# Exploring Demand Trends and Operational Scenarios for Virtual Coupling Railway Signalling Technology

Aoun, J.; Quaglietta, E.; Goverde, R.M.P.

**Publication date**
2020

**Document Version**
Accepted author manuscript

**Published in**
Proceedings of the IEEE ITS Conference

**Citation (APA)**
Aoun, J., Quaglietta, E., & Goverde, R. M. P. (2020). Exploring Demand Trends and Operational Scenarios for Virtual Coupling Railway Signalling Technology. In *Proceedings of the IEEE ITS Conference: Rhodes, Greece, 20th -23rd September, 2020* IEEE.

# Exploring Demand Trends and Operational Scenarios for Virtual Coupling Railway Signalling Technology*

Joelle Aoun, Egidio Quaglietta, and Rob M.P. Goverde, *Member, IEEE*

*Abstract*— **Virtual Coupling (VC) is a newly introduced concept of train-centric signalling technology that conceives trains to run autonomously in radio-connected platoons. These trains move synchronously at a relative braking distance to significantly improve railway capacity and address the forecasted increase in railway demand. The technical feasibility of VC depends on its strengths, weaknesses, opportunities and threats which can introduce radical changes to current train services, technologies and procedures. This paper investigates demand trends and operational scenarios of future train-centric signalling systems. To this end, stated travel preferences have been collected by means of a survey to have more insight on modal shares in the case of future VC applications. In addition, a Delphi method has been applied where another extensive survey has collected expert opinions about benefits and challenges of VC. Results show that VC can be very attractive to customers of high-speed and main line railways and have special benefits to the regional market where a manifest willing to pay more for using a more frequent train service was found. This concept therefore calls for a deeper understanding of possible Virtual Coupling operational scenarios and the impact on the railway industry.**

## I. INTRODUCTION

Many railways are running close to capacity saturation conditions while the transport demand of passengers and goods is continuously increasing. The lack of suitable solutions to mitigate the impact of oversaturated capacity has led to delays, overcrowding and limited train service frequencies. This affects the flexibility of railway customers in choosing an adequate train service that fits their travel needs. The constringency of customer satisfaction can therefore lead to modal shifts from trains to other travel alternatives. This challenges Infrastructure Managers (IMs) and Railway Undertakings (RUs) to deliver a better quality of railway services to potentially attract more railway customers.

Plain moving-block operations, enabled by the European Train Control System - ETCS Level 3 [1] envisages a railway with no more block segregation and track-side safety equipment, where train integrity and safe braking supervision is entirely controlled on-board of trains. The main limitation in capacity for plain moving-block is observed for high-speed lines where absolute braking distances and hence train separations, can reach up to 4-5 km at speeds around 300 km/h [2,3]. An absolute braking distance is defined as the distance needed by a train to slow down from its current speed to standstill (i.e. zero speed).

Virtual Coupling (VC) could provide substantial capacity benefits versus ETCS L3 as trains can move synchronously in platoons at a relative braking distance from each other (i.e. the distance needed by a train to slow down to standstill by taking into account the braking characteristics of the train ahead). Although the concept of platoons of vehicles separated by a relative braking distance is also explored in the field of road traffic, its adaptation to the railways raises profound challenges. This is mainly because of the much lower wheel-rail adhesion coefficient which makes train operations, such as braking and direction switching, significantly different from cars. The concept of VC introduces safety, technological and operational issues that need to be addressed to understand whether there can be potentials for market uptake, despite its supposed capacity benefits. There is hence a necessity for a deeper analysis of the advantages that VC can provide with respect to fixed- and moving- block signalling and the corresponding challenges to its implementation.

