Towards Railway Virtual Coupling

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***Abstract*—Virtual Coupling adds to Automatic Train Control (ATC) systems the further functionality of being able to virtually connect two or more trains, so drastically reducing their headways and increasing line capacity. For this reason it is considered among the most relevant innovations to be researched within the European Horizon 2020 Shift2Rail Joint Undertaking. Indeed, Virtual Coupling also introduces some critical issues related to potential hazards as well as strict requirements on tolerated latency associated to the channels used for train-to-trackside and train-to-train communications. In this paper, we introduce Virtual Coupling in the context of a standard ATC, that is ERTMS/ETCS. Considering a reference ATC simplifies the discussion about implementation and performance issues. We will provide some preliminary hints, models and results and draw conclusions about required safety analyses and future developments.**

***Index Terms*—railway, virtual coupling, platooning, modeling, ERTMS**

I. Introduction

Cooperative driving is an essential component of future intelligent transportation systems. It promises many advantages for ground transportation such as increased safety (i.e. reduced accidents due to less drivers distraction) and improved infrastructure utilization (i.e. increase of road capacity due to less traffic congestion). Improving infrastructure utilization and increasing capacity currently are also two primary objectives for railways addressed by the Shift2Rail [1]. Shift2Rail is the Joint Undertaking initiative established in 2014 to manage and coordinate all rail-focused research and innovation activities funded under the EU Horizon 2020 framework program. One of the solutions addressed in Shift2Rail to increase line capacity is Virtual Coupling that allows trains to virtually join by considerably reducing their headways.

Virtual Coupling is strictly related to cooperative driving as it aims at transferring to the railway sector some achievements and results of the automotive research in vehicle platooning on smart-highways and from some European aerospace research projects. In the railway domain, the concept of ATC (Automatic Train Control) includes ATP (Automatic Train Protection) and ATO (Automatic Train Operation). Most ATC systems are driverless, but some still depend on train drivers, providing them with information about the speed profile to be respected for optimal performance, whereas safety is guaranteed by the ATP. Platoons of trains are virtually-coupled via *train-to-train communication*, so that all connected trains are able to share information with neighbors and to receive the reference signals coming from infrastructure. On the basis of these information received from trains within the platoon, the on-board ATC systems is responsible of the safe tracking of speed profiles, while respecting the inter-train spacing policy. The goal of Virtual Coupling is to perform a reference tracking that allows followers to pursue the preceding train in a safe way and guarantee good transient dynamics.

Virtual Coupling is a really innovative scenario for future railways. This paper introduce Virtual Coupling in the context of ERTMS/ETCS, a standard ATC, and proposes some directions for ground-breaking research whose ultimate goal is to enable safe train platooning by designing control algorithms/protocols that are able to effectively operate on information exchanged between trains and with the trackside infrastructure.

The paper is structured as follows. Section II introduces the ERTMS/ETCS concepts and terminology and motivates the adoption of Virtual Coupling as a technique to significantly increase the capacity of current railway lines. Section III describes our vision about the possibility to introduce Virtual Coupling extending the current ERTMS (Level 3) standard, maintaining the backward compatibility with existing infrastructures and on-board equipments. In Section IV we propose a simple stochastic model as well as a preliminary simulation based on numerical analysis in order to estimate the effects of introducing Virtual Coupling. Section V contains a discussion about related works. Finally, Section VI provides closing remarks, open issues and hints about future work.

II. Background and Motivation

ERTMS/ETCS (European Railway Traffic Management System / European Train Control System) is the name of the set of standards for management and interoperability of

