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Joelle Aoun [a,*], Egidio Quaglietta [a], Rob M.P. Goverde [a], Martin Scheidt [b], Marcelo Blumenfeld [c], Anson Jack [c], Bill Redfern [d]

[a] Delft University of Technology, Department of Transport and Planning, Stevinweg 1, 2628 CN Delft, The Netherlands
[b] TU Braunschweig, Institute of railway systems engineering and traffic safety, Pockelsstrasse 3, 38106 Braunschweig, Germany
[c] University of Birmingham, College of Engineering and Physical Sciences, Edgbaston, Birmingham, B15 2TT Birmingham, United Kingdom
[d] PARK Signalling ltd., Houldsworth Mill, Houldsworth St., Reddish, Stockport SK5 6DA, United Kingdom

A B S T R A C T

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

1. Introduction

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

Moving Block (MB) signalling (Theeg and Vlasenko, 2009) envisages that the train is equipped with devices for continuous train positioning, Train Integrity Monitoring to guarantee a safe train-rear position, dynamic braking curve supervision, and wireless communication for sending position reports and receiving movement authorities from radio block centres. In this setup, traditional block sections can be removed together with corresponding line-side equipment so that train separation can be reduced to an absolute

braking distance (i.e. the distance needed to brake to a standstill). MB signalling for conventional railways finds an implementation in the European standard: European Train Control System (ETCS) Level 3. Therefore, new railway signalling and control technology are being developed that can significantly increase railway capacity and overall performance.

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

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

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

In Section 2 of this paper a literature review on train-centric signalling systems and multi-criteria methods is provided. The Multi-Criteria Analysis (MCA) methodological framework introduced in this study is described in Section 3. Section 4 presents operational scenarios and the methods used to compute each criterion. Section 5 displays case studies considered for the different railway market segments and reports the final results of the MCA. Conclusions and recommendations are eventually provided in Section 6.

2. Literature review

2.1. Train-centric signalling systems

In traditional fixed-block signalling systems, trains are separated by one or more block sections with movement authorities provided by line-side (multi-aspect) signals or radio-based cab signalling like ETCS Level 2 (Theeg and Vlasenko, 2009). MB signalling
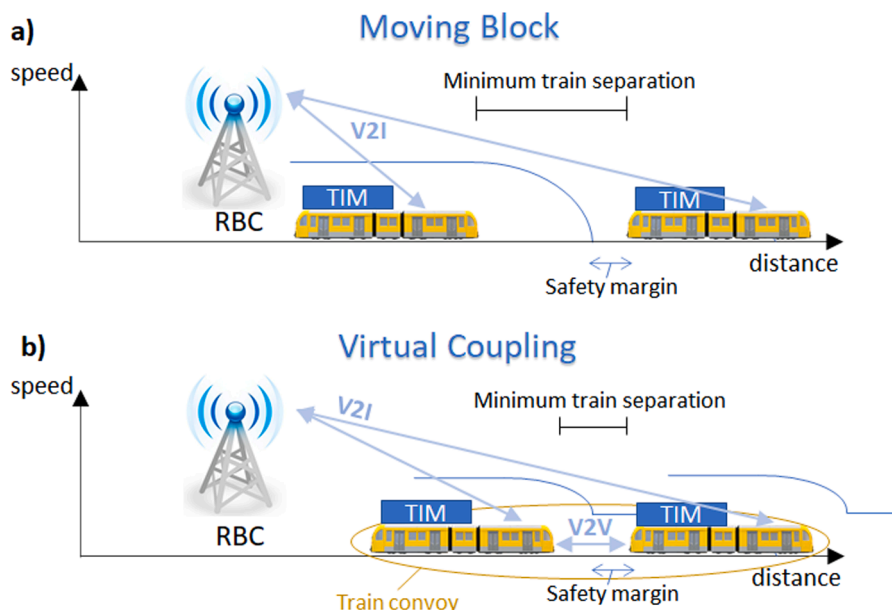

Fig. 1. Schematic architecture of train-centric signalling systems: Moving Block (a) and Virtual Coupling (b).

reduces train separation to an absolute braking distance by removing track block sectioning and migrating vital track-clear detection equipment to on-board integrity monitoring. The ETCS Level 3 standard gives requirements for MB railway operations (Fig. 1a). A track-side Radio Block Centre (RBC) sends Movement Authorities (MAs) to the trains indicating the maximum distance that the train can safely run based on regularly updated train position reports. The on-board European Vital Computer (EVC) ensures that the MAs are respected by computing and supervising dynamic speed profiles including continuous braking curves. Verification of train integrity is performed by an on-board device called Train Integrity Monitoring (TIM) which is still an open challenge for trains with variable composition such as freight trains. The British and Dutch railway infrastructure managers propose a hybrid version of ETCS Level 3 which leaves in place track-clear detection devices to monitor train integrity for trains unequipped with TIM (Furness et al., 2017). Legrand et al. (2016) propose instead an integrity monitoring technology that can meet required safety standards by combining Global Navigation Satellite Systems (GNSS) with Inertial Navigation Systems (INS). Biagi et al. (2017) show how missed train integrity and/or position reporting due to communication break-up in ETCS Level 3 can drastically reduce network capacity.

MB operations such as made possible by ETCS L3 have been upgraded recently by the concept of VC which postulates the possibility that trains could just be separated by a relative braking distance plus a safety margin, so to increase even further infrastructure capacity utilisation. As illustrated in Fig. 1b, VC enriches the basic MB architecture with a Vehicle-to-Vehicle (V2V) communication layer to allow trains to exchange dynamic information (e.g. position, speed and acceleration), which is needed to supervise relative braking and keep a safe separation. The virtually coupled trains form a train convoy that is treated as a single train at junctions, so that switches remain locked until the entire convoy has passed. VC also enables the formation of platoons where trains can move synchronously with each other at close distance, thereby increasing capacity. Due to the very short train separation, automatic train operation becomes essential for VC given that human driving reaction times would no longer be safe in this setup. Several challenges still need to be addressed for VC. One main issue regards diverging junctions where a separation shorter than a full braking distance is not yet possible as it could lead to unsafe train movements in case of longer switch setup times or switch locking failures. Another issue relates to the V2V communication architecture that requires high levels of reliability and low latency for the exchange of safety–critical information among trains. European projects such as X2Rail-3 (2018) and MOVINGRAIL (2018) have been investigating safe operational principles, scenarios and reliable communication architectures for the feasibility of VC. Fenner (2016) presented steps and scenarios for closer running, i.e. VC. Schumann (2017) simulated the 'Shinkansen' scenario to increase line capacity on the Tokaido high-speed line in Japan by following the VC principles. Flammini et al. (2019) proposed a quantitative model to analyse the effects of introducing Virtual Coupling according to the extension of the current ETCS Level 3 standard, by maintaining the backward compatibility with the information exchanged between trains and the trackside infrastructure. Felez et al. (2019) developed a preliminary Model Predictive Control approach for virtually coupled trains using a predecessor-following information structure that minimizes a function of desired safe relative distance, the speed of the predecessor train and the jerk. Di Meo et al. (2019) studied operational principles and communication configurations of VC in several stochastic scenarios by using a numerical analysis approach. Quaglietta et al. (2020) illustrated preliminary capacity benefits of VC over MB for a British mainline case study, by applying a multi-state train following model. The main question that literature has not clarified yet is whether the trade-off between overall benefits and costs of VC are more advantageous to the transport industry than MB signalling. This paper tries to address this fundamental research question by implementing an innovative multi-criteria analysis framework to compare impacts of VC with MB and traditional fixed-block signalling systems.