The MOVINGRAIL project is funded by the Shift2Rail programme [4] and addresses a multidimensional analysis framework to assess train-centric signalling from the operational, technological and business perspectives. This paper contributes to widen such an understanding by exploring a SWOT-based approach and define operational scenarios for Virtual Coupling train operations. To this aim, a Delphi method has been applied where a survey has collected opinions of a significant population of European railway Subject Matter Experts (SMEs) about VC benefits/challenges from the operational, technological and business perspectives. Another survey was spread among representatives of other socio-professional categories to gather general thinking and stated travel preferences of potential railway customers in futuristic scenarios of VC-enabled train operations. Five different market segments are defined by the Shift2Rail (S2R) Multi-Annual Action Plan [5], namely: high-speed, main line, regional, urban and freight. Advantages and challenges of VC can indeed differ depending on the type of railway market segment (MS), given that speeds and operational characteristics vary substantially. The focus of this paper will be on the results of the stated preference survey (i.e. passenger-related case studies) as well as the SWOT-based definition of operational scenarios.

---

*Research supported by the MOVINGRAIL project granted by the Shift2Rail JU of the European Commission under Grant Agreement GA 826347.

J. Aoun is with the Department of Transport & Planning at Delft University of Technology, Delft, the Netherlands (phone: +31 152784914; e-mail: j.aoun@tudelft.nl).

E. Quaglietta is with the Department of Transport & Planning at Delft University of Technology, Delft, the Netherlands (e-mail: e.quaglietta@tudelft.nl).

R.M.P. Goverde is with the Department of Transport & Planning at Delft University of Technology, Delft, the Netherlands (e-mail: r.m.p.goverde@tudelft.nl).

The following sections provide a more detailed description on the VC concept as well as its corresponding challenges in terms of safety, technology and operation. A description of the paper methodology is provided in Section III. Results of the stated preferences survey are then reported and evaluated together with a SWOT Analysis extracted from the SMEs opinions survey together with brainstorming sessions and workshops across railway stakeholders in Europe. After a brief discussion of the results, new operational scenarios are defined for Virtual Coupling railway operations. Finally, conclusions and future works are addressed in Section VI.

## II. VIRTUAL COUPLING CONCEPT

A few research attempts have been delivered to analyse train operations with a separation based on a relative braking distance. In 1973, two little cars running quite close to each other (without any mechanical coupling) were tested as the first Aramis prototype [6]. In 1987, two “nonmaterial coupling” pairs (i.e. a Multiple Unit consisting of two units/cars) were experimented on the boulevard Victor station [6]. In 1998, Ning [7] referred to relative braking distance train separation between trains. Quaglietta [2] introduced preliminary operational concepts for Virtual Coupling (VC) by defining an extended blocking time model for comparing capacity occupation of VC with ETCS Level 3 moving-block. 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 [8]. In a further work, Quaglietta et al. [3] developed a train-following model to describe train operations under VC and assess capacity performance under different operational settings.

The recent concept of Virtual Coupling (see Figure 1) is introduced to further increase network capacity so to accommodate the forecasted increase in railway demand (European Environment Agency, 2015) [8]. VC takes moving-block train operations to the next stage by aiming at separating trains by a relative braking distance and allowing them to move synchronously together in platoons of trains that can be treated as a single train convoy at junctions to increase capacity at bottlenecks. As in ETCS Level 3, train position reporting is performed via radio communication by means of a Radio Block Centre (RBC). The Movement Authority (MA) is also broadcasted to trains by the RBC. Due to the very short distances between trains under VC, sight and reaction times of human drivers are no longer safe and Automatic Train Operation (ATO) shall be equipped to all trains for automated driving. The communication via the RBC may also be too time consuming, so it is anticipated that trains need to exchange speed, acceleration and position information via a Vehicle-to-Vehicle (V2V) communication architecture [9].

The train convoy (platoon) concept consists in understanding the behaviour between a leading train and a following train. The concept of vehicle platooning has been tested already in the road sector for automated cars under cooperative adaptive cruise control [10], however the much longer braking curves of trains and the presence of moving track elements for direction switching (i.e. points), raise non-negligible safety, operational and technological challenges which need to be carefully addressed.

