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MULTICRITERIA TRAIN RUNNING MODEL AND SIMULATOR FOR RAILWAY CAPACITY ASSESSMENT

Summary. Railway line capacity is growing in importance as a criterion for the assessment of railroad infrastructure performance. This problem is becoming more and more relevant as the demand for rail transport increases, especially considering the transport policy related to the promotion of climate-neutral means of transport. Insufficient capacity affects the stability and reliability of railway traffic operations. The analytical methods used for capacity estimation are typically insufficient to solve problems of a multicriteria nature (i.e. problems which take traffic heterogeneity and human factors into account). Optimisation methods, on the other hand, usually yield the best results if the current timetable for a given line is known. Additionally, they do not strongly consider the impact of the running characteristics of a specific train type and of the system or several systems in operation on the line (e.g. national Class B system and ERTMS/ETCS system). Therefore, this paper proposes a model and a simulation program developed in the Matlab and Simulink environment to be used to simulate on-route train movement, to study railroad capacity with different control systems, as well as for predictive train control to minimise energy losses. The authors described the assumptions adopted for the simulation program and the input parameters configurable against a specific line segment. They also discussed selected results derived from simulations of controlling the departure of trains to a railway line with the purpose of energy loss reduction.

1. INTRODUCTION

Railway line capacity and utilisation are important parameters taken into account when designing timetables, lines, or traffic control systems. Sufficient railway line capacity makes it possible to provide adequate transport services, which is an important aspect of the promotion of low-carbon means of transport, such as rail transport [1, 2]. This capacity depends on numerous factors, including track layout, railway traffic control system, timetable, train type structure, potential interference between trains, as well as the human factor affecting the manner in which trains are controlled. The complexity of this process makes simple analytical methods typically applied for railway line capacity determination insufficient.

Modelling and simulating on-line train movement make it possible to estimate railway line capacity by considering the entire variety of simulated objects (i.e. trains, different lengths of block sections, the station layout, the complexity of traffic operations under a given control system, and the human factor associated with train control). Depending on the needs, such a simulation environment enables tests of individual interfaces and system behaviour based on input signals triggering the expected

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reactions of the tested system, as well as the simulation of events which would be difficult or impossible to test in a normal operating environment (e.g. emergency situations). An example of the foregoing is the use of a reference test stand for certification testing of railway traffic signalling devices and systems to confirm their compliance with the applicable safety, functionality, and technical compatibility requirements [3]. For the reason described above, an attempt has been made to develop such a model under this study.

This paper discusses a simulation model which makes it possible to simulate the on-route movements of trains with different characteristics and to study the effect of a railway traffic control system designed on such aspects as on-route train behaviour, railway line capacity and the possibility of increasing it by changing the control system configuration.

2. LITERATURE REVIEW

A number of methods and tools have been developed for railway line capacity studies. The classification of capacity assessment and testing methods proposed in papers [4] and [5] is as follows:

1. Analytical methods – used to model the railway environment using a mathematical apparatus. Analytical methods are typically applied to perform a preliminary capacity assessment by calculating values of minimum headway based on a blocking time model for block sections. Having established such grounds, one can determine the theoretical and practical capacity of a given railway line section. The practical capacity is a percentage of the theoretical capacity representing a maximum value that can never be reached considering the technique of handling railway traffic operations. Paper [6] describes some classical minimum headway and capacity formulas related to the number of aspects of the signalling equipment used in the railway network in Poland. A similar approach based on a method involving capacity calculation at a previously identified critical line segment entails using the mathematical apparatus described in paper [7], which also describes how to run calculations with a heterogeneous traffic structure.
2. Optimisation methods – aimed to provide a strategic method for solving the railway capacity problem and deliver solutions that are significantly superior to purely analytical formulas. The optimisation methods used for railway capacity assessment assume that optimally saturated timetables are developed. These timetables are typically designed by programming techniques. A distinctive kind of optimisation method is the saturation method, which makes it possible to establish railway line capacity by planning the maximum number of additional train services in a timetable (starting with an empty or preliminary timetable). An example of such a method is the timetable compression method applied by numerous railroad infrastructure operators (including PKP PLK S.A.), as defined in the charter of Union Internationale des Chemins de fer (UIC - International Union of Railways) [8]. Optimisation methods are also used to tackle the optimisation tasks related to the operations of large freight transport hubs. An example of such methods is the model described in paper [9] that can be used to optimise a marshalling schedule in a railway network combined with a siding which serves several areas of an industrial plant.
3. Simulation methods – simulation is the imitation of actual operations in processes or systems functioning in the real world over time. The literature on the subject showcases a number of applications for simulation methods for assessing railway line capacity under different control systems [10–16]. For example, simulation methods used to study the impact of a train traffic control system of the CBTC type or based on moving block sections have been described in paper [17]. This paper also discusses how the negative imaginary systems theory is used to study the mutual impact of control systems' commands on the dynamic of entire train sets, as well as on the interactions between individual cars.

Paper [18] implies that one should apply the multi-agent theory to solve multicriteria tasks such as capacity calculations for high-speed railroads. Using three levels of independent yet communicating and cooperating agents makes it possible to break down a large and complex system, such as a railway system, into smaller ones. Train control can be described as a process which comprises reserving and then occupying individual sections, line segments, and stations (resource agents) by a train (user agent).