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modern railways. ERTMS/ETCS ensures both technological compatibility among trans-European railway networks and integration of the signalling systems within the existing national interlocking systems. The ERTMS/ETCS specification identifies three functional levels of growing complexity, from Level 1 to Level 3, with Level 2 being currently the most successful especially on high-speed lines. ERTMS/ETCS Level 2 is currently based on the usage of GSM-R (Global System for Mobile Communications Railway) for train-to-ground communications and on the use of fixed block signalling with trackside train location equipment such as track circuits for safe train separation. Since ERTMS is the combination of ETCS with GSM-R, we can refer to ERTMS only in the following of this paper (we are not considering Level 1 here). In the future, these technologies will become rapidly obsolete and the railway industry has to take up the challenge of supporting a modal shift towards greener transportation, heavily relying on innovative and high capacity railways. Indeed, two important research areas addressed by Shift2Rail [1] in advanced traffic management and control systems (IP2) are: "Smart, fail-safe communications and positioning systems" and "Moving block, Train Integrity and Virtual Coupling". The first research area aims at enabling easy migration from GSM-R to new communication technologies (LTE, 5G) to support the current and future needs of signalling system and the shift from the vision of "network as an asset" to a more modern vision of "network as a service". The second research area aims at line capacity increase by exploiting ERTMS Level 3 *moving block* signalling and also considering the possibility of introducing Virtual Coupling, i.e. *a new way of operating trains* by creating multiple train convoys. In Virtual Coupling, trains can be coupled and decoupled dynamically, according to the service needs and in the respect of the safety requirements. That introduces the necessity for trains to communicate one with each other and also stresses the importance of the research on high performance communication and positioning systems.

Virtual Coupling requires ERTMS Level 3. The main difference between ERTMS Level 2 and ERTMS Level 3 is the way in which Movement Authorities (MAs) are computed, with Level 3 requiring an additional function of train integrity check due to the absence of train detection mechanisms based on track circuits. The trackside component responsible for train separation is a computer-based controller, namely the Radio Block Center (RBC). As shown in Fig. 1, in ERTMS Level 2, the train safe headways are computed by the RBC on the basis of the occupation status of the track, i.e. MAs must cover one or more track circuits (*fixed block*); in ERTMS Level 3, RBC uses the position and integrity information reported by the train to compute MAs (*moving block*).

The absence of trackside train detection equipment has several advantages but also poses some issues [2] that - compared to the advantages - discourage railway operators to adopt ERTMS Level 3. While Virtual Coupling can be implemented on any railway signalling systems (theoretically speaking), associated to ERTMS it can boost Level 3 adoption due to the expected full exploitation of railway line capacity, virtually

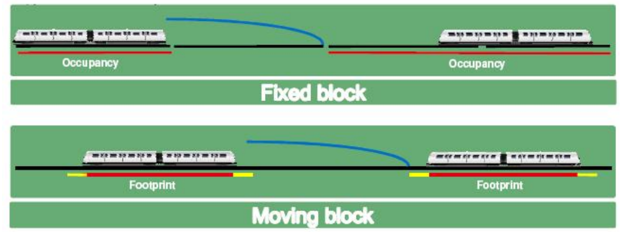


Fig. 1: Fixed block vs moving block.

eliminating waiting times for train dispatching. That is a huge advantage in terms of flexibility and efficiency of railway transportation against other transport modes, especially considering high traffic corridors that have currently reached their capacity limit with trains spaced of just a few minutes between them. Furthermore, the ERTMS standard specification includes a clear reference architecture, solid working principles, advanced ATC functionalities and a well structured language for messages, packets and variables, so that implementation of Virtual Coupling over ERTMS appears as much more viable compared to any ex-novo developments, as we will explain in more details in the following sections. This is why someone referred to Virtual Coupling over ERTMS as ERTMS Level 4 [3].

From now on, we will refer to ERMTS Level 2 and ERTMS Level 3 as ERTMS L2 and ERTMS L3, respectively.

III. A Virtual Coupling Vision for Future Railways

As introduced in the previous section, ERTMS L3 can achieve high capacity on railway lines thanks to the adoption of moving block instead of fixed block. The main advantage of ERTMS L3 is the possibility for a train to get a movement authority that reaches the minimum safe rear end of the preceding train that is not possible in ERTMS L2 due to the constraint of track circuit occupation. In ERTMS L3, each train reports its position, speed and integrity information to the Radio Block Centre (RBC). The RBC implements a supervision system and protects against overrun of the authority. Fixed balises are used as milestones for location referencing, although there are ongoing efforts to use satellite based positioning systems together with balises to increase precision in future generation ERTMS. These updates will allow ERTMS L3 to provide higher capacity, allowing more trains to run on a single line.