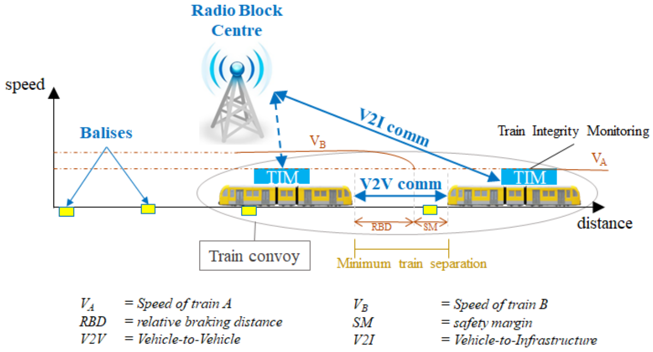

Figure 1. Schematic layout of Virtual Coupling train operations

## III. METHODOLOGY

To investigate the applicability of Virtual Coupling to each of the different passenger-related railway market segments, representative case studies have been considered based on the travel characteristics of real European railway corridors. Five scenarios have been defined as presented in Figure 2.

For each of the case studies, we proposed first the current scenario with existing travel alternatives and transport modes (e.g. car, airplane, bus, bike, etc.), as well as four future scenarios assuming that VC is operational. The second scenario envisions an ETCS L3 moving-block service with a headway reduction of 50% 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 [3]. Preliminary percentages have been derived/estimated together with railway experts across Europe for the other three scenarios of VC-enabled services. The third scenario considers a ticket price increase of 20% with a decrease in headways of 63% compared to multi-aspect signalling and of 61% compared to ETCS L2 [3]. The fourth scenario assumes short trains consisting of one Multiple Unit (MU), i.e. a fixed unit of multiple cars, for a fixed headway of 5 min to all market segments but for the urban market (which in this case is assumed a headway of 1 min) with a ticket price increase of 30%. Finally, the fifth scenario considers on-demand services operated by single self-propelled cars with a cost increase of 50%. The ticket fee percentages can be affected by the operational costs, the alignment of train services with demand patterns and/or the provision of customised train services to passengers according to their travel needs.

In all the scenarios, interviewees had the same set of modal alternatives as in the current baseline scenario, keeping the same performances and costs, except for railways where cost and frequency vary by virtue of the deployment of ETCS L3 or VC. In addition, interviewees were aware of the higher flexibility level that a VC-enabled train service could provide over other signalling systems given the fact that VC has the possibility of enabling a service more in line with the demand pattern rather than just a reduced service headway.

The stated preference travel survey aimed at collecting and understanding demand forecast and modal shifts to futuristic train-centric signalling applications. Railway experts' opinions were collected in another survey to perform a SWOT analysis which addresses Strengths, Weaknesses, Opportunities and Threats of Virtual Coupling. The SWOT has been also supported by a Delphi technique through brainstorming sessions and workshops with railway stakeholders across Europe. To this end, new operational scenarios have been defined and are elaborated in Section V.

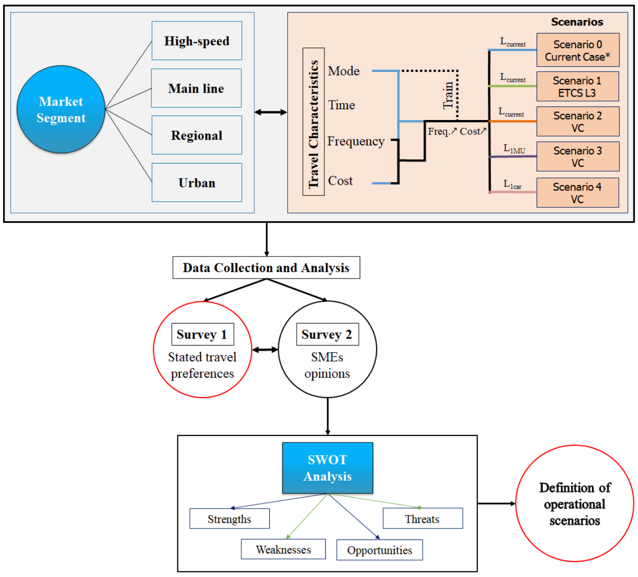

Figure 2. Framework for exploring demand trends and operational scenarios of Virtual Coupling

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

## IV. RESULTS

### A. *Stated Preferences of Travel Choices*

A specific analysis is performed to understand the modal split and the potential shift to railways that Virtual Coupling could bring in several future deployment scenarios. The survey has been completed by 235 interviewees with a 55% response rate, and sought the quasi-equal inclusion of students (48.4%) and employees/employers (51.6%) belonging to academic institutes (e.g. professors), railway industries (e.g. IM, RU) and other types of businesses.

