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A Simulation Environment for Moving Block Signalling Systems

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Abstract

In recent years, train-based signalling systems have drawn the infrastructure managers' attention, in the attempt to improve the line capacity and to optimize traffic. The development of a Moving Block (MVB) signalling system may offer a solution to achieve these objectives. MVB signalling relies on the definition of an occupied region which moves together with the train, which is continuously updated based on the information exchanged between the vehicle and the Radio-Block-Centre (RBC). Thus, it may safely operate an increased level of traffic on railway networks. Despite its potential benefits, there is still no real implementation of this system, which would require on-site testing operations, considering several scenarios. In the attempt to enhance the overall procedure moving towards the target of "zero on-site testing", in this work a simulation tool for MVB signalling is proposed. The simulator is developed in Matlab-Simulink environment and presents a modular and expandible architecture. It includes a behavioural model of the driver and allows for the injection of disturbances to the train motion, enabling to test unusual operational scenarios, without any risk.

Keywords: European train control system, European rail traffic management system, moving block signalling, simulation environment, longitudinal dynamics, driver behavioural model, radio block center model.

1 Introduction

Nowadays, fixed block (FXB) systems are typically adopted for railway signalling. The railway line is divided into block sections that can be occupied by one single train at a time to ensure the safety of the network. The blocks are identified a priori, at the design stage of the railway line, considering its maximum speed, gradient, etc. [1]. As a result, the system might not be reactive to the dynamic changes that may occur during operations [2].

New approaches for the railway signalling logics have been proposed in recent years, with the final aim of increasing the traffic capacity, still ensuring the overall safety of the system. These strategies rely on train-oriented solutions, such as moving block (MVB) signalling, which belongs to the third level (L3) of the ETCS hierarchy. In this case, an occupation zone is assigned to each vehicle, which must not be trespassed by any other vehicle to guarantee the safety of the whole network. Therefore, the movement authority is provided by comparing the distance between two subsequent trains and the minimum safety distance required to prevent any collision, also considering the critical case of a sudden stop of the leading train. However, this signalling system is still undergoing extensive study, to assess its effectiveness in guaranteeing the safety of the network and increasing its performance compared to fixed block distancing. To this end, simulations surely represent a convenient solution towards “zero-on-site” testing goal, thus shortening the assessment and validation process of the MVB signalling system.

Multiple simulation environments have been developed to describe the motion of the trains along railway lines and considering the signalling systems operation. Among these, two main categories can be recognised: event-based simulators [3,4,5], which rely on a discrete set of events that, when triggered, advance the simulation by performing the related computations; and time-based simulators [6,7,8], which divide the simulation time into evenly spaced intervals and perform the computation of all variables of the system at each time interval. As shown in [9], time-based simulations are more computationally demanding than event-based ones, but they better resemble the movement of the train across the line. In addition, they allow reaching a higher level of detail, making them more suitable for applications related to signalling system analysis.

Within this context, this paper presents a time-based simulation tool capable of simulating the interaction of rail vehicles within a MVB signalling logic, during their motion along a user defined line. The simulator has been developed using Matlab-Simulink software, considering a time-based approach, and with a particular focus on modularity, meaning that each component can be modified without compromising the operation of the overall system. Moreover, it is independent on the specific characteristics of any route, vehicle or timetable, since it is based on a thorough parametric customization. The simulator contains the model of the vehicle longitudinal dynamics as well as the speed control algorithm, which on the one hand is designed to emulate the behaviour of a human driver, and, on the other, includes an automatic speed regulation system to properly handle critical scenarios. Additionally, the model of the Radio-Block-Centre (RBC), for MVB signalling systems, has been designed, which allows movement of vehicles once their state along the line is given. The possibility to easily inject external disturbances in the simulation, such as anomalous station stopping time or loss of integrity, has been also included.

The present paper is organised as follows: Section 2 describes the environment realised to simulate the MVB signalling system; Section 3 presents the results of the first simulation; finally, in Section 4 conclusions are drawn.

2 Simulation environment

In this section, the virtual environment designed to simulate the moving block (MVB) signalling system is presented. Figure 1 shows the designed Simulink block diagram. A reference case is considered, consisting in a single-track railway line, where two trains are running to provide commuter service.