ERTMS L3 is still not enough to ensure the full track exploitation and some of its disadvantages could outperform its advantages. In case of lack of information about train position and integrity status, the Level 3 could not work due to unsafe conditions. If the radio connection between the train and the RBC is lost, the RBC will keep the last position report sent by the train and its MA. Therefore, it is essential to minimize the occurrence of those failure conditions. Virtual Coupling over ERTMS L3 will make communication issues even more critical although the fall-back on ERTMS L3 without Virtual Coupling will be always possible.

In Virtual Coupling scenarios, train-to-train communication becomes essential to maximize the probability of message delivery compared to train-to-track only (i.e., fully infrastructure based). In fact, Virtual Coupling requires extremely low reaction times and hence latency to synchronize multi-vehicle behaviors. Furthermore, in case of track-to-train communication issues, a train could receive information about its movement authorities from the preceding (and/or the following) train. In other words, *in case of train platoons, it is possible to imagine diverse communication topologies* in order to optimize bandwidth utilization and increase the reliability of message delivery.

Possible topologies include: "fully connected", in which the RBC communicates with the entire train fleet merged into a platoon and each train, in turn, forwards some information to its neighbours; "chain-like", in which the RBC communicates with the first train of the platoon that, in turn, forwards the messages to the following train like in multi-hop/mesh routing.

The synergy of diverse communication topologies with a distributed control algorithm paves the way to the application of Virtual Coupling in ERTMS. In fact, in our vision, the RBC evaluates the movement authorities of the train fleet and obtain information about the position and the integrity of each train in a fleet. Each train implements a local control algorithm that is able to evaluate its instantaneous acceleration and speed according to the fleet movement authority and the current speed, acceleration and position of the preceding train, received through train-to-train communications.

It is important to underline that the Shif2Rail research area IP2 asks for "continuity and backward compatibility with the current signalling and supervision systems through ERTMS standards". Currently, ERTMS defines several Operating Modes for the on-board European Vital Computer (EVC) according to different conditions affecting the status of the trackside and of the train itself, in order to guarantee the required performance and safety levels [4].

The main operating mode is the *Full Supervision (FS)*, that is when all train and track data required for complete supervision of the train are available on board. In Full Supervision, the system is able to operate at maximum performance and safety. Besides Full Supervision, there are other operating modes to manage degraded operational situations (e.g., *Shunting*, *On-Sight*, *Staff Responsible*, etc.), which can be grouped into *Partial Supervision (PS)*.

The Virtual Coupling proposal presented in this paper is such to ensure backward compatibility with ERTMS by adding a new operating mode, named *Full Supervision plus Virtual Coupling (FSVC)*, on top of the FS mode. This new operating mode is reachable from the FS mode. In order to switch from FS to FSVC, the ERTMS infrastructure should check and guarantee that all the necessary conditions are fulfilled, possibly including sufficient MA assigned to the preceding train, sufficient MA overlap between preceding and following train to ensure the same routing in stations, successful establishment of train-to-train communication, etc. The switch from FS to FSVC and is commanded through custom ERTMS "messages" sent by the RBC, orchestrating the coupling of vehicles in platoons and their decoupling while they are still in motion in case of different routes. When the RBC sends the "coupling" command to the trains, the EVC switches from FS to FSVC; the "decoupling" command will revert the EVC back in FS through an appropriate procedure. The transition from FSVC to FS/PS can be also initiated by the EVC in case of any failures: e.g. (minor) train-to-train communication failures will cause the EVC to switch from FSVC to FS, while (major) train-to-track communication losses will cause the EVC to switch from FSVC directly to PS. ERTMS allows to set train speed at the end of authority equal to the speed of the preceding train by properly setting the *Veoa*[1] variable in the Movement Authority messages sent from RBC to EVC (see Fig. 2).