By aggregating stated preferences collected in the survey, the modal share has been computed for each of the case studies for the current and the future transport scenarios. The results are illustrated Figure 3 for the passenger-related market segments. It should be noted that this study focused on the European railway markets. The results obtained in this paper are therefore biased towards the European railways.

Modal choices for the current scenario are reported with blue bars, while green bars represent modal preferences for the future scenario of ETCS L3-enabled train services with an increased frequency of almost 50% and ticket fares by 10%. The orange bars represent the Virtual Coupling scenario with the same train length of the current scenario, whereas the purple and pink bars show VC-enabled train services with a train length of one Multiple Unit (MU) or one self-propelled car, respectively.

*For the high-speed segment:* Most respondents (84%) prefer traveling by train in the current scenario for distances higher than 300 kilometres (blue bars in Figure 3). The proposed increase of 10% in the ticket fare (to reduce service headways by 15 minutes on a 3 hours journey) is not perceived as attractive to the interviewees. Having high-speed trains every 30 minutes seems already satisfactory for most of the respondents. The increase in the ticket cost proposed in the future scenario of a more frequent VC-enabled train service (headway less than 12 minutes) massively shifts travel preferences towards the car, the bus or the plane, as illustrated by the orange, purple and pink bars in the histogram. In general, such outcome shows that VC is not that attractive on high-speed corridors having already a service headway of 30 minutes over a given O-D (Origin to Destination) pair. However, VC is not only about shortening headways but also about addressing the headway shortening capabilities with respect to the demand. Therefore, VC is worth applying to address future massive demand in dense areas.

*For the main line segment:* Almost 60% of interviewees opt for railways in the current transport scenario, while only 14.8% use the car (see blue bars). A future scenario of a train service offering 10 minutes less waiting time for a ticket increase by 10% is not considered that attractive for 17% of the train users who in that case would prefer shifting to the other modes of transport, as clearly illustrated by the green bars. An increase in the ticket price of more than 10% for a headway reduction of a few minutes is indeed not perceived positively by railway customers for the defined VC-enabled train services represented by orange, pink and purple bars. Many respond that for this kind of journey, they would prefer arranging their travel schedules around a less frequent train service rather than paying that much more to use an improved main line connection.

*For the regional segment:* Most respondents would use the available railway connection (having a frequency of one train per 45 minutes) for the current transport scenario. The remaining part would rely instead on the car (26%), followed by bus users (16%). It is interesting to see that for the future VC-enabled scenarios of trains running more frequently for a ticket cost increase of 20% or 30%, a significant share of the sample would shift to railways. In addition, the modal shift from cars to railways is more perceived for VC-enabled services with one Multiple Unit than for ETCS L3 train services by 7.9%. This means that the proposed VC-enabled market scenarios, represented by the orange and purple bars, are attractive to passengers, since they are not currently satisfied with the delivered railway service and would be willing to pay more for a more frequent regional railway connection.

*For the urban segment:* The modal share for the current transport scenario is in net favor of the available metro line, having already a satisfying frequency of a train every 5 minutes. By looking at the blue bars, the other used transport modes are the bike (26%), with a minority travelling by car (3.1%) or bus (2.6%). In all the future scenarios of a metro train every 3 minutes or less for a ticket increase, many respondents would shift to other modes of transport, given that they are not willing to pay more for improving a service that is already satisfactory as it currently is. Paying even €0.30 more for a daily reduction by 60 seconds in the average waiting time, is not an attractive market scenario. Such a little saving in the waiting times is not perceived positively by passengers, which can already flexibly arrange their trips around the current service headway of 5 minutes. However, in case of a crowded metro, decreasing the headway 2 minutes would imply more seating and standing space to passengers who might be willing to pay more for an improved train service. Moreover, the deployment of VC on such lines could benefit railway stakeholders due to the increased capacity and possible mitigation of delay propagation. The on-demand services of one self-propelled car is positively appreciated by 7% of respondents. However, this would induce a massive shift by 26% from metro to bike (i.e. the number of bike users is doubled in the case of on-demand train services).

