenses instead refer to average unitary kWh costs in Europe as reported by Eurostat [17]. Both CAPEX and OPEX items have been assessed for the baseline S0 as well as the two signalling alternatives ETCS Level 3 (Alternative S1) and Virtual Coupling (Alternative S2).

5.1.2.1. Investment costs (CAPEX)

Investment costs (CAPEX) have been computed in two progressive signalling migration scenarios. The first scenario considers a migration from baseline signalling (either conventional fixed-block three-aspect or ETCS Level 2 for high-speed railways) to ETCS Level 3 Moving Block. The second scenario refers to the migration from ETCS Level 3 to Virtual Coupling. The summation of the investment costs for these two scenarios will provide the total cost to migrate from baseline signalling to Virtual Coupling. For both types of signalling migration, costs needed to support technology approval and the deployment authorisation process from Railway Regulatory Bodies are considered to range between 300 and 360M€ [50]. An average of €330M has been used in this analysis.

Capital Expenditure identified for the baselines (three-aspect and ETCS Level 2) and the two migration scenarios, are provided as follows.

<u>Baseline (conventional fixed-block multi-aspect) to ETCS Level 3 Moving Block</u>

This considers the conversion from conventional signalling to ETCS Level 3 and therefore includes cost and installation of the Vehicle On-Board Controller (VOBC), etc. onto the vehicle, trackside balises, signage (under Signalling Equivalent Unit (SEU)) and removal of the conventional equipment. The costs are provided per km, per Multiple Unit (MU) or per class depending on the considered item.

- Trackside cost (scheme design, equipment, installation & test) €1.1M/km
- Train equipment cost €425k/MU [51]
- Train equipment engineering cost per MU €150k/MU [50]
- Train equipment installation cost €40k/MU [50]
- Train Integrity Monitor equipment cost €24k/MU.

Baseline (ETCS L2) to ETCS level 3 Moving Block

This considers upgrading existing ETCS Level 2 scheme to ETCS Level 3, and therefore the cost of updating VOBC software and removal of train detection is included. It is assumed that vehicles are already fitted with VOBC. Costs associated with testing/commissioning and for the updating of the Traffic Management System (TMS) have not been included.

- Train Integrity Monitor equipment cost — €24k/MU
- EVC software upgrade cost — €50k/MU [50]
- Removal of unwanted train detection & signage — €100k/km.

ETCS Level 3 to Virtual Coupling

This considers upgrading an existing ETCS Level 3 scheme to include Virtual Coupling capability. This includes the VOBC software update and its direct communication. Scenario 3 includes the cost of Automatic Train Operation (ATO), as this is considered essential for Virtual Coupling. Costs associated with testing/commissioning or for control centre (TMS) upgrade cost have not been included.

- ATO equipment cost — €100k/MU
- ATO engineering per MU — €150k/MU[50]
- ATO installation cost — €40k/MU [50]
- V2V communication equipment cost — €20k/MU
- EVC software upgrade cost — €50k/MU [50].

The cost to convert a conventional railway to include Virtual Coupling is obtained by adding the costs from baseline to ETCS Level 3 and ETCS Level 3 to Virtual Coupling (VC without ETCS Level 3 is not considered).

Table 15 provides unitary costs for each item of the CAPEX for the three scenarios when considering a three-signalling aspect signalling (S01) as the baseline. Table 16 reports the same unitary CAPEX costs in the case that the baseline is ETCS L2.

Table 15 – CAPEX per signalling system transition with baseline three-aspect signalling

CAPEX	Signalling System		
	3-Aspect to L3	L3 to VC	3-Aspect to VC
Trackside (scheme design, equipment, installation and test)	€1,100,000/km	-	€1,100,000/km
Train equipment	€425,000/MU	-	€425,000/MU
Train equipment engineering First in class	€150,000/MU	-	€150,000/MU
Train equipment installation	€40,000/MU	-	€40,000/MU
TIM equipment	€24,000/MU	-	€24,000/MU
EVC software upgrade	-	€50,000/MU	€50,000/MU
ATO equipment	-	€100,000/MU	€100,000/MU
ATO engineering First in class	-	€150,000/MU	€150,000/MU
ATO installation	-	€40,000/MU	€40,000/MU
V2V communication equipment	-	€20,000/MU	€20,000/MU
Railway Authority deployment costs	€330,000,000	€330,000,000	€330,000,000

Table 16 – CAPEX per signalling system transition with baseline ETCS L2

CAPEX	Signalling System		
	L2 to L3	L3 to VC	L2 to VC
TIM equipment	€24,000/MU	-	€24,000/MU
Recovery of unwanted train detection and signage	€100,000/km	-	€100,000/km
EVC software upgrade	€50,000/MU	€50,000/MU	€100,000/MU
ATO equipment	-	€100,000/MU	€100,000/MU
ATO engineering First in class	-	€150,000/MU	€150,000/MU
ATO installation	-	€40,000/MU	€40,000/MU
V2V communication equipment	-	€20,000/MU	€20,000/MU
Railway Authority deployment costs	€330,000,000	€330,000,000	€330,000,000

The capital expenditures have been computed for each market segment based on the number of multiple units composing a trainset for each case study. The total number of multiple units (NMU) needed to operate the railway service for the baseline, the moving-block and virtual coupling signalling alternatives have been computed based on the equation

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

The scheduled service headway H_S for a given signalling system has been assumed to correspond to the line headway of a typical railway network with a varied infrastructure topology including plain lines, merging and diverging junctions. By setting the scheduled headway equal to the line headway it is possible to identify the maximum number of Multiple Units that are required when the network is utilised at its maximum capacity. Based on such an assumption the service headway considered for the computation of MUs coincides with the most critical train headway across all manoeuvres calculated for the infrastructure capacity scenarios (Section 5.1.1) for a given signalling system. Values adopted for H_S are provided in Table 17 for the different signalling alternatives. Service headways used for ETCS L3 and VC are the same given that the most critical headway is ruled by diverging manoeuvres where train separation equals an absolute braking distance for both signalling systems due to obvious safety reasons. Comparable line headways between VC and ETCS L3 are also observed for the urban market segment although no diverging manoeuvre has been considered here. Considering the same number of MUs for both ETCS L3 and VC also contributes to a fairer comparison in terms of installation costs. Indeed, VC does not necessarily require a larger vehicle fleet to operate more train services. It is reasonable to assume VC could run a higher frequency service than ETCS Level 3 for the same available amount of rolling stock units, since train services could be composed just by a single MU with the possibility of coupling/decoupling on the run with/from other services.

The waiting time of rolling stock to turn around at terminal stations is considered $T_w = 15$ minutes for all cases, whereas the scheduled one-way running time T_r and the number of MUs per train formation $N_{MU_{train}}$ depend on each case study as illustrated in Table 17.

Table 17 – Operational characteristics and number of MUs per train for each case study

Market segment	**Case study**	**Travel time** (min)	**Travel distance** (km)	H_S Baseline (min)	H_S ETCS L3 (min)	H_S VC (min)	**MUs per formation**	**Total MUs for ETCS L3 and VC**
High-speed	Rome-Bologna	115	305	9	6	6	2	59
Main line	Waterloo-Southampton	80	127	4	3	3	2	86
Regional	Leicester-Peterborough	55	84	3	2	2	1	93
Urban	Lancaster Gate-Liverpool St.	15	7	2	2	2	2	40
Freight	Rotterdam-Hamburg	450	503	6	5	5	1 train of 25 wagons + 1 loco	246

It should be noted that for the practical number of multiple units required to operate a railway service it is necessary to increase the number of MUs provided by the above equation by 10% to consider additional spares for facing unforeseen failures, and by another 20% for spares to allow vehicles in the depot for ordinary maintenance.

The total CAPEX costs obtained for the three signalling alternatives are displayed in Table 18, Table 19, Table 20, and Table 22 for high-speed, main line, regional, urban and freight case studies, respectively.

Table 18 – CAPEX for the high-speed case study (Rome-Bologna)

CAPEX for high-speed	**Signalling Systems**		
	L2 to L3	**L3 to VC**	**L2 to VC**
TIM equipment	€2,832,000	-	€2,832,000
Recovery of unwanted train detection and signage	€30,500,000	-	€30,500,000
EVC software upgrade	€5,900,000	€5,900,000	€11,800,000
ATO equipment	-	€11,800,000	€11,800,000
ATO engineering	-	€17,700,000	€17,700,000
ATO installation	-	€4,720,000	€4,720,000
V2V communication equipment	-	€2,360,000	€2,360,000
Railway regulatory body authorisation costs	€330,000,000	€330,000,000	€330,000,000
Total per alternative	**€369,232,000**	**€372,480,000**	**€411,712,000**

Table 19 – CAPEX for the main line case study (Waterloo-Southampton)

CAPEX for main line	Signalling System		
	Base to L3	L3 to VC	Base to VC
Trackside (scheme design, equipment, installation and test)	€139,700,000	-	€139,700,000
Train equipment	€73,100,000	-	€73,100,000
Train equipment engineering	€25,800,000	-	€25,800,000
Train equipment installation	€6,880,000	-	€6,880,000
TIM equipment	€4,128,000	-	€4,128,000
EVC software upgrade	-	€8,600,000	€8,600,000
ATO equipment	-	€17,200,000	€17,200,000
ATO engineering	-	€25,800,000	€25,800,000
ATO installation	-	€6,880,000	€6,880,000
V2V communication equipment	-	€3,440,000	€3,440,000
Railway regulatory body authorisation costs	€330,000,000	€330,000,000	€330,000,000
Total per alternative	**€579,608,000**	**€391,920,000**	**€641,528,000**

Table 20 – CAPEX for the regional case study (Leicester-Peterborough)

CAPEX for regional	Signalling System		
	Base to L3	L3 to VC	Base to VC
Trackside (scheme design, equipment, installation and test)	€92,400,000	-	€92,400,000
Train equipment	€39,525,000	-	€39,525,000
Train equipment engineering	€13,950,000	-	€13,950,000
Train equipment installation	€3,720,000	-	€3,720,000
TIM equipment	€2,232,000	-	€2,232,000
EVC software upgrade	-	€4,650,000	€4,650,000
ATO equipment	-	€9,300,000	€9,300,000
ATO engineering	-	€13,950,000	€13,950,000
ATO installation	-	€3,720,000	€3,720,000
V2V communication equipment	-	€1,860,000	€1,860,000
Railway regulatory body authorisation costs	€330,000,000	€330,000,000	€330,000,000
Total per alternative	**€481,827,000**	**€363,480,000**	**€515,307,000**

Table 21 – CAPEX for the urban case study (Lancaster Gate-Liverpool St.)

Cost for urban	Signalling Systems		
	Base to L3	L3 to VC	Base to VC
Trackside (scheme design, equipment, installation and test)	€7,700,000	-	€7,700,000
Train equipment	€34,000,000	-	€34,000,000
Train equipment engineering	€12,000,000	-	€12,000,000
Train equipment installation	€3,200,000	-	€3,200,000
TIM equipment	€1,920,000	-	€1,920,000
EVC software upgrade	-	€4,000,000	€4,000,000
ATO equipment	-	€8,000,000	€8,000,000
ATO engineering	-	€12,000,000	€12,000,000
ATO installation	-	€3,200,000	€3,200,000
V2V communication equipment	-	€1,600,000	€1,600,000
Railway regulatory body authorisation costs	€330,000,000	€330,000,000	€330,000,000
Total per alternative	**€388,820,000**	**€358,800,000**	**€417,620,000**

Table 22 – CAPEX for the freight case study (Rotterdam-Hamburg)

CAPEX for freight	Signalling System		
	Base to L3	L3 to VC	Base to VC
Trackside (scheme design, equipment, installation and test)	€553,300,000	-	€553,300,000
Train equipment	€104,550,000	-	€104,550,000
Train equipment engineering	€36,900,000	-	€36,900,000
Train equipment installation	€9,840,000	-	€9,840,000
TIM equipment (25 wagons + 1 loco)	€147,600,000	-	€147,600,000
EVC software upgrade	-	€12,300,000	€12,300,000
ATO equipment	-	€24,600,000	€24,600,000
ATO engineering	-	€36,900,000	€36,900,000
ATO installation	-	€9,840,000	€9,840,000
V2V communication equipment (1st and last wagon)	-	€9,840,000	€9,840,000
Railway regulatory body authorisation costs	€330,000,000	€330,000,000	€330,000,000
Total per alternative	**€1,182,190,000**	**€423,480,000**	**€1,275,670,000**

As can be seen that the most relevant share of the migration costs from moving block to VC is not represented by technological upgrades for the ATO, the EVC software and the V2V communication devices but by authorisation process fees for the approval from railway regulatory bodies. Technological upgrades for VC would indeed only be around 25% of the costs for migrating signalling technologies from baseline to moving block.

5.1.2.2. Operational costs (OPEX)

The operational expenditures (OPEX) are computed based on four components: the average infrastructure maintenance, the average rolling stock maintenance, the energy provision and

personnel wages. Since operational costs are held on a yearly basis over the lifecycle of a signalling alternative, the computation has considered discounting of future costs by using a yearly discount rate of 5% over a total lifecycle period of 30 years.

- The average infrastructure maintenance costs are considered to be the same as ETCS Level 3 Moving Block (€1.7k/km) [53], unless there is a significant change to point equipment. Track/infrastructure maintenance costs may be increased however through greater wear from increasing capacity. For three-aspect signalling, the average cost of infrastructure maintenance is considered €2.0k/km whereas for ETCS L2, the cost is €1.8k/km.
- The average rolling stock maintenance costs $C_{RSmaint}$ are computed as:

$$C_{RSmaint} = CU_{RSmaint} \cdot 2 \cdot D_{oneway} \cdot O_{RS} \cdot \frac{60}{2\,T_r + 2\,T_w} \cdot N_{MU_{train}}$$

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

- The energy provision costs C_{Ep} are considered per train service and computed as:

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

  where CU_{Ep} is the unitary electricity cost per train/km, D_T is the total travelled distance by a train service in 1 hour, N_T is the number of train services operated in an hour while N_O is the number of operating hours in one day. Unit costs per km for rolling stock maintenance ($CU_{RSmaint}$) and electricity (CU_{Ep}) have been collected by official sources and available literature and have been accordingly discounted based on yearly inflation rates starting from the source documentation year. These unit costs are given in Table 23. The number of working/operating hours is considered 18 per day whereas the waiting time at terminal is 15 minutes. The travel distance, running time and number of MUs per train formation can be found in Table 17 for each defined case study.