A Python language-based simulator intended to analyse train movement in junction areas has been described in paper [19]. The graph theory applied in the simulator makes it possible to simulate a timetable by assigning a train of a given category to a given curve connecting individual junctions and then selecting an optimal combination of movements via the junction.

Paper [20] proposes a brute force algorithm capable of operating multiple trains in real time to be used for the simulation environment and to assess railway line capacity and energy consumption attributable to traffic supervised in accordance with diverse ERTMS/ETCS implementation rules.

Simulation methods are also used to assess algorithms and resolve real-time traffic conflicts emerging in the network. Within a pre-established timetable where capacity utilisation approaches the maximum, stochastic phenomena related to delays or emergencies may cause the delays to propagate to an increasing number of trains. Therefore, the train traffic control process is based on the dynamic resolution of traffic conflicts and train departure handling to minimise the total delay time across the network [21–23].

Not only are simulation environments used for testing railway line capacity, but also for assessing railway traffic control systems. Paper [24] describes a reference test stand which enables the simulation of test scenarios related to train movements supervised by the ERTMS/ETCS. The simulation environment makes it possible to verify that the onboard ETCS equipment provides the required functionality in terms of the programmed component and hardware. A slightly different application of simulation methods was presented in paper [25], which describes the application of the Matlab and Simulink environment to simulate the Russian ALSC safe train movement control system. The mathematical model of the ALSC system's encoded circuits enables the verification of the system behaviour in normal operation, as well as the simulation of interferences and the probability of their occurrence, to improve the system's resilience to disturbances. Simulation methods are also used to define and subsequently test algorithms deployed for the predictive maintenance of railway systems. Paper [26] describes the potential for the application of discrete event simulations for algorithm design and verification purposes in predictive maintenance. Paper [27] proposes that the Monte Carlo method should be used to decrease simulation time by reducing variance and applying the paradigm of parallel computing in the Matlab environment.

The purpose of this paper is to discuss a simulation program developed in the Matlab and Simulink environment to assess the impact of the solution deployed in a railway traffic control system to possibly reduce train travel time and present preliminary results derived from such simulation.

3. ASSUMPTIONS FOR THE SIMULATION MODEL

The model developed in the current study was based on the following assumptions:

I. A static permissible speed profile is introduced for a line segment (Fig. 1a).
II. It is possible to apply any chosen speed profile for a train running on a line segment as a function of the train coordinate within the line segment (Fig. 1b). The speed profile can also be set as non-linear, thus corresponding to the actual movement profile.
III. Despite the pre-set speed profile (specified in Item II of these assumptions), it is possible for the simulation program to change during simulation the individual speed profile of each train on the line segment (e.g. when it is necessary to stop it at the *red S1* stop signal or to initiate braking as a consequence of the *yellow S5* aspect). Train speed should not be higher than the line segment's permissible speed, although it is possible to set a higher speed than the permissible one if the need arises.
IV. It is possible to apply individual lengths of successive trains included in the simulation.
V. The simulation considers the start (front) and end coordinates of each train running on a line segment, corresponding to the first and the last train axles.

VI. It is possible to enter the coordinates of block signals beginning a block section individually for a line segment.

a)

b)

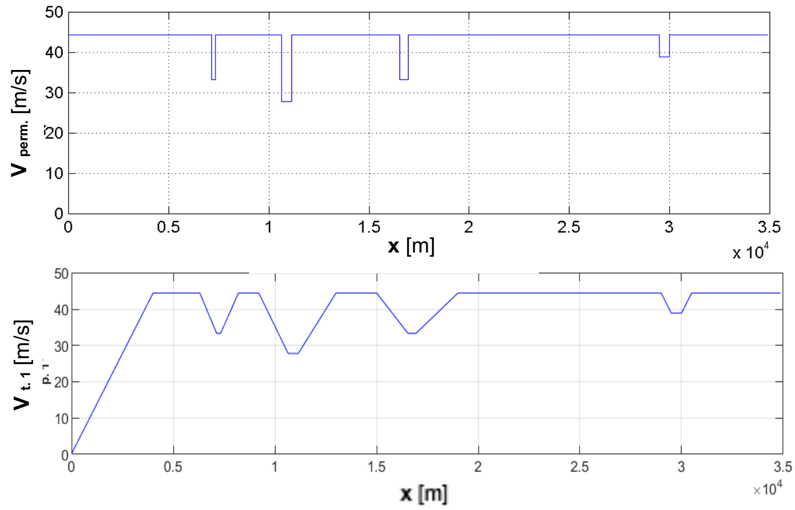

Fig. 1. (a) Permissible speed profile for a line segment and (b) maximum speed profile of train no. 1 on the line segment as a function of the line segment coordinate [source: in-house study]

VII. It is possible to individually set valid sighting distances for all signals per the applicable regulations, defined as distances from respective railway signals. According to Polish railway signalling rules, sighting distance depends on the maximum line segment speed, as well as on the railway signal type. Thus, for instance, for the maximum speed of 160 km/h, it is 533 m for entrance signals and 400 m for block signals.