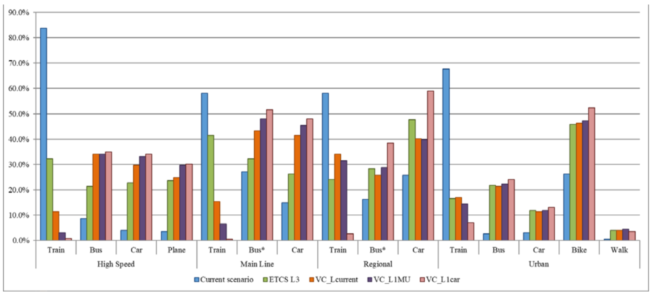

Figure 3. Modal share for each passenger-related case study for five different scenarios

### B. *SME Opinions*

By aggregating SME opinions collected from 48 railway representatives, a SWOT analysis has been derived for each of the case studies for the current and the future transport scenarios. In this paper, we present a brief summary of the SWOT for the regional market segment since based on the results of the stated preference survey (see Section IV.A), this market is the most VC-attractive to railway customers. The analyses for the other market segments (including freight) can be found in [11].

A SWOT analysis is a useful technique to define strengths and weaknesses of a given project variant, technology or operational strategy, and to identify opportunities and threats for the analysed market and/or business. A SWOT analysis is hence crucial to reckon the advantages and limitations of the novel concept of Virtual Coupling operations to understand potential gains and risks for the railway business. Interviews to collect expert opinions on the SWOT analysis have been performed by means of a survey held during an interactive European workshop where discussions have been raised among 42 representatives of the European railway industry and 26 respondents belonging to other socio-professional categories. The workshop has been followed by brainstorming sessions to discuss the outcomes of the SWOT analysis.

Specific examples and outcomes from the SWOT analysis highlight that VC has a potential reduction of operation costs (i.e. OPEX) due to full automation of train operations, reduction of communication latency, and mitigation of some types of accidents thanks to the V2V communication. However, the capital expenditure (CAPEX) can increase due to additional devices required for the V2V communication, updating of rolling stock on-board equipment and the overhead line system (i.e. redesigning the electrical power supply). Weaknesses arise due to the need of absolute braking distance (ABD) at diverging junctions for the current switches. Other safety risks concern the control of trainsets with heterogeneous braking characteristics in the same convoy. From the infrastructure perspective, upgrades are needed to the Overhead Line System (OLS), and there might be potential longer closures of level crossings to road users to allow the passage of a train convoy. In addition, due to non-sufficient interstation distances, coupling/decoupling in a convoy would potentially be only allowed at a standstill. On the other hand, the stated preference survey results showed that the increased service frequency/flexibility would lead to a substantial increase in the number of railway customers. The railway market would also be more attractive to deregulation as a direct consequence of an increase in available train paths and a decrease in operating costs, which opens opportunities for an affordable market to small transport operators. Virtual Coupling could also offer the railway industry a chance to accelerate the migration of current Control Command and Signalling (CCS) towards more future-proof digital railway architectures, as well as an upgrade of current switch technologies to faster and more reliable ones. Threats include potential modal shifts due to increased ticket costs and risks of approval from the industry as well as the need of additional investment costs to address the safety issues introduced by relative braking distance operations. Other threats regard the train control complexity and the partial redesign policies, regulations and engineering rules, which need agreement and endorsement across the rail industry.

## V. DEFINITION OF OPERATIONAL SCENARIOS

Based on the SWOT analysis derived in Section IV.B and [11], different challenges for the implementation of Virtual Coupling have been identified. Therefore, the SWOT results give rise to the identification of different operational scenarios based on typical characteristics of each market segment.

