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A modular simulation tool for fixed block and moving block railway signalling systems

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Abstract
The railway signalling system is a key player in controlling train traffic, with the purpose of guaranteeing safety while respecting transport demand. For rail vehicles, visual-based driving is unfeasible, and thus, railway signalling systems have been developed as answers to this issue. Moreover, the increasing demand for railway traffic requires improved signalling system performances. Recent developments have led to the theoretical definition of the Moving Block signalling system as an approach to overcome the limitations of the Fixed Block system, currently adopted in many applications worldwide. This paper focuses on the development of a modular time-based simulation tool for Fixed Block and Moving Block railway signalling systems. The simulator incorporates all main elements for the assessment of signalling system's performances, including the model of the Radio Block Centre, used for the communication among the trains, the On-Board Unit, which generates the reference speed profile, the vehicle longitudinal dynamics, and the speed control algorithm, emulating a human driver's behaviour. Different operational conditions have been considered to show the capabilities of the simulator, which may represent a first step towards the reduction of on-site testing of railway signalling systems.

Keywords Railway signalling system · Fixed block · Moving block · Railway system simulation · Railway vehicle dynamics · Driver behavioural model

1 Introduction

The basic function of a railway signalling system is to guarantee the safe operation of all trains along the network. This is obtained through a proper distancing among the vehicles, enforced by allowing or denying the access to a section of the railway line and imposing a speed limitation to the train, and related to its braking distance [1]. To this end, it is essential to set an exchange of information between each train and a ground control site. In applications under the European regulations (ERTMS/ETCS, European railway transport management system/European train control system), the ground control site is referred to as the radio block centre (RBC) [2]. During railway operations, the RBC receives information from each train in the area under its control, concerning their state (e.g. their position, speed, or integrity conditions). By observing the state of all the trains, the RBC then provides them with their movement authority (MA), which is the permission to move from one point of the line to another, following prescribed speed references and limitations.

Multiple modern signalling approaches may be identified, differing in the control strategies adopted to handle train distancing, as well as in the nature of the information exchanged between on-board equipment and ground devices. Two key approaches are identified as fixed block (FB) and moving block (MB) signalling systems. FB signalling is based on the segmentation of the line into blocks of fixed length and location that can be occupied by one single train at a time. Blocks are defined at the design stage of the line, depending on its specific characteristic and service requirements [3]. The train state consists of its block occupancy, while the MA consists of the allowance to enter and traverse the subsequent blocks, possibly following a reduced speed reference. On the other hand, MB signalling is based on the absolute distance between two consecutive trains. In this case, the train state consists of its position and speed, while the MA relies on the comparison between absolute and safety distance between each couple of trains, so as

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to prevent any collision. However, it is worth noting that along main lines MB signalling has not been yet adopted for commercial use, and only limited experimentations have been conducted so far. An exception is represented by the implementation of MB signalling within the framework of the communication-based train control (CBTC) system. In particular, light and urban railway lines are suitable for such technology, in the light of a more homogenous traffic and generally closed operation [4]. For instance, thanks to these features, one of the most recent metro lines that serve the city of Milan (Metro 4) implements an MB signalling system with CBTC standards and an autonomous driving system [5].

2 State of the art and scope of the research

This section is dedicated to a detailed presentation and critical discussion about the simulation approaches that could be used to enhance the reduction of on-site testing of signalling systems. In fact, before operating with a signalling system, a complex procedure must be followed, starting from modelling the single component up to the final on-site testing. However, the validation and testing process is long, expensive, and potentially dangerous, especially for the assessment of degraded scenarios. Therefore, simulation environments for railway signalling systems have been developed as means for the evaluation of their performances, aiming at the reduction of on-site testing.

Considering the research activity that tackled this topic, two main simulation approaches have been adopted: event-based and time-based simulations. The former relies on a discrete set of events that, when triggered, advance the simulation by performing the related computations. For instance, Ref. [6] presents a model of the vehicle dynamics based on discrete events, considering its response to the action of an FB signalling system, while in [7], the MB signalling system is also included. The event-based simulator presented in [8] enables an in-depth analysis of specific ERTMS functionalities in controlled settings, ensuring compliance with the railway systems. Finally, in [9], a microscopic simulator is presented for metro systems, relying on the events of trains and passengers' arrival, and studying the problem of skip-stop policies as a mean to reduce travel time.

On the other hand, time-based simulations rely on even time intervals and perform the computation of all variables of the system at each time step. As a result, time-based simulations are more computationally demanding than event-based ones, but they better resemble the movement of the train across the line and can reach a higher level of detail. Thus, they are more suitable for applications related to signalling system analysis in degraded conditions [10]. Among them, TrainDy [11] is a software that performs longitudinal dynamics computation including pneumatic brake dynamics: It was developed in MATLAB® and validated by representatives of the Union Internationale des Chemins de Fer (UIC). In [12], the authors present the Train Dynamics and Energy Analyser/Train Simulator (TDEAS), which models longitudinal dynamics with a focus on energy analyses, vehicle connection, and interaction with lateral and vertical dynamics. In [13], a model that can be calibrated without any mechanical data was presented, making it ideal for implementation in transportation simulators. Moreover, time-based simulation enhances performance evaluation of the signalling systems. For instance, in [14], a model for the assessment of the energy consumption, theoretical line capacity, and travel duration for multi-train applications was proposed, considering FB and MB signalling systems and implementing an asynchronous strategy to assess the impact of each train to the one following it. Most software for intelligent transport system and decision support system are developed according to a time-based approach, such as Opentrack [15, 16] and the rail traffic controller [17]. As it is evident by the above presentation, commercial software can be adopted by train dispatchers to optimize the resources utilization and to assess the overall traffic capacity. Finally, it is worth noting that these software may also allow simulating other distancing logics, such as virtual coupling, in which train-to-train communication is established [18, 19]. It follows that this logic can be regarded as a further advancement with respect to MB signalling system, since the relative braking distance is considered in place of the absolute one. In case of virtual coupling, both trains speeds are considered to evaluate their distancing, and shorter headways can be obtained by implementing the platooning system. However, this approach is not considered for analysis at this stage of the work, since the focus is posed on FB and MB signalling systems.

Within this context of research, this paper presents a time-based simulation tool purposely developed to handle both FB and MB signalling systems. With respect to other works in the field, the simulator simplifies the vehicle dynamics, for instance by considering only one degree of freedom and excluding pneumatic braking. This allows to reduce the simulation time without compromising the relevance of the results, which focus on railway. At the same time, the control architecture contains all the main elements of the real system, such as a multi-functional RBC and a speed regulator that emulates the behaviour of a real driver with a discrete event subsystem. The speed regulator includes coasting phases and possible delays in the reaction to warning signals. Moreover, the interaction between different trains within the simulation is synchronous, meaning that it is possible to disturb the motion of one train and observe, within the same simulation, its effect on the motion of the following train.

Finally, the simulator has been built with a particular focus on modularity, such that each component can be modified without impacting the operation of the overall system.

It is worth noting that the desired level of detail of the model is that so simulation time can be reduced without compromising the relevance of the results towards the performance assessment of MB signalling. Therefore, the modelling approach leans operation towards the macroscopic one, even if elements typical of microsimulation are considered [20]. Therefore, abstraction is utilized to simplify some intricacies of the railway signalling system, as will be furtherly explained in Sect. 3, and the aggregation of data allows to reduce the degrees of freedom of the model. On the other hand, elements such as the reference speed generation contain a higher level of detail, to manage the complex topic of accurate deceleration and stopping due to the continuous update of signalling-related information.

The objective of this research is the development of a simulation tool capable of reproducing different signalling logics, including the most important elements that participate in railway signalling operation. For instance, in this work, a simplified vehicle model, a realistic driver behavioural model, and the RBC are considered. At this stage of the research, the main focus is on the realization of a flexible tool able to simulate FB and MB signalling logics, rather than performing a detailed comparative analysis of the performance of the two systems. Nevertheless, future developments include the adoption of the tool to assess the performance of FB and MB systems by means of appropriate performance indicators, in different operating scenarios. It is here anticipated that the comparative analysis of such distancing logics is, however, out of the scope of the present work.

This paper is organized as follows. In Sect. 3, the simulation environment will be described, starting with an overview of the high-level architecture, and later delving into the two main components defining the railway signalling module and the train one. Section 4 is then devoted to presenting the application of the simulator to a given set of operational scenarios. Finally, in Sect. 5, main conclusions are drawn, and future developments are described.

3 Description of the simulation environment

This section provides an overview of the simulation environment. The simulator has been developed in MATLAB® and Simulink® software, and its high-level architecture consists of two main components, the Trackside and Trainborne modules, as shown in the block diagram in Fig. 1.

The Trackside module (green-shaded box in Fig. 1) includes the model of the RBC and the generation of the speed limit profile, referred to as the most restrictive speed profile (MRSP). It receives as inputs the state of the trains (represented by block occupancy for FB and position and speed for MB), as well as the general characteristics of the infrastructure (reported as grey blocks) and returns as outputs the reference speed profile that the trains must follow to comply with their MA.