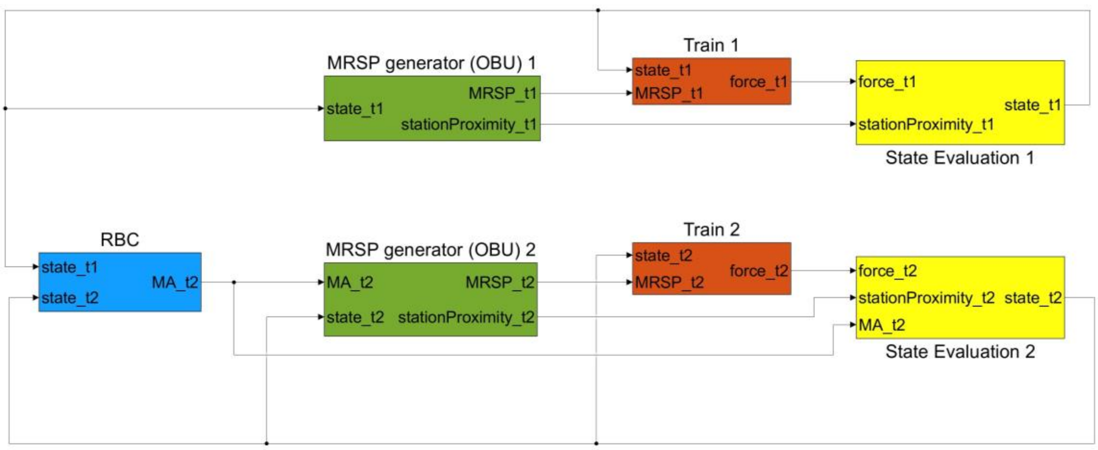

Figure 1: Overview of the Simulink simulation environment for MVB signalling. One RBC is modelled to control the motion of two vehicles.

The main blocks appearing in Figure 1 are hereafter described, posing the attention on the specific tasks accomplished by each of them.

2.1 RBC model

The "RBC" block contains the model of the Radio-Block-Centre, that is a trackside device which considers and continuously evaluates the state of each train, composed of its position and speed. The RBC computes the train Movement Authority (MA), that is the permission to move from one point to another on the line in compliance with the overall state of the network. In the presented model, the RBC always considers two trains, referred to as leading and trailing ones. For each couple of trains, the RBC performs three operations, as shown in Figure 2 and hereafter described.

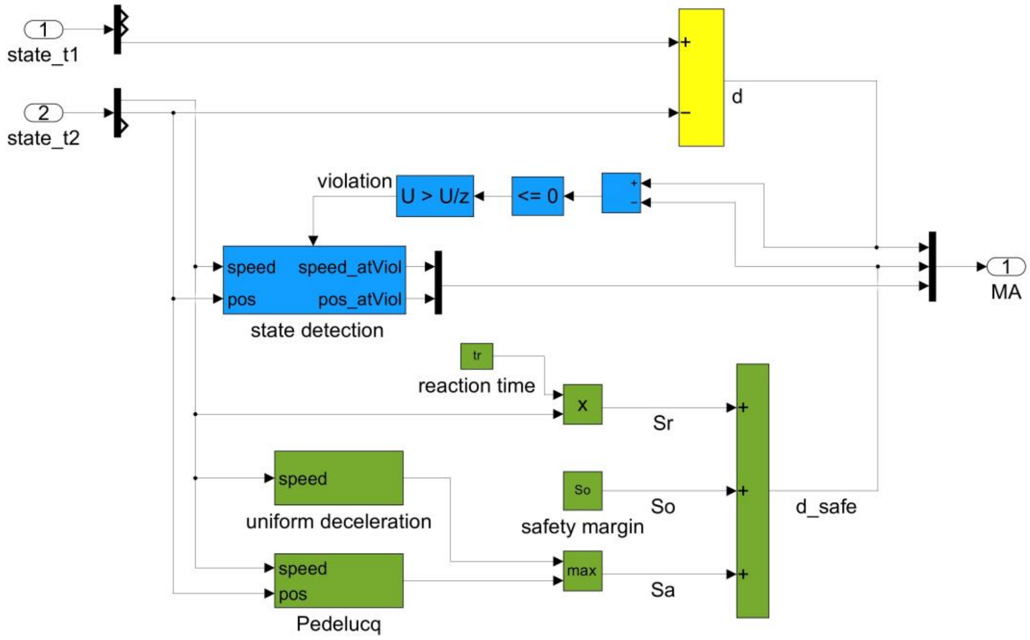

Figure 2: Model of the RBC for MVB signalling.