Table 23 – Unit RS maintenance and electricity costs per market segment

MS	$CU_{RSmaint}$	CU_{Ep}
High-speed	€9.4366/km	€2.8085/km
Main line	€14.7960/km	€0.9453/km
Regional	€13.3164/km	€1.5892/km
Urban	€11.8368/km	€0.7521/km
Freight	€8.6310/km	€3.2880/km

- Average personnel salaries have been computed by referring to the European Benchmarking of the rail Infrastructure Managers (IMs) [54], as well as the costs, performance and revenues of Great Britain (GB) Train Operating Companies (TOCs) [55]. Unit average costs for train driver per km used in this investigation are reported in Table 24. For all market segments, salary costs for a conductor are considered 20% less than those of a driver. For the baseline scenarios and ETCS L3, one driver and two conductors are assumed in the computation, whereas for Virtual Coupling, the driver cost is removed given that the driver will be replaced by an ATO.

Table 24 – Driver costs per train-km for each market segment

MS	Driver cost/train-km
High-speed	€3.05/km
Main line	€2.54/km
Regional	€2.50/km
Urban	€3.37/km
Freight	€2.79/km

Total costs per OPEX item are illustrated in Table 25 for the baselines as well as the two signalling alternatives for the different market segments.

Table 25 – OPEX for different market segments per signalling system

OPEX item	Market Segment	Signalling System			
		3-Aspect	ETCS L2	ETCS L3	VC
Average infrastructure maintenance	High-speed	-	€8,988,476	€8,489,116	€8,489,116
	Main line	€4,158,603	-	€3,534,812	€3,534,812
	Regional	€2,750,572	-	€2,337,986	€2,337,986
	Urban	€229,214	-	€194,832	€194,832
	Freight	€16,470,686	-	€14,000,083	€14,000,083
Average rolling stock maintenance	High-speed	-	€21,864,785.72	€33,174,157.65	€33,174,157.65
	Main line	€29,534,728.08	-	€39,379,637.43	€39,379,637.43
	Regional	€12,050,517.89	-	€17,947,579.84	€17,947,579.84
	Urban	€2,930,217.12	-	€2,930,217.12	€2,930,217.12
	Freight	€22,034,565.73	-	€26,441,478.87	€26,441,478.87
Energy provision	High-speed	-	€1,767,089.36	€2,524,413.38	€2,524,413.38
	Main line	€530,702.15	-	€707,602.86	€707,602.86
	Regional	€786,817.56	-	€1,180,226.34	€1,180,226.34
	Urban	€46,547.72	-	€46,547.72	€46,547.72
	Freight	€4,874,005.32	-	€5,848,806.39	€5,848,806.39
Personnel	High-speed	-	€39,573.26	€39,573.26	€24,352.78
	Main line	€13,731.71	-	€13,731.71	€8,450.28
	Regional	€8,939.36	-	€8,939.36	€5,501.14
	Urban	€1,004.19	-	€1,004.19	€617.96
	Freight	€23,009.55	-	€23,009.55	€0.00

The total OPEX for each market segment and signalling alternative are provided in the tables below.

Table 26 – Total OPEX for the high-speed case study

OPEX for high-speed	Signalling Systems	
	L3	VC
Average infrastructure maintenance	€8,489,116	€8,489,116
Average rolling stock maintenance	€33,174,157.65	€33,174,157.65
Energy provision	€2,524,413.38	€2,524,413.38
Personnel	€39,573.26	€24,352.78
Total per alternative	**€44,227,260**	**€44,212,040**

Table 27 – Total OPEX for the main line case study

OPEX for main line	Signalling Systems	
	L3	VC
Average infrastructure maintenance	€3,534,812	€3,534,812
Average rolling stock maintenance	€39,379,637.43	€39,379,637.43
Energy provision	€707,602.86	€707,602.86
Personnel	€13,731.71	€8,450.28
Total per alternative	**€43,635,784**	**€43,630,503**

Table 28 – Total OPEX for the regional case study

OPEX for Regional	Signalling Systems	
	L3	VC
Average infrastructure maintenance	€2,337,986	€2,337,986
Average rolling stock maintenance	€17,947,579.84	€17,947,579.84
Energy provision	€1,180,226.34	€1,180,226.34
Personnel	€8,939.36	€5,501.14
Total per alternative	**€21,474,732**	**€21,471,293**

Table 29 – Total OPEX for the urban case study

OPEX for Urban	Signalling Systems	
	L3	VC
Average infrastructure maintenance	€194,832	€194,832
Average rolling stock maintenance	€2,930,217.12	€2,930,217.12
Energy provision	€46,547.72	€46,547.72
Personnel	€1,004.19	€617.96
Total per alternative	**€3,172,601**	**€3,172,215**

Table 30 – Total OPEX for the freight case study

OPEX for Freight	Signalling Systems	
	L3	VC
Average infrastructure maintenance	€14,000,083	€14,000,083
Average rolling stock maintenance	€26,441,478.87	€26,441,478.87
Energy provision	€5,848,806.39	€5,848,806.39
Personnel	€23,009.55	€0.00
Total per alternative	**€46,313,378**	**€46,290,368**

Operational expenditure for virtual coupling is a few thousand euros lower than moving block for all market segments, given the reduced crew which is needed to operate a train because of the ATO. This means that similar operational costs to VC could be achieved when deploying ATO over plain moving block. A summary of the total CAPEX and OPEX costs as well as the total costs for each alternative per market segment is displayed in Table 31. Figure 15 shows the final total cost scores per market segment for MB and VC.

Table 31 – Summary of CAPEX, OPEX and total costs

		Market Segment	Total CAPEX	Total OPEX	Total Costs
Alternatives	ETCS L3	High-Speed	€369,232,000	€44,227,260	**€413,459,260**
		Main line	€579,608,000	€43,635,784	**€623,243,784**
		Regional	€481,827,000	€21,474,732	**€503,301,732**
		Urban	€388,820,000	€3,172,601	**€391,992,601**
		Freight	€1,182,190,000	€46,313,378	**€1,228,503,378**
	VC	High-Speed	€411,712,000	€44,212,040	**€455,924,040**
		Main line	€641,528,000	€43,630,503	**€685,158,503**
		Regional	€515,307,000	€21,471,293	**€536,778,293**
		Urban	€417,620,000	€3,172,215	**€420,792,215**
		Freight	€1,275,670,000	€46,290,368	**€1,321,960,368**

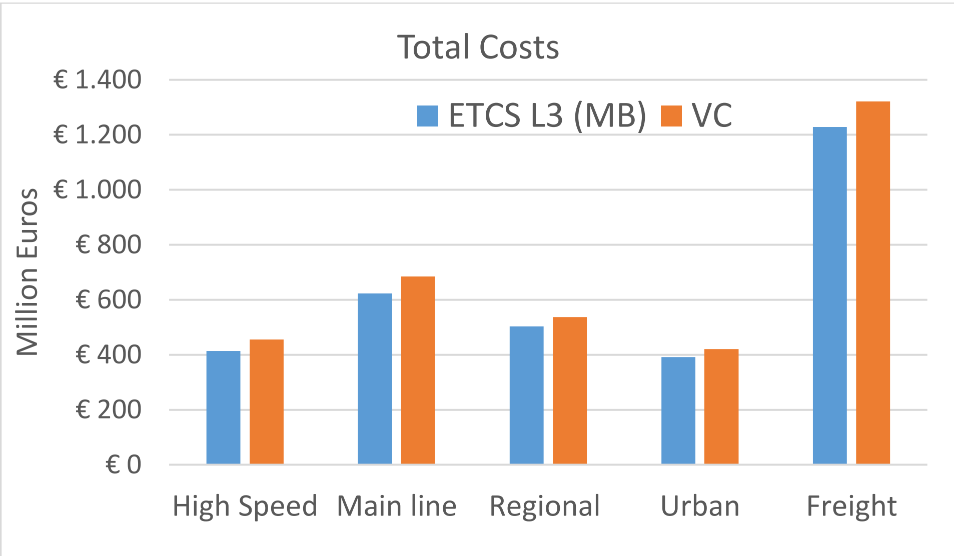

Figure 15 – Total costs per market segment and signalling alternative

5.1.3. System stability

System stability is defined as the capability of a railway system to mitigate delay propagation across the network. Stability depends on the timetable structure (train frequency and traffic heterogeneity), as well as the infrastructure layout and signalling system. It can be measured in terms of the total buffer time available per time unit and is thus related to infrastructure occupation. The system stability can be computed when the infrastructure layout, signalling system and detailed timetable are known. In this study we aim at deriving a generic measure for system stability for the various market segments without focusing on specific infrastructure

layouts and timetable structures. Therefore, we define here a stability index based on an average minimum headway over various operational scenarios and a given typical train frequency per hour.

To compute system stability of the different signalling alternatives, an abstract railway system has therefore been considered for each market segment with a given train frequency and typical operational scenarios. For each market segment, it is considered that an hourly timetable runs the same amount of trains that are currently operated in the peak hour on the representative case study corridors. A compressed timetable has been obtained for the baseline and the two signalling alternatives based on minimum line headways computed for the different manoeuvres and stopping patterns. Specifically, for both stopping and non-stopping train patterns an average minimum line headway has been calculated as a mean value across all manoeuvres. Resulting average minimum line headways are reported in the fourth column of Table 32, Table 33 and Table 34 for the baseline, moving block and VC, respectively.

These average minimum line headways have been used to compress the hourly timetable according to the UIC Code 406 and to calculate a corresponding average infrastructure occupation rate, illustrated in the eighth column in Table 32, Table 33 and Table 34. A stability index $I_{stability}$ has been computed as the complementary of the infrastructure occupation rate, averaged over all of the operational scenarios:

$$I_{stability}(S_k) = 1 - \frac{1}{N_k}\sum_{i=1}^{N_k}\frac{N_T H_i(S_k)}{3600}$$

for $k \in \{0,1,2\}$. The stability index is hence computed for each of the signalling alternatives S_k considering the total number of train services N_T operating in a reference hour multiplied by an average minimum line headway across all the operational scenarios $i \in \{1, \dots, N_k\}$ applicable to S_k. The minimum headways $H_i(S_k)$ of each operational scenario i in signalling alternative S_k are computed in seconds, so the division by 3600 translates the minimum headways to a fraction of an hour (3600 s). The stability indices can also be given in percentage by multiplying them by 100%.

Stability indices obtained for each market segment are given in the last column of Table 32, Table 33 and Table 34 respectively for the baseline, moving block and VC signalling. A graphical comparison of the stability indices for the three signalling alternative is provided in Figure 16.

Table 32 – Stability index for the baseline scenarios per market segment

Market Segment	Manoeuvre	Stopping pattern	Minimum headway (s)	Hourly trains N_T	Average minimum headway over manoeuvres (s)		Infrastructure occupation time (s)	Infrastructure occupation rate over 1 h	Stability Index (%)
High-Speed (ETCS L2)	Plain	Stopping	481.2	6	Stopping	368.5	2211.0	61.42	60.54
		Non-Stopping	134.9						
	Merge	Stopping	418.4						
		Non-Stopping	99.5		Non-stopping	105.0	630.2	17.51	
	Diverge	Stopping	205.9						
		Non-Stopping	80.7						
Main-line (3-Aspect)	Plain	Stopping	182.5	17	Stopping	143.2	2434.4	67.62	51.20
		Non-Stopping	62.3						
	Merge	Stopping	191						
		Non-Stopping	72.4		Non-stopping	63.5	1079.5	29.99	
	Diverge	Stopping	56.1						
		Non-Stopping	55.8						
Regional (3-Aspect)	Plain	Stopping	156	6	Stopping	127.8	766.8	21.30	78.70
	Merge	Stopping	163.1						
	Diverge	Stopping	64.3						
Urban (3-Aspect)	Plain	Stopping	114.4	30	Stopping	114.4	3432.0	95.33	4.67
Freight (3-Aspect)	Plain	Stopping	350.1	10	Stopping	306.6	3066.3	85.18	43.13
		Non-Stopping	103.4						
	Merge	Stopping	357.4						
		Non-Stopping	114.9		Non-stopping	102.8	1028.0	28.56	
	Diverge	Stopping	212.4						
		Non-Stopping	90.1						

Table 33 – Stability index for the ETCS Level 3 scenarios per market segment

Market Segment	Manoeuvre	Stopping pattern	Minimum headway (s)	Hourly trains N_T	Average minimum headway over manoeuvres (s)		Infrastructure occupation time (s)	Infrastructure occupation rate over 1 h	Stability Index (%)
High-Speed (ETCS L3)	Plain	Stopping	334.1	6	Stopping	289.1	1734.4	48.18	69.19
		Non-Stopping	74						
	Merge	Stopping	332.2						
		Non-Stopping	92.3		Non-stopping	80.67	484	13.44	
	Diverge	Stopping	200.9						
		Non-Stopping	75.7						
Main-line (ETCS L3)	Plain	Stopping	133.2	17	Stopping	104.1	1769.7	49.16	63.16
		Non-Stopping	46.5						
	Merge	Stopping	125.8						
		Non-Stopping	56.2		Non-stopping	51.9	882.9	24.52	
	Diverge	Stopping	53.3						
		Non-Stopping	53.1						
Regional (ETCS L3)	Plain	Stopping	112.5	6	Stopping	91.4	548.6	15.24	84.76
	Merge	Stopping	105						
	Diverge	Stopping	56.8						
Urban (CBTC)	Plain	Stopping	84.2	30	Stopping	84.2	2526	70.17	29.83
Freight (ETCS L3)	Plain	Stopping	284.4	10	Stopping	255.3	2553	70.92	52.64
		Non-Stopping	81.8						
	Merge	Stopping	270.1						
		Non-Stopping	86.2		Non-stopping	85.7	857	23.81	
	Diverge	Stopping	211.4						
		Non-Stopping	89.1						

Table 34 – Stability index for the VC scenarios per market segment

Market Segment	Manoeuvre	Stopping pattern	Minimum headway (s)	Hourly trains N_T	Average minimum headway over manoeuvres (s)		infrastructure occupation time (s)	Infrastructure occupation rate over 1 h	Stability Index (%)
High-Speed (VC)	Plain	Stopping	329.8	6	Stopping	285.6	1713.6	47.60	71.22
		Non-Stopping	11.4						
	Merge	Stopping	326.1						
		Non-Stopping	92.3		Non-stopping	59.8	358.8	9.97	
	Diverge	Stopping	200.9						
		Non-Stopping	75.7						
Main-line (VC)	Plain	Stopping	130.2	17	Stopping	101.2	1720.4	47.79	66.54
		Non-Stopping	12.3						
	Merge	Stopping	120.1						
		Non-Stopping	56.2		Non-stopping	40.5	689.1	19.14	
	Diverge	Stopping	53.3						
		Non-Stopping	53.1						
Regional (VC)	Plain	Stopping	110.7	6	Stopping	89.3	535.8	14.88	85.12
	Merge	Stopping	100.4						
	Diverge	Stopping	56.8						
Urban (VC)	Plain	Stopping	79.6	30	Stopping	79.6	2388.0	66.33	33.67
Freight (VC)	Plain	Stopping	276.9	10	Stopping	248.8	2488.3	69.12	56.06
		Non-Stopping	27.2						
	Merge	Stopping	258.2						
		Non-Stopping	86.2		Non-stopping	67.5	675.0	18.75	
	Diverge	Stopping	211.4						
		Non-Stopping	89.1						

The final stability index values that will be used in the MCA analysis (Section 5.3) for each of the market segments and signalling alternative are displayed in Table 35.