The Trainborne module (red-shaded box in Fig. 1) contains both the vehicle dynamics and the driver's behavioural

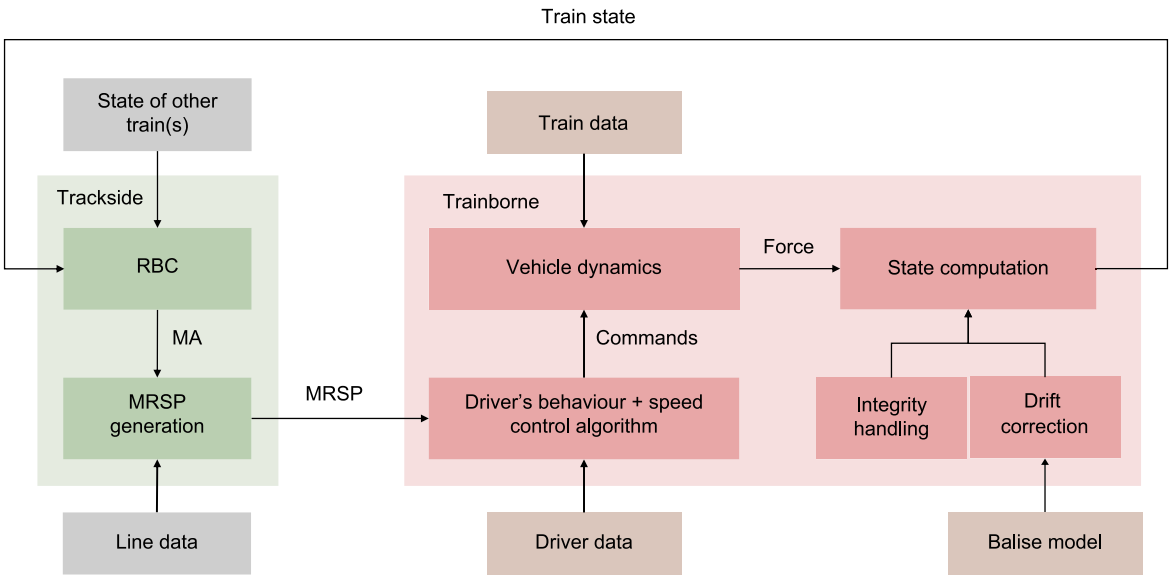

Fig. 1 Overview of the simulation environment architecture. The green-shaded blocks represent the Trackside components, with grey input blocks; the red-shaded blocks correspond to the Trainborne components, with brown input blocks

model (used as speed control algorithm). These two components evaluate the traction force to be applied to the train to follow the MRSP provided by the Trackside module. Additionally, the state of the train is computed to realize the feedback loop with the Trackside module. The inputs of the Trainborne module are the MRSP, the train and driver features, and the signals from the balises, which are transponders installed at fixed locations along the line with the aim of conveying safety-related information to the train, such as its accurate positioning [21] (brown blocks). Finally, the output of the Trainborne module is the state of the train.

The real railway infrastructure system includes many other components, which have not been included in the simulation environment due to the simplifying assumptions under consideration. For instance, mention can be made to interlocking, multi-aspect FB signalling, and RBC handover. Interlocking [22] refers to the system that handles route reservation, with the aim of preventing overlapping and potential collisions. Multi-aspect FB signalling systems make use of a multitude of signals to prescribed different speed targets to reach within one block; for instance, Italian railway lines consider up to nine aspects [23], while in this work, the simplified assumption of three aspects FB signalling is made. Finally, RBC handovers [24] refer to the practice of delivering the supervision of each train motion to a different RBC, when it enters its control area. The presented simulator contains abstraction with respect to these components and features, but it still guarantees a sufficient accuracy and relevance to compare FB and MB signalling systems on a level of detail between micro and macroscopic.

In the following, a detailed description of both modules is provided. Specifically, Sect. 3.1 presents the Trackside module while Sect. 3.2 is dedicated to the Trainborne one.

3.1 Trackside module

The main elements of the Trackside module are the RBC and the MRSP generator. These components significantly depend on the signalling system, since they deal with the conveyance of the relevant information to and from the trains.

3.1.1 Radio block centre (RBC)

The RBC is essentially a switchboard that communicates with the trains travelling in its area of influence, receiving the relevant information on their train state and reporting their MA. The RBC model will be described separately for FB and MB signalling systems.

In FB signalling systems, the train state is provided in terms of the block occupancy specifying within which block it is currently travelling. The MA is provided in terms of signal aspects (corresponding to a set of coloured signal lights), indicating the reference speed profile over the following blocks. In particular, a three-aspect system has been implemented in this work, with the following features:

- A green aspect indicates a free block. Therefore, the train can continue its motion without hindrance.
- A yellow aspect indicates a free block followed by an occupied one. In this case, the train must start decelerating in order not to enter the occupied block.
- A red aspect identifies an occupied block. Thus, the train is not allowed to enter the block.

The reason for implementing a three-aspect FB signalling system, instead of more advanced multi-aspect approaches, lies in its conceptual and modelling simplicity, as well as on its broad applicability. Nevertheless, future development of the simulation environment will include other FB signalling approaches, including up to nine aspects.

In the simulation tool, the coloured signal is determined by comparing the block occupancy of two consecutive trains. If a block changes its clearance, the MA of the following train changes as well. For instance, a train that encountered a yellow signal at the entrance of a block may then receive a green signal if the following section clears.

A crucial issue of this kind of signalling systems lies in the design of the blocks length. They are dimensioned so that any train travelling at the maximum allowed speed can comfortably stop (maximum deceleration of 1 m/s^2) within their length, considering the minimum friction coefficient between wheel and rail. The fixed block length (FBL) can be evaluated to fit the specification of the line as shown in Eqs. (1)–(3):

$$\mathrm{FBL} = S_\mathrm{s} + S_\mathrm{r} + S_\mathrm{o}, \tag{1}$$

$$S_\mathrm{s} = \frac{v_\mathrm{max}^2}{2a_\mathrm{pr}}, \tag{2}$$

$$S_\mathrm{r} = v_\mathrm{max} t_\mathrm{r}, \tag{3}$$

where S_s is the stopping distance from the maximum speed (v_max) allowed in that section, considering a prescribed deceleration rate (a_pr); S_r is the distance covered during the driver's reaction time (t_r); and S_o is an additional fixed margin introduced for safety and robustness. For instance, considering a railway line with $v_\mathrm{max} = 160$ km/h, a prescribed deceleration rate $a_\mathrm{pr} = 1$ m/s^2, and a reaction time $t_\mathrm{r} = 3$ s, the fixed block length must be higher than 1124 m, with the specific value depending on the margin S_o. For simplicity, in this work, a constant fixed margin $S_\mathrm{o} = 226$ m was assumed, so that in total FBL = 1350 m. Note that this is a typical vale for FB signalling systems along the Italian railway lines [23].

Focusing now on MB signalling systems, significant changes can be recognised for the RBC. First, the input/output variables are different, as the train state is provided to the RBC in terms of vehicle speed and position of both its front and rear ends. Moreover, considering a scenario with two trains (referred to as leading and trailing trains), the MA is provided in terms of the comparison between safety and absolute distances between them, together with the state of the trailing train if the safety distance is violated.

A schematic representation of the RBC architecture for MB signalling system is shown in Fig. 2. The train state is represented by the grey input blocks, and the result of the operations is reported to the generator of the reference speed profile (dMRSP), represented by the grey output block.

As shown in Fig. 2 and presented in [25], in case of MB signalling, the RBC performs three main operations:

- Absolute distance computation as the actual space between the rear end of the leading train and the front end of the trailing one,
- Safety distance computation, and
- State detection in case of safety distance violation, which is crucial for the design of an appropriate deceleration curve.

Major attention should be paid to safety distance evaluation, which guarantees that the trailing train can stop with no collisions even in the case of a sudden stop of the leading train, still assuming a comfortable deceleration for passengers. Therefore, the safety distance (d_{safe}) can be obtained as shown in Eqs. (4)–(6).

$$d_{\text{safe}} = d_{\text{s}} + d_{\text{r}} + d_{\text{o}}, \tag{4}$$

$$d_{\text{s}} = \frac{v^2}{2a_{\text{pr}}}, \tag{5}$$

$$d_{\text{r}} = vt_{\text{r}}, \tag{6}$$

where d_{s} is the distance required to stop the train from its current speed (v) with a prescribed deceleration rate (a_{pr}); d_{r} is the distance covered during the driver's reaction time (t_{r}) at the current speed (v); and d_{o} is a fixed margin added for safety reasons. Equations (4)–6) resemble (1)–(3), since the violation of the safety distance can be considered dual to the reception of a yellow aspect in case of FB signalling system. Indeed, when the safety distance is violated, a braking curve is imposed on the trailing train, so that it decelerates as it gets closer to the leading train, eventually stopping before colliding. The important difference is that Eqs. (4)–6) consider the actual speed of the train (v) instead of the maximum one (v_{max}) allowed in any section of the line. Consequently, the safety distance d_{safe} of Eq. (4) is generally shorter than the fixed block length FBL of Eq. (1) for an equivalent service.

3.1.2 Most Restrictive Speed Profile (MRSP) generation

The MRSP is the speed reference that the trains must follow to comply with the MA assigned by the RBC itself. The process for its generation includes multiple steps, the first being the realization of a look-up table that associates a reference speed to each point on the line. The speed changes at fixed locations, referred to as speed variation points (SVP). When the speed limit increases, an instantaneous change is introduced in correspondence with the SVP; then, the actual speed will vary according to the vehicle dynamics and the speed control algorithm. When the reference speed decreases, it follows a curve defined to ensure that the train can reach the target speed in correspondence with the SVP, by following a prescribed uniformly decelerated motion. The braking distance is evaluated as

$$l_{\text{brk}} = \frac{v_{\text{in}}^2 - v_{\text{out}}^2}{2a_{\text{pr}}}, \tag{7}$$

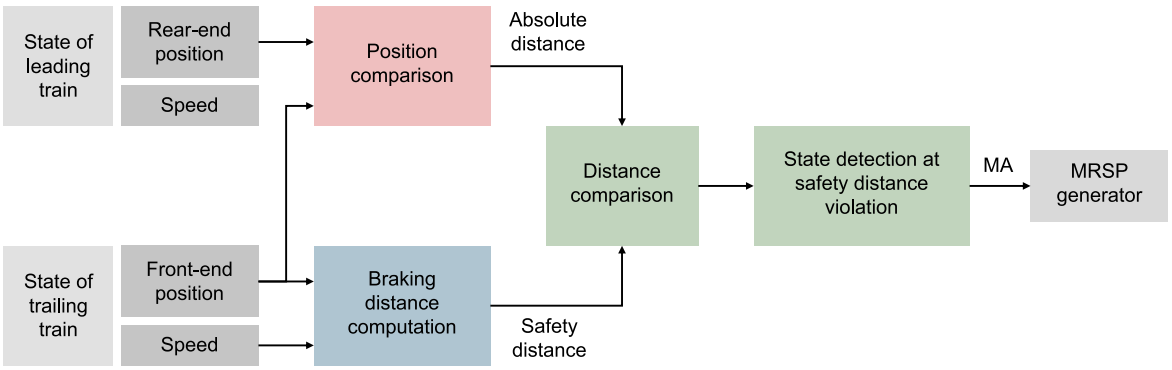

Fig. 2 RBC architecture for MB signalling

where l_{brk} is the space needed to decelerate the train from v_{in} (speed while approaching the SVP) to v_{out} (allowed speed when leaving the SVP), with prescribed deceleration rate. Therefore, in the space immediately before the SVP, the reference speed (v_{ref}) changes parabolically with respect to space:

$$v_{ref}(s) = \sqrt{v_{in}^2 - 2a_{pr}\left(s - \left(s_{SVP} - l_{brk}\right)\right)} \text{ for } s \in \left[s_{VCP} - l_{brk}, s_{VCP}\right], \tag{8}$$

where s is the position of the train, and s_{SVP} is the position of the SVP.