2.2. Multi-criteria analysis methods

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

The Multi-Criteria Decision Making (MCDM) methods provide decision makers with some tools to solve a complex problem where different points of view are taken into account (Vincke,1992). The first step for performing a MCA is to correctly identify the main criteria which need to be assessed to address a specific design/evaluation problem. One of the main approaches applied in literature to determine critical evaluation criteria is the Delphi method which has been firstly introduced in 1950s (Dalkey and Helmer, 1963; Linstone, 1978). Delphi consists of combining points of view and opinions from a group of individuals by means of iterative questionnaires with controlled feedback. Four key features are regarded as necessary to define a 'Delphi' procedure: anonymity, iteration, controlled feedback and statistical aggregation of group responses (Rowe and Wright, 1999). The Delphi technique has been extensively used in various sectors including forecasting, planning, curriculum development (Thangaratinam and Redman, 2005), health care (Morgan, 1982) and transportation (Da Cruz et al., 2013). Once the main criteria are identified, several MCDM methods are available in literature to an objective criteria assessment. The Analytic Network Process (ANP) facilitates feedback and interaction capabilities among different cited elements within and between groups (Saaty, 2001). The ELimination Et Choix Traduisant la REalité (ELECTRE) method is used to choose the best actions from a given set of actions. Main applications of the ELECTRE are usually found to solve three types of problems: choosing, ranking and sorting. The main limitation of this approach is due to the high subjectivity of calculated ELECTRE thresholds which might lead to unreliable results (Gavade, 2014). The Weighted Sum Method (WSM) is one of the earliest and simplest techniques that supports single dimensional problems and where overall results are provided in a qualitative form such as 'good, better, best' (Singh and Malik, 2014). The Multi-Attribute Utility Theory (MAUT) is a "rigorous methodology to incorporate risk preferences and uncertainty into multi criteria decision support methods" (Loken, 2007), but it has the shortcoming of being data intensive requiring an incredible amount of input at every step of the procedure in order to accurately record the decision

maker's preferences (Velasquez and Hester, 2013). The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) was developed by Hwang and Yoon (1981) and is based on selecting the shortest distance from the positive ideal solution (i.e. best possible combination of criteria) and the longest distance from the negative ideal solution (i.e. worst criterion values). TOPSIS is an easy deterministic method which does not consider uncertainty in weightings (Gavade, 2014).

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

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

3. Methodology

In this section, the MCA framework is introduced where the focus is on the Analytic Hierarchy Process (AHP) and the Delphi methods. Sections 3.2 and 3.3 are part of existing theories available in the literature review (Section 2), whereas the innovative framework is built on combinatorial methods, consolidated mathematical techniques, engineering procedures, and extensive Subject Matter Expert (SME) interviews and workshops to assess each of the criteria defined in Section 1. The elements of this framework are further detailed in Section 4 where the developed methodologies are applied in Section 5.

3.1. MCA framework

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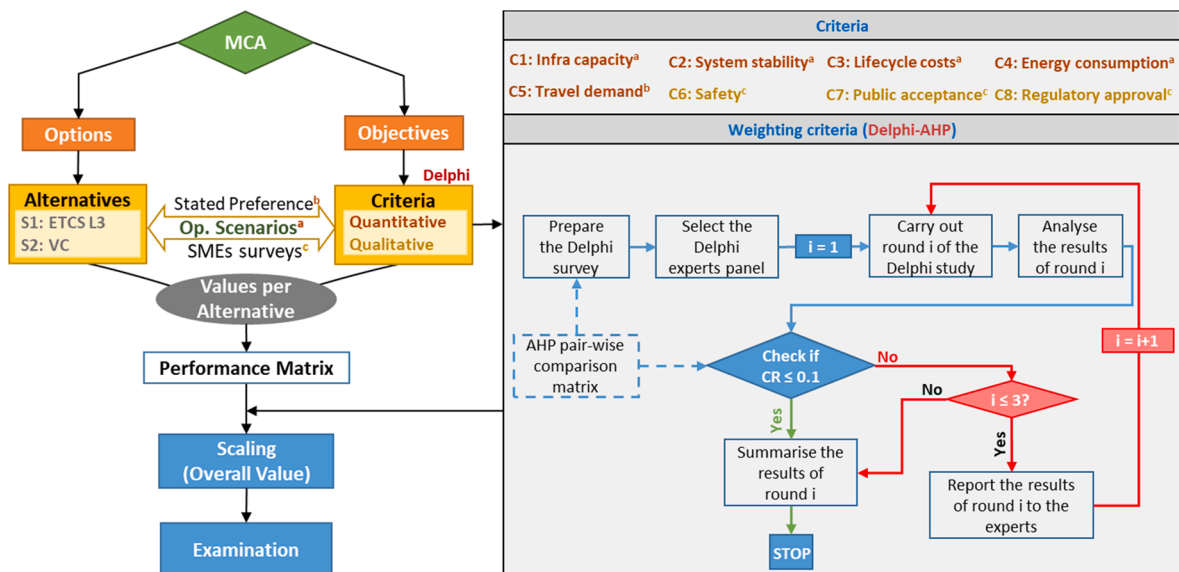

Fig. 2. MCA Framework.

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 comfort $X_{1,2}$, A2 is assigned with $X_{2,2}$, etc.

In this paper, the interactions between alternatives and almost all of the quantitative criteria (i.e. infrastructure capacity, system stability, lifecycle costs and energy consumption) depend on different operational scenarios described in Section 4. Stated preference surveys are involved to assess travel demand distribution, and stakeholders' judgement is used for safety, public acceptance and regulatory approval. After combining the different combinations of criteria values per alternative, a performance matrix is constructed. Criteria are weighted by means of the hybrid Delphi-AHP method (Section 3.3). Based on the set of expertise required for the survey, a panel of experts is accordingly selected. Then a round of the Delphi survey is performed and survey results are analysed in terms of consistency of the AHP pairwise comparison matrix. In case the consistency ratio of the relative criteria assessment is above the threshold of 0.1, all the respondents providing inconsistent matrices are required to re-do the survey so to give consistent responses (i. e. Consistency Ratio $CR \leq 0.1$). After each round of the AHP pairwise comparison matrix, the survey results are distributed anonymously to the interviewed panel for further feedback until final consistent results are returned. The Delphi rounds are further discussed in Section 5.3 and the number of rounds has been limited to three as Walker and Selfe (1996) claim that "repeated rounds may lead to fatigue by respondents", and most studies use two or three rounds (Arof, 2015). After the first round of the hybrid Delphi-AHP method, we further guided the interviewees to provide consistent responses. Particularly, we created a dynamic Excel sheet that automatically syncs the matrix with the final value of the consistency ratio, so that the interviewees can alter the values of their matrices accordingly until reaching a $CR \leq 0.1$. Then, decision matrices are normalized and weighted to ultimately provide an overall value for each alternative. In this paper, the examination process consists of enabling cohesion among the different points of view of the involved SMEs, and evaluating consistency to reach a reasonable consensus matrix by statistically aggregating responses. Finally, results are evaluated and shared with the respondents. This framework can be also applicable to other fields by just modifying the alternatives and criteria according to the investigating study.