Operational scenarios have been defined based on different combinations among manoeuvers and signalling system configurations. A manoeuver is defined as a movement of a train over a track or an interlocking area. The movement of trains is affected by stopping patterns for each manoeuver. The type of movement that the train will perform depends on the layout of the track and/or junction as well as on the interaction with other trains running on the same track. A system configuration is defined as a specific set of values of design variables of the signalling system. Design variables of Virtual Coupling would for instance be the frequency and latency of the V2V communication layer, the communication delay between the train and the RBC to exchange the position report and the MA, the safety margin between two trains in a virtually coupled convoy, etc. More details about the combinations of manoeuvers and system configurations are provided in the following sections.

### A. Manoeuvers

As illustrated in Figure 4, three manoeuvers 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 manoeuvers relate to trains following each other in the same direction. Manoeuver M1 refers to the case of a plain line, Manoeuver M2 considers trains merging at a junction and Manoeuver M3 relates to trains diverging at a junction. In the case of stopping patterns for M2, the station is assumed to be located 500 meters from the switching point where both trains stop. In the case of M3, the leading train stops and dwells at the station -located 300 meters from the switching point- and the follower diverges to the track above.

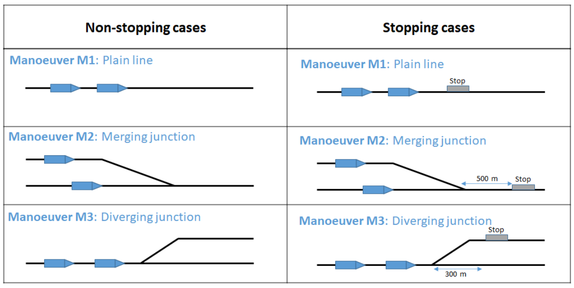

Figure 4. Manoeuvers for investigating the benefits of Virtual Coupling over previous railway signalling systems

### B. System Configurations

Six system configurations are considered in this paper. All the configurations are based on a combination of four main design variables that vary based on the adopted signalling system and/or the market segment. The main design variables defining a system configuration are here considered to be:

- the train length;
- the safety margin;
- the system reaction time, which is the time for the signalling system to update its status, e.g. the communication delay between the train and the RBC to exchange the position report and the MA, the occupation status of a track circuit, or the V2V communication latency;
- the setup time to set and lock a route.

Train lengths are 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 MS.

The baseline system configuration S0 is considered for the conventional signalling system currently installed for a given market segment. For the main line, regional and urban markets we mainly refer to a 3-aspect fixed-block signalling, i.e. S01. For the high-speed segment, the baseline signalling is ETCS Level 2, i.e. S02 (see TABLE I).

The system configuration S1 refers to ETCS L3 moving-block signalling, while the system configurations S2, S3 and S4 correspond to the Virtual Coupling scenarios. The value of the train separation for the signalling alternatives "Virtual Coupling" is affected by other parameters such as the train positioning inaccuracy and/or the communication latency of the V2V communication layer. Similarly, the system reaction time depends on the technology used to report train position and to safely control train movements. For a conventional fixed-block multi-aspect signalling, the system reaction/delay will depend on the track-clear detection technologies (e.g. axle counter or track circuit) and the time to update the signal aspects. For ETCS L3, the system reaction time depends on the communication delay to report train positions to the RBC as well as the latency to send a MA from the RBC to a train. For Virtual Coupling besides the train-RBC communication delay, the V2V communication latency shall also be added. Therefore, the safety margin and the system reaction times will be denoted as functions of the signalling system alternatives S0 (i.e. S01 and S02), S1, S2, S3 and S4, as well as the Market Segment.