To account also for the presence of the stations, additional SVPs are introduced. Specifically, each station is represented by two coincident SVPs: The first one is associated to a speed decrease required to stop the train at the station, therefore requiring the design of a deceleration curve; the second SVP prescribes a speed increase with null approach speed, and a leaving speed equal to the nominal reference in that point of the line.

Two examples of the designed look-up table are presented in Fig. 3a, b, with both figures obtained from the same railway line. In Fig. 3a, the train must stop at each one of the 12 stations of the line. Conversely, in Fig. 3b, a reduced service where the train skips most intermediate stations is considered. Therefore, referring to the static reference speed profile, it is possible to identify some differences in the performed service, even if based on the same physical route.

The following step in the MRSP generation consists in the transposition of the look-up in the time domain. This is achieved by running the simulation, thus considering the time-based motion law of the train while it follows the space-based reference speed, such as the ones presented in Fig. 3a, b. The result is referred to as the static most restrictive speed profile (sMRSP), which expresses the relationship between reference speed and travel time. As expected, the speed decreases following a linear deceleration curve with respect to time. Moreover, for each station, a dwell time of 60 s is considered, and a reduced speed limit of 30 km/h is imposed within the station area, before reconnecting to the overall reference speed 100 m after the station. Figure 4 represents with a black solid line the static MRSP, resulting from the simulation of a service considering the space-based reference speed profile presented in Fig. 3b.

The last step in the procedure concerns with the inclusion of the speed decreases associated to the signalling system due to the presence of the other trains. A new signal is generated which represents the dynamic Most Restrictive Speed Profile (dMRSP). Since the dMRSP generation involves the signalling system, it must be treated separately in the case of FB and MB systems.

For FB signalling, the dMRSP generation module detects when the train encounters a yellow signal and measures the speed of the train at that time instant. When a yellow signal has not been encountered, the dynamic MRSP follows the static one; otherwise, it follows a deceleration curve that starts from the current position and

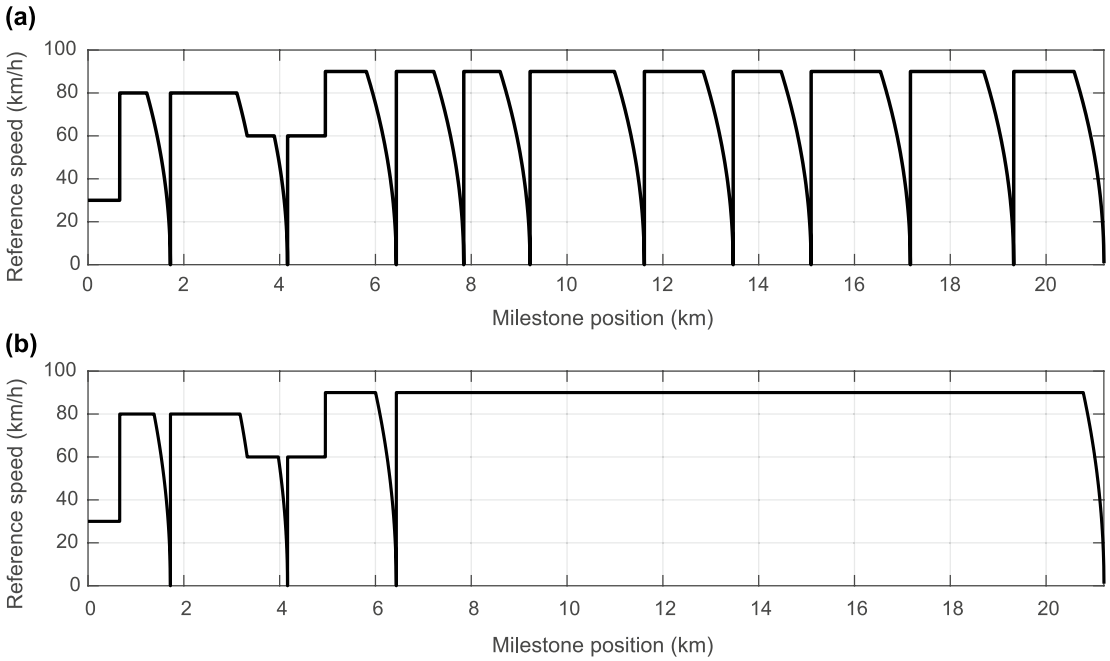

Fig. 3 Space-based reference speed look-up table of **a** a service that includes 12 stations and **b** a service that includes 5 stations

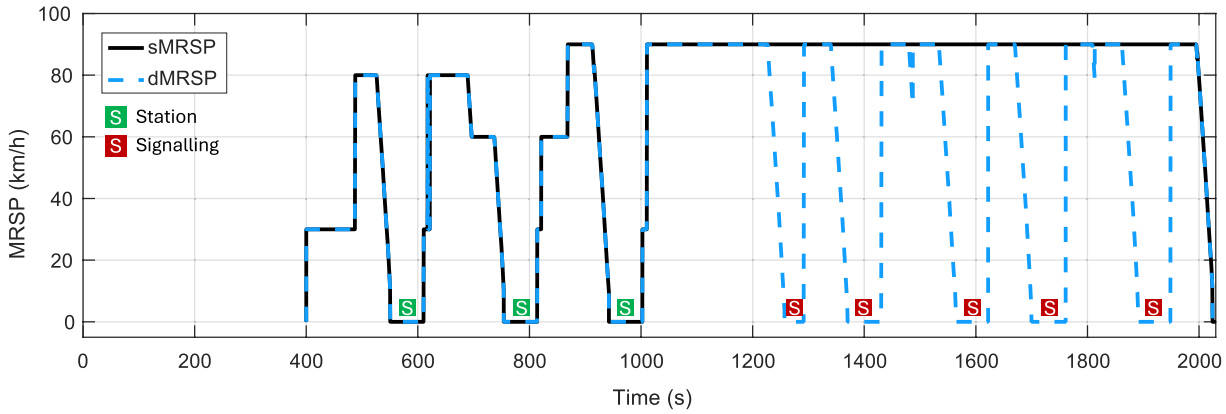

Fig. 4 Time-based sMRSP and dMRSP obtained considering the space-based reference speed represented in Fig. 3b and an FB signalling system. Green and red squares indicate stop due to, respectively, the presence of a station and the constraining action of the signalling system

speed, and prescribes a zero-target speed in correspondence of the end of the block:

$$\mathrm{dMRSP}_{\mathrm{FXB}}(s) = \sqrt{v_{\mathrm{y}}^2 - 2a_{\mathrm{pr}}\left(s - s_{\mathrm{b}}\right)} \text{ for } s \in \left[s_{\mathrm{b}}, s_{\mathrm{b}} + \frac{v_{\mathrm{y}}^2}{2a_{\mathrm{pr}}}\right], \quad (9)$$

where $\mathrm{dMRSP}_{\mathrm{FXB}}$ is the dynamic MRSP evaluated for an FB signalling system; v_{y} is the speed measured at yellow signal detection; and s_{b} is the position of the initial section of the block that the train is currently occupying.

In case of MB system, when a violation of the safety distance is not detected, the dynamic MRSP follows the static one; if this is not the case, the dMRSP generation module receives as inputs the state of the two trains at safety distance violation, and it imposes a braking curve designed so that the trailing train decelerates at a constant rate and stops before colliding with the leading one:

$$\mathrm{dMRSP}_{\mathrm{MVB}}(s) = \sqrt{v_{\mathrm{v}}^2 - 2a_{\mathrm{pr}}\left(s - s_{\mathrm{v}}\right)} \text{ for } s \in \left[s_{\mathrm{v}}, s_{\mathrm{v}} + \frac{v_{\mathrm{v}}^2}{2a_{\mathrm{pr}}}\right], \quad (10)$$

where $\mathrm{dMRSP}_{\mathrm{MVB}}$ is the dynamic MRSP evaluated for an MB signalling system; and $\left(s_{\mathrm{v}}, v_{\mathrm{v}}\right)$ defines the state of a train (position and speed) when it violates the safety distance with the train ahead.

If Eqs. (9) and (10) are compared, it can be observed that the expressions of the dMRSP for FB and MB are similar, remarking the parallelism between the effect of a yellow aspect and the violation of the safety distance. It should be noted that if the leading train resumes the motion, it may free the block it was occupying (in case of FB), and the distance between the two vehicles may overcome the safety distance (if MB is considered). In these cases, the dMRSP coincides with the sMRSP, until a new yellow signal (FB) or safety distance violation (MB) occurs.