Table 35 – Stability index per market segment and signalling alternative

Stability Index $I_{stability}$ (%)			
Market Segment	**Baseline**	**ETCS L3**	**VC**
High-speed	60.539	69.189	71.217
Main line	51.196	63.159	66.535
Regional	78.700	84.761	85.117
Urban	4.667	29.833	33.667
Freight	43.134	52.639	56.065

As can be seen moving block can greatly improve system stability over baseline signalling systems for all market segments. Particularly significant is the increase in stability for the urban market where the high frequency service strongly requires moving-block operations to avoid capacity saturation that occurs if a three-aspect fixed-block signalling is adopted. VC can provide a further improvement to moving block system stability which is however marginal with respect to stability gains that moving block brings over baseline signalling. In detail, the biggest stability enhancements brought by VC over MB are observed for the urban (+12%) and the main-line (+5%) markets. This is intuitive given that these two markets are characterised by a high number of hourly trains where delays are easily propagated in a snow-ball effect. Reducing the safe separation from an absolute braking distance to a relative braking distance would therefore contribute to further mitigate delay transmission. VC could also improve by 5% moving block stability for the freight market. Only little gains have been obtained for the high speed market (+2%). This is due to the average minimum headway that is affected by the headway of the

operational scenario with Manoeuvre M1 (i.e. plain line) and stopping trains, where only a marginal difference exists between moving block and virtual coupling. As already mentioned for capacity, system stability gains for VC over MB are much higher when considering only following movements in a platoon of virtually coupled trains (where the corresponding headway is given by manoeuvre M1 with non-stopping trains).

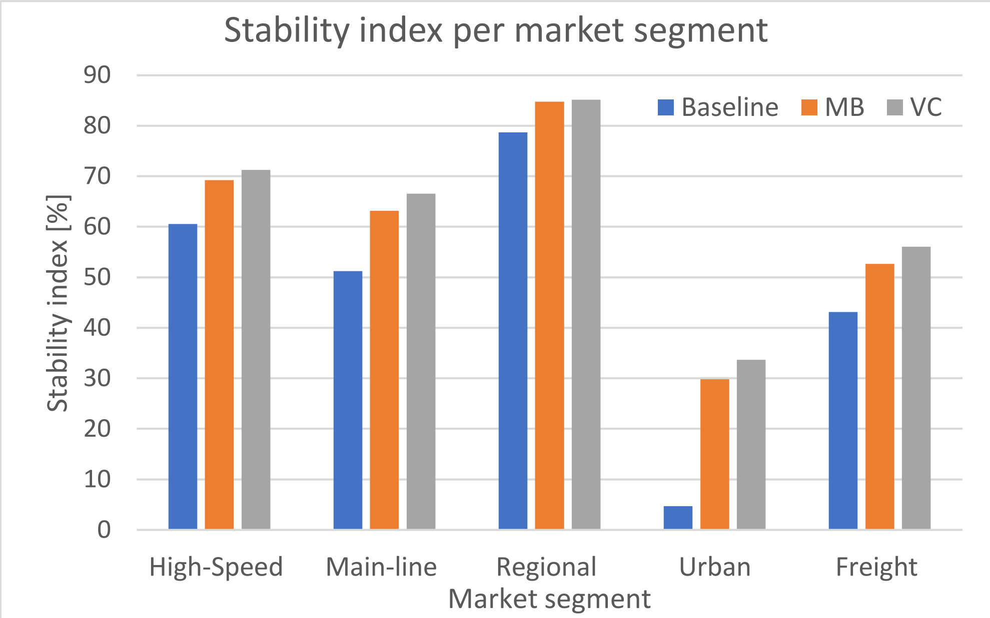

Figure 16 – System stability index per market segment and signalling alternative

In the case of the regional segment, VC does not provide any practical stability improvement over MB (only 0.3%), mostly because of a combined effect of the lower number of hourly regional train services (much lower than the urban market) and the low speeds which make differences between absolute and relative braking distance only marginal.

5.1.4. Travel demand

A specific analysis is performed to understand the modal split and the potential shift to railways of the travel demand due to the introduction of ETCS L3 moving block and Virtual Coupling. This analysis is an extension of the study developed in D4.1. To this end, a summary of the case studies and their characteristics are displayed in Table 36. By aggregating stated travel preferences collected from 229 respondents in a survey, the resulting modal share has been computed for each of the case studies for the current and the future transport scenarios. This is illustrated in Figure 17 for the passenger market segments (i.e. high-speed, main line, regional, and urban).

Table 36 – Summary of Virtual Coupling case studies for each Market Segment

	Railway market segment				
	High speed	Main line	Regional	Urban/Suburban	Freight
Case study	Rome–Bologna (305 km)	Waterloo–Southampton (127 km)	Leicester–Peterborough (84 km)	London Lancaster–London Liverpool Street (7 km)	Rotterdam–Hamburg (503 km)
Travel time (HH:MM)	01:55	01:20	00:55	00:15	07:30
Current scenario	1 train/15 min €45.90	1 train/30 min €28.45	1 train/60 min €13.45	1 train/2 min €2.80	3 trains/day €1,235
Future scenario (cost ↗ frequency ↗)	1 train/6 min €55.10 (+20%)	1 train/11 min €34.15 (+20%)	1 train/22 min €16.15 (+20%)	1 train/45 s €3.35 (+20%)	7 trains/day €1,480 (+20%)

Available alternative transport modes (HH:MM, frequency, cost)					
Bus[a]	05:00, 1 bus/4 h, €14.00	02:20, 1 bus/h, €9.00	01:15, 2 buses/day, €8.20	00:50, 1 bus/6 min, €1.75	N/A
Car	04:20, on demand, €44.15	02:10, on demand, €14.40	01:00, on demand, €15.00	00:45, on demand, €1.10	N/A
Bike	N/A	N/A	N/A	00:36, on demand, free	N/A
Walk	N/A	N/A	N/A	01:27, on demand, free	N/A
Plane	00:55, 3 planes/day, €66.30	N/A	N/A	N/A	N/A
Truck	N/A	N/A	N/A	N/A	08:00, on demand, €504.45
Ship	N/A	N/A	N/A	N/A	16:00, 1 ship/day, €1,160.77
Air cargo	N/A	N/A	N/A	N/A	01:00, 1 cargo/day, €1,506.20

Note: HH:MM = "Hour:Minute" time format, [a]For main-line and regional segments a bus is a regional bus, also known as coach

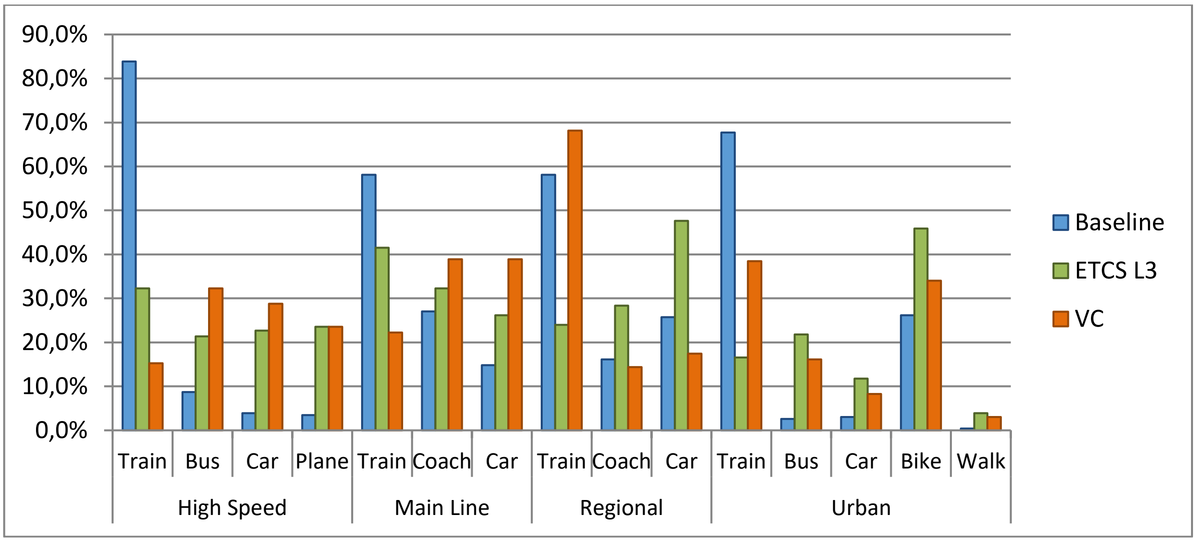

Figure 17 – Modal share for each passenger-related case study

Modal choices for the baseline are reported with blue bars, while green bars represent modal preferences for the future scenario of ETCS L3-enabled train services with increased frequency and ticket fares (by 10%). The orange bars represent the Virtual Coupling scenario with ticket fees increased by 20%. The ticket fees increase with the decrease of train length which enables more flexible and/or exclusive on-demand train services. Analysis on optimised train compositions that would best fit with VC operations is however out of the scope of this deliverable. For a fair multicriteria comparison between Virtual Coupling and Moving Block, train compositions have been considered the same for both signalling alternatives.

The percentages considered in the following analysis are extracted from Section 5.1.1.2 and [49] as follows: a headway reduction of 50% for ETCS L3 moving-block compared to the baseline scenario that considers multi-aspect signalling on main line, regional and urban market segments. For high-speed railways, the base configuration is ETCS L2 with a headway reduction of 47% if ETCS L3 is implemented. The third scenario (VC) considers a decrease in headways of 63% compared to multi-aspect signalling and of 61% compared to ETCS L2.

For the high-speed segment, most respondents (84%) still prefer traveling by a train service as it is currently operated in the baseline scenario (blue bars in Figure 17). The proposed increase of 10% in the ticket fare to use an 8 min frequency ETCS Level 3-enabled train service is not perceived

as attractive to the interviewees. Having high-speed trains as currently operated every 15 minutes seems already satisfactory for most of the respondents. A ticket cost increase by 20% to avail of a 6 min frequency VC-enabled train service greatly shifts travel preferences towards the car, the bus or the plane, as shown by the orange bars in the histogram. In general, such outcome shows that VC would not be a demand-attractive alternative on high-speed corridors having already a 15 min train frequency over a given O-D. The deployment of VC would however provide the benefit of adjusting headways between consecutive trains based on the demand to satisfy, so that service frequency could better match peaks in the hourly variation of the demand. This also means that VC operations could better respond to massive railway demand increase forecasted between densely populated areas.

For the main line segment, 58% of interviewees opt for using the train as operated in the current transport scenario (baseline), while only a small share uses the car (see blue bars). A future scenario of an ETCS Level 3-enabled train service offering around 15 minutes less waiting time for a ticket increase by 10% is not considered that attractive as 17% of the train users would then prefer shifting to the other modes of transport, as clearly illustrated by the green bars. Similarly a 20% increase in the ticket fee would not seem attractive to passengers to avail of a more frequent VC-enabled train service as shown by orange bars. Many respondents state that for this kind of journey, they would prefer arranging their travel schedules around a less frequent train service rather than paying more to use an improved main line connection.

For the regional segment, most respondents would use the available railway connection (having a frequency of one train every 60 minutes) for the current transport scenario. The remaining part would rely instead on the car (26%), followed by the bus (16%). It is interesting to see that for the future VC-enabled scenario of trains running more frequently for a 20% ticket cost increase, a significant share of the sample would shift to railways. In addition, modal shift from cars to railways is perceived for VC-enabled services by 10% more compared to ETCS L3. This means that the proposed market scenario is attractive to passengers, since they are not currently satisfied with the delivered railway service and would be even willing to pay a higher fee for a more frequent regional railway connection.

For the urban segment, a metro service with a 5-minutes frequency has been considered for the current transport scenario. A metro with such a service frequency is already attractive to the travel demand given that 68% would avail of it while the remaining share would split across the bike mode (26%), the car (3.1%) and the bus (2.6%). In the scenario of a moving block equipped metro service running every 3 minutes for a 10% ticket cost increase, more than half of the respondents would shift to other modes of transport, given that they are not willing to pay more for improving a service that is already satisfactory as it currently is. Paying even €0.30 more for a reduction by 60 seconds in the average waiting time, would hence not be a demand-attractive market scenario. Such a little saving in the waiting times is indeed not perceived positively by passengers, who can already flexibly arrange their trips around the current service headway of 5 minutes. It is remarkable to observe that if the metro service frequency drops below 2 minutes because of the deployment of VC, the attractiveness of the service would be 22% higher than plain moving block, despite the 20% increase in the ticket fee. The proposed VC market scenario would anyway reduce the overall number of metro passengers with respect to the baseline given the non-attractive ticket cost increase. It should be noted however that Virtual Coupling can particularly benefit crowded urban connections since beyond increasing train frequencies it can provide a more

flexible service adaptable to the seating requirements of the travel demand which is at the moment unaddressed. The possibility provided by Virtual Coupling of composing/decomposing convoys on-the-run, depending on their origin/destination pair and the demand patterns, would allow a homogeneous distribution of stopping patterns within the hour offering more regular service even to customers of minor stations. Therefore, Virtual Coupling would allow a more demand-responsive train service that could not be otherwise possible with other signalling systems including moving-block. Deployment of VC on such lines could also benefit railway stakeholders due to the increased capacity and possible mitigation of delay propagation. It is worth mentioning that the idea of having an on-demand VC-enabled metro service consisting of one self-propelled car operating as an Uber-like pooling on the rails has been positively appreciated by 7% of respondents.