3.2. The Analytic Hierarchy Process (AHP)

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

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

Step 1: Building the hierarchical model
The hierarchical model consists of three main layers. The top layer represents the overall goal for determining the ranking of importance. The middle level displays the multiple criteria which influence the goal. Those criteria are used for evaluating the alternatives that constitute the bottom level of the hierarchical model (Bhushan and Rai, 2004). In other words, each alternative has its own values of criteria associated with it. Fig. 3 shows the Analytic Hierarchy Process model where the goal layer is denoted as A, the middle level consists of n criteria denoted as C_1, C_2, ..., C_n and the bottom level consists of m (signalling) alternatives denoted by S_1, S_2, ..., S_m.

Step 2: Constructing the pairwise comparison judgement matrix
A judgement matrix evaluates and prioritizes a list of options where the decision-maker provides weighted criteria that are assessed with respect to each other in a $n \times n$ matrix. The judgement matrix for criteria weighing is constructed by pairwise comparing two elements (Saaty, 2008; Dieter and Schmidt, 2013). The pairwise comparisons are used to determine the relative importance of each element of one layer to the element of the above layer. In this paper, we consider one level of pairwise comparison which consists of
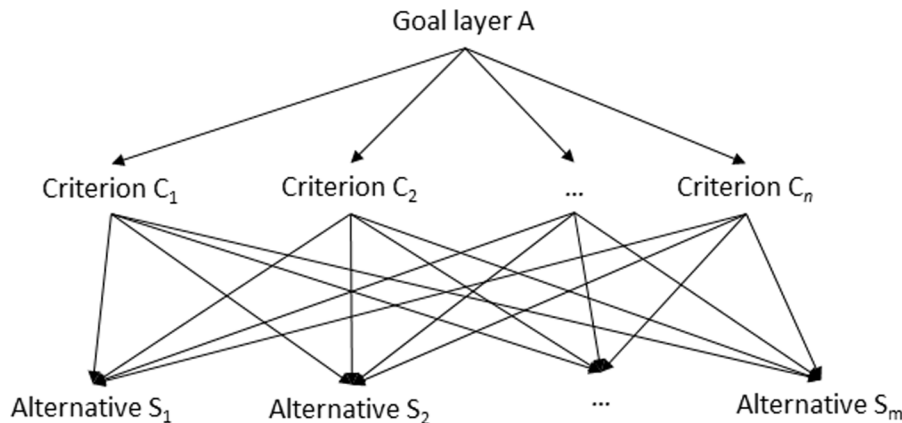

Fig. 3. Analytic Hierarchy Process model.

determining the relative importance of each criterion $C_1, C_2, ..., C_n$ with respect to the goal A (see Fig. 3). The other level of assessing each alternative $S_1, S_2, ..., S_m$ with respect to each criterion $C_1, C_2, ..., C_n$ is out of the scope of this analysis since decision makers considered railway signalling alternatives equally important with respect to each criterion. The decision-maker has to express his/her opinion about the value of one single pairwise comparison at a time based on a scale of relative importance that ranges from 1 to 9 where a value of 1 means that the compared criteria are of equal importance. The lower bound of 2 signifies weak or slight importance whereas a value of 9 refers to absolute or extreme importance. The remaining values are uniformly intermediate ranging from 3 (moderate importance) to 8 (very strong importance). The judgment value of the importance of element i with respect to element j is r_{ij}, the reciprocal value is $1/r_{ij}$. For instance, a matrix value of 9 means that the criterion on the row is absolutely more important than the one on the column, whereas a value of 1/9 means that the criterion on the column is absolutely more important than the one on the row. The number of comparisons within the level is based on the equation: $n(n-1)/2$ where n is the number of comparable elements (i. e. in this case the number of criteria).

Step 3: Checking consistency

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

$$\overline{C}_{i,j} = \sum_{l=1}^{n} \frac{C_{i,j}}{C_{l,j}}, \ i,j \in \{1, \cdots, n\} \tag{1}$$

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

$$C_{w,i} = \sum_{j=1}^{n} \frac{\overline{C}_{i,j}}{n}, \ i \in \{1, \cdots, n\} \tag{2}$$

The vector of weights is called priority vector or 'normalized principle Eigenvector' (Kumru and Kumru, 2014). An eigenvector is computed based on the normalized judgement matrix. However, inconsistencies might arise when many pairwise comparisons are performed (i.e. high number of criteria). For example, if a decision-maker evaluates criterion C_1 as more important than criterion C_2 and criterion C_2 more important than criterion C_3, an inconsistency arises if criterion C_3 is assessed as more important than criterion C_1. The purpose of matrix consistency is to ensure that the judgement is rational and avoid conflicting results.

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

$$\lambda_{max} = \sum_{i=1}^{n} \frac{\lambda_i}{n}, \ \text{with} \ \lambda_i = \sum_{j=1}^{n} \frac{C_{i,j}C_{w,j}}{C_{w,i}}. \tag{3}$$

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

$$CI = \frac{(\lambda_{max} - n)}{n - 1}. \tag{4}$$

Finally, the Consistency Ratio (CR) is obtained by dividing CI by the Random Index (RI) associated with the number of comparable elements n with values as displayed in Table 1 (Saaty, 1980), i.e.,

$$CR = \frac{CI}{RI}. \tag{5}$$

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

- For beneficial criteria: $\overline{X}_{m,n} = X_{m,n}/\max_{l}(X_{l,n})$.
- For non-beneficial criteria: $\overline{X}_{m,n} = \min_{l}(X_{l,n})/X_{m,n}$.

Finally, the ranking of alternatives is obtained by computing the weighted MCA performance scores P_m (6) defined as the weighted sum (by the criterion weights $C_{w,n}$) over the total number Nc of criteria n per signalling alternative m, for a given market segment.

Table 1
The RI Values.

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

$$P_m = \sum_{n=1}^{Nc} \overline{X}_{m,n} \cdot C_{w,n}.$$ (6)

3.3. A hybrid Delphi-AHP approach

The hybrid Delphi-AHP technique aims at combining the Delphi technique with the AHP MCDM method described in Sections 2.2 and 3.2. This technique has been traced in many research areas such as project management (Lee and Kim, 2001), logistics (Cheng et al., 2008), shipping (Lee et al., 2014), forecasting (Mishra et al., 2002) and safety (Chung and Her, 2013). However, to the best of our knowledge, it has not been used in the railway sector. Arof (2015) showed that usually the number of participants involved in a Delphi survey is different than those involved in an AHP survey. The number of panellists generally depends on the level of expertise required, the availability of experts and their willingness to participate in the study.