For the sake of clarity, an example of dMRSP is presented in Fig. 4 with a blue dashed line, considering the trailing train behaviour under FB signalling system. Stops caused by the presence of a station are indicated by green squares, while the ones induced by the signalling system action are indicated by red squares. Data are reported from time t = 400 s onwards, since the considered trailing train starts moving with an initial headway with respect to the start of the simulation (t = 0 s). After the 4th station (departure time t = 1000 s), the train encounters a series of yellow signals due to the presence of a train in front of it. Therefore, the dMRSP deviates from the sMRSP, leading to unscheduled decelerations and stops.

For sake of simplicity, if not furtherly specified, in the following, the dMRSP will be simply indicated as MRSP, as it is the reference speed profile provided to the trains by the RBC.

3.2 Trainborne module

Once the module devoted to the simulation of the RBC and the generation of the MRSP has been described, attention will be posed to the Trainborne block of the simulator. This block consists of the following sub-modules:

- Vehicle dynamics model,
- Speed control algorithm and driver behavioural model, specifically designed to evaluate the driver effect over the signalling system, and
- Computation of the train state.

These components are mostly shared among different signalling systems, with the only exceptions of the computation of the train state, which includes sub-components specifically designed for FB or MB signalling systems.

3.2.1 Vehicle dynamics

The longitudinal dynamics of the vehicle is modelled as a lumped mass on which three main actions are applied, namely motor output force (F_{mot}), longitudinal gradient (F_{grd}), and motion resistance (F_{res}), as shown in Eq. (11):

$$F = F_{\text{mot}} + F_{\text{grd}} + F_{\text{res}}, \tag{11}$$

where F represents the total longitudinal force acting on the train, modelled as a lumped mass.

The motor output force (F_{mot}) heavily depends on the train model and its electrical motor. In general, a distinction is made to account for traction, service braking, emergency braking, and coasting phases.

Traction and service braking forces are functions of the train speed, with an expression that can be customized depending on the specific train. In the following, reference is made to the characteristics of a typical vehicle running along main lines. At this stage of the research, pneumatic braking is not included in the model, and no distinction between rheostatic and regenerative electric braking [26] is made. Therefore, the electric braking force is set to its maximum for low-speed value, emulating a more complex braking system which can rely on different braking sources, which blend depending on vehicle speed. Concerning the emergency braking, this is modelled as the maximum braking force that can be delivered. Finally, coasting refers to the instance when the motor is not generating any force. An in-depth description of the choice of the specific action to be delivered in terms of motor force will be provided in Sect. 4.2, where the driver model and the speed control algorithm are presented. For the sake of completeness, Fig. 5 shows the maximum traction and braking forces as a function of speed, for the train considered in this work.

For what concerns the force component associated with the longitudinal gradient (F_{grd}), both uphills and downhills are included, assuming the slope of the line to be a satisfactory approximation of its grade angle [27], as shown in Eq. (12):

$$F_{\text{grd}} = mg \sin(\alpha(x)) \cong mg \ \text{slope}(x), \tag{12}$$

where m is the mass of the train, and $\alpha(x)$ and slope(x) represent the grade angle and gradient of the line at position x in terms of vertical displacement over horizontal displacement. For completeness, the longitudinal gradient profile of the railway line considered in this work is presented in Fig. 6.

Finally, the motion resistance (F_{res}) includes the contributions of aerodynamic drag and rolling resistance, as presented in Eq. (13):

$$F_{\text{res}} = -mg\left(C_{\text{d}}v^2 + C_{\text{f}}\right), \tag{13}$$

where C_{d} and C_{f} represent the simplified motion resistance parameters.

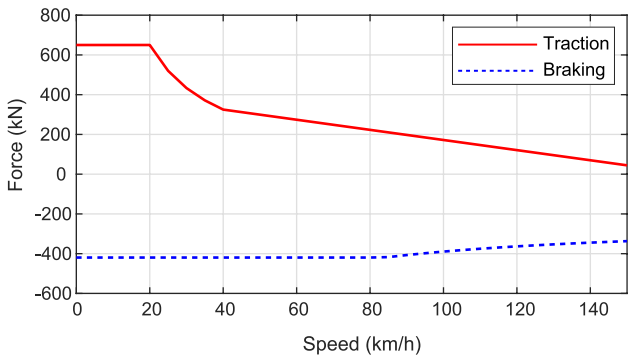

Fig. 5 Maximum force that can be generated by the electrical motor of the train, both in traction and braking phases

3.2.2 Driver behavioural model and speed control algorithm

The second main component of the Trainborne block is represented by the driver behavioural model, that provides the commands that the train must follow (namely traction, braking, emergency braking, and coasting) to comply with the prescribed MRSP.

The underlying logic to the driver's behaviour is the speed control algorithm, which can be described by introducing additional reference curves built upon the MRSP. The main idea is to provide upper and lower limits around the MRSP, so that the commands will be issued to maintain the speed within that range and then add further curves for automatic braking in critical scenarios. This strategy implemented in the simulation tool is an abstraction of how real braking curves are defined by the ETCS equipment [28]. In ETCS, the emergency braking deceleration curve is computed to comply with the speed target provided by the trackside devices. The emergency braking intervention (EBI) is thus determined as the location beyond which supervision is assigned to the ETCS, rather than the human driver to execute the emergency braking procedure. Similarly, the service brake intervention (SBI) is defined to advance the automatic supervision to comply with the MRSP, without needing to rely on emergency brake (which can be detrimental for both rolling stock and track). Furthermore, other supervision limits are computed to guide the driver in respecting the MRSP (and thus the MA), without the need for the intervention of the automatic braking system: namely the indication (I), permitted (P), and warning (W) curves. Each of these curves acts as a threshold to provide the driver with the necessary indication not to cross other supervision limits.

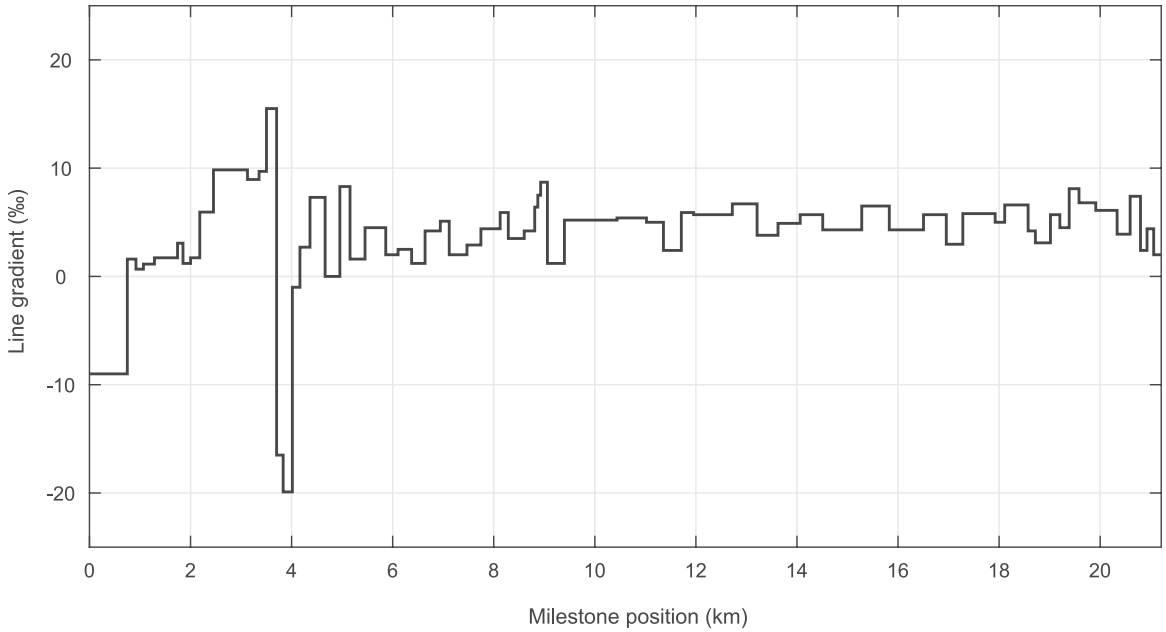

Fig. 6 Longitudinal gradient profile of the line considered in the simulations

In the presented simulation environment, the MRSP corresponds to the permitted curve, 5 km/h above which the warning curve (WC) is defined, in agreement with [29] and corresponding to the warning supervision limit. When the speed exceeds the WC, the driver will be alarmed with a warning signal and may respond by commanding braking. Therefore, the speed will decrease down to the MRSP and below, reaching another threshold referred to as the lower curve (LC), which is set 5 km/h below the MRSP and represents the point where the driver will command traction. It should be noted that while the offset between MRSP and WC is regulated by the ETCS standards, the one between MRSP and LC is part of the driver's behavioural model, therefore making it an editable input to the simulation environment. To model the driver's non-idealities, a Gaussian probabilistic model has been designed, with mean equal to the nominal LC value and variance assigned as a parameter of the driver. Therefore, the speed at which the driver commands traction varies around the LC, and traction could be activated slightly above or below that threshold depending on the driver's behavioural model. In order to reduce the redundancy and complexity of the overall speed control algorithm, and to assign precise duties to each threshold, the indication curve has not been included in the simulation environment. Still, the main elements of this threshold-based speed control system have been accounted for and are coherent with the ETCS regulations.

The LC–WC range is referred to as the nominal speed control range, within which the driver can command traction, braking, and coasting. To clarify the designed control logic, a block scheme is proposed in Fig. 7. Each state is represented by a rectangle associated to a specific command of the driver. Note that if no new commands are provided, the previous one remains active.