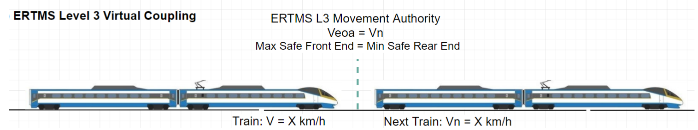


Fig. 2: Virtual Coupling.

That serves as an easy ploy to enable Virtual Coupling from the viewpoint of train braking curve updating, although there are other issues to be tackled from the viewpoint of safety and performance in non-stationary scenarios. Let us consider a stationary scenario in order to forecast Virtual Coupling performability against some classes of non safety-critical failures.

IV. Preliminary analysis of the ERTMS Virtual Coupling operating mode

A. Stochastic Capacity Modeling and Evaluation

The switches between the ERTMS operating modes discussed in the previous Section, including the additional FSVC, can be modeled by the Stochastic Petri Net in Fig. 4.

The delays associated to the stochastic transitions representing mode changes have a negative-exponential distribution. That assumption is realistic since those transitions represent concepts of time-to-fail (i.e., leaving a higher supervision mode) and time-to-repair (i.e., getting again in a higher supervision mode) whose stochastic variables are widely demonstrated in the reliability theory to be well-modeled by negative exponential distributions. The transitions *T_FSVC* and *T_FS* have deterministic firing rates as they represent the frequency of trains when running at FSVC and FS operating modes, respectively.

As an example, if we assume the trains running at 300 km/h in the Rome-Naples high-speed ERTMS track in Italy, with realistic MAs at full speed of 15 km (safe headways), then the maximum frequency would be 15 / 300 = 0.05 h (i.e., 3 minutes minimum theoretical dispatching time). Fig. 3 shows that the minimum dispatching time increases linearly with the headway distance.

At FSVC, the distance between train will only be given by the train minimum/maximum safe rear/front ends that

[1] Velocity at the End Of Authority

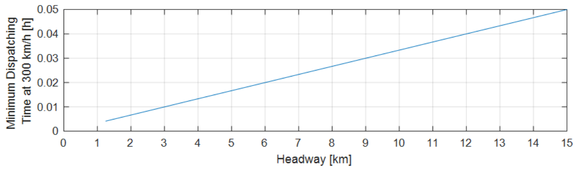


Fig. 3: Dispatching time.

are the train extremes augmented by the odometric errors. We assumed an inter-distance of 3 km at 300 km/h, which correspond to a frequency of 3 / 300 = 0.01 h (i.e., 36 seconds minimum theoretical dispatching time).

The places *P_T* and *P_R* and the transition *T* have been added to evaluate the train frequency on the track in function of the sojourn times in FSVC, FS and PS operating modes. Specifically, the throughput of transition *T* will provide an upper bound to the number of trains the system is able to manage in the time unit (i.e., the theoretical system's capacity) in function of the provided model parameters.

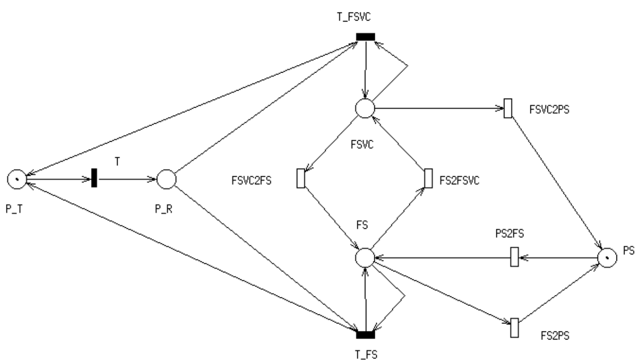


Fig. 4: Theoretical capacity model.

As the firing rates of the transitions *FSVC2FS*/*FS2FSVC*, *FSVC2PS* and *FS2PS*/*PS2FS*, we used the values reported in [5].

Specifically, the firing rates of transitions *FS2PS* and *FSVC2PS* have been both set to 1.0E-06, which is the maximum failure rate of the RBC, as required by the standard. The rate of transition *PS2FS* represents the repair rate of the RBC, as evaluated in [5]. The rates of transitions *FSVC2FS* and *FS2FSVC* are parametric. Transitions *T_FS* and *T_FSVC* are deterministic and we have used the firing rates discussed for the high speed trains example above (i.e., 0.05 and 0.01 respectively) .