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

The advantages of this hybrid technique include:

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

The adopted approach ensures the following:

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

4. Operational scenarios and criteria

Five market segments are defined by the Shift2Rail Joint Undertaking Multi-Annual Action Plan (S2R JU MAAP, 2015), namely high-speed, mainline, regional, urban and freight. Operational scenarios are used to compute the quantitative criteria listed in Section 1. They are based on different combinations of train manoeuvres (with or without stops) and configurations of the signalling system. We consider three types of train manoeuvres, namely on a plain line, at a merging junction or a diverging junction (Fig. 4). The combination of manoeuvres, stopping patterns and system configurations is based on the defined market segment. For instance, the infrastructure layout of the urban market segment is usually simplistic (i.e. very few junctions or crossings), and metro trains stop frequently on the line. Therefore, for this specific market segment, we only consider the plain line manoeuvre with stopping patterns. For the regional market, trains indeed stop frequently but the infrastructure layout is more complex than the one for the urban market,
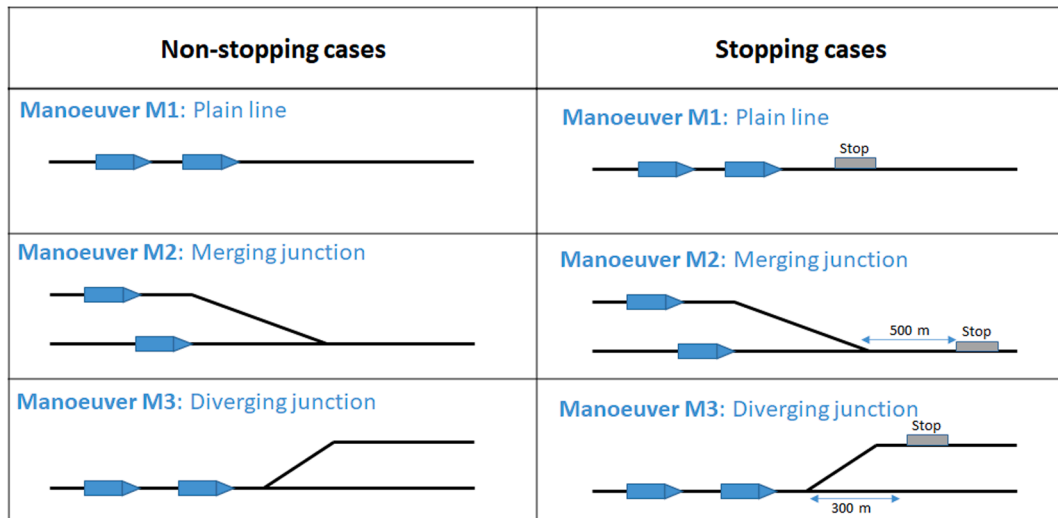
Fig. 4. Manoeuvres for investigating the benefits of Virtual Coupling over previous railway signalling systems.

Table 2
Definition of operational scenarios for each market segment.

Market Segment	No. Operational Scenarios	Manoeuvres	Stopping Trains	System Configurations
Urban	3	Plain	Yes	3-Aspect, ETCS L3, VC
Regional	9	Plain, Merging, Diverging	Yes	3-Aspect, ETCS L3, VC
Mainline	18	Plain, Merging, Diverging	Yes and No	3-Aspect, ETCS L3, VC
High-speed	18	Plain, Merging, Diverging	Yes and No	ETCS L2, ETCS L3, VC
Freight	18	Plain, Merging, Diverging	Yes and No	3-Aspect, ETCS L3, VC
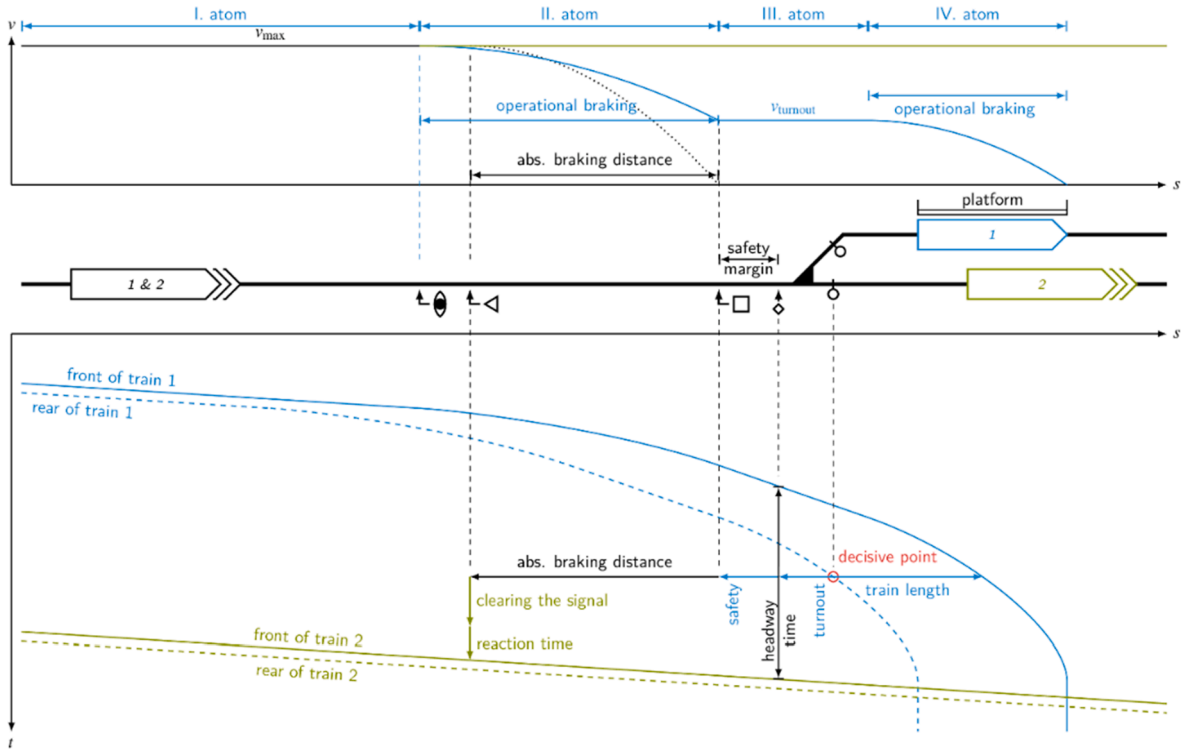
Fig. 5. Diverging junction manoeuvre with stopping case including atoms, speed-distance diagram, time-distance diagram and blocking-time theory.

as it also includes merging and diverging junctions. For stopping train manoeuvres, both trains will dwell at the station for the case of a plain line (M1). In the case of the merging junction (M2), the station is assumed to be located 500 m from the switching point where both trains will be stopping. In the case of the diverging junction (M3), the leading train (i.e. train in front) stops at the station located 300 m from the switching point and the follower carries on over the other track overtaking the leader while this latter is dwelling at the station. Configurations selected for the signalling systems are instead based on a combination of three main design variables typical of a given signalling system and/or the selected market segment. Those design variables are the safety margin (SM), the system update delay or system reaction time (ΔT) and the setup time (t_s) to change the switch in the desired direction if needed, set and lock a route. More details on the definition of operational scenarios and each of the design variables can be found in MOVINGRAIL (2020).