VIII. It is possible to set real-life sighting distances, defined as distances from respective railway signals, individually for a signal and train. If the train's front location in a real-life sighting distance of a railway signal is known, it is possible for the simulation to account for the driver's reaction to a change in the signal's indication as a result of a next block being released by a preceding train. Real-life sighting distances of railway signals may be larger or smaller than the valid sighting distance per the regulations. This makes it possible to simulate the effect of local conditions (e.g., curves) and atmospheric conditions on the train movement.

IX. It is possible to set the coordinates of wheel detectors, defined as distances from corresponding railway signals, individually for all signals. This makes it possible to simulate movement on a line segment with a multi-section line block, where this distance should be 15–30 m, and crossing a station, where this distance can be longer (e.g., 50–100 m for overlaps past exit signals), depending on the assumed maximum train running speed). A detector (D23) situated 100 m past the last railway signal (next station's entrance signal) is also integrated into the simulation software, which allows the last line block section to be released.

X. Braking initiation advancing (or retarding) distances [m] are entered individually for a railway signal relative to the railway signal with the *yellow S5* aspect. These are entered as a function of the on-route train number and the railway signal number. This allows the model to comprise the following:

   A. The delay between the instant when the driver notices the railway signal aspect and when the driver potentially initiates braking, referred to as the driver response time;
   B. The specificity of the driver's behaviour upon applying brakes of trains differing in weight and braking efficiency, thus being characterised by different braking distances and braking system inertia typical of the train;
   C. The specificity of braking initiation before a railway signal, depending on how visible it is;

D. The specificity of the driver's behaviour, depending on the longitudinal profile of the section of a line segment (e.g., retarding the braking initiation relative to a railway signal with the *yellow S5* aspect while running uphill or advancing the braking initiation when approaching a railway signal showing *red S1*, located on a descent).

XI. Braking is initiated when the train front reaches a coordinate of braking initiation advancing (or retarding) distance [m], set individually for the railway signal and train, against the railway signal with the *yellow S5* aspect. The simulation program makes it possible to establish real-life sighting distances individually for a railway signal and train. Optionally, it can be assumed that the braking initiation advancing distance equals the sighting distance for one or all trains.

XII. Braking proceeds according to at least one train braking characteristic curve in a function of the distance covered (*v=f(s)*) (Fig. 2). The specific braking characteristic curve applied is stated in the description of the simulation results.

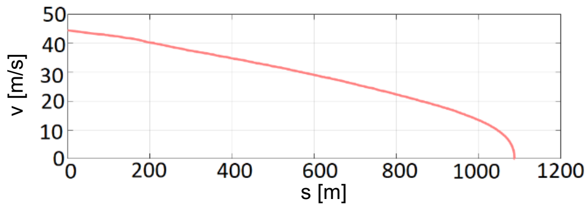

Fig. 2. Example of a train braking characteristic curve (*v=f(s)*) [source: in-house study]

XIII. If a train running on a line segment is in block 5 and its end has not yet passed wheel detector D5 located past railway signal Sig. 5 (Fig. 3), then:

A. The railway signal preceding block 5 (Sig. 5 in Fig. 3) shows *red S1* applicable to the next train. The railway signal preceding block 4 (Sig. 4 in Fig. 3) also shows *red S1*. Both the train length and the distance from the wheel detector (D5 in this case) to the preceding railway signal (Sig. 5 in this case) are considered. The *red S1* stop signal means that the train must be stopped before reaching the railway signal in question.

B. The railway signal preceding block 3 (Sig. 3 in Fig. 3) shows the *yellow S5* aspect applicable to the next train. The *yellow S5* signal is a warning that the train must be stopped before the next railway signal, which is already showing *red S1* (stop).

C. The railway signal preceding block 2 (Sig. 2 in Fig. 3) shows *green S2* for clear, applicable to the next train. This means that the train can continue running at the maximum speed allowed since the next two blocks are unoccupied.

XIV. If a train running first on a line segment is in block 5 and its end has passed wheel detector D5 located past signal Sig. 5 (Fig. 4), then:

A. The railway signal preceding block 5 (Sig. 5 in Fig 4) shows *red S1* stop aspect, applicable to the next train. Both the train length and the distance from the wheel detector (D5 in this case) to the preceding railway signal (Sig. 5 in this case) are considered.

B. The railway signal preceding block 4 (Sig. 4 in Fig. 4) shows the *yellow S5* aspect applicable to the next train. The *yellow S5* signal is a warning that the train must be stopped before the next railway signal, which is already showing *red S1* (stop).

C. The railway signals preceding blocks 2 and 3 (Sig. 2 and Sig. 3 in Fig. 4) show *green S2* for clear, applicable to the next train. This means that the train can continue running at the maximum speed allowed since the next two blocks are unoccupied.

The aforementioned signals are marked in the following diagrams, as well as in the reports generated by the simulation program as *s. SIG*, and are assigned the corresponding numerical values stated above.

XV. Braking is not to be initiated if the train front has already passed the railway signal when it begins to show the *yellow S5* aspect. Similarly, the brake is not to be released if the train front has already passed the railway signal when it begins to show the *green S2* aspect. However, if the railway signal displays the *yellow S5* aspect when the train front has not yet passed the railway signal, braking can start past this signal, having taken per Items X and XI, among others.