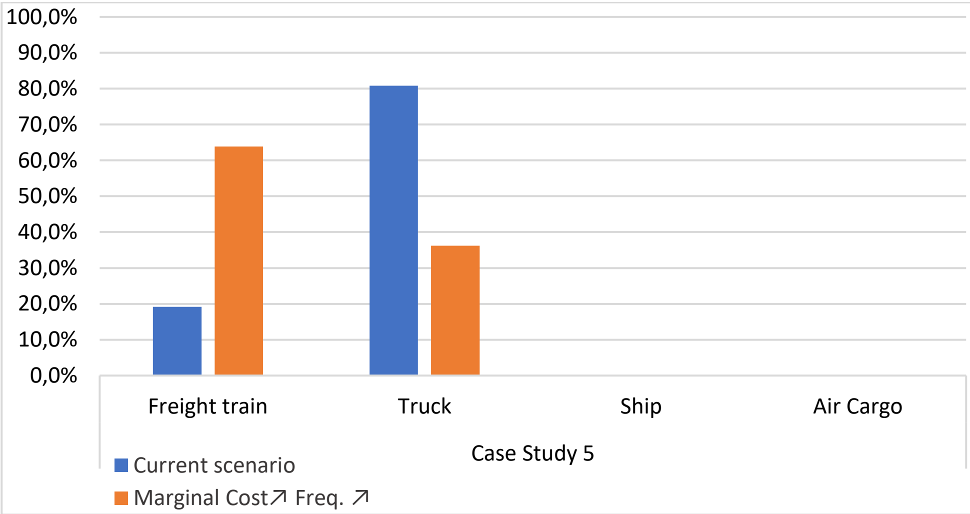

Figure 18 – Modal share for freight-related case study

For the freight segment, we used the analysis elaborated from the responses of 47 SMEs (see Deliverable 4.1). The ship and air cargo mode alternatives have been proposed in the survey, however none of the respondents opted for any of these two options. The modal split in the current transport scenario is in the advantage of the road trucks as shown by the blue bars in Figure 18. Such a result indeed matches with the modal share observed in real life, because of a more flexible and cheaper truck delivery. Instead, in the future scenario of more flexible and frequent freight trains enabled by VC, a significant modal shift from road trucks would be observed even in the case of an increase in the marginal delivery cost. Such a shift is mainly dictated by the fact that customers perceive railways as a more reliable mean of transport. A higher flexibility and delivery capacity would be appealing despite potential raises in the marginal cost, since these latter would be widely compensated by the larger number of units delivered. The study showed that 46.6% of truck users would shift to freight trains if more flexible and frequent services are provided. Such an outcome shows that the implementation of VC on freight railways would be very attractive to the freight transport market with consequent benefits to the environment due to the reduction of road trucks.

An additional investigation has been performed to identify the travel demand modal split that the introduction of moving block and virtual coupling would bring in the case that ticket fares would remain the same despite the increase in service frequency enabled by the two signalling

alternatives. Figure 19 illustrates the aggregated travel demand shares which would shift from all the other modes of transport (i.e. car, bus, airplane and truck for the freight market) to railways in the case of no ticket cost increase for using a train service enabled by the two signalling alternatives. Such an analysis has been performed for all the market segments. For the high-speed case study, it is clear that a significant modal shift from other modes of transport would already happen with the introdcution of ETCS Level 3 moving block (38%) while VC would only lead to an additional 4% (for a total of 42%). This is because a 15 minutes headway in the current scenario was already satisfying to most respondents, while the service frequency increase proposed by VC was only slightly higher than the one of ETCS L3. Similar results are observed for the main line and urban railways, where VC would only bring an additional modal shift of 7.8% and 7.1% with respect to ETCS Level 3. Almost all interviewees who would shift from other modes to VC for the main-line and the urban markets stated that the main reason behind that would be the possibility of availing of a service that is on-demand or better adaptable to the demand. Remarkable results are observed for regional trains where VC could increase the modal shift by 19 percentage points over ETCS L3 moving block. This is again because of the unsatisfactory service of currently delivered regional service which leads interviewees towards a service that could be better adapted to an on-demand paradigm or more effectively respond to daily demand variations. Also for the freight market, VC is considered more beneficial than ETCS L3 moving block given that a more flexible freight service could be delivered with self-propelled wagons that could couple/decouple at merging/diverging junctions to reach delivery destinations of the different commodities more efficiently. Results show that a total of 46.6% of the respondents would consider shifting from road trucks to trains in the case of virtual coupling signalling.

The percentages per signalling alternative and market segment displayed in Table 37 have been used in the MCA analysis (Section 5.3) for the travel demand criterion. The values are also illustrated in Figure 19.

Table 37 – Aggregated shares of travel demand modal shift from all other transport modes to railways for each market segment per signalling alternative

Modal shifts (%)		
Market Segment	**ETCS L3**	**VC**
High-speed	37.8%	41.9%
Main line	39.6%	47.4%
Regional	30.2%	49.1%
Urban	23.1%	30.2%
Freight	30.0%	46.6%

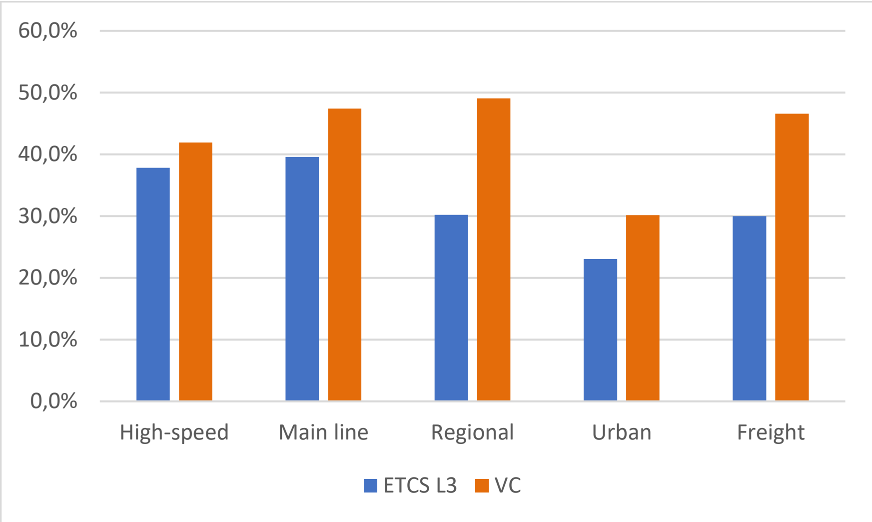

Figure 19 – Aggregated shares of travel demand modal shift from all other transport modes to railways for each market segment per signalling alternative

5.1.5. Energy consumption

The energy consumption has been measured in terms of an energy consumption index $I_E(S_k)$ defined as the average across the total number of operational scenarios N_k of the ratio between the unitary train energy consumption per km $E_i(S_k)$ for a scenario i of a signalling alternative S_k with respect to that of the baseline S_0:

$$I_E(S_k) = \frac{1}{N_k}\sum_{i=1}^{N_k}\frac{E_i(S_k)}{E_i(S_0)}$$

for $k \in \{1,2\}$. The microscopic railway traffic simulation model EGTRAIN has been used to compute train energy consumption by considering two trains following each other under a given signalling alternative. The simulation experiments used typical rolling stock circulating on the representative case studies used for each market segment, in line with the input data used for capacity computation in section 5.1.1. Specifically, a twelve-car ETR 500 has been used for the high-speed segment, an eight-car BR Class 455 for the Main-line, a three-car BR Class 428 for the Regional, a six-car BR Class 430 for the urban and a Es64F locomotive with 25 freight wagons has been considered for the freight market segment. The same infrastructure network has been used for all of the market segments to compute mechanical energy consumed when operating each specific rolling stock. In particular, a railway track of 20.406 km has been used with an average gradient of 0.2 per mil. The simulation did not include any optimised energy-efficient control strategies of the trains or coasting phases before braking. No energy-efficient driving algorithms were considered. For Virtual Coupling a train in a platoon simply followed the speed and acceleration/braking indications from the leader without any control algorithms specifically addressed to minimise energy consumption. The simulated energy consumption of the follower train has been used as a reference to calculate the unitary train consumption per km (measured in kWh/km). Average and unitary energy consumption are provided together with the energy consumption index for each market segment and signalling alternative per stopping pattern in Table 38 - Table 42. The unitary average energy per train/km (fourth columns) is simply obtained by dividing the average energy per train (third columns) by the length of the track considered of 20.406 km.

Table 38 – Energy Index computation for high-speed trains per signalling system

High-speed					
Signalling system	Stopping pattern	Average energy per train [kWh]	Average energy per train/km [kWh/km]	Relative ratio	Energy Index I_E
ETCS L2	Stopping	191.47	8.92	1	1
	Non-stopping	154.07	7.18	1	
ETCS L3	Stopping	189.11	8.81	0.987642668	0.991793444
	Non-stopping	153.45	7.15	0.995944221	
VC	Stopping	187.76	8.75	0.980600006	0.985339681
	Non-stopping	152.55	7.11	0.990079356	
	Non-stopping	122.04	5.68	0.980940802	

Table 39 – Energy Index computation for main line trains per signalling system

Main-line					
Signalling system	Stopping pattern	Average energy per train [kWh]	Average energy per train/km [kWh/km]	Relative ratio	Energy Index I_E
3-Aspect	Stopping	155.80	7.26	1	1
	Non-stopping	124.41	5.79	1	
ETCS L3	Stopping	151.29	7.05	0.971018631	0.978885082
	Non-stopping	122.76	5.72	0.986751533	
VC	Stopping	150.21	7.00	0.964094511	0.972517656
	Non-stopping	122.04	5.68	0.980940802	

Table 40 – Energy Index computation for regional trains per signalling system

Regional					
Signalling system	Stopping pattern	Average energy per train [kWh]	Average energy per train/km [kWh/km]	Relative ratio	Energy Index I_E
3-Aspect	Stopping	140.09	6.52	1	1
	Non-stopping	111.862	5.21	1	
ETCS L3	Stopping	136.03	6.34	0.971018631	0.978885082
	Non-stopping	110.38	5.14	0.986751533	
VC	Stopping	135.06	6.29	0.964094511	0.972517656
	Non-stopping	109.73	5.11	0.980940802	

Table 41 – Energy Index computation for urban trains per signalling system

Urban					
Signalling system	Stopping pattern	Average energy per train [kWh]	Average energy per train/km [kWh/km]	Relative ratio	Energy Index I_E
3-Aspect	Stopping	121.8783	5.68	1	1
	Non-stopping	97.31994	4.53	1	
ETCS L3	Stopping	118.3461	5.51	0.971018631	0.978885082
	Non-stopping	96.0306	4.47	0.986751533	
VC	Stopping	117.5022	5.47	0.964094511	0.972517656
	Non-stopping	95.4651	4.45	0.980940802	

Table 42 – Energy Index computation for freight trains per signalling system

Freight					
Signalling system	**Stopping pattern**	**Average energy per train [kWh]**	**Average energy per train/km [kWh/km]**	**Relative ratio**	**Energy Index I_E**
3-Aspect	Stopping	533.7429	24.86	1	1
	Non-stopping	426.19422	19.85	1	
ETCS L3	Stopping	518.2743	24.14	0.971018631	0.978885082
	Non-stopping	420.5478	19.59	0.986751533	
VC	Stopping	514.5786	23.97	0.964094511	0.972517656
	Non-stopping	418.0713	19.47	0.980940802	

Values of the energy index show that on average VC can slightly reduce energy consumption with respect to moving block. If under VC a train slows down to cruise at a lower speed, then the train behind has the possibility to slow down and cruise synchronously with the train ahead. Under moving block instead when a train slows down to cruise at a lower speed, the train behind will initially decelerate as it approaches the End of Authority and then will reaccelerate to the maximum allowed speed and not cruise at the same speed of the train ahead (unless optimal control algorithms manage the traffic). Such a behaviour might hence cause repetitive braking/acceleration phases which make moving block more energy consuming than VC, which has instead a movement control paradigm between trains in the same convoy.

5.1.5.1. CO_2 emissions

Environmental impacts have been measured in terms of CO_2 emissions which would be saved by the modal shift from motorised transport modes that a certain railway signalling alternative would induce. For each market segment, savings in CO_2 have been computed based on the modal shifts identified in Section 6.1.4 for the scenarios of no increase in ticket fares for using more frequent train services under the two signalling alternatives. These modal shifts are displayed in Table 43 and illustrated in Figure 20.