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

The baseline system configuration is the conventional signalling system currently installed for a given market segment. For the mainline, regional, urban and freight markets, we refer to a three-aspect fixed-block signalling. For the high-speed segment, the baseline signalling system is ETCS L2. In the MCA (Section 5), the alternative system configuration S1 refers to the migration from a baseline system configuration to ETCS L3 MB signalling system while the alternative system configuration S2 corresponds to the migration from baseline to VC. The number and distribution of the operational scenarios among manoeuvres and system configurations for each market segment are summarized in Table 2.

4.1. Quantitative criteria

The evaluation of the defined quantitative criteria for the different signalling alternatives are reported from Section 4.1.1 to Section 4.1.5.

4.1.1. Infrastructure capacity

Capacity is the maximum number of trains that can operate with a chosen level of service on a section of infrastructure during a period. The level of service is determined by the imposed traffic and the operational condition for a given timetable. So capacity depends on both the timetable and the infrastructure. The classical method to determine the capacity is the timetable compression method from the UIC Code 406 (UIC, 2013), which reveals the excess buffer time in a timetable. We estimate the impact on capacity

with VC by considering no changes in the infrastructure.

However, the change of the infrastructure can be calculated via the occupation time as the signalling principles must change to accompany VC. The occupation time of a small infrastructure section can be seen as "atoms" of a timetable. One atom contains a change in a time-speed-distance diagram from the blocking-time theory (Hansen and Pachl, 2014). The combination of atoms will then form manoeuvres (Fig. 5). The combination of manoeuvres with operational parameters are then operational scenarios where a headway between the involved trains can be calculated. Preliminary aspects of manoeuvres and operational scenarios can be found in Aoun et al. (2020a, 2020b). The manoeuvres (Fig. 4) can then be used to represent the component of a timetable in the capacity assessment. The impact of VC and MB on infrastructure capacity is then expressed in terms of the minimum headway computed as the minimum time between two consecutive trains which allows for the safe completion of their manoeuvres over a given infrastructure location. For example, in the diverging junction illustrated in Fig. 5, the minimum headway is computed for a reasonable reference point between the fronts of two trains; in this case, the danger point at the turnout. Next, the decisive point was determined, by marking where the rear of the first train clears the turnout. From the decisive point, the calculation occurred in two directions. Forward via the train length and along the braking curve. Backwards starting with the length of the turnout, the safety margin, the absolute braking distance, adding the time components of the system time to clear the signal and the reaction time for the train to acknowledge to information and further along the running curve.

A capacity index $I_{cap}(S_k)$ has been defined to compare capacity effects of the signalling alternatives S_k (for $k = 1, 2$) versus the baseline S_0. The capacity index is used in the MCA results (Section 5) and represents the reciprocal of the ratio between the minimum headway H_i of operational scenario i for signalling alternative S_k and baseline S_0, averaged over the total number of operational scenarios N_k applicable to S_k, i.e.,

$$I_{cap}(S_k) = N_k \left(\sum_{i=1}^{N_k} \frac{H_i(S_k)}{H_i(S_o)} \right)^{-1}, \ k \in \{1, 2\}. \tag{7}$$

4.1.2. System stability

System stability is evaluated based on the UIC Code 406 recommendations (UIC, 2013) on maximum thresholds of occupation time to have stable train operations on a given market segment. In this study, we aim at deriving a generic measure for system stability for the various market segments without focusing on a case-specific infrastructure layout or timetable. Therefore, we define here a stability index based on an average minimum headway over the various operational scenarios defined in Section 4 and a given typical train frequency per hour. For each market segment, it is considered that an hourly timetable runs the same amount of trains that are currently operated in the peak hour on the representative case study corridors (Section 5.1). A compressed timetable has been obtained for the baseline S_0 and the two futuristic signalling alternatives, S_1 for ETCS L3 and S_2 for VC, based on minimum line headways computed for the different manoeuvres and stopping patterns in Section 4.1.1. Specifically, for both stopping and non-stopping train patterns, an average minimum line headway has been calculated as a mean value across all manoeuvres.

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

$$I_{stability}(S_k) = 1 - \frac{1}{N_k} \sum_{i=1}^{N_k} \frac{N_T H_i(S_k)}{3600}, \ k \in \{0, 1, 2\} \tag{8}$$

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

4.1.3. Lifecycle costs

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

4.1.3.1. Capital costs (CAPEX).

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

$$N_{MU} = \frac{2T_r + 2T_w}{H_S} N_{MU_{train}}. \tag{9}$$

The waiting time of rolling stock to turn around at terminal stations (T_w) is considered 15 min for all cases, whereas the scheduled one-way running time (T_r) and the number of MUs per train formation ($N_{MU_{train}}$) depend on each case study (Section 5.1). The scheduled service headway (H_S) for a given signalling system has been assumed to be corresponding to the line headway of a typical railway network with a varied infrastructure topology including plain lines, merging and diverging junctions. By setting the scheduled headway equal to the line headway, it is possible to identify the maximum number of MUs that are required when the network is utilized at its maximum capacity. Based on this assumption, the service headway considered for the computation of MUs coincides with the most critical train headway across all manoeuvres calculated for the infrastructure capacity scenarios (Section 4.1.1) for a given signalling system. As mentioned before, we consider the same fleet size, therefore the same number of MUs for both ETCS L3 and VC so to compare these systems only from the differences in terms of installation costs for the signalling equipment. It should be noted that for the practical number of multiple units required to operate a railway service, we increased 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.

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

$$C_{RSmaint} = CU_{RSmaint} \cdot D_{oneway} \cdot O_{RS} \cdot \frac{60}{T_r + T_w} N_{MU_{train}}, \tag{10}$$

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

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

$$C_{Ep} = CU_{Ep} \cdot D_T \cdot N_T \cdot N_O, \tag{11}$$

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

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

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

4.1.4. Energy consumption

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

$$I_E(S_k) = \frac{1}{N_k} \sum_{i=1}^{N_k} \frac{E_i(S_k)}{E_i(S_0)}, \ k = \{1, 2\} \tag{12}$$

EGTRAIN has been used to compute train energy consumption by considering two trains following each other under a given signalling alternative. Simulation experiments have referred to typical rolling stocks circulating on the representative case studies used for each market segment (Section 5.1), in line with the input data used for capacity computation in Section 4.1.1.