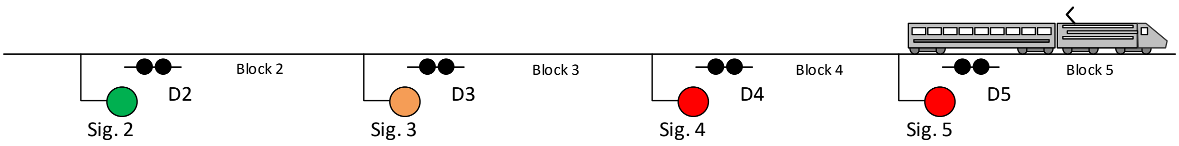

Fig. 3. Example of railway signal behaviour (sequence of indications) considered in the model in which the end of the first train has not yet passed wheel detector D5 located past the railway signal designated as Sig. 5 [source: in-house study]

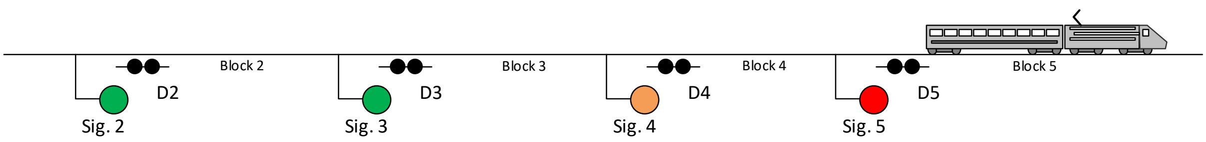

Fig. 4. Example of railway signal behaviour considered in the model in which the end of the first train has just passed wheel detector D5 located past the railway signal designated as Sig. 5 [source: in-house study]

XVI. The wheel detectors included in the simulation model are capable of distinguishing the number of the next train on the line segment, and they adopt the status described below for the train:

A. If the train front has not reached the detector's coordinate, the detector generates a "-1" signal in the simulation model.

B. If the train front has already passed the detector's coordinate but the end has not yet passed the coordinate of the detector in question, the detector generates a "0" signal in the simulation model, as in real life. This corresponds to the initiation of train axle counting in real-life conditions.

C. If both the train front and train end have already passed the detector's coordinate, the detector generates a "1" signal in the simulation model. This corresponds to the completion of train axle counting in real-life conditions, which is tantamount to the entire train set having passed the detector.

The proposed solution makes it possible to verify the simulation results obtained (e.g., by generating reports for all detectors and analysing whether the front and end of a train have passed a wheel detector, and if so, at what instant). The foregoing can also be collated with:

- a report on the status of the indications of various railway signals for a train at different instants;
- instants at which braking is potentially initiated as a consequence of the railway signal indications while also considering the braking initiation advancing distance described in Items X and XI individually for a railway signal and train.

XVII. Indications of each trackside signal may be *red S1*, *yellow S5* or *green S2*. Table 1 shows an example of the effect exerted by the type of the signal generated by detectors D3–D5 on the indication of railway signal Sig. 3. The operation of other railway signals is analogous, except for the next-to-last-one (the last line block signal) and the last one (the next station's entrance signal).

XVIII. The effect of the type of the signals generated by detectors D21–D23 on the indication of the last but one railway signal (the last line block signal) (e.g. Sig. 21) has been presented in Table 2. Detectors D21 and D22 are located just behind the corresponding railway signals, Sig. 21 and Sig. 22, and they are responsible for simulating the process of covering the block which the train has entered with the *red S1* stop signal analogically to the case described in Item XVII. Detector D23, located 100 m behind railway signal Sig. 22 (which performs the function of a station's entrance signal), is responsible for the possibility of releasing the last block between railway signals Sig. 21 and Sig. 22. It also affects the indication of the penultimate railway signal Sig. 21 (last line block signal), changing from *red S1* to *yellow S5*. Consequently, according to the assumed operational logic, if both D21 and D22 have a value of 1, the indication of railway signal Sig. 21 depends on the status of the last railway signal (the next site's entrance signal) (i.e. Sig. 22) as a result of the relevant sequence of indications. In practice, the last railway signal Sig. 22 (the next site's entrance signal) is a signal operated by a traffic dispatcher (*Dis. 1,* Table 2). One of the model's assumptions is that if the dispatcher sets the entrance route to the station for the next train starting from railway signal 22, then the value of parameter *Dis. 1* for the last but one and the last railway signal (Tab. 3) will change from -1 to 1.

Table 1

Effect of the type of the signals generated by detectors D3–D5
on the indication of railway signal Sig. 3

Detector signal			Control signal in the model for railway signal designated as "Sig. 3": D3+D4+D5	Railway signal indication Sig. 3.
D3	D4	D5		
-1	-1	-1	(-1)+(-1)+(-1) = -3	If: D3+D4+D5=-3, then the *green S2* aspect is shown
0	-1	-1	0+(-1)+(-1) = -2	If: -3<D3+D4+D5≤0, then the *red S1* aspect is shown
1	-1	-1	1+(-1)+(-1) = -1	If: -3<D3+D4+D5≤0, then the *red S1* aspect is shown
1	0	-1	1+0+(-1) = 0	If: -3<D3+D4+D5≤0, then the *red S1* aspect is shown
1	1	-1	1+1+(-1) = 1	If: 0<D3+D4+D5≤2, then the *yellow S5* aspect is shown
1	1	0	1+1+0 = 2	If: 0<D3+D4+D5≤2, then the *yellow S5* aspect is shown
1	1	1	1+1+0 = 3	If: D3+D4+D5≥3, then the *green S2* aspect is shown