The coloured blocks of Figure 2 perform different tasks. The yellow block computes the instantaneous distance between the two trains by comparing their positions. In addition, the safety distance that should be maintained between them is computed by the green blocks. This is considered as the sum of the braking distance of the trailing train, the space travelled during the reaction time of the driver and a fixed safety margin. Note that the braking distance can be computed in two separate ways: on the one hand, applying a uniformly decelerated motion with prescribed deceleration; on the other, applying the Pedelucq formula, which accounts for the gradient of the line. In order to be robust to the most critical scenario, the braking distance is computed at the maximum value between the two. The final operation performed by the RBC is the state detection at safety distance violation, which is performed in the blue blocks of Figure 2. This is crucial to design the braking curve that the trailing train has to follow if it breaches the safety distance.

2.2 MRSP generator

Moving on with the simulator overview shown in Figure 1, the "MRSP generator" blocks contain the model of the On-Board Unit (OBU) of each train, which is responsible for the generation of the speed limit curve that the vehicle must follow to perform its service, ensuring network safety. This speed limit is referred to as Most Restrictive Speed Profile (MRSP), and it is determined by multiple factors, as hereafter described. First, an upper speed limit must be imposed on each section of the line to account for the infrastructural characteristics of the line, such as curve radii and junctions. Moreover, the presence of stations is considered imposing a deceleration curve before approaching them and null velocity in correspondence of the platforms. To clarify, Figure 3 shows the reference speed plotted as a function of the milestone position for a railway line composed by eight stations (also considering the departing one, located at the initial position). It is worth noting that during the simulation, static MRSP is computed for each time instant, considering the information contained in Figure 3 as well as train longitudinal dynamics, moving from a space representation (Figure 3) to a time one.

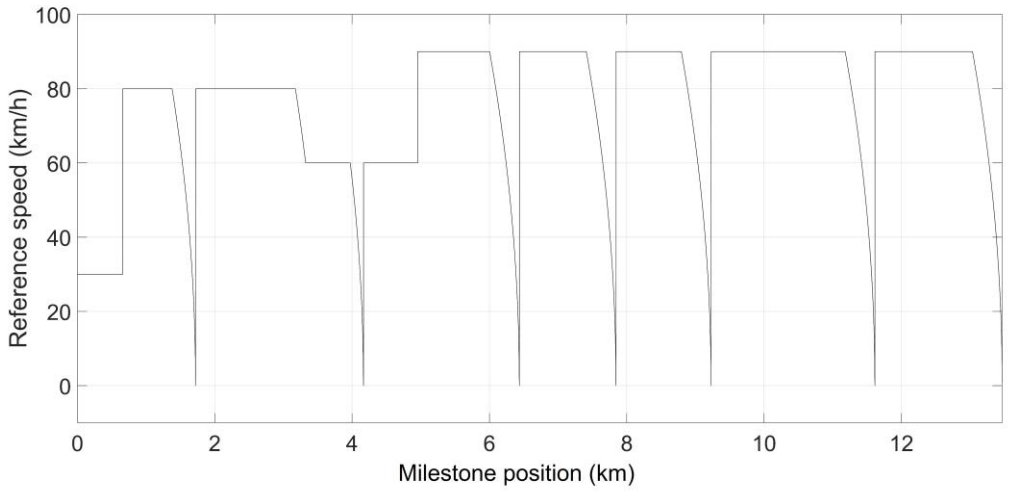

Figure 3: Reference speed profile of a railway line composed of eight stations.