4.1.5. Travel demand

Travel demand distribution is forecasted by means of a statistical analysis based on stated travel preference surveys distributed over a sample of 229 interviewees for the passenger-related case studies and of 47 SMEs for the freight case, to capture potential modal shifts to railways that the introduction of MB and VC could lead to. By aggregating stated travel preferences, the resulting modal shifts have been computed for each of the case studies (Section 5.1) in the current and future transport scenarios.

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

In the MCA (Section 5), we consider an aggregation of travel demand shares that would shift from all other motorized modes of transport (i.e. car, bus/coach and/or airplane for the passenger-related markets, and truck for the freight market) to railways in the case of no ticket cost increase for using a train service enabled by either ETCS L3 or VC. A more detailed analysis on the demand trends of both ETCS L3 and VC with an increase in ticket fees can be found in Aoun et al. (2020b).

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

4.2. Qualitative criteria

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

4.2.1. Safety

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

The values used in the MCA results (Section 5.2.6) are based on the safety index I_{safe} computed in (13), where $S_{5,safe}$ is the mean score defined for the likelihood of safety issues to be solved in the next five years and $S_{Pr,safe}$ is the assessed priority mean score of all safety issues. A similar analogy is used in Sections 4.2.2 and 4.2.3.

$$I_{safe} = \frac{S_{5,safe}}{S_{Pr,safe}}. \tag{13}$$

4.2.2. Public acceptance

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

The values used in the MCA results (Section 5.2.7) are based on the public acceptance index I_{pubacc} computed in (14). $S_{5,pubacc}$ is the mean score defined for the likelihood of public acceptance issues to be solved in the next five years and $S_{Pr,pubacc}$ is the assessed priority mean score of all public acceptance issues.

Table 3
Values of parameters and design variables for each market segment.

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

$$I_{pubacc} = \frac{S_{5,pubacc}}{S_{Pr,pubacc}}.$$

(14)

4.2.3. Regulatory approval

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

The values used in the MCA results (Section 5.2.8) are based on the regulatory approval index $I_{regappr}$ computed in (15). $S_{5,regappr}$ is the mean score defined for the likelihood of regulatory approval issues to be solved in the next five years and $S_{Pr,regappr}$ is the assessed priority mean score of all regulatory approval issues.

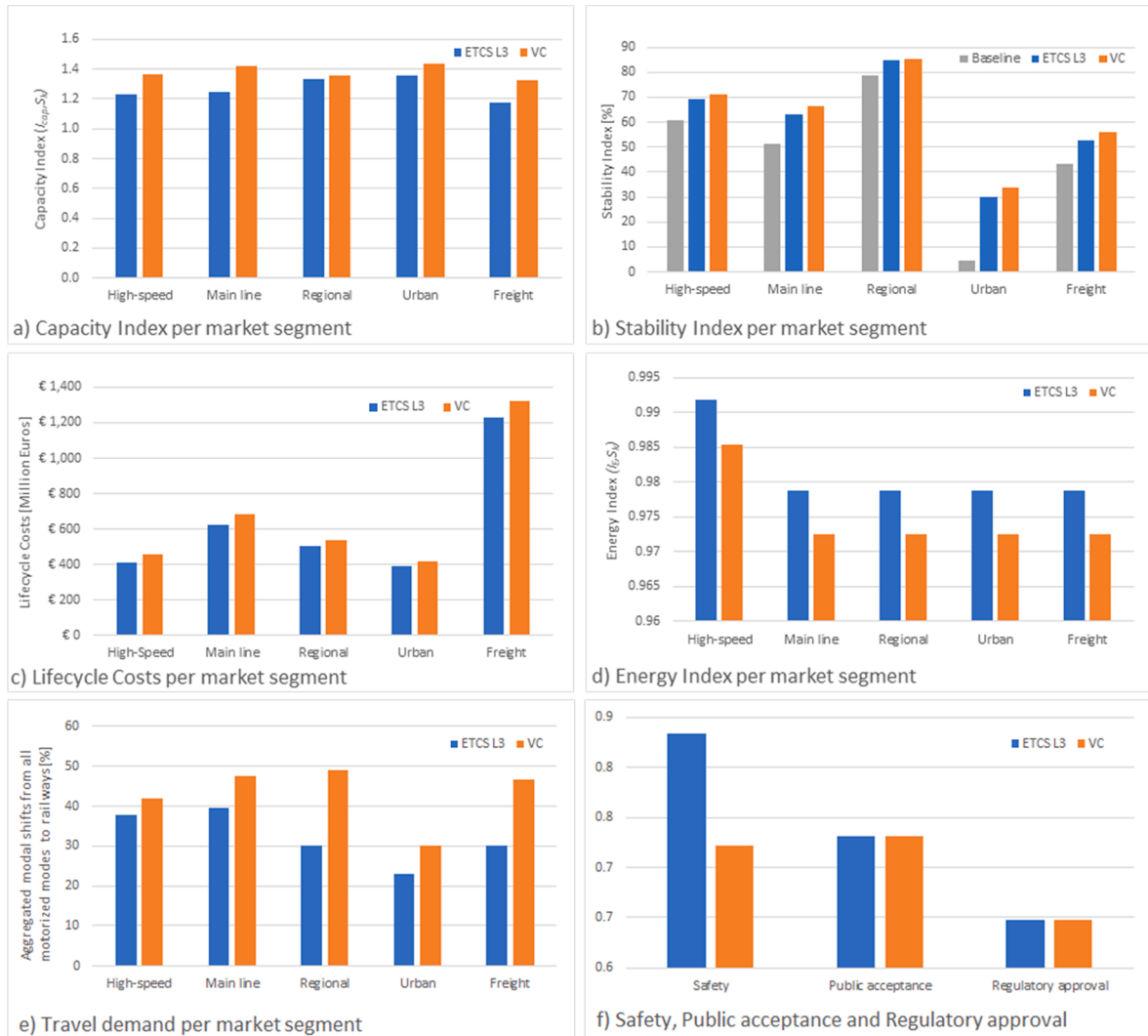$$I_{regappr} = \frac{S_{5,regappr}}{S_{Pr,regappr}}.$$

(15)

Fig. 6. Results of criteria assessment.

Table 4

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

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

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

✓: Stopping trains

✗: Non-stopping trains

5. MCA results for Moving Block and Virtual Coupling

5.1. Case studies

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

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

The values adopted in this paper for maximum speed, block section length, three design variables (i.e. safety margin, system reaction time and setup time), and three headway variables (i.e. turnout branch speed, turnout length and dwell time) are displayed in Table 3 for each market segment. The system configurations represent the migration from the baseline signalling system S_0 (ETCS L2 for high-speed and 3-aspect block signalling otherwise) to either ETCS L3 (Signalling alternative S_1) or VC (Signalling alternative S_2). In our study, we have made the assumption to have the same safety margins for both MB and VC to keep the capacity comparison of these two signalling systems consistent. In this way, we were able to assess the impact of the reduction in train separations just due to the transition from an absolute braking distance in MB to a relative braking distance under VC, while keeping the same SM. The design variables are assumed and used to analyse the operational scenarios defined in Section 4 whilst the other parameters are input for the infrastructure capacity computation.