To better emulate the behaviour of a human driver, the possibility of a missed warning signal has been implemented with a probabilistic approach: As the speed exceeds the WC, the warning signal is activated, and the driver is characterized by a probability of responding to it (by commanding braking) which increases as time goes by. The baseline

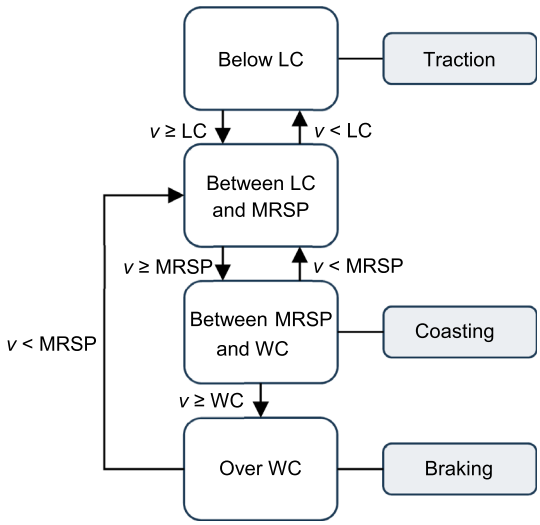

Fig. 7 Speed control algorithm flowchart in the nominal range LC–WC

probability and the rate of its increase are two parameters that characterize the driver, so that it is possible to model the reactiveness of the driver to warning signals.

The possibility that the current vehicle speed exceeds the WC without a prompt response from the driver makes it mandatory to include additional reference profiles to activate an automatic response, to guarantee the safety of the whole system. To this end, the SBI is defined 5 km/h above the WC. If this threshold is reached, braking is automatically commanded, making the speed return in the nominal LC–WC range. In addition, the EBI is defined another 5 km/h above the SBI. When the speed exceeds this threshold, and if no action is taken by the driver within 3.5 s (in accordance with [28]), the emergency braking is issued until the train reaches a final stop (end of simulation). Note that SBI and EBI correspond to the homonymous curves defined within the ETCS regulations, while the EBD curve is represented by requesting the lapse of a timer before activating the emergency braking in case of an EBI crossing.

Figure 8 represents the outcome of a simulation that shows how the model responds to a breaching of the SBI and EBI limits. Notice that the speed exceeds the SBI in multiple instances, starting from time t_1, due to the simulated reduction of the driver's reactiveness, and the safety system can revert it to the nominal range LC–WC. Moreover, a breaching of the EBI occurs at time t_2, when a malfunctioning of the service brake activation system is simulated: The emergency braking procedure is initiated, thus stopping the train. It should be noted that to show these features of the simulator, a steep downhill line has been considered, so that the speed increases even during the coasting phases.

Once the control algorithm implemented in the driver model has been addressed, a final comment can be made. It is worth recalling that each vehicle is characterized by specific traction and braking diagrams. In this regard, additional parameters of the driver behavioural model concern the utilization of the maximum traction and braking forces. Indeed, when these commands are provided by the driver, the traction and braking forces are multiplied by utilization coefficients. These parameters may differ in case of traction and braking, thus characterizing the general driving attitude of the driver, which results in faster or slower acceleration and deceleration.

3.2.3 Train state computation

By combining the dynamic model of the vehicle and the behavioural model of the driver, it is possible to precisely evaluate the force acting on the train. Therefore, to realize the feedback loop between the train and the RBC, the state of the train must be computed in terms of block occupancy for FB signalling, and train position and speed in the case of MB signalling. This is performed in three steps, namely numerical integration, injection, and correction of a positional drift and handling of the train integrity (only for MB signalling).

At first, the equation of motion of the vehicle is considered, and the speed and position are computed by numeric integration. As mentioned before, to guarantee the passengers' safety and comfort, the acceleration is saturated at ± 1 m/s^2. The only exception is represented by the case of the emergency braking, when the maximum deceleration allowed is considered.

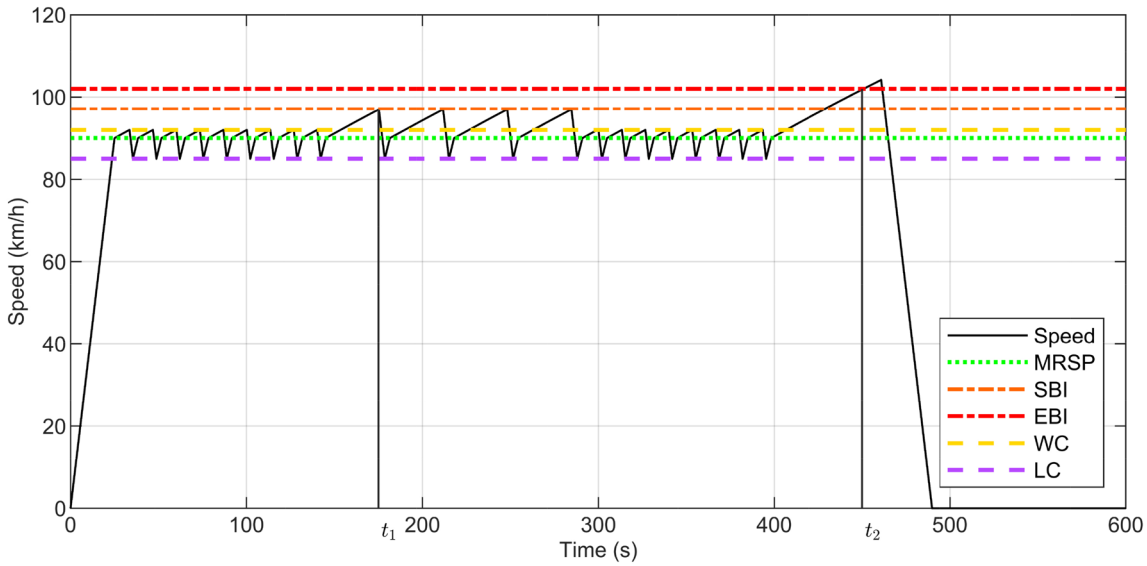

Fig. 8 Response of the model to a breach of the SBI (from time t_1) and EBI (at time t_2)

As a second step, peculiar aspects of the railway system are considered. Specifically, reference is made to wheel creepage (deviation from ideal rolling kinematic conditions) that generally occur during the acceleration and braking phases of the train trip. In such cases, the odometry, that is the signal representative of the travelled space, typically shows some drifts with respect to the actual train position along the railway line [30]. To cope with this phenomenon, railway lines are equipped with balises. The odometry drift is simulated by adding a ramp (with slope equal to 0.05) to the signal of the train position, which will deviate from the nominal value for increasing simulation time. This results in an increase of 50 m for each travelled kilometre, which is added gradually along the train motion. Concerning the balises, any time a train passes in correspondence of these devices, the train position is calibrated to match the nominal one, compensating for the drift (i.e. the drift ramp resets to 0). At the current stage, a simplified scenario consisting in single balises (instead of clusters of 1–8 balises) evenly spread across the railway line (with spacing equal to 450 m) is considered, simulating perfect communication capabilities.

The correction of the train position is implemented regardless of the signalling system. Then, only in the case of FB signalling, the railway line is discretized according to the designed block length, and the block occupancy is thus evaluated. Note that the block length is generally different along a railway line, as it is dependent on speed limitations, presence of railway stations, etc. For what concerns the simulation environment, the simplifying assumption of uniform block length along the entire line was made, either computed to fit the specification of the line (Eqs. (1)–(3)) or set to the standard value (Sect. 3.1).

Only in the case of MB signalling, a further step is implemented regarding train integrity confirmation and handling, which is duty of Trainborne equipment, conversely to FB signalling where trackside circuitry-based sensors can be used. Therefore, this feature is implemented within the Trainborne block, and it consists in an indicator stating whether the train integrity is checked and confirmed. On a real vehicle, the train integrity can be identified with different techniques, such as the on-board train integrity (OTI-I) and train length determination (OTI-L) functions, compliant with ETCS [31]. On the other hand, within the simulation environment, it is modelled as a Boolean variable virtually generated, which assumes value 1 if integrity is confirmed and 0 otherwise, and can be modified to simulate degraded operational scenarios.

To handle the critical occurrence of an integrity loss, the rear end position of each train is modified in case of a null integrity signal. The position of the rear end of a train that has lost its integrity remains constant and equal to the last recorded position. This way, the RBC can evaluate the MA for the trailing train based on the rear end position of the leading one.

Furthermore, the model considers the possibility that an integrity loss is caused by a communication error rather than an actual detachment. Therefore, it is possible to restore the integrity once the communication error has been resolved. In this case, the train rear end instantaneously reverts to its nominal position, assuming a distance from the front end equal to the train length. In Fig. 9, an example of communication error leading to the loss of train integrity is presented. Specifically, the leading train integrity is lost at time $t = 300$ s: From that instant on, the rear end positions is kept constant until integrity is restored, at time $t = 400$ s. The trailing train decelerates and stops accordingly, thus preventing any collision.

The description of the simulation environment and all the most relevant features has been addressed, posing the attention on the train state in terms of block occupancy for FB signalling and position and speed for MB signalling. This information is then provided to the RBC model for the computation of the MA, which will complete the simulation loop.

4 Simulation results

4.1 Simulation parameters and operational scenarios

In this section, some examples of simulation results will be presented considering a reference case, to show the model capability to simulate both FB and MB signalling systems. All the simulations refer to two trains (leading and trailing) travelling on a single-track railway segment with no junctions or intersections. The modular architecture of the designed simulator allows realizing a wide range of scenarios, as different choices can be made in terms of vehicle dynamics, driver behavioural model, and infrastructure characteristics, as summarized in Table 1. Out of these parameters, the ones that will be considered in the simulations presented in Sects. 4.2 and 4.3 have been identified with bold type in Table 1. It is here reminded that the scope of this paper is not to provide an extensive comparative analysis of FB and MB signalling using the simulation environment, but rather to present the tool functionality and capability in selected operational scenarios.