TABLE I. SYSTEM CONFIGURATIONS

| **System Config** | **Design Variables** | | | |
|---|---|---|---|---|
| | ***Train length (m)*** | ***Safety margin (m)*** | ***System reaction time (s)*** | ***Setup time (s)*** |
| S01[a] | $L_{current}$ | N/A | $\Delta T_{(S01,L,MS)}$ | $t_{s(MS)}$ |
| S02[b] | $L_{current}$ | N/A | $\Delta T_{(S02,L,MS)}$ | $t_{s(MS)}$ |
| S1 | $L_{current}$ | $SM_{(S1,L,MS)}$ | $\Delta T_{(S1,L,MS)}$ | $t_{s(MS)}$ |
| S2 | $L_{current}$ | $SM_{(S2,L,MS)}$ | $\Delta T_{(S2,L,MS)}$ | $t_{s(MS)}$ |
| S3 | $L_{MU}$ | $SM_{(S3,LMU,MS)}$ | $\Delta T_{(S3,LMU,MS)}$ | $t_{s(MS)}$ |
| S4 | $L_{car}$ | $SM_{(S4,Lcar,MS)}$ | $\Delta T_{(S4, Lcar,MS)}$ | $t_{s(MS)}$ |

[a]: Multi-aspect signalling is considered for main line, regional and urban railways.
[b]: ETCS L2 is considered for high-speed railways.

The route setup times are independent from the signalling system and exclusively depend on the technology of the point machine as well as the length of the beam of the switch, which differs for each market segment. For this reason, the switching time is independent from the signalling alternatives (S0, S1, S2, S3 and S4) and only depends on the MS. In the future, advanced technologies for fast switching could be installed such as Railtaxi [12] or REPOINT [13].

A summary of the notation to indicate the design variables of the system configurations is provided in TABLE I.

### C. Operational Scenarios

An operational scenario is defined as the combination of manoeuvers and system configurations, either with or without stopping operations. For a given market segment, we mainly investigate manoeuvers that are typical to be observed in that specific market as explained in the following sections.

For urban railway lines, only five operational scenarios with stopping trains are defined. They consist of the system configurations S01, S1, S2, S3 and S4 defined in Section V.B for manoeuver M1 (Section V.A). This means that the first operational scenario consists of the combination of manoeuver M1 with stopping trains at stations under a 3-aspect signalling. The second scenario relates to manoeuver M1 for stopping trains under ETCS L3 whereas the operational scenarios S2, S3 and S4 represent manoeuver M1 for stopping trains under VC for the current length, the length composition of one MU and the length of one self-propelled car, respectively.

For the regional market segment, fifteen operational scenarios are investigated with stopping trains for the three defined manoeuvers M1, M2 and M3 with the system configurations S01, S1, S2, S3 and S4.

For the high-speed and main line market segments, all the combinations extracted from the defined manoeuvers in Section V.A are considered. The baseline configurations are S01 (3-aspect signalling) and S02 (ETCS L2) for the main line and high-speed market segments, respectively. Therefore, each of the mentioned market segments holds thirty operational scenarios based on the same manner explained above for urban railways. These scenarios refer to five system configurations with six combinations for each manoeuver (i.e. three with stopping trains and three with non-stopping trains). The inclusion of non-stopping trains allows the investigation and evaluation of the operation of virtually coupled trains on-the-run.

In total, 80 operational scenarios are considered for the passenger-related market segments (high-speed, main line, regional and urban). Those operational scenarios would provide a detailed evaluation of railway capacity for Virtual Coupling railway operations.

## VI. CONCLUSIONS AND FUTURE WORK

A description of the Virtual Coupling concept has been provided in this paper by discussing safety, technological and operational challenges. The core of this paper provides results from two extensive surveys. The first survey aims at collecting stated preferences for travel choice of potential railway customers in futuristic scenarios of ETCS L3 and VC-enabled train operations. The second survey focused on representatives of the European railway industry to collect expert opinions on the potentials and challenges of VC to feed a SWOT analysis.

Results of the stated preferences survey highlight that VC can make the railway transport mode more attractive to customers if an increase in ticket costs is restrained to all the different socio-economic categories. For dedicated high-speed lines, VC can be beneficial to high-speed lines currently operating with lower frequencies (e.g. 1 hour) and in dense areas of massive demand. A negligible attractiveness to VC has been observed for urban lines where passengers seem to be already satisfied with the current train services having headways of 5 minutes or less. Virtual Coupling is instead very appealing to customers of regional market segments, where a manifest willing to pay more for using a more frequent train service has been recorded. In other words, if VC is proposed to improve the customers' satisfaction, then the ticket price increase would not be perceived as negative, since Virtual Coupling would not just merely increase capacity but improve the entire customer experience by delivering a more flexible service in line with passengers' travel needs.