5.2. Criteria assessment per market segment

5.2.1. Infrastructure capacity

The method from Section 4.1.1 was used to calculate the capacity gain for VC for each manoeuvre. The calculation was done via the headway times with the maximum utilization of the infrastructure. The decisive point in the time-distance diagram was determined for the headway times (Fig. 5). The outcome of this procedure is a compressed path-time calculation of two trains in one operational scenario without any buffer time. All results should be considered carefully since the infrastructure in front and behind the manoeuvres was neglected.

Fig. 6a compares the capacity indexes of ETCS L3 MB and VC per market segment based on Equation (7). VC provides relevant capacity improvements over MB for mainline railways (+14%), freight lines (+13%) and high-speed (+11%). VC would have a positive homogenising effect on mainline railways due to the possibility for trains to follow each other in synchronised platoons. For high-speed railways, VC can provide significant capacity benefits for following train movements. However, headway reductions due to VC are only marginal (in the order of 10 s) with respect to ETCS L3, if stopping high-speed trains on a plain line are separated by a relative braking distance. Significant headway reductions (up to 1 min) are instead observed when high-speed trains can move synchronously at a quasi-constant separation in a coupled platoon, as the headway comparison between VC and ETCS L3 shows for the plain line manoeuvre with non-stopping trains (Table 4). Train platooning can be also particularly beneficial for freight trains which usually have non-stopping operations. Despite the relatively low running speeds, VC can still provide capacity gains over MB thanks to

platooning where trains can keep synchronous stable movements over long distances with relative braking distances. For the regional and the urban segments, VC only shows a little capacity improvement of 1.8% for the former and 5.8% for the latter. This is mainly due to frequent stopping and low operational speeds where a relative braking distance separation would not significantly reduce headways with respect to an absolute braking one. For these two markets, VC could still be beneficial over MB due to platooning, thus enabling stable cooperative operation. However, given the short interstation distances and the frequent stopping patterns of these railway segments, composition/decomposition of platoons would need to occur when trains are at a standstill at stations instead of coupling/decoupling operations "on-the-run" (i.e. as is the case for manoeuvres with non-stopping patterns). This also entails that the first deployment of VC could be made on these two market segments since they would only require algorithms for synchronous train movements, instead of additional algorithms for controlling trains when shifting between absolute and relative braking distance under VC signalling.

5.2.2. Stability

As can be seen in Fig. 6b, MB can greatly improve system stability over the baseline signalling systems for all market segments. Particularly significant is the increase in stability for the urban market where the high frequency service strongly requires MB operations to avoid capacity saturation that occurs if a three-aspect fixed-block signalling system is adopted. VC can provide a further improvement to MB system stability –computed by Equation (8)– which is however marginal with respect to stability gains that MB brings over baseline signalling. The biggest stability enhancements brought by VC over MB are observed for the urban (+12%) and the mainline (+5%) market segments. This is because those two markets are characterised by a high number of hourly trains where delays are easily propagated in a snow-ball effect. Reducing the safe separation from an absolute braking distance to a relative braking distance would therefore contribute to further mitigate delay transmission. VC could improve by 5% MB stability for the freight market and by only 2% for the high-speed market. However, system stability gains for VC over MB are much higher when considering only following movements in a platoon of virtually coupled trains (where the corresponding headway is given by the plain line manoeuvre with non-stopping trains). In the case of the regional segment, VC does not provide any practical stability improvement over MB (only 0.3%), mostly because of a combined effect of the lower number of hourly regional train services (much lower than the urban market) and the low speeds that make differences between absolute and relative braking distance only marginal.

5.2.3. Lifecycle costs

The total deployment costs for ETCS L3 are lower than VC given that the latter signalling system requires the installation of additional intelligent software solutions such as automation, European Vital Computer (EVC) software upgrades and the V2V communication layer. Railway Authority deployment costs and infrastructure costs represent the highest share of CAPEX and depend on the distance between a specific origin and destination (see Section 5.1 for the case studies considered in this paper). However, the technological upgrades for VC would only be up to 11.5% higher than the costs of migrating from baseline to ETCS L3. This percentage was found based on the analysis discussed in Section 4.1.3. Total operational expenditures for VC are a few thousand euros lower than MB for all market segments, given the reduced number of crew which is needed to operate a train because of the automation. This means that similar operational costs to VC could be achieved when deploying automatic train operation over plain MB. Differences in lifecycle costs of the two signalling alternatives are very limited since total migration costs from baseline to ETCS L3 or VC are almost the same (Fig. 6c).

5.2.4. Energy consumption

Values of the energy index (Fig. 6d) show that on average VC can slightly reduce energy consumption with respect to MB. If under VC a train slows down to cruise at a lower speed, then the train behind has the possibility to slow down and cruise synchronously with the train ahead. Under MB when a train slows down to cruise at a lower speed, the train behind will initially decelerate as it approaches the End of Authority and then will reaccelerate to the maximum allowed speed instead of cruising at the same speed of the train ahead (unless optimal control algorithms manage the traffic). This behaviour might hence cause repetitive braking/acceleration phases that make MB more energy consuming than VC, which has a movement control paradigm between trains in the same convoy.

5.2.5. Travel demand

For the high-speed case study, it is clear in Fig. 6e that a significant modal shift from other modes of transport would already happen with the introduction of ETCS Level 3 MB (38%) while VC would only lead to an additional 4% (for a total of 42%). This is because a 15 min headway in the current situation (Rome-Bologna) was already satisfying to most respondents, while the service frequency increase proposed by VC was only slightly higher than the one of ETCS L3. Similar results are observed for the mainline and urban railways, where VC would only bring an additional modal shift of 7.8% and 7.1% with respect to ETCS Level 3, respectively. Almost all interviewees who would shift from other modes to VC for the mainline and the urban markets, stated that one of the main reasons behind that would be the possibility of availing of a service that is on-demand or better adaptable to passengers' travel needs. Remarkable results are observed for regional trains where VC could increase the modal shift by 19 percentage points over ETCS L3 MB. This is because of the unsatisfactory level of the currently delivered regional service from Leicester to Peterborough, which encourages interviewees towards a service that could be better adapted to an on-demand paradigm or more effectively respond to daily demand variations. Also for the freight market, VC is considered more beneficial than ETCS L3 MB given that a more flexible freight service could be delivered with self-propelled units that could couple/decouple at merging/diverging junctions to reach delivery destinations of the different commodities more efficiently. Results show that a total of 46.6% of the respondents would consider shifting from road trucks to trains in the case of VC signalling (Fig. 6e).

Table 5
Consolidated pairwise comparison matrix.

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

Table 6
Consolidated performance matrix.