Finally, during the simulation, the signalling action further reduces the speed limit in accordance with the MA prescribed by the RBC, which also considers the distance between the two vehicles. In this way, it is possible to move from static MRSP to its dynamic version, which also accounts for the effect of the signalling system on trailing train motion. If the actual distance is reduced below the safety distance, a deceleration curve is imposed by the OBU, to stop the train before a collision occurs, even in the unlikely scenario of the leading train stopping in place.

2.3 Train model

Once the description of the "MRSP generation" block has been addressed, attention is paid to the modelling strategy adopted to simulate the rail vehicle dynamics together with the driver behavioural model, contained in each "Train" block of Figure 1. The simplified assumption of a point mass is considered to introduce the longitudinal dynamics of the vehicle, considering the following force components to compute the overall reduced force acting on the vehicle:

- traction and braking characteristic curves;
- equivalent motion resistance depending on the square value of vehicle speed;
- effect of longitudinal gradient of the railway line.

In addition, the possibility of varying the speed around the MRSP has been introduced, considering the characteristics of the typical driver. The driver's behaviour consists in commanding traction, braking or coasting so that the speed remains in an interval around the MRSP, bounded by the Lower Curve (LC) and the Warning Curve (WC). The LC-WC range is referred to as the nominal range for the speed control: in standard travelling conditions, the speed will vary within this range according to the algorithm schematically summarized in Figure 4. Each white block represents a state of the speed control system, identified by the corresponding range, while the light-blue blocks specify the driver commands that are executed at each state.

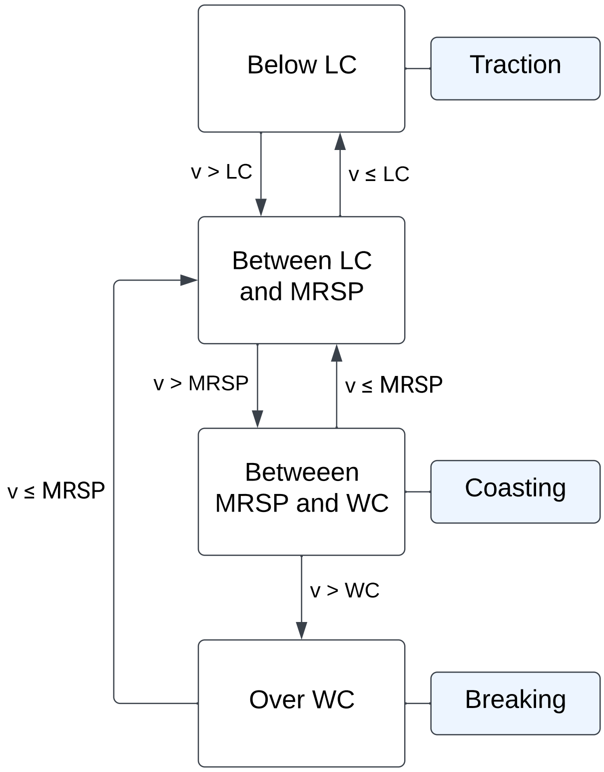

Figure 4: Algorithm of the driver behavioural model governing the standard travelling condition (speed bounded between LC and WC curves).

To increase the realism, when the speed reaches the WC a warning signal is shown to the driver, who will be prone to respond based on its reactiveness. This way, the possibility to exceed the WC can be simulated. Therefore, to ensure the safety of the network in the latter case, additional thresholds have been also introduced to automatically prescribe Service and Emergency Braking Intervention (respectively SBI and EBI), without the driver's intervention. Note that a breaching of the SBI automatically activates the service brake, reducing the vehicle speed down to the nominal LC-WC range; on the other hand, exceeding the EBI starts a timer after which the emergency brake is automatically issued, stopping the train for the remaining simulation time.

In Figure 5, the different speed curves introduced in the simulation environment are reported with different colours and hatching. In addition, the actual speed of the train is reported as a black solid line, which results from the speed control algorithm defining the driver's behaviour, the speed reference curves and the dynamic characteristics of the vehicle.