Table 2

Effect of the type of signals generated by detectors D21, D22, D23, and Dis. 1
on the indication of railway signal Sig. 21 (the last line block signal within the line segment)

Signal from detectors and Dis. 1				Signal controlling railway signal *Sig. 21* in the model: D21+D22+D23+Dis. 1	Railway signal indication Sig. 21
D21	D22	D23	Dis. 1		
-1	-1	-1	-1	(-1)+(-1)+(-1) +(-1) = -4	If: D21+D22+D23+Dis. 1=-4, then the *green S2* aspect is shown
0	-1	-1	-1	0+(-1)+(-1) +(-1) = -3	If: -3≤D21+D22+ D23+Dis.≤1, then the *red S1* aspect is shown
1	-1	-1	-1	1+(-1)+(-1) +(-1) = -2	If: -3≤D21+D22+ D23+Dis.≤1, then the *red S1* aspect is shown
1	0	-1	-1	1+0+(-1) +(-1) = -1	If: -3≤D21+D22+ D23+Dis.≤1, then the *red S1* aspect is shown
1	1	-1	-1	1+1+(-1) +(-1) = 0	If: -3≤D21+D22+ D23+Dis.≤1, then the *red S1* aspect is shown
1	1	0	-1	1+1+(-1)+0 = 1	If: -3≤D21+D22+ D23+Dis.≤1, then the *red S1* aspect is shown
1	1	1	-1	1+1+(-1)+1 = 2	If: D21+D22+ D23+Dis.= 2, then the *yellow S5* aspect is shown
1	1	1	1	1+1+1+1 = 4	If: D21+D22+ D23+Dis.=4, then the *green S2* aspect is shown

The model assumes that the dispatcher decides to change the *Dis. 1* signal from "-1" to "1", which occurs when the end coordinate of a train which has completed its movement on the analysed line segment is 1,000 m behind the last railway signal, which is signal 22 in this case. This makes it possible to simulate the operation of stopping the train at a station track within a station and setting the entrance route for the next train to another station track. The model disregards the effect of speed restriction on the movement at rail switches in diverging directions within the station area.

Table 3

Effect of the type of signals generated by detectors D22, D23, and Dis. 1 on the indication of railway signal Sig. 22 (the next site's entrance signal)

Signal from detectors and Dis. 1			Signal controlling railway signal *Sig. 22* in the model: D22+D23+Dis. 1	Railway signal indication Sig. 22
D22	D23	Dis. 1		
-1	-1	-1	(-1)+(-1) +(-1) = -3	If: D21+D23+Dis. 1=-3, then the *green S2* aspect is shown
0	-1	-1	0+(-1) +(-1) = -2	If: -2≤D22+D23+Dis. 1≤1, then the *red S1* aspect is shown
1	-1	-1	1+(-1) +(-1) = -1	If: -2≤D22+D23+Dis. 1≤1, then the *red S1* aspect is shown
1	0	-1	1+(-1)+0 = 0	If: -2≤D22+D23+Dis. 1≤1, then the *red S1* aspect is shown
1	1	-1	1+1+(-1) = 1	If: -2≤D22+D23+Dis. 1≤1, then the *red S1* aspect is shown
1	1	1	1+1+1 = 3	If: D22+D23+Dis. 1=3, then the *green S2* aspect is shown

XIX. For each railway signal and each train, four ranges of the effect of the indication displayed by the railway signal on the driver's (train's) behaviour have been established in the model (Fig. 5).

A. Ranges no. 1 and 4: the model assumes that when the train front is situated within these ranges, then the driver's (train's) behaviour is not affected by any change of the indication of railway signal *n*. Range no. 1 set for railway signal *n* partially overlaps ranges no. 2 and 3, among others, set for railway signal *n-1*, while range no. 4 set for railway signal *n* partially overlaps ranges no. 2 and 3, among others, set for railway signal *n+1*. The driver makes decisions within these ranges by relying on the indications of railway signals *n-1* and *n+1*, respectively.

Range no. 1 starts at the line segment start coordinate and ends immediately before the coordinate of the real-life sighting distance of railway signal *n* (open interval). The concept of a coordinate of the real-life sighting distance of railway signal *n* has been explained in Item VIII of these assumptions, and it takes individual values for a railway signal and train since the sighting property of even the very same railway signal may change with the lapse of time, after which another train passes by the same point of the line segment.

Range no. 4 starts at the coordinate of the real-life sighting distance of railway signal *n+1*, and it ends where the line segment terminates.

B. Range no. 2 (also referred to as range *RE*) starts at the coordinate of the real-life sighting distance of railway signal *n,* and it ends immediately before the coordinate of railway signal *n* (open interval). When the train front is within this range, the driver sees the railway signal's indication and can, for instance, initiate braking or, once the *green S2* or *yellow S5* aspects are shown, change the decision previously made and refrain from braking. The driver can also start accelerating if railway signal *n-1* shows that S5 has already been passed, seeing that railway signal *n* now shows aspect *S5* or *S2*. In the model, the instant when the driver initiates braking depends on the train- and signal-specific distance of advancing (or even retarding) of braking initiation [m] relative to railway signal *n*, as specified in Item X of these assumptions.