Two simulations have been designed to show the features of the simulator. The first one, referred to as simulation A, considers two identical drivers and trains travelling on a line with twelve stations. Therefore, provided that the initial headway with the trailing train is compliant with the time schedule correctly designed, the motion of both vehicles is identical, and no interventions from the signalling system

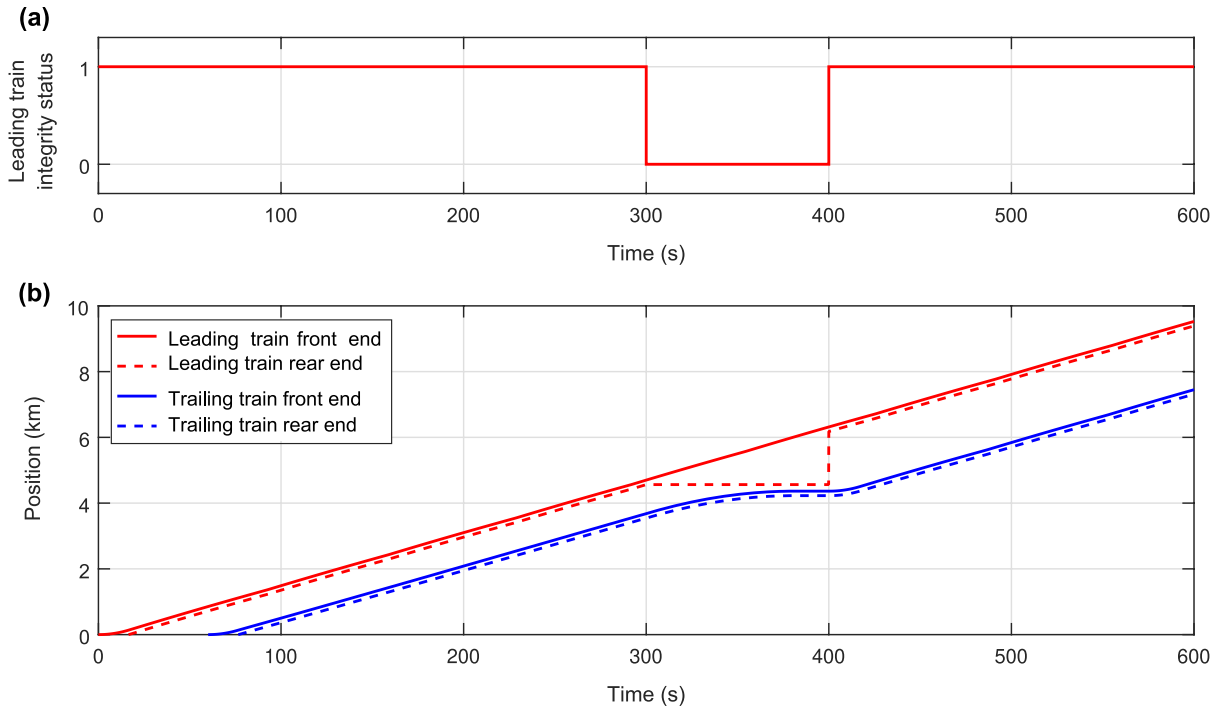

Fig. 9 **a** Integrity signal of the leading train and **b** its effect on the position of the leading (red lines) and trailing (blue lines) trains. Solid lines refer to the trains front ends and dashed lines to their rear ends

Table 1 Parameters of the simulator

Vehicle dynamics	Driver behaviour	Infrastructure features	Service features and disturbances
Train mass	**Warning signal responsiveness**	Line speed limit profile	**Adopted signalling system**
Train length	**Mean and variance of the lower curve threshold**	Number and location of stations	Initial headway of the trailing train
Traction force map	**Traction utilization coefficient**	Longitudinal gradient profile	Subset of station served by each train
Braking force map	**Braking utilization coefficient**	Block length (FB signalling)	**Delays in station departures**
Emergency braking force value	Minimum distance from of occupied block (FB signalling)	Balise spacing	Loss of train integrity (MB signalling)
Motion resistance force parameters	Minimum distance from tail of leading train (MB signalling)	/	**Decreases in the driver's reaction capability**

The factors to be considered in the simulations in Sects. 4.2 and 4.3 are indicated in bold

are expected. However, by injecting an unexpected delay of the leading train in the departure from the fifth station, it is possible to observe the effect of the signalling system as the trailing train approaches the leading one. It will be shown how the constraining action of the signalling system changes by varying the amount of delay. Simulation A will be presented considering the MB signalling system only, to provide a preliminary assessment of the signalling system within simplified scenarios.

Simulation B considers simulation A as a baseline, also including the modification of the parameters of the trailing train driver, which is characterized by a less responsive attitude to the Warning Signals and a more aggressive driving strategy (higher traction utilization coefficient, lower braking utilization coefficient, and lower minimum distance from the end of the movement authority, in accordance with Table 1). All these changes make the trailing train on average faster than the leading one, thus further emphasizing the effect of the signalling system. The results of simulation B will be shown considering both FB and MB signalling systems, allowing for their qualitative comparison.

4.2 Simulation A: MB signalling system and leading train delay

Focusing on simulation A, the initial headway between leading and trailing train is set to 360 s. In this scenario, the leading train is subject to an unexpected delay of 540 s at the fifth station, in addition to the nominal dwell time of 60 s prescribed at each station. Figure 10a, b represents the speed profile of the leading (red) and the trailing (blue) trains plotted as a function of absolute time. Green and red squares, respectively, represent stops due to the presence of a station and due to the constraining action of the signalling system. Note that for clarity purposes, the origin and destination stations of the route are not reported. Considering the leading train, only stops at stations (marked with green squares) are visible in Fig. 10a, since its motion is not hindered by any other vehicle. On the other hand, the trailing train catches up to the leading one, thus requiring a constraining action from the signalling system, as highlighted by the red square in Fig. 10b. This can be observed also in Fig. 11, which shows the position of the leading (red) and trailing (blue) trains as a function of time. Precisely, the stopping delay of the first train clearly causes a forced stop of the second one.

As highlighted with the black and red arrows in Figs. 10 and 11, the unexpected longer stop of the leading train causes the reduction of the distance between the two vehicles, down to safety distance evaluated by the RBC, which from a speed of 90 km/h yields to 900 m. Therefore, the motion of the trailing train is hindered accordingly, and an additional stop (not present in its original timetable) is required to prevent any collision. It can be also observed that the time delay influences the motion of the trailing train for the entire remaining trip, since the safety distance with the leading vehicle is violated at each station beyond the fifth, thus engaging the signalling system. Therefore, the MRSP profile of the trailing train presents irregularities even after the fifth station (which are associated to the oscillations in Fig. 10b, e.g. in the deceleration at $t = 1500$ s).

One possible application of the simulation environment is hereafter proposed. To show the impact of this disturbance to the activation of the signalling system, several different values (ranging from 0 to 900 s) of the departure delay of the leading train have been considered. The outcomes of these simulations are presented in Fig. 12, which shows on the y-axis the time needed to complete the route by each train, and on the x-axis, the additional delay imposed to the leading train. Moreover, the overall activation time of the signalling system is reported as a black line, which indicates for how long the signalling system hindered the trailing train motion, depending on the duration of the delay experienced by the leading train.

The results reported in Fig. 12 show that the leading train route completion time (red line) increases linearly with the leading train delay. Moreover, a lower threshold value of 240 s for which the signalling system never activates can be identified through iterative simulation:

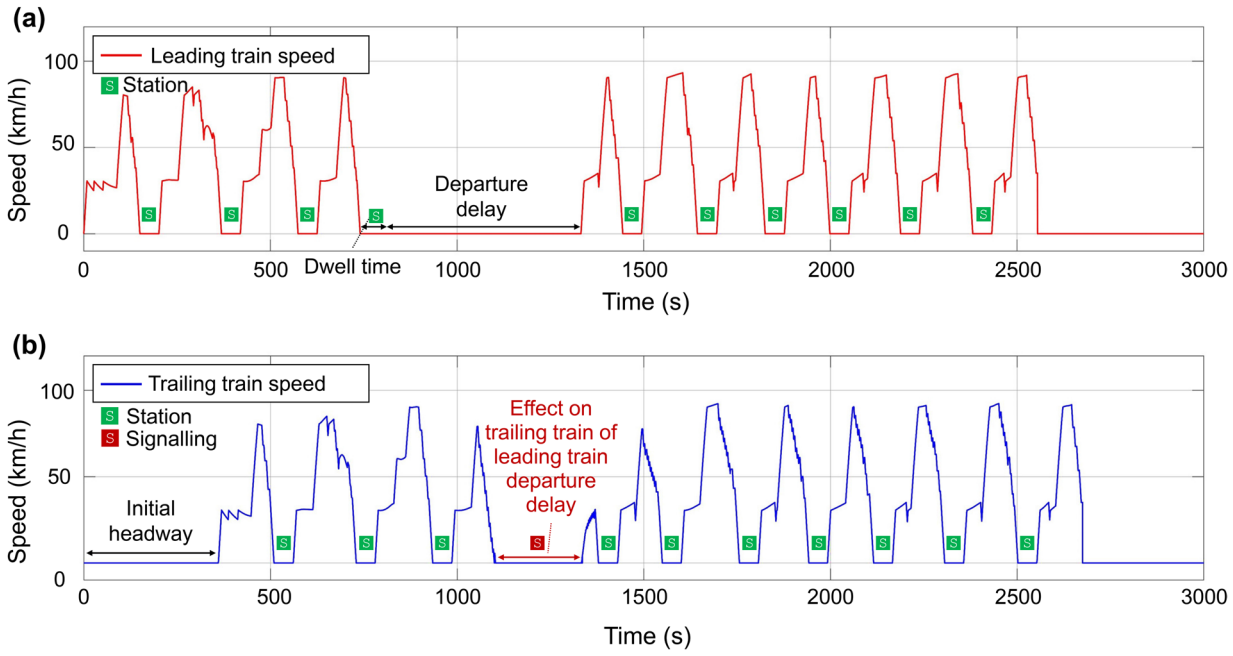

Fig. 10 Results of simulation A considering an MB signalling system and representing the speed profile of **a** the leading train and **b** the trailing train, respectively, in red and blue lines. In **a**, all stops are caused by the presence of stations; in **b**, stops due to stations and due to the constraining action of the signalling system are indicated by green and red squares