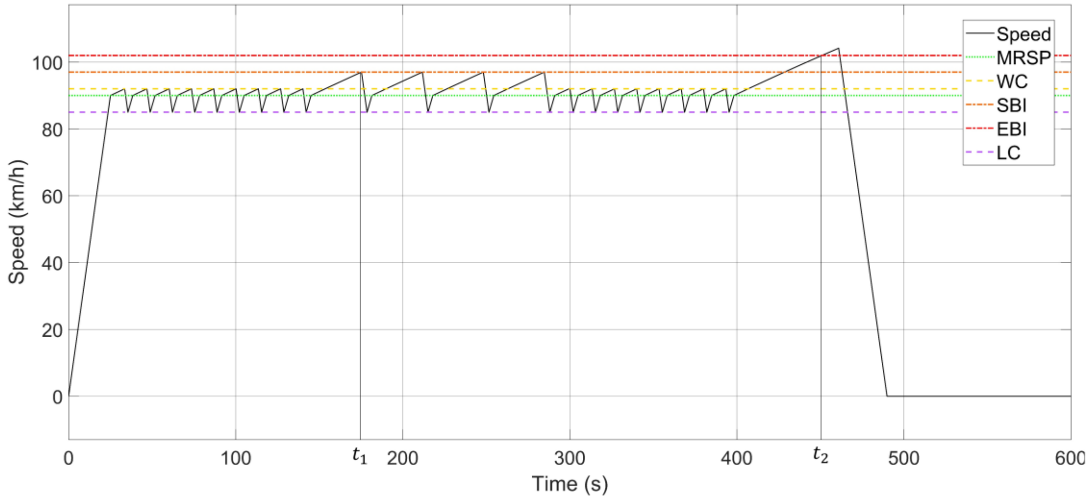

Figure 5: Example of speed limit curves defined within the control algorithm and actual vehicle speed as a function of time: t_1 is the first time instant from which the speed exceeds the SBI; t_2 is the time instant at which the speed exceeds the EBI.

While the driver is responsive, the speed remains within the nominal speed control range (between the LC and WC). Figure 5 also shows how the model responds to a breaching in the SBI and EBI. Note that the speed exceeds the SBI in multiple instances, starting from time t_1, and the safety system is able to revert it to the nominal range LC-WC. Moreover, a breaching of the EBI occurs at time t_2, and the system activates the emergency braking after a timer of 10 seconds has elapsed, thus stopping the train motion.

2.4 State evaluation

With reference to the simulator scheme presented in Figure 1, the State evaluation blocks are now presented. Their main task is that of solving the equations of motion to compute the speed and position of each train, which constitute their state for MVB signalling system. To be closer to reality, the block also introduces some drifts (that typically occur due to wheel lock and slip during braking and acceleration phases), which are periodically compensated by balise devices, also included in the model. As a result, the train instantaneous position along the line is computed.

In addition, the State evaluation block handles the train integrity, which represents a crucial aspect to ensure the safety of the network, especially in the case of MVB signalling (where no trackside devices are expected to accomplish this task). In the proposed simulation tool, the detection of a loss of train integrity is not modelled. However, a Boolean signal is adopted to report the integrity state of the train: a value of 1 is associated to the verified integrity, while 0 stands for non-confirmed integrity of the train. This signal is provided to the State evaluation block, which will modify the position of the rear end of the compromised train by considering it as detached from the rest of the convoy. As a result, its position remains still at the last recorded value. Since the MA of each train is evaluated by considering the rear end of the preceding vehicle, in case of integrity loss of the leading train, the trailing one decelerates and stops to prevent a collision with the detached wagon. Most commonly, however, integrity losses are due to communication errors, meaning that the wagon has not actually detached. This possibility has been also implemented in the simulation, allowing the Boolean value to temporarily assume a null value (loss of integrity) and then restoring its usual value of 1 (confirmed integrity).

Once the description of the simulation environment has been presented, in the next section the first results of the simulations will be shown. Major attention will be dedicated to the response of the second train, due to a different number of scheduled stops with respect to the leading one. Moreover, the influence of the driver characteristics over the signalling actions and consequent train movement will be highlighted.