C. Range no. 3 (also referred to as range BRE) starts at the coordinate of railway signal *n* and ends immediately before the coordinate of the real-life sighting distance of railway signal *n+1* (open interval). If the train front is within range no. 3, then, as opposed to range no. 2, the driver does not see the railway signal indication. If the indication of railway signal *n* has obliged the driver to stop the train before reaching railway signal *n+1*, then even if the indication of signal *n* changed to *green S2* shortly after the train front enters range no. 3, the driver will not react to the change. Whether the driver has already initiated braking or is about to initiate it (having remembered the indication of railway signal *n*) depends on the train- and signal-specific distance of braking initiation advancing, as well as (in range no. 3) the distance of braking initiation retarding [m] relative to railway signal *n*. The notion of this distance has been explained in Item X of these assumptions.

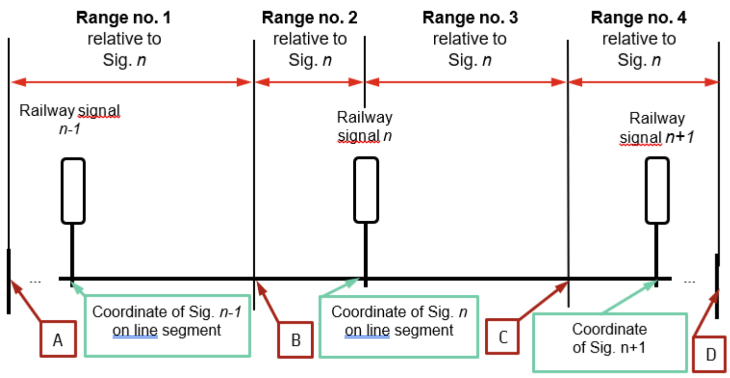

Fig. 5. Ranges of impact or absence of impact of signal indication on the driver's (train's) behaviour: A – line segment start coordinate, B – coordinate of real-life sighting distance of Sig. *n*, assuming individual values for a railway signal and train, C – coordinate of real-life sighting distance of Sig. *n+1*, assuming individual values for a railway signal and train, D – line segment end coordinate [source: in-house study]

XX. The next train will not depart from exit signal Sig. 1 (i.e. it will not depart to the line segment) until this railway signal's indication is *green S2*. In addition, the next train will not depart from railway signal Sig. 1 until this signal's indication changes from *orange S5* to *green S2* (as a consequence of the previous train having passed), which makes it possible to ensure that two blocks separating the trains are unoccupied.

The second of the above conditions results from the possibility that the distance between the first detector (D1) and railway signal Sig. 1 corresponds to the assumed overlap. Until the train front reaches the coordinate of detector D1 (e.g., 100 m past railway signal Sig. 1), the indication of railway signal Sig. 1 remains to be *green S2*, which has enabled this train to depart to the line and to move past railway signal Sig. 1 to block no. 1 (Fig. 6). Therefore, one can avoid a situation in which the next train might be allowed to depart to the line segment when the preceding train, being shorter than the assumed overlap (e.g., shorter than 100 m), remains in the section between the exit railway signal *Sig. 1* and the first detector *D1*. On account of the driver's ability to observe the processes in progress and their knowledge of the applicable regulations, such a situation is practically impossible in normal traffic. However, a model lacking the aforementioned condition could cause the next train to be mistakenly allowed to depart after the preceding one to the same block no. 1.

XXI. Another signal introduced into the model is *brake* (designated as *s. BR.*), which denotes the initiation of braking on particular train or preventing to start of the train from standstill.

The *brake* signal value of "1" means no braking and train movement, whereas the *brake* signal value of "0" or "-1" means that the train initiated braking or cannot start (further stopping). The *brake* signal can assume the following values, depending on the movement status:

A. "1" when a train's front is within ranges no. 1 or no. 4 against a railway signal, regardless of this signal's indication since it is when the train's front is within ranges no. 2 or no. 3 of another railway signal;

B. "1" when the railway signal shows the *green S2* aspect while the train's front is within range no. 2 against this railway signal;

C. "1" when the railway signal shows the *green S2* aspect while the train's front was at the end of range no. 2 against this railway signal, and the front of the analysed train is currently within range no. 3 against the railway signal. In this the case, the value of the *brake* signal will be as stated (i.e. "1") regardless of the railway signal's indication since the driver cannot notice any indication change on the railway signal the train has passed;

D. "1" when the railway signal shows the *yellow S5* aspect while the train's front is within range no. 2 against this railway signal, and the value of the train front coordinate at the instant is lower than the coordinate of the braking initiation advancing/retarding distance [m] assigned to that railway signal and train (see Items X and XI of these model assumptions);

E. "0" when the railway signal shows the yellow S5 aspect while the train's front is within range no. 2 against this railway signal, and the value of the train front coordinate at the instant is higher than or equal to the coordinate of the braking initiation advancing/retarding distance [m] assigned to that railway signal and train;