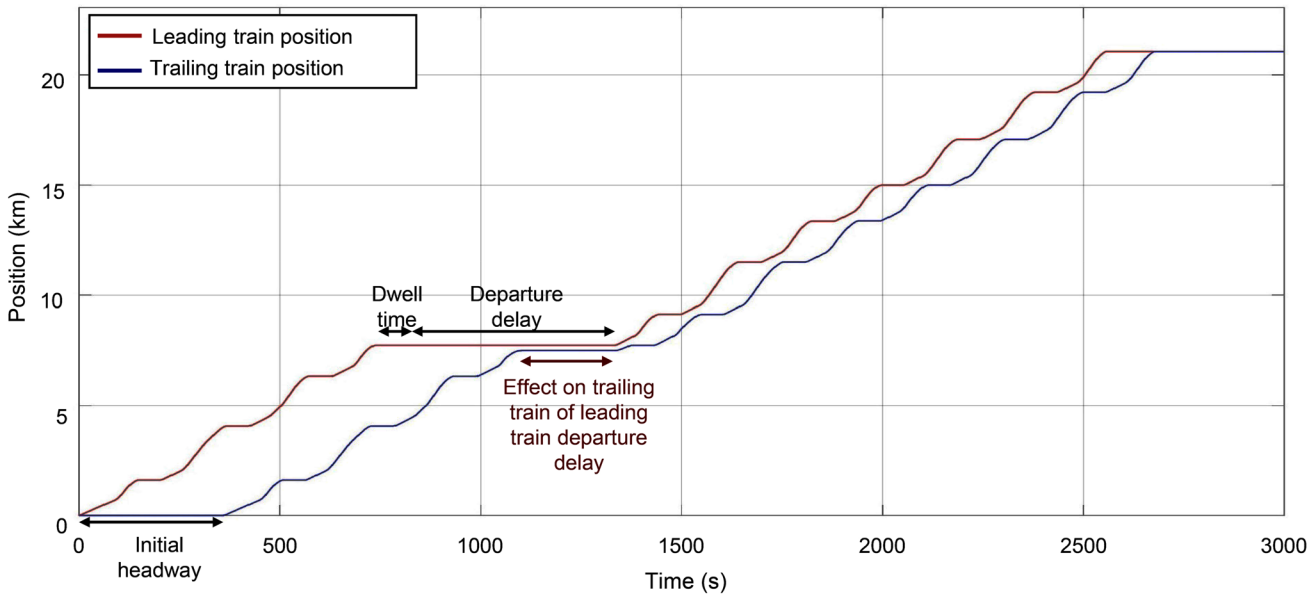

Fig. 11 Results of simulation A considering an MB signalling system and representing the position of the leading and trailing train, respectively, in red and blue lines

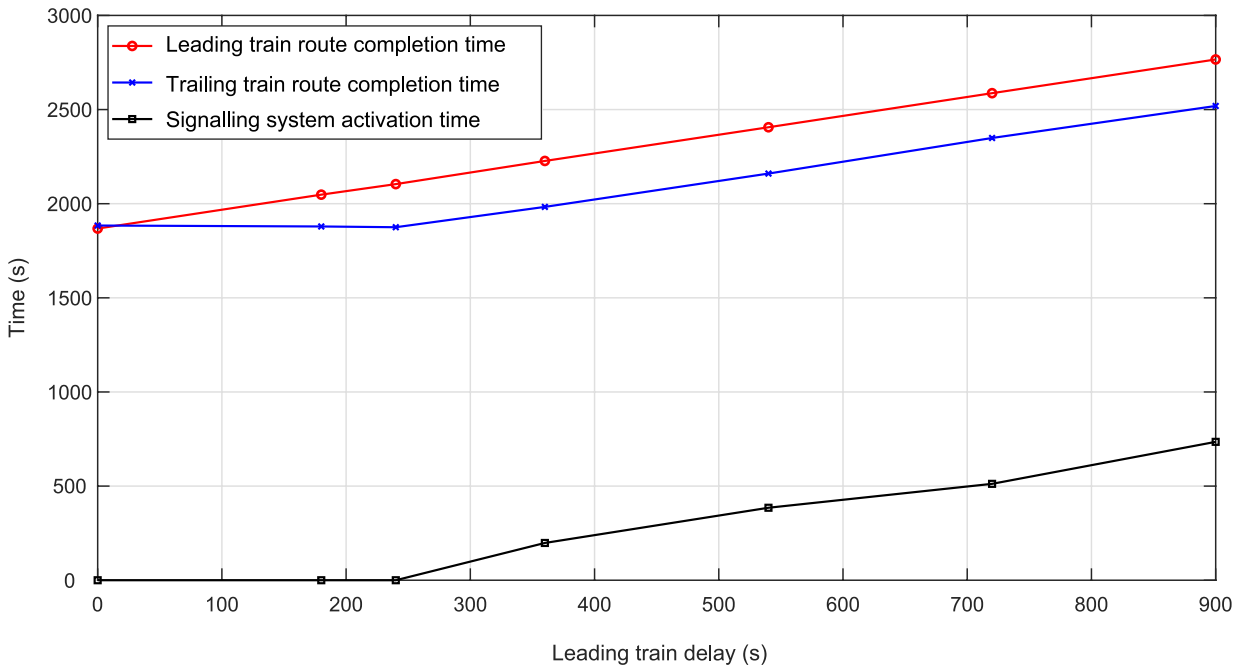

Fig. 12 Simulation A: results with different values of the leading train unexpected delay

Multiple simulations have been run with increasing initial headway, until the minimum value is found. This value allows respecting a green wave policy without increasing the dwell time at further stations [32], making the trailing train (blue line) unaffected by the presence of the leading one. Above this threshold, a linear trend is in fact observed for the trailing train. Concerning the signalling system activation, its profile is less regular, but it is still possible to observe a relation between an increase in the leading train delay and a greater signalling system activation time.

4.3 Simulation B: comparison between MB and FB signalling systems

Once simulation A has been addressed, an example of preliminary comparison between FB and MB signalling systems will be presented. It is here recalled that in simulation B, different parameters of the drivers' models are adopted, to simulate a less reactive and more aggressive attitude of the trailing train driver (which makes on average the trailing train faster than the leading one). Therefore, the influence of the signalling system is expected to become more significant. Figure 13 represents the speed profile of the trailing train, adopting MB and FB signalling systems, respectively, shown in Fig. 13a, b. A departure delay of 360 s is considered.

At first, it can be noticed that the overall duration of the simulation carried out under the MB signalling system (Fig. 13a) is 70 s shorter (2.5% of the total trailing train travel time) than the one performed under FB signalling (Fig. 13b), as highlighted by the green arrow. This outcome can be associated to the management of the MRSP signal, which varies more rapidly when the MB signalling is implemented. The delay of the leading train has a different effect on the trailing one depending on the signalling system employed, as highlighted with the red double arrows in Fig. 13. Considering MB signalling (Fig. 13a), some motion is allowed for the trailing train while the leading one is subjected to the disturbance, resulting in an unexpected stop at around 1100 s: This is due to that the MRSP generation/update and the speed control are based on the absolute positioning of the trains, allowing for a higher resolution in the operations and a lower minimum distance that can be safely maintained between leading and trailing trains. On the other hand, with FB signalling (Fig. 13b), the trailing train stops slightly after 1000 s (almost 100 s before the MB case) and remains stationary until the leading one resumes its motion, since the MRSP generation and speed control must comply with the discretization given by FB system, thus decreasing the resolution of the operations.

Once the simulation results have been discussed in terms of the speed profiles, the attention can be posed to the trains movement along the line according to both MB and FB signalling systems, respectively, in terms of position along the line and block occupancy (block length set to 1350 m, see Sect. 3.1). Figure 14a shows the trains position under MB signalling, while Fig. 14b presents the results in terms of block occupancy under FB signalling, for both the leading and trailing trains. For clarity, in Fig. 14b, the absolute positioning of the trains is also reported with dashed lines (normalized with respect to the block length), even though this information is not available to the RBC.