The SWOT analysis provides clear advantages and limitations of Virtual Coupling in terms of costs, operations and technology. Weaknesses result mainly from increased CAPEX and safety at diverging junctions especially for trains with heterogeneous compositions. Some threats are introduced by the VC implementation due to high complexity from V2V communication, safety issues due to the relative braking distance, the market deregulation as well as potential increase in ticket fees. On the other hand, these marginal increases in utilisation costs are compensated or even nullified by full railway automation which removes costs for on-board personnel and for coupling/decoupling trains at stations. Moreover, Virtual Coupling could open opportunities to both IMs and RUs. Benefits include reduced OPEX and increased profits, a deregulated railway market as well as potentials for cooperative consortia of railway operators leading to higher Cost/Benefit ratios. VC can also result in a possible migration towards more digital railway architectures with upgraded technologies, potentially increasing the number of railway customers. In addition, VC include the possibility of a better service coverage of the network which is more in line with hourly demand patterns. In the future, VC would facilitate the implementation of on-demand train services which could possibly revolutionize the entire idea of timetabling.

A new set of operational scenarios was defined based on combinations of manoeuvers and system configurations to assess the benefits of VC over previous railway signalling technologies. The operational scenarios will be further investigated in terms of capacity, energy efficiency and service stability. Safe operational principles will be investigated in future work by analysing system performance with respect to changes and dependencies among different design variables.

## REFERENCES

[1] G. Theeg, and S. Vlasenko, "Railway Signalling & Interlocking: International Compendium", *Eurailpress*, Hamburg, 2009.

[2] E. Quaglietta, "Analysis of Platooning Train Operations under V2V Communication-Based Signaling: Fundamental Modelling and Capacity Impacts of Virtual Coupling", *Transportation Research Board: The TRIS and ITRD database*, December 2018.

[3] E. Quaglietta, M. Wang, R.M.P. Goverde, "A multi-state train-following model for the analysis of Virtual Coupling railway operations", *Journal of Rail Transport Planning & Management*, 2020.

[4] Shift2Rail, *R&I Programme*, https://shift2rail.org/research-development/.

[5] Shift2Rail Joint Undertaking, Multi-Annual Action Plan, Brussels, November 2015.

[6] B. Latour, "Aramis, or, The love of technology", *Harvard University Press*, Cambridge, 1996.

[7] B. Ning, "Absolute braking and relative distance braking – train operation control modes in moving block systems", *Transactions on the Built Environment*, vol. 34, pp. 991-1001, 1998.

[8] Flammini F., Marrone S., Nardone R., Petrillo A., Santini S., & Vittorini V. (2019). "Towards Railway Virtual Coupling", *2018 IEEE International Conference on Electrical Systems for Aircraft, Railway, Ship Propulsion and Road Vehicles and International Transportation Electrification Conference, ESARS-ITEC 2018*, July 2019.

[9] European Environment Agency, "Passenger Transport Demand, Outlook from WBCSD", https://www.eea.europa.eu/data-and-maps/indicators/passenger-transport-demand-version-2/assessment.

[10] I. Mitchell et al., "ERTMS Level 4, Train Convoys or Virtual Coupling", *IRSE News*, Issue 219, pp. 1-3, 2016.

[11] I. Herman, D. Martinec, Z. Huràk, and M. Sebek,, "Scaling in bidirectional platoons with dynamic controllers and proportional asymmetry", *IEEE Transactions on Automatic Control*, vol. 63(4), pp. 2034–2040, 2017.

[12] MOVINGRAIL, "Market Potential and Operational Scenarios for Virtual Coupling", Deliverable D4.1, 2019.

[13] B. Müller, "Railtaxi", https://www.astrail.de/bahntaxe.htm.

[14] S. Bemmet, "Repoint: revolutionising track switch, Rail Technology Magazine", January 2019.