Table 43 – Modal shift from motorized transport modes to railways for each market segment per signalling alternative

ETCS L3				
MS	**Mode of transport**			
	Bus	Car	Plane	Truck
High-speed	40.0%	33.3%	37.5%	-
Main line	41.9%	35.3%	-	-
Regional	32.4%	28.8%	-	-
Urban	16.7%	21.6%	-	-
Freight	-	-	-	30%

VC				
MS	**Mode of transport**			
	Bus	Car	Plane	Truck
High-speed	44.0%	37.0%	42.2%	-
Main line	48.7%	44.6%	-	-
Regional	50.0%	48.3%	-	-
Urban	25.0%	23.1%	-	-
Freight	-	-	-	46.6%

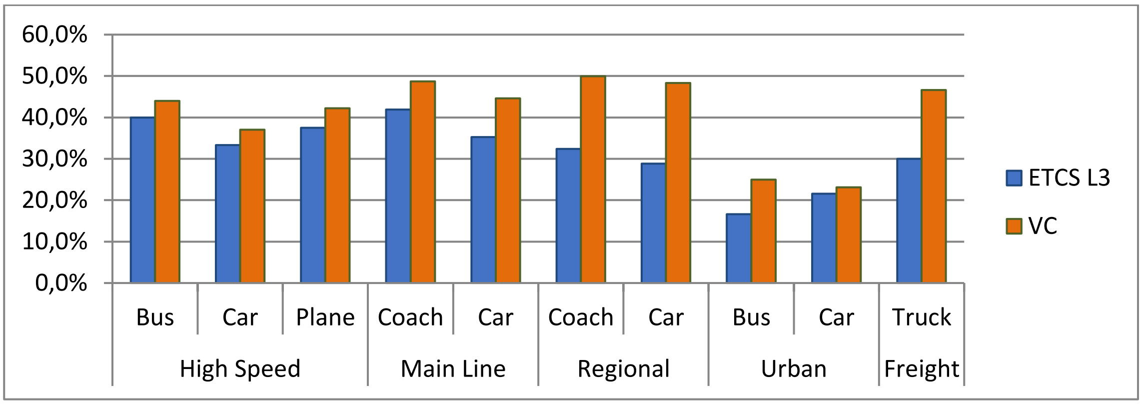

Figure 20 – Modal shifts from each motorized transport mode to railways for each market segment per signalling alternative

Initial values of CO_2 emissions for each case study have been extracted from publicly available online sources such as EcoPassenger [44] and the UK government [46]. Results are shown in Table 44 where the green cells show the original CO_2 emissions in real life data. Values in the white cells refer to the reduced amount of CO_2 emissions of a specific motorised transport mode if ETCS L3 moving block or VC are introduced. For example, in the main line case study, ETCS L3 could reduce CO_2 car emissions (i.e. 'L3 (car)') from 13.570 kg to 9.047 kg (reduction by 4.789 kg), while VC (see 'VC (car)') to 8.544 kg meaning a reduction by 6.057 kg. Similarly, ETCS L3 (i.e. 'L3 (bus)') could reduce CO_2 coach emissions from 3.430 kg to 2.058 kg (reduction by 1.438 kg per passenger), while VC could bring the reduction down to 1.921 kg (i.e. 1.670 kg less per passenger). The same analogy is followed for the other passenger-related market segments. For freight instead, the initial CO_2 emissions were derived from [45]. A one-way trip from Rotterdam to Hamburg would consume around 530 kg by truck. Those emissions are predicted to be reduced by 160 kg in the case of freight trains equipped with ETCS L3 and by 247 kg if self-propelled virtually coupled wagons are introduced.

Table 44 – CO_2 emission per transport mode based on signalling alternative

	CO_2 Emissions (kg)			
	High-speed	**Main line**	**Regional**	**Urban**
Car	42.900	13.570	8.980	0.750
L3 (car)	28.600	9.047	5.987	0.500
VC (car)	27.011	8.544	5.654	0.472
Bus*	11.940	3.430	2.270	0.570
L3 (bus*)	7.164	2.058	1.362	0.342
VC (bus*)	6.686	1.921	1.271	0.319
Plane	117.5	-	-	-
L3 (plane)	73.438	-	-	-
VC (plane)	67.930	-	-	-

* For main line and regional segments, the bus is considered a regional bus, also known as coach.

Freight	**CO_2 Emissions (Kg)**
Truck	531.118
L3 (truck)	371.783
VC (truck)	283.729

The results obtained from the above reported analysis on potential modal shifts of the travel demand (Figure 20) and corresponding CO_2 emissions for the different motorised transport modes (Table 44) have been combined to identify percentage emission reduction with respect to the baseline scenario, i.e. the current transport condition. Figure 21 illustrates the percentage of CO_2

emissions with respect to the baseline that are predicted for each motorised transport mode in the case ETCS L3 moving-block and VC would become operational without any fair increase of the railway service. The introduction of ETCS L3 might bring today's emissions down to 66.7% for cars, 60% for buses, 62.5% for planes and 70% for trucks. This brings to an expected reduction of today's CO_2 emissions by 35.2% on average across all motorised transport modes. The deployment of VC would instead contribute to an even deeper reduction of today's emissions to 62.9% for cars, 56.0% for buses, 57.8% for planes and 53.4% for trucks. Current CO_2 emissions could be therefore reduced by 42.5% on average across all motorised transport modes with the introduction of VC, which would greatly help achieving the goal set for 2050 by the EC white paper on transport [58] of 60% reduction in Green House Gases (GHG) emissions from transport.

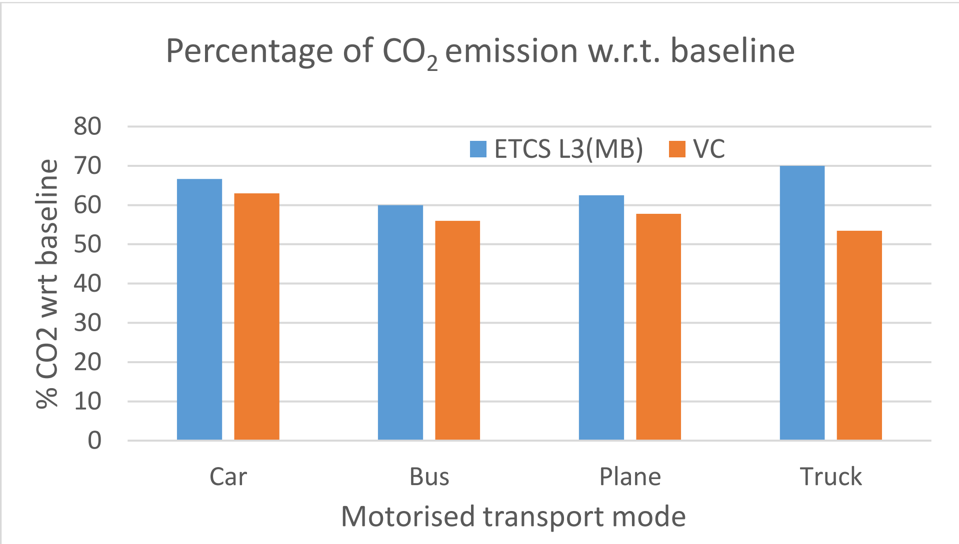

Figure 21. Forecasted reduction of CO2 emission with respect to baseline scenario per motorised transport mode

5.2. Qualitative criteria

Qualitative parameters were assessed by means of a Delphi technique where experts and non-experts have been asked to predict the issues which might influence the feasibility and deployment of moving block and virtual coupling signalling. In subsequent rounds, Excel spreadsheets were circulated and the participants were asked to raise and rate potential issues using a five-point scale (e.g. 1 = definitely unnecessary; 2 = not important; 3 = advisable; 4 = important; 5 = essential). The second question consisted on scoring the likelihood that each issue might occur. A third question required to score from 1 to 5 the likelihood that a given issue would be solved within the next 5 years. A fourth question asked interviewed experts to identify and rate necessary procedures and steps towards regulatory approval of Moving Block and VC. Participants were asked to review and reconsider their ratings with respect to those of the panel as a whole and amend them if desired. These steps were repeated until a consensus was reached by the second round. These issues and assessments of their significance were undertaken generically and did not distinguish between the four market segments given that issues like public acceptance and regulatory approval would be indistinctly common to all segments.

5.2.1. Safety

The level of safety and the perception of safety are evaluated to be the highest level of significance and risk. There was near unanimous agreement among stakeholders that the key risk related to achieving public and regulatory acceptance is in the safety area and of the comments made about safety the notable ones are: an incident (wrong-side failure) during development/testing/early deployment would undermine public and regulatory confidence. There is also awareness that the technical trade press will be very interested in the development and will focus on how confident they are that the solutions will be effective and fail-safe. A notable finding from the stakeholder reviews was that for all of the safety issues, no stakeholder expects them to be fully resolved in the next 5 years (see Table 45). The table shows the evaluated priority levels and likelihood of being solved in the next 5 years. The higher the number, the higher the priority, and the higher the number in the '5 year' column, the more likely it is to be resolved in 5 years. An evaluation of 5 would indicate confidence (from the individual expert who made the entry) that the issue will be resolved or closed out within 5 years.

Table 45 – Assessment reliability and safety of MB and VC

System	Aspects for safe and reliable operations	Score Priority	Score 5 years
ETCS L3 MB	Harmonised non-functional requirements on train integrity (safety and performance)	4	3
	Trains are able to stop within their MA	5	5
	MAs are exclusively issued for a given section of track for only one train at a time	5	5
	Routes are held until the train has passed	5	5
	Reliability of communications system	3	5
	Have a full view over the performance railway network in software and see what the safety levels are	5	5
	Have a full view over the performance railway network in software and see where the remaining capacity is (or where bottlenecks are)	4	4
	Have a full view over the energy consumption of the railway network in software	3	3
	Central co-ordination of the switching system in software to find the appropriate balance between capacity utilisation, safety and energy consumption dynamically	2	2
	Spacing	5	5
	Capacity gain	5	3
	Costs	5	3
	Arithmetic Mean of assessments	**4.33**	**3.61**
	Standard Deviations	**0.88**	**1.16**
VC	Standardised communication to following vehicles	4	3
	System behaviour and operations defined for degraded situations	4	3
	Trains are able to stop within their MA	4	5
	MAs are exclusively issued for a given section of track for only one train at a time	4	5
	Routes are held until the train has passed	4	5
	Formations virtually coupled in rear will not crash into formations in front without causing any more Fatality Weighted Injuries (FWIs)	5	1

System	Aspects for safe and reliable operations	Score Priority	Score 5 years
	Reliability of communications system	5	2
	Have a full view over the performance railways network in software and see what the safety levels of individual convoys, consists and units are	5	5
	Have a full view over the performance railways network in software and see where the remaining capacity is (or bottlenecks are)	4	4
	Spacing	5	3
	Capacity	5	1
	Costs	5	2
	Arithmetic Mean of assessments	**4.5**	**3.25**
	Standard Deviations	**0.5**	**1.48**

Taking this data together, the arithmetic averages of each of the assessments show that the experts rated the priority for each of the technical issues as very high with a general finding that most experts did not expect the technical issues to be resolved fully within five years. There was slightly more confidence that some of the Virtual Coupling issues would be resolved than the Moving Block, but given the nature of the exercise, it is suggested that this is not a significant difference. A further feature of this analysis, measured by looking at the standard deviation of the inputs is that the experts are much more confident of the nature of the technical issues that need to be resolved, and their high importance, than they are of the likelihood of the issues being resolved within five years. These observations apply to both Moving Block and Virtual Coupling but looking at the Standard Deviation (SD) of the latter (1.48 with a mean of 3.25) reflects significant uncertainty in the confidence of experts on the likelihood of achieving solutions within 5 years.

The values used in the MCA results (Section 5.3) are based on the safety index I_{safe} computed as

$$I_{safe} = \frac{Score_{5years}}{Score_{Priority}}.$$

By applying the equation above to the values in Table 45, the safety index for ETCS L3 is 0.834 whereas for VC, it is equal to 0.722.

5.2.2. Public acceptance

The question of public acceptance and regulatory approval is closely related to safety as the benefits that follow from Virtual Coupling will in effect be automatically banked by the public and passengers, while the potential risks could influence the public to have a low tolerance of technical failures. There is a symbiotic relationship between these two factors and the regulatory approval, as regulators are unlikely to take risks upon themselves by approving technologies that the public have concerns about. Therefore, the whole challenge for the project is to get through to the implementation without any uncontrolled or wrong side failures. Table 46 shows the input from the respondents. Missing numbers indicate that a respondent added an issue but did not quantify it.

Table 46 – Assessment of public acceptance

Issue	Score Priority	Score 5 years
Culture that expects transportation delivered by organisations (rather than personally) to be 100% safe	5	1
Safety	5	1
Safety incident causes public concern	5	2
Populist politicians oppose new technology	3	2
Interoperable solution (working cross-border and cross-supplier)	5	3
Convincing politicians that if they allow VC and a VC train crashes, that there is not going to be a massive backlash	5	3
Reliability	5	3
Costs	5	3
Railway press analysis raises concerns	4	3
Passenger pressure groups raise concerns	4	3
Difficult explaining link MovingRail and capacity	3	3
Non realisation of capacity benefits - public apathy	2	3
Technical delays/issues raise concerns over safety	5	4
Mainstream media raising fears	4	4
Opacity	5	5
Fear of collision – passengers	3	5
People are safe	5	
Rail is reliable	4	
Rail is a flexible (as much as realistically possible) in the transport / journey chain	3	
People feel safe (perception)	2	
View of maturity vs road sector - expectation for similar capability		
Expectation of almost guaranteed no train on train collision lost		
Expectation to work unnoticed to traveller		
Unwillingness to pay more		
Arithmetic Mean of numerical assessments	4.1	3.0
Standard Deviation	1.01	1.12

The values used in the MCA results (Section 5.3) are based on the public acceptance index I_{pubacc} computed as

$$I_{pubacc} = \frac{Score_{5years}}{Score_{Priority}}.$$

By applying the equation above to the values in Table 45, the public acceptance is equal to 0.732 to all of the considered market segments and signalling alternatives.

5.2.3. Regulatory approval

As for public acceptance, the regulatory approval of Virtual Coupling is symbiotically related to technological safety and the general tolerance of customers to potential technical failures, as regulators are unlikely to take risks upon themselves by approving technologies that the public have concerns about. Therefore, the whole challenge for the project is to get through to the implementation without any uncontrolled or wrong side failures.

Stakeholders were asked to identify the issues and barriers to regulatory approval, and then the potential interventions that would help to secure or promote regulatory approval. The following tables show the results. Missing numbers indicate that a respondent added an issue but did not quantify it.

Table 47 – Issues identified to achieve regulatory approval

Regulatory approval		
Issue	**Score Priority**	**Score 5 years**
Clear articulation of the new system	4	3
Route through the Common Safety Method	5	5
Multiple NSA's or European Agency approval	5	5
Public concerns put pressure on regulators	3	2
Technical complexity makes demonstration of safety for Movingrail challenging	5	3
Any safety incident has potential to set back approval	5	1
Approval through ERA will make ERA careful and slow	5	3
BREXIT creates confusion over approvals for use in UK	3	5
Demonstrate at least same safety level as today	5	2
Safety must always be improved	5	2
Overcoming 2 centuries of the principle of no closer than the absolute braking distance	5	1
Time (as the inverse of speed difference) between two consists or units	5	5
Maximum length of a convoy	4	4
Safety	5	1
Reliability	5	3
Costs	5	3
Proper ability to evaluate risk needed		
Arithmetic Mean of assessments **Standard Deviation**	**4.63** **0.70**	**3.0** **1.41**

Stakeholders identified a number of strategies to achieve regulatory approval, and they all depend upon the assumption that the system as designed will work to a very high level of reliability and safety, and that there will be no wrong side failures during the full scale testing phase. Regulators are effectively well informed versions of the public, when it comes to acceptance, and would have similar concerns were there to be any technical failures and safety events, during the development phase.