3 Results of the simulations

This section will present the results of the simulations performed with the developed tool. The simulations consider a line with eight stations (also including the departure one), as shown in Figure 3. Two trains are modelled, which perform different passenger services, as they do not stop at the same stations. In particular, the leading train stops at every station of the line, while the trailing one only stops at the first three and last two stations. Moreover, in order to show the effect of different driver attitudes on the trains motion, two drivers have been considered: driver A is highly responsive to warning signals, relies only on the 50% of the vehicle traction curve (while in case of braking, the full curve is followed) and prescribes a low threshold for commanding traction; driver B presents opposite features, as he is less reactive and presents a more aggressive driving attitude. In the simulations, the leading train is always controlled by driver A, while both drivers A and B have been employed to guide the trailing train.

In order to highlight the impact of the driver model on the simulation, a timetable was purposely not considered: when a train stops at any station, 60 seconds are waited (simulating passengers getting on and off the train) before departure. As a consequence, if a train reaches a station earlier than expected, it will not wait for a predefined scheduled departure but rather leave after 60 seconds, therefore increasing the impact of the driver model onto the performance of the train motion.

Figures 6 and 7 represent the results of the simulations in terms of trains speed and position as a function of time. To ease the comparison in case of the trailing train, the results obtained with both drivers A and B are superimposed on the same figure. Additionally, the reason for each train stop (namely the presence of a station or the action of the signalling system) is reported. Note that the signalling actions affect only the second train, in case of reduced distancing from the first one.

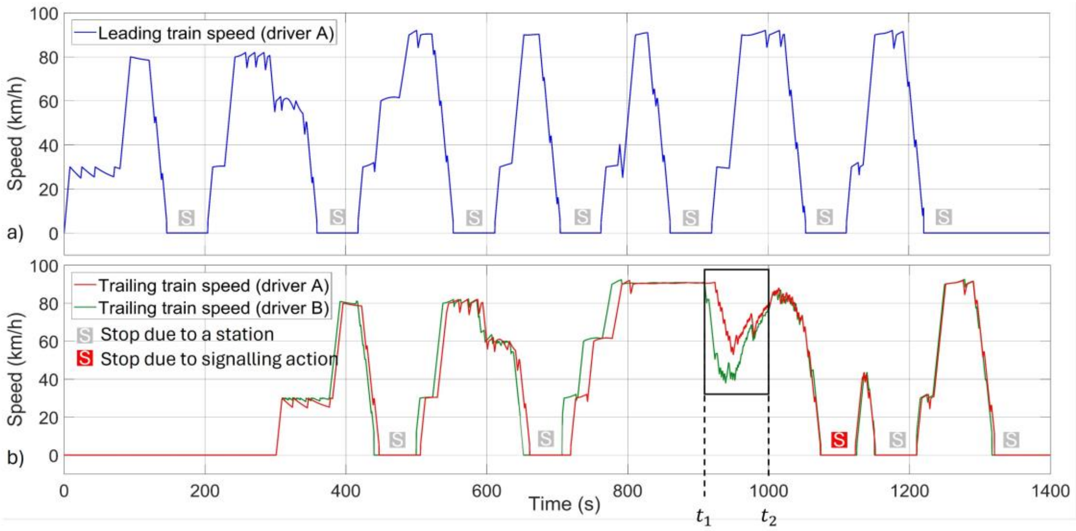

Figure 6: Results of the simulations in terms of trains speed: a) leading train, b) trailing train guided by driver A (in red) and B (in green).