Comparing the results of Fig. 14a, b, a significant difference can be observed in terms of the minimum distance kept between the vehicles, as previously mentioned. With

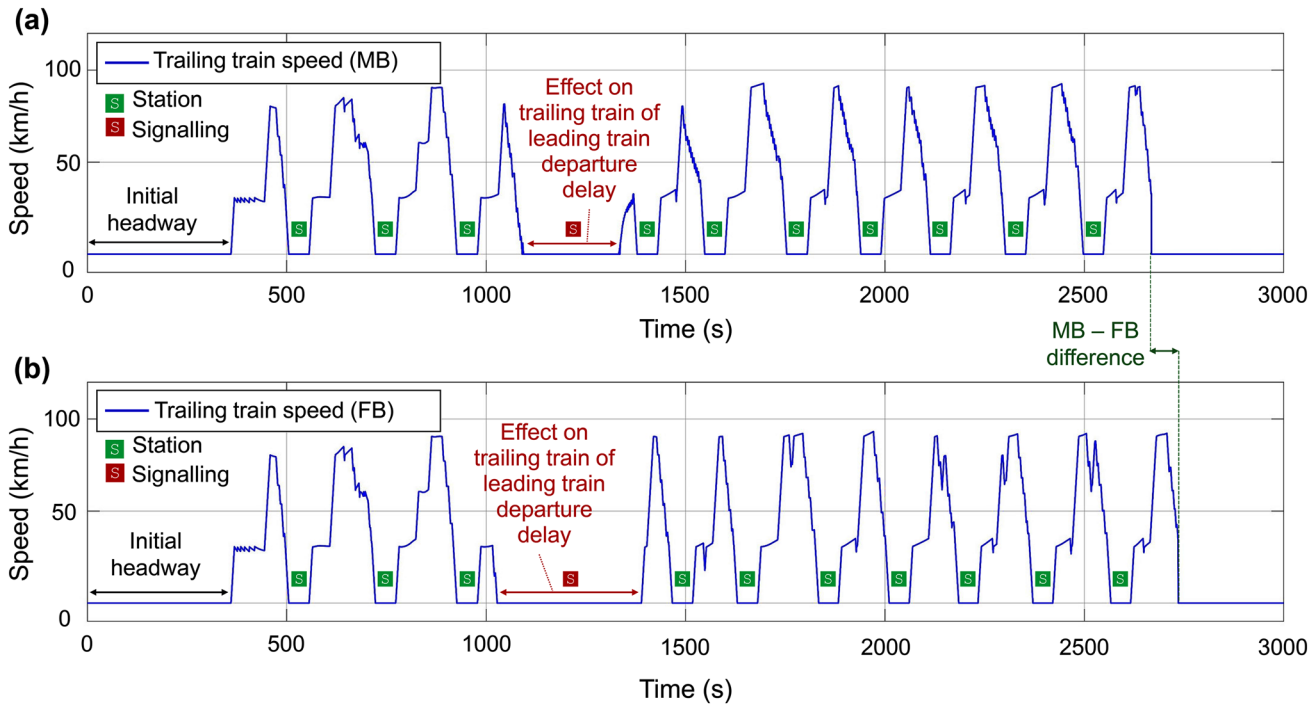

Fig. 13 Results of simulation B in terms of trailing train speed, considering the implementation of both **a** MB and **b** FB signalling systems. Green and red squares indicate stop due to, respectively, the presence of a station and the constraint action of the signalling system

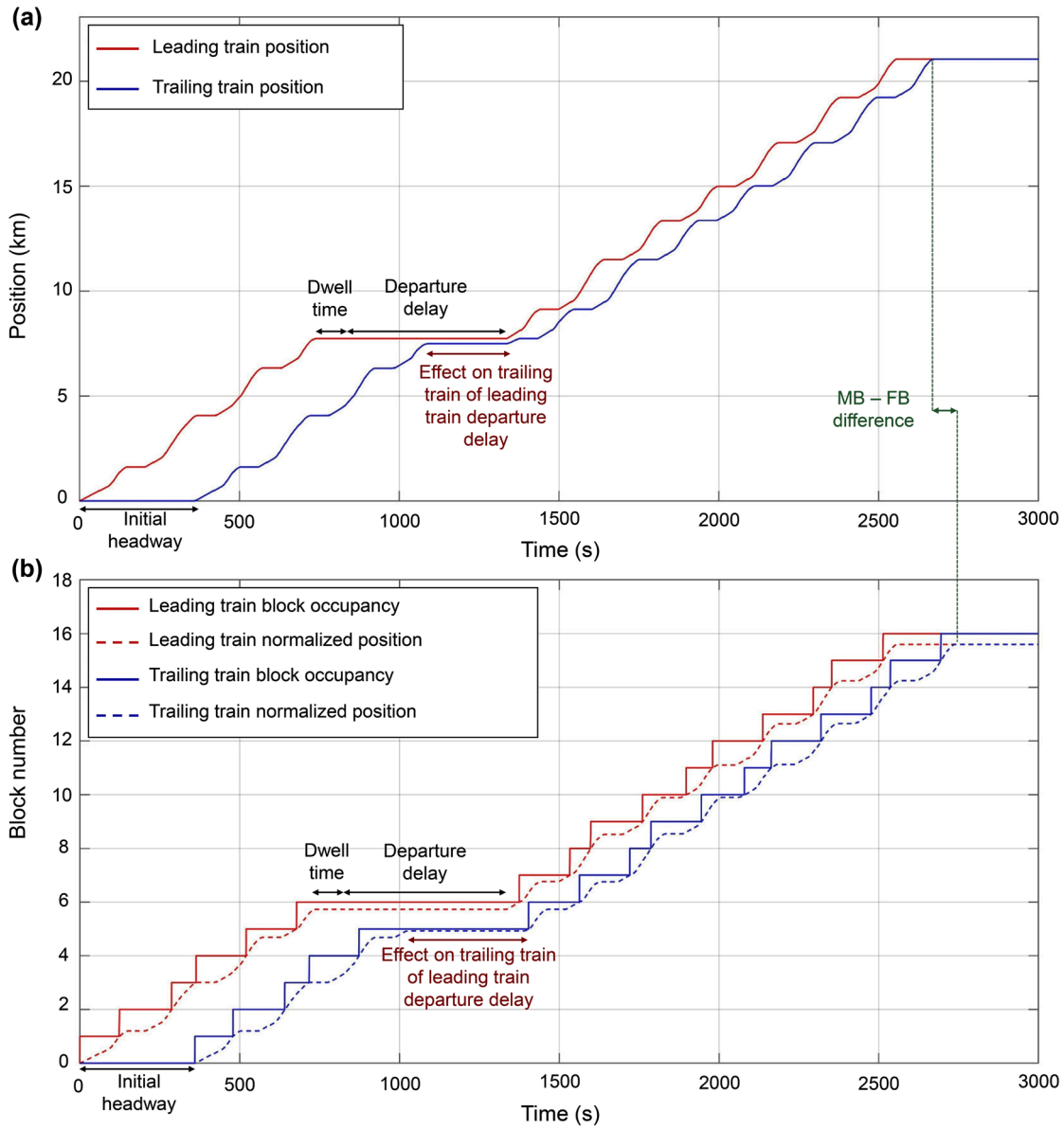

Fig. 14 Results of simulation B in terms of trains position: **a** absolute position of leading and trailing trains according to MB signalling and **b** block occupancy of both trains and their normalized positions within the FB signalling system (dashed lines)

MB signalling, the distance between the trains can reach the safety margin imposed by the driver behaviour model, which in this simulation yields to 200 m (Fig. 14a). Conversely, within FB signalling, the trains distance depends on the positioning of the leading vehicle within the block. As a consequence, even in case the leading vehicle is located close to the exit of the block currently occupied, the trailing train is still constrained to the previous block, making the average absolute distance between them considerably higher. This has an impact on the effect on trailing train of leading train departure delay (red double arrows in Fig. 14), as well as on the overall route completion time, which is 70 s shorter when the MB signalling system is employed (green double arrow).

The presented results show the capability of the simulation tool to emulate the function of FB and MB signalling systems in a unique environment. Although the considered scenarios were simple, they presented a significant level of realism, due to the possibility to inject disturbances and differences in the driver behavioural models. Given the same degraded scenario (departure delay at a station), differences were observed between the service operated through MB and FB signalling. In particular, when an MB signalling system is implemented, the trailing train can postpone its response to the leading train delay, since a lower absolute

distance is allowed. Coherently, the total travel time of the trailing train is reduced, at the cost of a more jagged speed profile. However, it is important to stress that the obtained results are not general but rather limited the two case studies under analysis (simulations A and B). Therefore, to draw more generalized conclusions, a comprehensive parametric investigation is necessary, starting from the parameters gathered in Table 1. This investigation represents one of the first targets to be achieved in the next future.

5 Conclusions

This paper presents a time-based simulation tool implemented in MATLAB® and Simulink® software for testing different railway signalling systems. The developed model allows to time efficiently simulate a wide set of scenarios, acting on several factors such as railway signalling logics, train mechanical parameters, and driver behavioural models. It includes subsystems of both the Trackside and the Trainborne blocks, to provide a representation of all the components acting in the railway system.

Two simulations have been adopted to present the model features, both relative to a realistic main railway line, composed by twelve stations and travelled by two trains (leading and trailing) with identical mechanical features. The timetable has been represented by setting an initial headway between the two trains, and prescribing a fixed dwell time at each station. However, an unexpected delay has been injected in the departure of leading train from the fifth station, therefore reducing the distance with the trailing one, and requiring a constraining action from the signalling system.

Additionally, attention has been paid to the driver's behavioural model of the leading and trailing trains. In simulation A, the two vehicles are driven with the same conduct parameters. Conversely, for simulation B, an aggressive and less responsive driver has been assigned to the trailing train. As a result, getting closer to the leading vehicle in a faster way, a more significant action of the signalling system was observed.

Considering simulation B, both FB and MB signalling systems have been simulated, and the outcomes show that MB signalling systems are featured by a prompter reaction to the modelled departure delay. In fact, a decrease in the travel time of 70 s (2.5% of the total time) was observed when the MB signalling logic is adopted. On the other hand, MB signalling tends to produce a more jagged speed profile, due to its more frequent activation.

For the sake of clarity, no other simulation scenarios are presented to the reader. In fact, the aim of this paper is not to provide a thorough comparison of FB and MB signalling systems performances, but rather to develop a simulation tool that can reproduce different signalling logics, including the most important elements that determine the railway signalling operation (a simplified vehicle model, a realistic driver model, and the RBC). In the presented operational scenarios, injected with an external disturbance, the simulator managed to guarantee the safety of the railway vehicles, handling train distancing to avoid any collision without compromising service completion time.

Next steps of this research activity will take advantage of the modular and expandable architecture of the simulator to define even more realistic scenarios. Among them, a higher number of vehicles and the handover between several RBCs can be listed. Additionally, a quantitative comparison between the FB and MB signalling systems could be targeted, by defining the relevant operational scenarios and the proper performance indicators, such as traffic capacity or energetic efficiency. Finally, these performance indicators could be adopted together with the developed simulation tool to optimize railway operations. To this end, a parametric analysis of the most impactful components, such as the MRSP generation or the driving behaviour, could be conducted.

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