The values used in the MCA results (Section 5.3) are based on the regulatory approval index $I_{regappr}$ computed as

$$I_{regappr} = \frac{Score_{5years}}{Score_{Priority}}.$$

By applying the equation above to the values in Table 45, the public acceptance is equal to 0.648 to all of the considered market segments and signalling alternatives.

Table 48 – Steps identified to achieve regulatory approval

Regulatory approval		
Steps towards regulatory approval of VC	**Score Priority**	**Score 5 Years**
Early engagement with Regulator/s	5	5
Decision to seek approval from EUAR (not NSA's)	5	5
Clarify with EU Commission that EUAR can approve	5	4
Creation of clear system definition and draft specifications	5	3
Set up simulation and test track for testing system	5	3
Sponsorship of specifications/standards through EU Processes	5	3
Description of operations and system	3	4
Hazard analysis	4	3
Prototype on test track	4	2
Pilot in regular operation	4	1
Talk to the regulators as soon as possible	5	5
Build evidence that VC is at least as safe as whatever it will replace	5	1
Demonstrate that the benefits of VC cannot be delivered by any other safer means	5	1
Build a safety case based on the previous two points	5	1
Safety	5	1
Reliability	5	3
Costs	5	3
Conspicuity of a convoy (see e.g. military pelotons on the road using flags to explain what the beginning and end of the peloton is)	5	
Software centric approach including continuous integration and continuous delivery	4	
Software centric approach including non-deterministic artificial intelligence (AI)	3	
Demonstrable step change improvement in capacity		
Communication of safety principles to necessary stakeholders		
Demonstration of potential public acceptance		
Arithmetic mean of assessments	**4.6**	**2.82**
Standard Deviation	**0.66**	**1.42**

Given that railways have always been controlled through mechanisms that are designed around maintaining safe absolute braking distances between trains, it is non-trivial to be asking regulators to accept that this fundamental signalling principle can be modified. However, the thinking that has gone into the development of Virtual Coupling is recognised as an innovation that could achieve benefits for the railway and its users, and a calm evaluation of the factors that will impact on the safety of the system, involving the regulatory community directly, could get to the position where the basic principle can be proposed for amendment through the TSI and Standards development processes.

The key features of the strategies for achieving regulatory approval are: agreement on where it

will be sought (EU or NSA level – recommended ERA), early engagement with relevant regulator (ERA), development of very clear system definition, development of the Specifications and Standards that will apply to the system (to enable Notified Body and EUAR sign off), ability to test systems in simulation or test track mode to ensure failures don't impact on live railway/customers, and public acceptance. There is a low level of confidence that regulatory approval can be gained within 5 years, with most experts putting the likelihood in the range of 1 (low) to 3 (medium) and a mean value of 2.82. However, with a standard deviation of 1.42 this analysis demonstrates a significant variance in the expert confidence of achieving regulatory approval. All experts agreed on the need to engage early and to put resources into developing a plan with milestones to achieve regulatory approval – presuming that the business case/market analysis shows that it is justified to go on to the implementation phase.

In summary, the exercise undertaken with stakeholders/experts identified that safety is a major issue for all market segments, that the risk of a significant failure could jeopardise both public and regulatory acceptance, and that early clarification of the regulatory process, and engagement with the relevant regulator/s is critical to achieving successful implementation of the technology. Those experts that expressed a view proposed engagement with the European Union Agency for Railways as they are the body that would be most directly involved and would also be the body that developed revisions to the CCS TSI to permit the introduction into operational systems. In general, there was greater confidence in the identification of important factors and issues that would need to be resolved to implement Virtual Coupling, than there was over the likelihood of those issues being resolved in the next five years. There were very varied views on this aspect, ranging from optimistic to pessimistic.

5.3. MCA results

The multi-criteria analysis of moving block and virtual coupling has been performed by combining the results obtained for each of the considered criteria by means of a pairwise criteria comparison matrix. The pairwise comparison matrix contains relative importance weights among the different criteria as provided by railway experts and stakeholders. The relative criteria importance weights have been collected through anonymous surveys of 15 railway SMEs from both academic institutions and railway companies, including experts of the MOVINGRAIL Advisory Board. The Delphi-AHP technique has been used to gather a consistent pairwise criteria comparison matrix of relative importance weights where three survey rounds were necessary to achieve a consensus among the experts. The first Delphi survey round started with a brainstorming session gathering railway experts across Europe and members of the MOVINGRAIL Advisory Board. The second round consisted of a follow-up by email to all stakeholders to fill in matrices with relative criteria importance weights with the objective of providing a matrix with a Consistency Rate (CR) lower than 0.10. For those experts who did not manage to give a consistent pairwise matrix (i.e. with CR<0.1) at the second round, a third one-by-one email round was needed for the interviewees to adjust their matrices so to be consistent.

The hierarchical model applied for the MCA is shown in Figure 22. The top layer represents the overall goal of choosing the appropriate signalling alternative for each market segment. The middle level displays the eight criteria (discussed in Section 4.7) which influence the goal of the MCA, i.e. total costs, infrastructure capacity, system stability, travel demand distribution, energy consumption, safety, public acceptance and regulatory approval. Those criteria are used for

evaluating the two signalling alternatives (ETCS L3 and VC; see Section 4.5) which are illustrated at the bottom level of the hierarchical model.

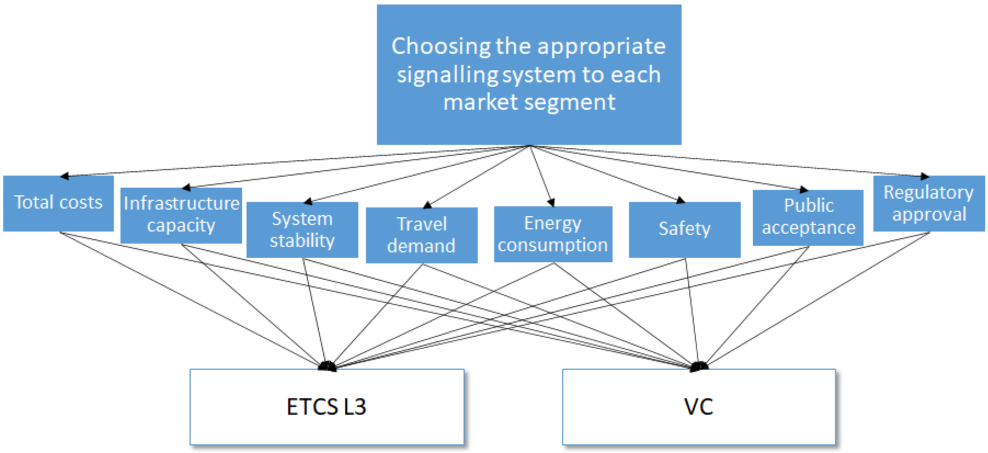

Figure 22 – Hierarchical structure of the AHP technique for the applicability of VC to each Market Segment

According to the hierarchical model defined in Section 4.4, the 8x8 square pairwise criteria comparison matrix C (where the column-row dimensions are given by the 8 criteria) with respect to the goal A has been built.

A geometric mean has been used to consolidate all the consistent pairwise comparison matrices provided by the interviewed railway SMEs. The consolidated pairwise criteria comparison matrix A is shown in Table 49. The matrices of the 15 participants are given in the Appendix. The weights of relative criteria importance are given as a ratio between a criterion on the row and a criterion on the column of the matrix, using a scale ranging from 1 (the lowest importance) to 9 (the highest importance), as defined in Table 3. A matrix value of 1/9 hence means that the criterion on the column is absolutely more important than the one on the row. A value of 1 instead indicates that the criteria on the column and the row have the same importance to the interviewee. A value of 9 means that the criterion on the row is absolutely more important than the one on the column.

Table 49 – Consolidated pairwise comparison matrix

		Total costs	Infra capacity	System stability	Travel demand	Energy consumption	Safety	Public acceptance	Regulatory approval
		C1	C2	C3	C4	C5	C6	C7	C8
Total costs	**C1**	1.000	0.960	2.031	2.525	5.284	0.154	1.385	0.152
Infra capacity	**C2**	1.042	1.000	2.769	1.861	6.322	0.117	0.931	0.090
System stability	**C3**	0.492	0.361	1.000	1.914	3.503	0.049	0.634	0.081
Travel demand	**C4**	0.396	0.537	0.523	1.000	2.783	0.073	0.848	0.095
Energy consumption	**C5**	0.189	0.158	0.285	0.359	1.000	0.041	0.570	0.092
Safety	**C6**	6.478	8.564	20.412	13.769	24.398	1.000	13.533	1.897
Public acceptance	**C7**	0.722	1.075	1.578	1.180	1.755	0.074	1.000	0.150
Regulatory approval	**C8**	6.600	11.118	12.347	10.520	10.922	0.527	6.664	1.000
Total		**16.92**	**23.77**	**40.94**	**33.13**	**55.97**	**2.03**	**25.56**	**3.56**

Using the method explained in Section 4.2 the matrix values $C_{i,j}$ on row i and column j are normalized over the rows for each column to $\bar{C}_{i,j}$ and then weights $C_{w,i}$ for a criterion on row i are computed as the average of the normalized values $\bar{C}_{i,j}$ over the columns of that row. The resulting criteria weights are given in the last column in Table 50.

Table 50 – Normalized comparison matrix and criteria weights

		Total costs	Infra capacity	System stability	Travel demand	Energy consumption	Safety	Public acceptance	Regulatory approval	Criteria weight
		C1	C2	C3	C4	C5	C6	C7	C8	
Total costs	**C1**	0.059	0.040	0.050	0.076	0.094	0.076	0.054	0.043	**0.0615**
Infra capacity	**C2**	0.062	0.042	0.068	0.056	0.113	0.057	0.036	0.025	**0.0574**
System stability	**C3**	0.029	0.015	0.024	0.058	0.063	0.024	0.025	0.023	**0.0326**
Travel demand	**C4**	0.023	0.023	0.013	0.030	0.050	0.036	0.033	0.027	**0.0293**
Energy consumption	**C5**	0.011	0.007	0.007	0.011	0.018	0.020	0.022	0.026	**0.0152**
Safety	**C6**	0.383	0.360	0.499	0.416	0.436	0.491	0.529	0.534	**0.4559**
Public acceptance	**C7**	0.043	0.045	0.039	0.036	0.031	0.036	0.039	0.042	**0.0389**
Regulatory approval	**C8**	0.390	0.468	0.302	0.318	0.195	0.259	0.261	0.281	**0.3091**

Before computing the Consistency Ratio (CR) of the consolidated pairwise criteria comparison matrix, the maximum criteria eigenvalue λ_{max} needs to be calculated as the average of the values λ_i over the rows i, with λ_i the sum of $\left(C_{i,j}C_{w,j}\right)/C_{w,i}$ over the columns j. The computation of the weighted sums and the maximum eigenvalue are displayed in Table 51.

Table 51 – Computation of the maximum eigenvalue

	C1	C2	C3	C4	C5	C7	C8	C9	Weighted sum value	Ratio λ_i
C1	0.062	0.055	0.066	0.074	0.080	0.070	0.054	0.047	0.5082	8.2581
C2	0.064	0.057	0.090	0.055	0.096	0.053	0.036	0.028	0.4797	8.3518
C3	0.030	0.021	0.033	0.056	0.053	0.022	0.025	0.025	0.2650	8.1308
C4	0.024	0.031	0.017	0.029	0.042	0.033	0.033	0.029	0.2393	8.1732
C5	0.012	0.009	0.009	0.011	0.015	0.019	0.022	0.028	0.1249	8.2110
C7	0.399	0.492	0.665	0.403	0.371	0.456	0.526	0.587	3.8987	8.5509
C8	0.044	0.062	0.051	0.035	0.027	0.034	0.039	0.046	0.3378	8.6885
C9	0.406	0.639	0.402	0.308	0.166	0.240	0.259	0.309	2.7298	8.8313
										8.3994

The Consistency Index (CI) can now be calculated based on the maximum eigenvalue λ_{max}= 8.3994 and the matrix dimension $n = 8$ as $CI = (\lambda_{max} - n)/(n - 1) = (8.3994 - 8)/(8 - 1) =$ 0.0571. The Consistency Ratio (CR) is now finally obtained using the Random Index $RI = 1.41$ for $n = 8$ elements as given in Table 4, as

$$CR = \frac{CI}{RI} = \frac{0.0571}{1.41} = 0.0405 \leq 0.1$$

Since CR is lower than 10%, the final weights associated with each criterion are confirmed to be $C_i = C_{w,i}$, i.e.,

- Total costs $C_1 = 0.0615$
- Infrastructure capacity $C_2 = 0.0574$
- System stability C_3 =0.0326
- Travel demand distribution $C_4 = 0.0293$
- Energy consumption $C_5 = 0.0152$
- Safety $C_6 = 0.4559$
- Public acceptance $C_7 = 0.0389$
- Regulatory approval $C_8 = 0.3091.$

The performance matrices for each market segment are displayed in
Table 52. Each number is represented by a value $X_{m,n}$ which is the performance value of the m-th alternative over the n-th criterion.