The model in Fig. 4 has been analyzed by simulation. The plot in Fig. 5 reports the simulation results. We evaluated the throughput of transition *T*, with respect to the frequency of the switches between the states FSVC and FS by varying the rates of transitions *FSVC2FS* and *FS2FSVC* in the interval (0.1,0.9) with step 0.1. As expected, the maximum throughput has been obtained in correspondence with the maximum value of the *FS2FSVC* rate and the minimum of the *FSVC2FS* rate.

We can use the results sketched in Fig. 5 to validate the model and draw some general considerations about the expected effects of mode transition frequencies.

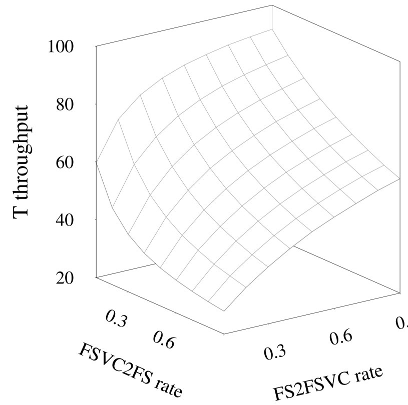


Fig. 5: Theoretical trains frequency for ERTMS with VC.

If we had FS only, from previous discussion the T frequency would be 20 trains per hour that is to say one train each 3 minutes. Such theoretical minimum is in the closest corner of the graph (i.e., lowest point), where the rate of the transition towards FS is higher and the rate of the transition towards FSVC is lower. In other words, that corresponds to maximum time spent in FS due to improper implementation of VC and/or faulty train-to-train communication channel.

On the opposite, if FSVC was implemented correctly with a low rate of faulty conditions, then we would have something similar to the farther corner of the graph (i.e., highest point), where the rate of the transition towards FSVC is very high while the rate of the transition towards FS is much lower. In such a condition, where the trains stay in FSVC most of the time, the graph shows a value close to 100 trains per hour, that is one train each 36 seconds as in the calculation reported above.

In the middle, we can find all the other combinations of mode transitions frequencies. For instance, if we had implemented a VC mechanism that is very reliable once it had reached a stationary condition, with a very low rate associated to the transition from FSVC to FS, but if at the same time the VC mechanism used to get to the FSVC operating mode was very slow, then we would be in the extreme left corner of the graph, corresponding to a rate of about 60 trains per hour that is 1 train per minute: such a frequency would be still 3 times better than FS only.

Finally, we would have a very similar result (see extreme right corner of the graph) if - on the contrary - we had a rather efficient yet unstable VC mechanism, with trains easily getting from FS to FSVC but also leaving FSVC often due to e.g. communication faults.

It is interesting to note that while the effect on overall train frequency of decreasing the rate of transition from FSVC to FS is exponential, the same does not hold when we increase the rate of transition from FS to FSVC, which shows an opposite behavior. That means that for lower rates of FS2FSVC and higher rates of FSVC2FS (i.e. closer to the bottom point of the graph), it is more convenient to invest on improving the efficiency of the mechanism to get to FSVC rather than the reliability in keeping the FSVC mode. On the opposite, for lower rates of FSVC2FS and higher rates of FS2FSVC (i.e. close to the upper point of the graph), it would be more convenient to improve the reliability of keeping the FSVC operating mode (e.g. by reducing communication errors) rather than making the mechanism to get to FSVC more efficient.

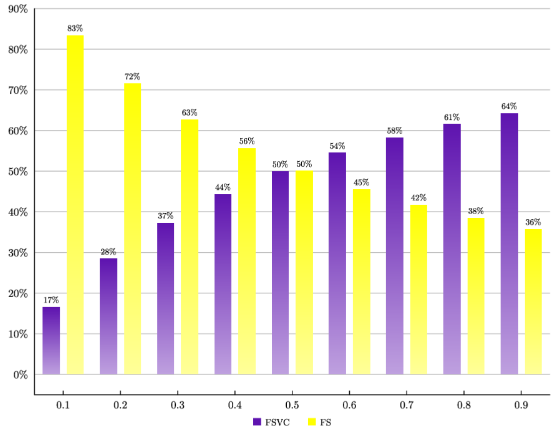


Fig. 6: Average sojourn times in FS and FSVC modes.