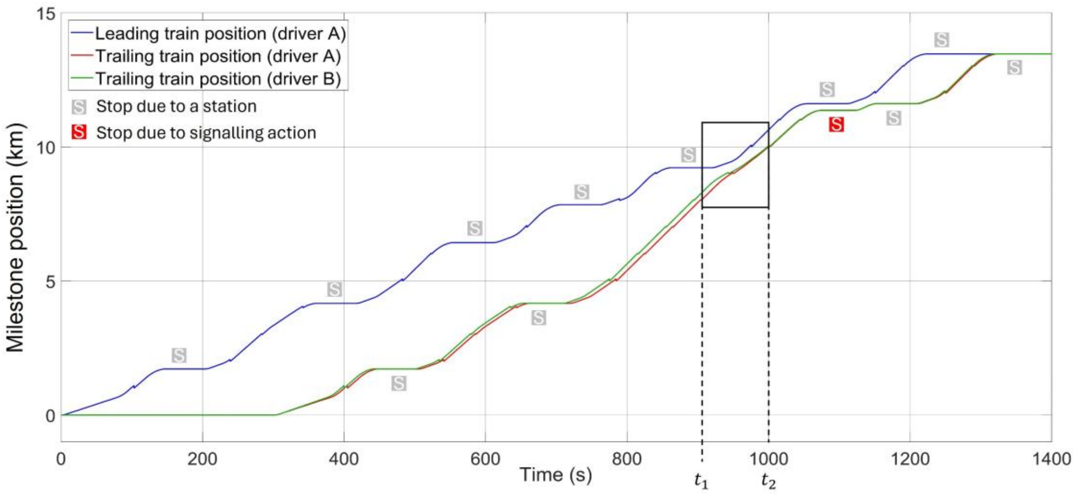

Figure 7: Results of the simulations in terms of trains position for both leading train (in blue) and trailing train results (driver A in red, driver B in green).

The results show the main achievement of the simulator, which is to guarantee the safety by continuously ensuring an adequate distancing between the trains. Therefore, even if the initial lag of 300 seconds allows the trailing train to reach the leading one (given the reduced number of stations to be served), the signalling system prevents any collision. It is worth noting that this occurrence should be avoided by a proper scheduling of the departure of the second train and the introduction of a timetable, that were instead purposely neglected to show the action of the signalling system.

For what concerns the different drivers of the trailing train, their impact can be evaluated by considering three sections of Figure 6 b), identified by dashed vertical lines. Up to t_1, the simulation is characterized by no action by the signalling system. In this section, given the presence of just the stopping time of 60 seconds at each station, driver B (in green) turns out to gain advantage with respect to driver A (in red) since he reaches the cruise speed faster and generally maintains a higher average speed. Therefore, the time the trailing train needs to reach the first three intermediate stations reduces if the aggressiveness of its driver increases. Moreover, at time t_1 the trailing train is closer to the leading one if it is controlled by driver B, as visible in Figure 7. Therefore, the signalling system will activate later for the trailing train when driver A is employed, as shown in Figure 6.

The second section of the simulation spans between times t_1 and t_2. In this case, the signalling system heavily impacts on the motion of the trailing train. Due to the characteristics of driver B, the trailing train is closer to the leading one (compared to the case of driver A) and the signalling system prescribes the trailing train with a more demanding deceleration in order to maintain the safety distance, as also highlighted within the black box in Figure 7.

Finally, after time t_2 the signalling system is regularly activated since the two trains are now travelling at close distance. Therefore, the differences between drivers A and B become negligible if compared to the hindrance imposed by the signalling system. As a result, while the time needed to reach some intermediate stations is lower with an aggressive driver, there are no significant differences in the duration of the overall trip when the trailing train is operated by drivers A or B.

4 Conclusions and Contributions

This paper presents a time-based simulation tool implemented in Matlab and Simulink software for testing the MVB signalling system. The model offers a detailed and modular representation of the railway system components, exhibiting a high degree of expandability and customization. The Radio Block Centre is modelled to assess the state of the network, to provide the trains with their Movement Authority and to issue the signalling actions when required. This information is provided to the On-Board Units, which generate the speed limit that the vehicles must respect. Moreover, the simulator incorporates the vehicle dynamics and driver behavioural models, which serves as the speed control algorithm. Thus, it maintains the speed within a nominal range and prescribes the necessary actions in case the speed breaches predetermined thresholds.

A case study considering two trains performing different stops along the same railway line was considered. The capability of the signalling system to correctly slow down and prevent the trains collision was assessed. Moreover, a comparison between different driving attitudes was provided, showing that driver’s features have significant impact on the train motion when no timetable is considered and signalling system does not come into play. On the other hand, when the motion of the trailing train is hindered by the signalling system (or, likewise, by the definition of a timetable that regulates the arrival and departure time at each station), its overall performance does not improve with the employment of an aggressive driver.

Future steps in this research include the application of the simulator in a variety of operational scenarios, to test the limits of the tool and the capabilities of the MVB signalling system. Moreover, thanks to the modularity of the simulator, it will be possible to realize a hybrid simulation environment, including virtual and physical components, for testing and validation of the signalling system.

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