Table 52 – Performance matrices for each Market Segment

		Criteria							
High-speed		Total costs	Infra capacity [I_{cap}]	System stability [$I_{stability}$]	Travel demand [% modal shifts]	Energy consumption [I_E]	Safety [I_{Safe}]	Public acceptance [I_{pubacc}]	Regulatory approval [$I_{regappr}$]
Alternatives	ETCS L3	€413,459,260	1.2300	69.19	0.3784	0.9918	0.834	0.732	0.648
	VC	€455,924,040	1.3665	71.22	0.4193	0.9853	0.722	0.732	0.648

		Criteria							
Main line		Total costs	Infra capacity [I_{cap}]	System stability [$I_{stability}$]	Travel demand [% modal shifts]	Energy consumption [I_E]	Safety [I_{Safe}]	Public acceptance [I_{pubacc}]	Regulatory approval [$I_{regappr}$]
Alternatives	ETCS L3	€623,243,784	1.2467	63.16	0.3958	0.9789	0.834	0.732	0.648
	VC	€685,158,503	1.4226	66.54	0.4742	0.9725	0.722	0.732	0.648

		Criteria							
Regional		Total costs	Infra capacity [I_{cap}]	System stability [$I_{stability}$]	Travel demand [% modal shifts]	Energy consumption [I_E]	Safety [I_{Safe}]	Public acceptance [I_{pubacc}]	Regulatory approval [$I_{regappr}$]
Alternatives	ETCS L3	€503,301,732	1.3343	84.76	0.3021	0.9789	0.834	0.732	0.648
	VC	€536,778,293	1.3584	85.12	0.4909	0.9725	0.722	0.732	0.648

		Criteria							
Urban		Total costs	Infra capacity [I_{cap}]	System stability [$I_{stability}$]	Travel demand [% modal shifts]	Energy consumption [I_E]	Safety [I_{Safe}]	Public acceptance [I_{pubacc}]	Regulatory approval [$I_{regappr}$]
Alternatives	ETCS L3	€391,992,601	1.3587	29.83	0.2308	0.9789	0.834	0.732	0.648
	VC	€420,792,215	1.4372	33.67	0.3018	0.9725	0.722	0.732	0.648

		Criteria							
Freight		Total costs	Infra capacity [I_{cap}]	System stability [$I_{stability}$]	Travel demand [% modal shifts]	Energy consumption [I_E]	Safety [I_{Safe}]	Public acceptance [I_{pubacc}]	Regulatory approval [$I_{regappr}$]
Alternatives	ETCS L3	€1,228,503,378	1.1780	52.64	0.300	0.9789	0.834	0.732	0.648
	VC	€1,321,960,368	1.3301	56.06	0.466	0.9725	0.722	0.732	0.648

The consolidated performance matrix for all market segments is summarized in Table 53.

Table 53 – Consolidated performance matrix

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

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

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

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

The normalised consolidated results are shown in Table 54.

Table 54 – Normalised consolidated decision matrix

		Market Segment	Criteria: Total costs	Infra capacity	System stability	Travel demand	Energy consumption	Safety	Public acceptance	Regulatory approval
Alternatives	ETCS L3	High-Speed	1.000	0.900	0.972	0.902	0.993	1.000	1.000	1.000
		Main line	1.000	0.876	0.949	0.835	0.993	1.000	1.000	1.000
		Regional	1.000	0.982	0.996	0.615	0.993	1.000	1.000	1.000
		Urban	1.000	0.945	0.886	0.765	0.993	1.000	1.000	1.000
		Freight	1.000	0.886	0.939	0.644	0.993	1.000	1.000	1.000
	VC	High-Speed	0.907	1.000	1.000	1.000	1.000	0.866	1.000	1.000
		Main line	0.910	1.000	1.000	1.000	1.000	0.866	1.000	1.000
		Regional	0.938	1.000	1.000	1.000	1.000	0.866	1.000	1.000
		Urban	0.932	1.000	1.000	1.000	1.000	0.866	1.000	1.000
		Freight	0.929	1.000	1.000	1.000	1.000	0.866	1.000	1.000

Performance values for each criterion are then multiplied by the corresponding criterion weight computed by means of the hybrid Delphi-AHP method described above. The weighted normalized decision matrix is given in Table 55.

Table 55 – Weighted normalized decision matrix

		Market Segment	Criteria							
			Total costs	Infra capacity	System stability	Travel demand	Energy consumption	Safety	Public acceptance	Regulatory approval
Alternatives	ETCS L3	High-Speed	0.062	0.052	0.032	0.026	0.015	0.456	0.039	0.309
		Main line	0.062	0.050	0.031	0.024	0.015	0.456	0.039	0.309
		Regional	0.062	0.056	0.032	0.018	0.015	0.456	0.039	0.309
		Urban	0.062	0.054	0.029	0.022	0.015	0.456	0.039	0.309
		Freight	0.062	0.051	0.031	0.019	0.015	0.456	0.039	0.309
	VC	High-Speed	0.056	0.057	0.033	0.029	0.015	0.395	0.039	0.309
		Main line	0.056	0.057	0.033	0.029	0.015	0.395	0.039	0.309
		Regional	0.058	0.057	0.033	0.029	0.015	0.395	0.039	0.309
		Urban	0.057	0.057	0.033	0.029	0.015	0.395	0.039	0.309
		Freight	0.057	0.057	0.033	0.029	0.015	0.395	0.039	0.309

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

$$P_m = \sum_{i=1}^{8} C_i \bar{X}_{m,i}.$$

The computed scores of the two signalling alternatives (ETCS Level 3 moving-block and virtual coupling) per market segment are reported in Table 56 and graphically illustrated in Figure 23 .

Table 56 – Performance Score for each Market Segment per signalling alternative

	P_m	
Market Segment	**ETCS L3**	**VC**
High-Speed	0.99028	0.93320
Main line	0.98621	0.93337
Regional	0.98738	0.93510
Urban	0.98606	0.93472
Freight	0.98081	0.93458

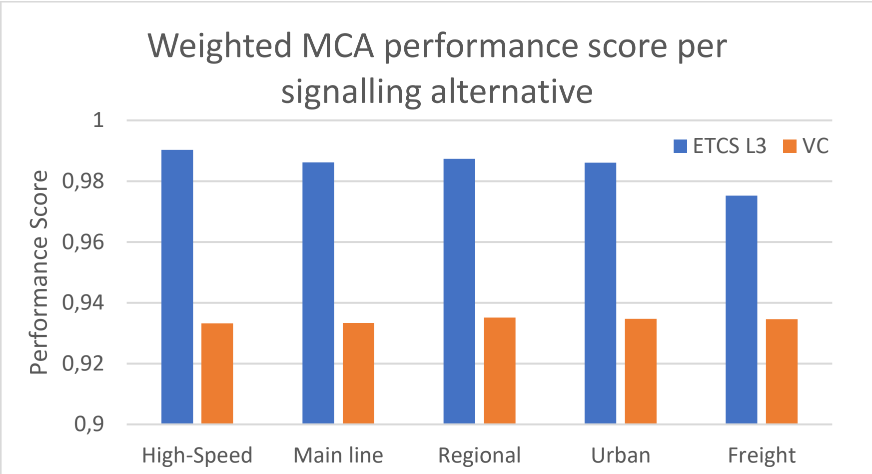

Figure 23 – Weighted MCA performance score of ETCS Level 3 and VC per market segment

The MCA performance scores show that ETCS Level 3 moving block outperforms VC for all market segments, despite the separate analysis of each criterion such as infrastructure capacity, stability, travel demand and energy consumption that are in favour of VC (see Sections 5.1.1, 5.1.3, 5.1.4 and 5.1.5). The reason behind such a result is mainly due to the very high weight (46%) associated by the interviewed stakeholders to the criterion “safety” (refer to Table 50 and Table 53) where VC scores are lower than ETCS Level 3 due to its lower technology maturity level and the consequent higher number of open safety-critical issues.

Based on Table 53 and Table 54, VC provides better scores in capacity, stability, travel demand and energy consumption over ETCS L3 for all the market segments. On the other hand, the total deployment and operation costs for ETCS L3 would be lower than VC given that this latter signalling system requires the installation of additional intelligent software solutions such as automation (ATO), EVC software upgrades and the V2V communication layer. However, differences in total costs of the two signalling alternatives are very limited since total migration costs from baseline to ETCS L3 or VC are almost the same (Section 5.1.2). Infrastructure costs represent the highest share of CAPEX and depend on the distance between a specific origin and destination (see Table 17 for the case studies considered in this deliverable).

A fairer comparison of technical and business performances of two different technologies would require the technologies to have the same or at least a similar technology maturity level. To this end, the MCA has been reiterated considering a future point in time where VC would have the same technological maturity of ETCS L3 moving-block and therefore a comparable safety performance. Results of such a MCA are displayed in Table 57 and Figure 24, clearly showing that then VC outperforms ETCS Level 3 for all market segments. The highest performance score is associated to the regional and the freight market segments, mostly because the deployment of VC would provide the service flexibility required by the customer demand over these two market segments, thereby attracting more travellers from other transport modes.

Table 57 – Performance Score for each Market Segment in the case of equal safety indices to both signalling alternatives

	P_m	
Market Segment	**ETCS L3**	**VC**
High-Speed	0.99012	0.99417
Main line	0.98605	0.99434
Regional	0.98723	0.99606
Urban	0.98591	0.99569
Freight	0.98066	0.99555

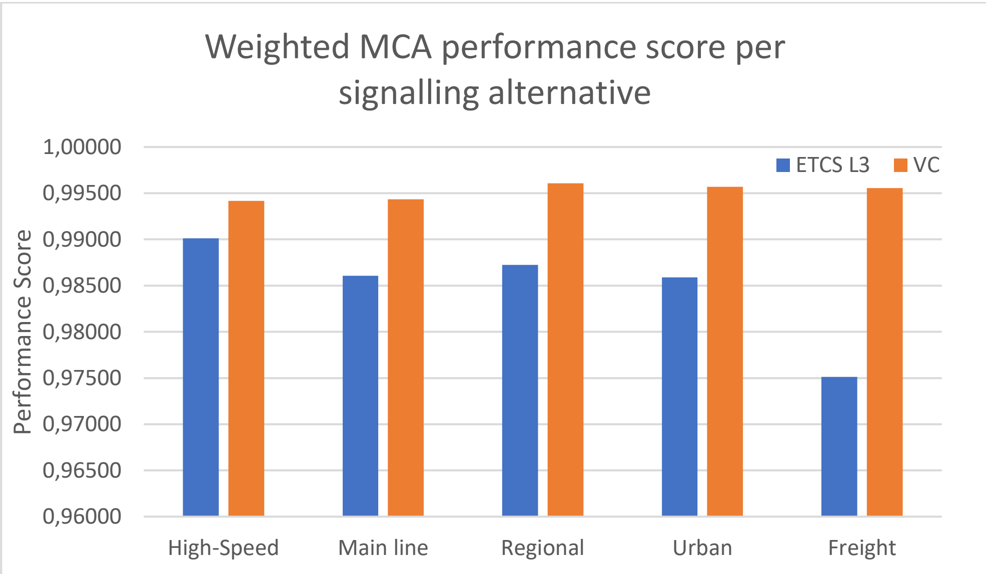

Figure 24 – Weighted MCA performance score per market segment considering the same maturity level for ETCS L3 and VC

6. Conclusions and recommendations

This deliverable provides a comprehensive multi-criteria analysis (MCA) to compare the two signalling alternatives ETCS Level 3 Moving Block (MB) and Virtual Coupling (VC) from the operational, technological and business perspectives, in line with the main objectives of the MOVINGRAIL project. The analysis has been performed for all the railway market segments identified by the Shift2Rail MAAP namely high-speed, main-line, regional, urban/suburban and freight. A total of eight different criteria have been considered which refer to both quantitative and qualitative key performance measures. Quantitative criteria include total costs, infrastructure capacity, system stability, travel demand and energy consumption. These criteria have been measured by relying on consolidated financial and economic forecasting methods to assess costs, analytical and specific simulation techniques for the computation of capacity, stability and energy, and stated preference surveys to forecast future travel demand patterns. Instead qualitative criteria cover safety, public acceptance and regulatory approval. These criteria have been assessed by means of a Delphi method where expert judgements have been collected through several interview rounds with Subject Matter Experts (SMEs) and stakeholders of the railway sector, including members of the MOVINGRAIL Advisory Board.

A hybrid Delphi-AHP technique has been adopted to identify relative importance weights assigned by interviewed pool of experts to the eight criteria for the MCA. The Delphi-AHP technique has proved successful in enhancing the decision-making process as it effectively combines quantitative criteria with stakeholder judgements for both quantitative and qualitative criteria by implementing a controlled feedback of the relative importance of criteria.

The analysis of single criteria such as infrastructure capacity, system stability, energy consumption and travel demand, shows that VC outperforms MB for all market segments. In terms of capacity, VC could effectively reduce headways for following train manoeuvres. Such capacity gains would be relevant only when trains move synchronously in virtually coupled platoons, as running at a relative-braking distance only (without cooperative driving in a platoon) would only provide marginal headway reductions with respect to MB, especially when operational speeds are low (e.g. regional market). Capacity indices computed in section 5.1.1 for non-stopping operations on the plain line have for instance showed that minimum headways on high-speed segments could be reduced from 74 s for Moving block to about 11 s in case of Virtually Coupled train platoons. Therefore, an important aspect of VC lies in advanced cooperative train control algorithms to enable efficient coupling/decoupling and coupled running of convoys. An advanced traffic management system is required to optimise the formation of virtually coupled platoons based on multiple factors such as track speeds and interstation distances. For instance, for the urban and regional segments trains may not have enough speed and/or distance to couple/decouple on-the-run. Further targeted research is hence needed to develop joint traffic management and cooperative train control algorithms that effectively compose/decompose virtually coupled platoons depending on the specific characteristics of a given rail market segment. Also, the real potential of VC would be unleashed when redesigning switch technologies since the capacity analysis here performed assumed current switches where diverging virtually coupled trains in a convoy will need to be separated by an absolute braking distance as it occurs for MB. Introducing completely new fail-safe switching technologies with passive turnouts could however shift the problem to the vehicles instead of the infrastructure and additional research must be made. Capacity improvements of VC are consequently reflected also in terms of system stability since the

possibility of trains to run closer than an absolute braking distance would provide an increased capability of the network to mitigate delay propagation. Energy savings could also be achieved given that VC would allow a virtually coupled train to follow harmoniously a preceding train in the convoy given that the V2V communication layer would provide accurate exchange of train speed and acceleration information. In the case of a speed reduction of a preceding train, MB (given the unavailability of speed/acceleration train information) might instead trigger repetitive decelerations and acceleration phases to reach again the track speed which are energy consuming. VC has also shown to attract a greater share of the travel demand from other modes of transport especially for the regional and the freight markets, and in case of no relevant increases in fares. VC would be particularly beneficial for those two markets since it would provide service flexibility desired by the customers of those markets which is currently poorly satisfied.