F. "0" when the railway signal shows the *yellow S5* aspect while the train's front was at the end of range no. 2 against this railway signal, and the front of the analysed train is currently within range no. 3 against the railway signal. In this case, the value of the brake signal will be as stated (i.e., "0") regardless of the railway signal's indication since the driver cannot notice any indication change on the railway signal the train has passed;

G. "-1" when the train's front is within range no. 2 against the railway signal and the signal's indication is *red S1* stop aspect, indicating an emergency situation. In this case, the *brake* signal value will immediately become "-1" regardless of the value of the train front coordinate relative to the coordinate of the braking initiation advancing/retarding distance [m] assigned to that same railway signal and train;

H. "-1" when the railway signal shows the *red S1* aspect while the train's front is at the end of range no. 2 against this railway signal and the front of the analysed train is currently within range no. 3 against the railway signal. In this the case, the value of the brake signal will "-1" regardless of the railway signal's indication since the driver cannot notice any indication change on the railway signal the train has passed;

Fig. 6b shows the values of the *brake* signal described above as applicable to the next train in movement. In this case, if the train considered as the preceding one in the model is shorter than the length of the overlap past the exit railway signal (as described above), then, theoretically, the next train could enter directly following the former while the entrance railway signal's indication is *green S2*. Such an irregularity in the model has been avoided by introducing a dedicated condition for the train to enter the line segment, namely that the indication of railway signal Sig. 1 should change from *yellow S5* to *green S2*. Consequently, while the next train is beginning its movement in a line segment and until the aforementioned change of indications takes place, the *brake* signal is generated, preventing the next train from entering the line segment directly following the preceding one (Fig. 6c).

XXII. The start of the next train can be delayed further by the dispatcher's operations. The delay option will prove particularly useful while performing some other functions to avoid unjustified braking and re-accelerating a train on a line segment as a consequence of the preceding train being caught up by the next one, thus saving energy on braking and re-accelerating is saved.

XXIII. The model does not essentially change the existing rules pertaining to the safety rationale behind the operation of the railway traffic control equipment. However, some specific safeguards have been deployed in the model in case of a failure by which a train runs into the back of a preceding train, whereby the simulation is immediately interrupted and adequate messages are displayed. When this happens, one should perform an analysis to detect why the event occurred (e.g., erroneously defined train braking characteristics).

XXIV. Train movement time recording starts when the coordinate of the train front is a higher value than that of the coordinate of the line segment's entrance railway signal and ends when the coordinate of the train end is a higher value than that of the coordinate of the last detector on the line segment since this is when the train ceases to affect the detectors, as well as the last but one and the very last railway signal.

XXV. The model in question disregards the operating time of railway traffic control equipment.

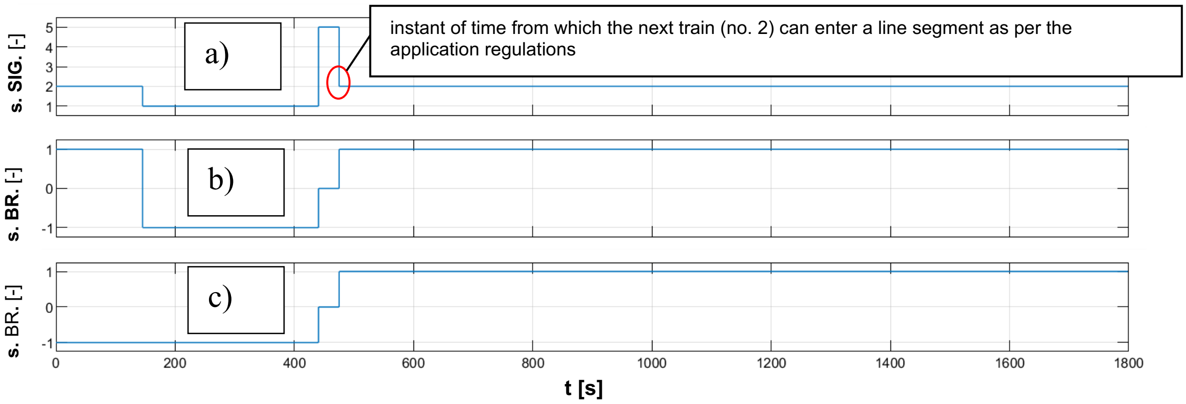

Fig. 6. Signals: a) the indication of railway signal Sig. 1 as a consequence of train no. 1 having passed (s. SIG.), b) the *brake* signal (s. BR.) allowing train no. 2 to enter a line segment directly following train no. 1, and c) the *brake* signal (s. BR.) prohibiting train no. 2 from entering a line segment directly following train no. 1 [source: in-house study]

4. SIMULATION RESULTS CONCERNING THE INSTANT OF TIME CORRESPONDING TO A TRAIN DEPARTURE TO A LINE SEGMENT AND ITS EFFECT ON THE TRAIN TRAVEL TIME

Based on the model developed for the purposes of this study, as well as the simulation software described in detail in Section 2, the effect of a delay in the train departure from a station relative to the *green S2* indication of the station's exit railway signal on the train travel time was verified. In this way, it was additionally confirmed that one can reduce the energy losses attributable to a train's acceleration and braking due to the movement of a preceding train.