Finally, Fig. 6 reports the probability of the system to be in the FSVC and in the FS modes. For this analysis we fixed the FSVC2FS rate to the value 0.5 and we varied the FS2FSVC from 0.1 to 0.9. By increasing the rate of the transition FS2FSVC, the probability of being in the FSVC state (purple bars) increases from 17% up to 64%, while the the probability of being in the FS state (yellow bars) decreases coherently.

B. Numerical Analysis in a Sample Scenario

Consider 4 trains in FSVC mode moving as a fleet and sharing their state information via a chain-like communication topology. The train fleet travels at the constant speed of 210 $[\mathrm{km/h}]$ with a relative inter-train distance of 100 $[\mathrm{m}]$ when a new train in FS mode, labeled as train 5 and initially located at 500 $[\mathrm{m}]$ from the fourth vehicle of the fleet, performs a join maneuver (see Fig. 7a). The fifth train, which moves with a constant speed of 205 $[\mathrm{km/h}]$, sends a request to join the fleet at $t = 300$ $[\mathrm{s}]$. After the RBC sends the coupling command to the trains, the EVC of train 5 switches from FS to FSVC mode. In doing so, the train 5 is now able to communicate with the first and fourth trains within the fleet (see Fig. 7b). On the basis of the these shared information, the local control algorithm computes the desired acceleration profile that has to be set on the fifth train's dynamics in order to join the existing fleet. Results in Fig.8 show that, under the action of the local control strategy, the fifth train accelerates so to achieve the required spacing policy of 100 $[\mathrm{m}]$ from train 4, and then it decelerates until it reaches the constant speed of 210 $[\mathrm{km/h}]$ as set by the first vehicle of the fleet.

V. Related Work

ERTMS L3 is being widely investigated as some pilot implementations are currently deployed and it is expected to be operational in the near future. Hence, a number of works address performance and dependability issues related to ERTMS/ETCS L3, for example in [6]–[9]. Virtual Coupling open completely new scenarios in railways. It is considered by the International Union of Railways (UIC) still far away from technical maturity and currently under study[2] and, at time of writing, few works in the scientific literature address the challenge posed by virtually coupled trains. Some recent reports from international railway organizations and professional institutions introduce Virtual Coupling related concepts (e.g., [1], [3]), some works focus on the technologies required for its implementation (for example see [10], [11]), but just few pioneer studies exist addressing the evaluation of qualitative and quantitative aspects of Virtual Coupling. In [12] the authors investigate the use and the performance of 5G technology for train-to-train communications in coupling/decoupling and platooning scenarios, the simulation described in [13] is meant to study the expected capacity increase. These works present some preliminary results, in particular in [13] Virtual Coupling operational scenarios at low speed are simulated (e.g. in the proximity of a station) with respect to an existing high-speed line in Japan. Our research is meant to investigate the implications of Virtual Coupling in ERTMS, considering a reference ATC system and the current standards; in particular, our ongoing work is investigating the platooning concept borrowed from the automotive domain in the context of ERTMS L3 moving block signalling [14].