Total costs computed as CAPEX and OPEX are instead higher for VC, given the additional automation that is required with respect to MB for the ATO, the V2V communication and the EVC software upgrades. However, development and deployment costs for that automation have been assessed to be much cheaper than infrastructure enhancements that need to be made to migrate from the baseline scenario to MB. Indeed, the overall total costs for rolling out and operating the two signalling alternatives are comparable.

Regulatory approval and public acceptance were evaluated for the qualitative point of view collecting expert opinions and open issues which were rated in terms of priority and likelihood to be solved within 5 years. Although interview results for those criteria are overall in slight favour of MB, there were not significant differences with VC.

Safety has also been evaluated only from a qualitative point of view where interviewed stakeholders have expressed their view on critical safety issues to be solved for the two signalling alternatives and the likelihood that those are going to be solved within five years. Based on such a judgement format, VC has scored lower than MB, given the much lower technological maturity level and the consequent higher number of open safety-critical issues.

Final MCA scores show that ETCS Level 3 performs better than VC for all market segments, despite the latter signalling alternative being more advantageous when considering single criteria analyses such as capacity, stability, energy consumption and travel demand. The motivation of this outcome is due to the very high weight that interviewed experts have attributed to the criterion of “safety” which alone is responsible for 46% of the overall MCA score. The lower safety performance value associated by SMEs to VC because of the lower technological maturity level has mostly set the outcome of the MCA. A fairer comparison between economic and technical performances of two different technologies would instead require a comparable technological maturity level. Results of the MCA have been hence assessed for a future time point when VC will have a technological maturity similar to MB. In such a scenario, the MCA shows that VC outperforms MB for all market segments, especially for the regional and freight markets due to the greater modal shift that a more flexible VC-enabled train service would provide to the demand on those segments.

The aspect of safety has been judged to cover a prominent role and tip the scales in the acceptance and deployment of VC and MB. It is strongly recommended that future research is addressed in performing a comprehensive quantitative analysis of safety factors of VC and MB which can make the comparison more detailed with respect to this essential criterion.

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Appendix A

This appendix shows the consistent matrices by the 15 participants for weighting the criteria in this study. The consolidated version is found in Table 49. The last three matrices have a consistency ratio slightly greater than 10% (margin of 3%) but were still considered in the computation of the consolidated matrix given the fact that the relatively high number of criteria makes the identification of inconsistency difficult (see Section 4.2).

		Total Costs	Capacity	Delay propagation	Demand	Energy consumption	Safety	Public acceptance	Regulatory approval
		C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**
Total Cost	**C1**	1	1	3	1	3	1/9	1/5	1/3
Capacity	**C2**	1	1	3	1	1	1/9	1	1/7
Delay propagation	**C3**	1/3	1/3	1	1/3	1/3	1/9	1/3	1/9
Demand	**C4**	1	1	3	1	1	1/9	1	1/7
Energy consumption	**C5**	1/3	1	3	1	1	1/9	1	1/9
Safety	**C6**	9	9	9	9	9	1	7	1
Public acceptance	**C7**	5	1	3	1	1	1/7	1	1/7
Regulatory approval	**C8**	3	7	9	7	9	1	7	1

		Total Costs	Capacity	Delay propagation	Demand	Energy consumption	Safety	Public acceptance	Regulatory approval
		C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**
Total Costs	**C1**	1	1/5	2	1/7	1/7	1/9	1/8	1/8
Capacity	**C2**	5	1	1	1/3	1/3	1/7	1/8	1/8
Delay propagation	**C3**	1/2	1	1	1/3	1/3	1/7	1/8	1/8
Demand	**C4**	7	3	3	1	1	1/3	1/5	1/5
Energy consumption	**C5**	7	3	3	1	1	1/3	1/5	1/5
Safety	**C6**	9	7	7	3	3	1	1/3	1/3
Public acceptance	**C7**	8	8	8	5	5	3	1	1
Regulatory approval	**C8**	8	8	8	5	5	3	1	1

		Total Costs	Capacity	Delay propagation	Demand	Energy consumption	Safety	Public acceptance	Regulatory approval
		C1	C2	C3	C4	C5	C6	C7	C8
Total Costs	**C1**	1	1	3	2	4	1	1/2	1/6
Capacity	**C2**	1	1	4	1	3	1	1/4	1/6
Delay propagation	**C3**	1/3	1/4	1	1	1/2	1/6	1/4	1/6
Demand	**C4**	1/2	1	1	1	1	1/6	1/3	1/6
Energy consumption	**C5**	1/4	1/3	2	1	1	1/6	1/3	1/6
Safety	**C6**	1	1	6	6	6	1	3	1
Public acceptance	**C7**	2	4	4	3	3	1/3	1	1/6
Regulatory approval	**C8**	6	6	6	6	6	1	6	1

		Total Costs	Capacity	Delay propagation	Demand	Energy consumption	Safety	Public acceptance	Regulatory approval
		C1	C2	C3	C4	C5	C6	C7	C8
Total Costs	C1	1	2	5	4	5	1	8	1
Capacity	C2	1/2	1	3	2	5	1	9	1
Delay propagation	C3	1/5	1/3	1	1	4	1/5	3	1
Demand	C4	1/4	1/2	1	1	3	1	2	1
Energy consumption	C5	1/5	1/5	1/4	1/3	1	1/5	1	1
Safety	C6	1	1	5	1	5	1	5	1
Public acceptance	C7	1/8	1/9	1/3	1/2	1	1/5	1	1
Regulatory approval	C8	1	1	1	1	1	1	1	1

		Total Costs	Capacity	Delay propagation	Demand	Energy consumption	Safety	Public acceptance	Regulatory approval
		C1	C2	C3	C4	C5	C6	C7	C8
Total Costs	C1	1	1/5	1/7	1/7	1	1/9	1/3	1/9
Capacity	C2	5	1	2	2	3	1/9	1	1/9
Delay propagation	C3	7	1/2	1	2	2	1/5	1	1/9
Demand	C4	7	1/2	1/2	1	4	1/5	3	1/9
Energy consumption	C5	1	1/3	1/2	1/4	1	1/9	1	1/9
Safety	C6	9	9	5	5	9	1	9	1
Public acceptance	C7	3	1	1	1/3	1	1/9	1	1/9
Regulatory approval	C8	9	9	9	9	9	1	9	1

		Total Costs	Capacity	Delay propagation	Demand	Energy consumption	Safety	Public acceptance	Regulatory approval
		C1	C2	C3	C4	C5	C6	C7	C8
Total Costs	C1	1	3	5	5	5	5	5	5
Capacity	C2	1/3	1	3	3	5	5	5	3
Delay propagation	C3	1/5	1/3	1	3	3	5	5	3
Demand	C4	1/5	1/3	1/3	1	2	2	5	3
Energy consumption	C5	1/5	1/5	1/3	1/2	1	1	5	3
Safety	C6	1/5	1/5	1/5	1/2	1	1	5	2
Public acceptance	C7	1/5	1/5	1/5	1/5	1/5	1/5	1	1
Regulatory approval	C8	1/5	1/3	1/3	1/3	1/3	1/2	1	1

		Total Costs	Capacity	Delay propagation	Demand	Energy consumption	Safety	Public acceptance	Regulatory approval
		C1	C2	C3	C4	C5	C6	C7	C8
Total Costs	C1	1	1	1/3	1/2	7	1/5	5	1
Capacity	C2	1	1	2	3	9	1	5	1
Delay propagation	C3	3	1/2	1	1/3	5	1/5	3	1/3
Demand	C4	2	1/3	3	1	5	1/3	3	1/3
Energy consumption	C5	1/7	1/9	1/5	1/5	1	1/9	1/5	1/9
Safety	C6	5	1	5	3	9	1	7	2

Public acceptance	C7	1/5	1/5	1/3	1/3	5	1/7	1	1/3
Regulatory approval	C8	1	1	3	3	9	1/2	3	1

		Total Costs	Capacity	Delay propagation	Demand	Energy consumption	Safety	Public acceptance	Regulatory approval
		C1	C2	C3	C4	C5	C6	C7	C8
Total Costs	C1	1	1/5	1/5	1/2	5	1/9	1/2	1/7
Capacity	C2	5	1	1	2	7	1/9	2	1/7
Delay propagation	C3	5	1	1	2	7	1/9	2	1/7
Demand	C4	2	1/2	1/2	1	5	1/9	2	1/7
Energy consumption	C5	1/5	1/7	1/7	1/5	1	1/9	1/2	1/7
Safety	C6	9	9	9	9	9	1	7	1
Public acceptance	C7	2	1/2	1/2	1/2	2	1/7	1	1/7
Regulatory approval	C8	7	7	7	7	7	1	7	1

		Total Costs	Capacity	Delay propagation	Demand	Energy consumption	Safety	Public acceptance	Regulatory approval
		C1	C2	C3	C4	C5	C6	C7	C8
Total Costs	C1	1	5	5	5	5	5	5	2
Capacity	C2	1/5	1	1	3	3	1/2	1/2	1/5
Delay propagation	C3	1/5	1	1	5	3	1/5	1	1/5
Demand	C4	1/5	1/3	1/5	1	1	1/5	1/5	1/5
Energy consumption	C5	1/5	1/3	1/3	1	1	1/3	1	1/2
Safety	C6	1/5	2	5	5	3	1	5	1
Public acceptance	C7	1/5	2	1	5	1	1/5	1	1/5
Regulatory approval	C8	1/2	5	5	5	2	1	5	1

		Total Costs	Capacity	Delay propagation	Demand	Energy consumption	Safety	Public acceptance	Regulatory approval
		C1	C2	C3	C4	C5	C6	C7	C8
Total Costs	C1	1	1	1/4	1/4	1	1/5	1	1
Capacity	C2	1	1	3	1/5	2	1/5	1/2	1
Delay propagation	C3	4	1/3	1	1	2	1/5	1/3	1
Demand	C4	4	5	1	1	2	1/5	1	1
Energy consumption	C5	1	1/2	1/2	1/2	1	1/5	1/5	1
Safety	C6	5	5	5	5	5	1	2	7
Public acceptance	C7	1	2	3	1	5	1/2	1	3
Regulatory approval	C8	1	1	1	1	1	1/7	1/3	1

		Total Costs	Capacity	Delay propagation	Demand	Energy consumption	Safety	Public acceptance	Regulatory approval
		C1	C2	C3	C4	C5	C6	C7	C8
Total Costs	C1	1	1/3	1	5	1	1/9	5	1/7
Capacity	C2	3	1	3	3	3	1/9	3	1/7
Delay propagation	C3	1	1/3	1	3	3	1/9	3	1/7
Demand	C4	1/5	1/3	1/3	1	1/3	1/9	1	1/4

Energy consumption	**C5**	1	1/3	1/3	3	1	1/9	3	1/7
Safety	**C6**	9	9	9	9	9	1	9	2
Public acceptance	**C7**	1/5	1/3	1/3	1	1/3	1/9	1	1/7
Regulatory approval	**C8**	7	7	7	4	7	1/2	7	1

		Total Costs	**Capacity**	**Delay propagation**	**Demand**	**Energy consumption**	**Safety**	**Public acceptance**	**Regulatory approval**
		C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**
Total Costs	**C1**	1	1	3	4	3	1	1/3	1/9
Capacity	**C2**	1	1	4	1	2	1	1/5	1/7
Delay propagation	**C3**	1/3	1/4	1	1	1/2	1/5	1/4	1/3
Demand	**C4**	1/4	1	1	1	1	1/5	1/3	1/3
Energy consumption	**C5**	1/3	1/2	2	1	1	1/5	1/3	1/3
Safety	**C6**	1	1	5	5	5	1	1	1
Public acceptance	**C7**	3	5	4	3	3	1	1	1/2
Regulatory approval	C8	9	7	3	3	3	1	2	1

		Total Costs	**Capacity**	**Delay propagation**	**Demand**	**Energy consumption**	**Safety**	**Public acceptance**	**Regulatory approval**
		C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**
Total Costs	**C1**	1	9	2	9	9	1/3	1/3	1/3
Capacity	**C2**	1/9	1	1/9	1	1	1/9	1/9	1/9
Delay propagation	**C3**	1/2	9	1	9	9	1/9	1/9	1/9
Demand	**C4**	1/9	1	1/9	1	1	1/9	1/9	1/9
Energy consumption	**C5**	1/9	1	1/9	1	1	1/9	1/9	1/9
Safety	**C6**	3	9	9	9	9	1	2	1
Public acceptance	**C7**	3	9	9	9	9	1/2	1	1
Regulatory approval	**C8**	3	9	9	9	9	1	1	1

		Total Costs	**Capacity**	**Delay propagation**	**Demand**	**Energy consumption**	**Safety**	**Public acceptance**	**Regulatory approval**
		C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**
Total Costs	**C1**	1	5	3	3	3	1/5	7	1/3
Capacity	**C2**	1/5	1	1	1/3	3	1/5	3	1/3
Delay propagation	**C3**	1/3	1	1	3	3	1/5	1	1/3
Demand	**C4**	1/3	3	1/3	1	3	1/5	3	1/3
Energy consumption	**C5**	1/3	1/3	1/3	1/3	1	1/5	3	1/3
Safety	**C6**	5	5	5	5	5	1	9	1
Public acceptance	**C7**	1/7	1/3	1	1/3	1/3	1/9	1	1/3
Regulatory approval	**C8**	3	3	3	3	3	1	3	1

		Total Costs	**Capacity**	**Delay propagation**	**Demand**	**Energy consumption**	**Safety**	**Public acceptance**	**Regulatory approval**
		C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**
Total Costs	**C1**	1	1/5	1	4	1	1/7	5	1/7
Capacity	**C2**	5	1	1	5	5	1/7	4	1/5

Delay propagation	**C3**	1	1	1	1	1	1/7	1	1/7
Demand	**C4**	1/4	1/5	1	1	3	1/7	1	1/7
Energy consumption	**C5**	1	1/5	1	1/3	1	1/7	5	1/7
Safety	**C6**	7	7	7	7	7	1	9	1
Public acceptance	**C7**	1/5	1/4	1	1	1/5	1/9	1	1/7
Regulatory approval	**C8**	7	5	7	7	7	1	7	1