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

Based on Section 4.1.5, CO_2 emissions' results showed that the introduction of ETCS L3 might bring today's emissions down to 70.2% for cars, 67.2% for buses, 62.5% for planes and 70% for trucks. This brings to an expected reduction of today's CO_2 emissions by 36.5% on average across all motorised transport modes. The deployment of VC would instead contribute to an even deeper reduction of today's emissions to 61.7% for cars, 58.1% for buses, 57.8% for planes and 53.4% for trucks. Current CO_2 emissions could be therefore reduced by 42% on average across all motorised transport modes with the introduction of VC, which would greatly help in achieving the goal set for 2050 by the EC white paper on transport (European Commission, 2011) of 60% reduction in Green House Gases (GHG) emissions from transport.

5.2.6. Safety

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

The main identified safety issues include harmonised non-functional requirements on train integrity, the risk of having trains not being able to stop within their MAs, having MAs exclusively issued for a given section of track for only one train at a time, and the reliability of the communications system. In addition, stakeholders identified as a major issue the central coordination of the switching system in software to find dynamically the appropriate balance between capacity utilization, safety and energy consumption, together with system behaviour and operations defined for degraded situations.

The arithmetic averages of the assessments showed that the experts rated the priority for each of the technical issues as very high with a general finding that most stakeholders did not expect the technical issues to be fully resolved within five years. The standard deviation (SD) of the input showed that the experts are much more confident of the nature of the technical issues that need to be resolved and their high importance ($S_{Pr,safe}$), than they are of the likelihood of the issues being resolved in the next five years ($S_{5,safe}$). This observation applies to both MB (SD = 1.16 with a mean of 3.61) and VC (SD = 1.48 with a mean of 3.25). The SD value for VC reflects significant uncertainty in the confidence of experts on the likelihood of achieving solutions within five years. Therefore, the system under VC has a higher demand for safety compared to the system under MB.

5.2.7. Public acceptance

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

5.2.8. Regulatory approval

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

Table 7
Weighted normalized decision matrix.

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

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

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

5.3. Multi-criteria impact assessment

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

According to the hierarchical model defined in Section 3.2, the 8x8 pairwise criteria comparison matrix (where the row-column dimensions are given by the eight criteria) with respect to the goal of "choosing the appropriate signalling system to each market segment" has been built. A geometric mean has been used to consolidate all the consistent pairwise comparison matrices provided by the interviewed railway SMEs. The consolidated pairwise comparison matrix is shown in Table 5. The weights of relative criteria importance have been computed based on the hybrid Delphi-AHP technique (see Sections 3.3, 1), and are given as a ratio between a criterion on the row and a criterion on the column of the matrix using the AHP scale of relative importance as explained in Section 3.2.

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

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

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

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

Since CR is lower than 10%, the final weights associated with each criterion are then confirmed as listed in Table 5.

The consolidated performance matrix for each market segment per signalling alternative is displayed in Table 6. Each number of the performance matrix is represented by a value $X_{m,n}$ which is the performance value of the m-th alternative over the n-th criterion based on the criteria assessment per market segment (Section 5.2).

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 lifecycle cost is instead a non-beneficial criterion since a high value is not beneficial to the choice of a given signalling alternative that would be an expensive option. Therefore, beneficial criteria in this analysis are: infrastructure capacity, system stability, travel demand, safety, public acceptance and regulatory approval. The non-beneficial criteria are: lifecycle costs and energy consumption.

For each criterion, performance values $X_{m,n}$ obtained for criterion n and signalling alternative m have been normalised ($\overline{X}_{m,n}$) with respect to the maximum (for beneficial criteria) or the minimum (for non-beneficial criteria) value over all the signalling alternatives as provided in Section 3.2. Performance values for each criterion are then multiplied by the corresponding criterion weight computed by means of the hybrid Delphi-AHP method. The weighted normalized decision matrix per market segment is given in Table 7.

Finally, the ranking of alternatives is obtained by computing the weighted MCA performance scores P_m defined in Section 3.2. The computed scores of the two signalling alternatives (ETCS Level 3 MB and VC) per market segment are graphically reported in Fig. 7a.

The MCA performance scores show that ETCS Level 3 MB outperforms VC for all market segments, despite the analysis of individual criteria such as capacity, stability, travel demand and energy consumption that show the opposite (i.e. VC more beneficial than ETCS Level 3) for all the market segments. The reason behind this result is mainly due to the very high weight (45%) associated by the interviewed stakeholders to the criterion "safety" where VC scores are lower than ETCS Level 3 due to its lower technology maturity
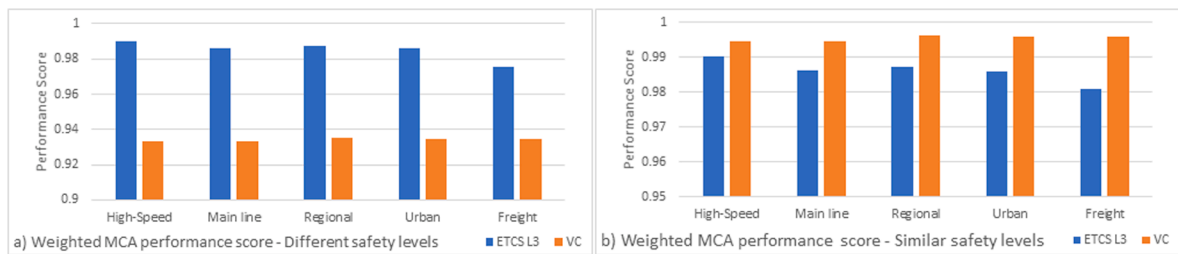
Fig. 7. Weighted MCA performance score P_m of ETCS Level 3 and VC per market segment for (a) different safety levels and (b) the same safety levels.

level and the consequent higher number of open safety–critical issues.

In order to avoid the bias of comparing two signalling technologies with different levels of safety (holding a significant percentage of criteria weight), the MCA has been reiterated considering a future point in time where VC would have the same technological maturity of ETCS L3 MB and therefore a comparable safety performance. Results of the repeated MCA are displayed in Fig. 7b, clearly showing that VC would outperform ETCS Level 3 for all market segments. This result mainly derives from the much shorter train separations that VC can provide over plain lines with respect to MB, which leads to a reduction of the capacity index that is bigger than the corresponding increase in the lifecycle costs. The slight increase in CAPEX is due to the installation of the V2V communication layer, the automatic train operation and the EVC updates, while the OPEX remains basically the same as for MB. Therefore, parameters like shorter braking distances, shorter communication delays, and relatively small additional CAPEX items make VC more advantageous than MB if the same safety levels are considered. The highest performance score is associated to the regional market segment, mostly because the deployment of VC would provide the service flexibility required by the customer demand over this segment, thereby attracting more travellers from other transport modes.

6. Conclusions

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

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

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

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

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

CRediT authorship contribution statement

Joelle Aoun: Methodology, Investigation, Formal analysis, Visualization, Writing - original draft. **Egidio Quaglietta:** Conceptualization, Writing - review & editing, Supervision, Project administration. **Rob M.P. Goverde:** Validation, Writing - review & editing, Funding acquisition. **Martin Scheidt:** Formal analysis, Visualization. **Marcelo Blumenfeld:** Formal analysis, Resources. **Anson Jack:** Formal analysis. **Bill Redfern:** Resources.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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