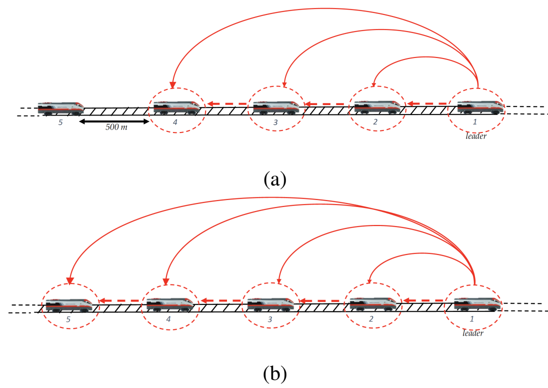
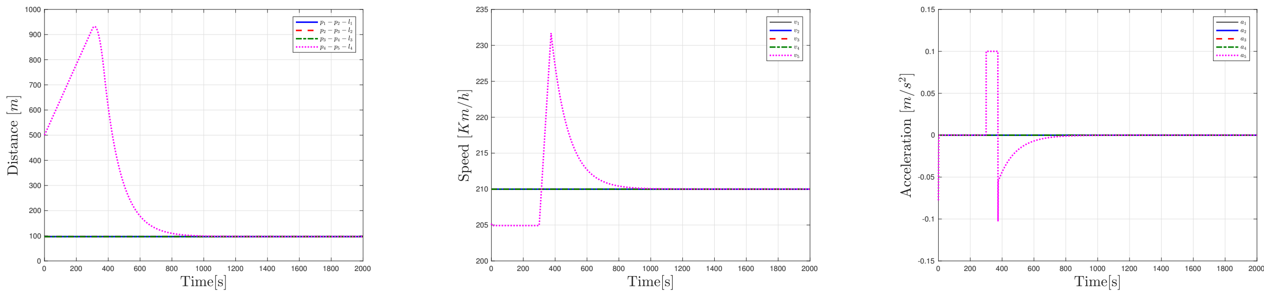


Fig. 7: Chain-like communication topology: a) before join maneuver; b) after join maneuver.

VI. Conclusions and Future Work

There is a huge effort ongoing at the European level to push the modal shift towards greener transportation and thus railways. However, high-traffic corridors are currently congested having reached their maximum capacity with current technology limits. Many high-speed railways are currently based on ERTMS L2 that is continuous radio-signalling with fixed block operation. ERTMS L2 allows a good exploitation of line capacity but still far from the theoretical maximum efficiency. The EU Shift2Rail JU foresaw Virtual Coupling as one of the few (if not the only) viable option as an alternative to just increasing train speed, acceleration and braking

[2] www.railway-energy.org/static/Virtually_coupled_trains_86.php



(a) (b) (c)

Fig. 8: Join Maneuver. Time histories of: (a): inter-train distances computed as the difference between consecutive trains positions, i.e. $p_i(t)-p_{i-1}(t)-l_{i-1}$ (being l_{i-1} the length of the train $i-1$) $\forall i=1,\cdots,5$; (b): train speeds $v_i(t)$ $\forall i=1,\cdots,5$; (c): train accelerations $a_i(t)$ $\forall i=1,\cdots,5$.

capabilities, due to electrical and mechanical constraints that are not easy to overcome. With Virtual Coupling, trains could be dispatched on the lines one after the other as they were a single convoy, virtually eliminating waiting times. At high speeds, safe headways are reduced to the minimum accounting for communication latency and response times.

However, real-world adoption of Virtual Coupling requires advanced technological developments, model-based performance evaluation, hazard analysis and safety assessment that are not straightforward. In this paper, we have introduced the main advantages, current obstacles and future developments for the effective implementation of Virtual Coupling within the ERTMS standard specification. Future efforts will be aimed at: evaluating the usage of 5G technologies for inter-train communications; evaluating the performance of novel large-bandwidth communication technologies against bit errors, faults and latency by means of appropriate stochastic models; assessing the safety of Virtual Coupling against hazardous scenarios and critical failures.

In our preliminary analysis, we have used Stochastic Petri Nets to jointly model performance and dependability (i.e. performability) of Virtual Coupling in normal as well as in degraded modes of operation; on that base, we aim at developing and evaluating further stochastic models to address the aforementioned challenges and open issues. We have also performed a preliminary simulation of Virtual Coupling using numerical analysis in a sample scenario. The same approach will be used to extend our analysis to a set of real-world operational scenarios in order to predict VC performance and safety during the critical phases of join maneuvers.

Future works will also address further analysis of coupling control algorithms by simulating new scenarios accounting for topology variations and time-varying delays affecting the Train-to-Train and Infrastructure-to-Train communication links.

Acknowledgment

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