The coordinates of trackside signals entered into the model corresponded to a real-life line segment and were as follows: 0; 2,411; 3,871; 5,568; 7,043; 8,592; 10,412; 12,699; 14,120; 15,765; 18,044; 19,693; 21,716; 23,512; 24,967; 26,573; 28,033; 29,401; 30,805; 32,206; 33,518; 34,877 [m]. The coordinates of wheel detectors (impact points), expressed as distances from their corresponding railway signals, were 15 [m], except for wheel detectors D1 and D23, for which the assumed distances were 100 m (see Assumption IX). When validating the model in operation and the obtained results, it was assumed that train no. 1, with a length of 800 m (i.e. running first), moved according to the speed profile shown in Fig. 1b. Meanwhile, train no. 2, with a length of 400 m (i.e. following train no. 1), moved with the maximum permissible speeds on the line segment depicted in Fig. 1a. This means that the train acceleration and braking distance of train no. 2 approached zero since the *brake* signal assumed values lower than 1 (see Assumption XXI).

The simulations discussed in this section assume that, individually, for a railway signal and train no. 2, the braking initiation advancing distances relative to railway signals Sig. 2–22 on the line segment are 1 m. This means that a train starts braking in advance when 1 m in front of a railway signal with the *S5* aspect. Consequently, even if the signal changed its indication from *yellow S5* to *green S2* while the train was covering that 1 m distance, it was assumed that the driver would not be able to notice the aspect change and react accordingly. It was further assumed for train no. 2 and railway signal Sig. 1 that the braking initiation distance relative to that railway signal was 0.1 m. In practice, this means that the train is halted in front of the railway signal, while the actual sighting distances for individual railway signals are 533 m (see Assumption VIII).

Figure 7 illustrates the *brake* signal changes (as referred to in Assumption XXI) for train no. 2 as a consequence of train no. 1 having passed. This signal is composed of all relevant fragments of the *brake* signal generated for individual ranges no. 2 and no. 3 (as explained in Assumption XIX). Based on the simulation performed, it was concluded that train no. 2 should brake at the following railway signals: Sig. 5 (period no. 1 in Fig. 7), Sig. 6 (period no. 2), Sig. 9 (period no. 3), and Sig. 10 (period no. 4).

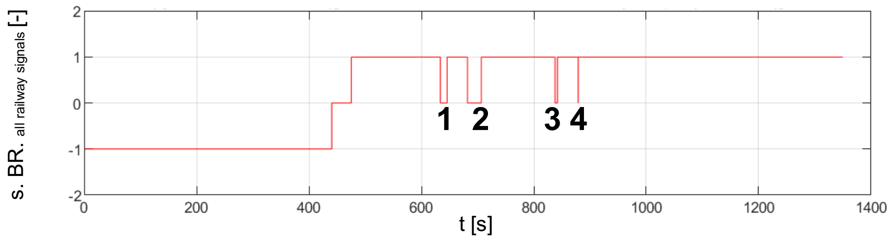

Fig. 7. *Brake* signal (s. BR.) for train no. 2 from all railway signals as a consequence of train no. 1 having passed [source: in-house study]

The number of braking operations in train no. 2 was reduced by delaying the start of train no. 2 on the line segment in relation to the instant of time (marked as a dot in Fig. 6a). This corresponds to the moment when railway signal Sig. 1 shows the *green S2* indication for train no. 2. In the event that the start of train no. 2 was delayed and the successive delays were 13, 37, 41, and 41.1 [s], the braking of train no. 2 was eliminated at railway signals Sig. 5, Sig. 5 and 6, Sig. 5, 6 and 9, and Sig. 5, 6, 9 and 10, respectively.

Fig. 8 shows the travel times of trains no. 1 and no. 2 and the total travel time of both trains relative to the delay of the departure of train no. 2.

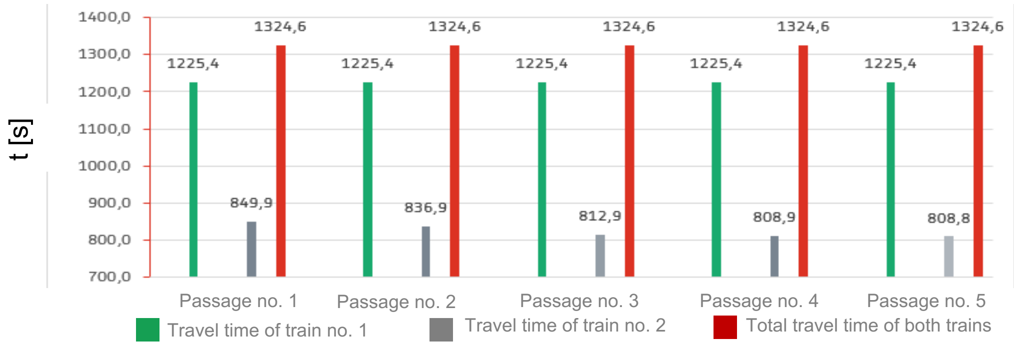

Fig. 8. Travel times of trains no. 1 and no. 2 and the total travel time of both trains relative to the delay of the departure of train no. 2: 0 [s]; 13 [s]; 37 [s]; 41 [s]; 41.1 [s]; [source: in-house study]

Even though the total travel time of both trains did not decrease under the simulation conditions, it was clearly possible to successfully eliminate avoidable braking and accelerating operations and decrease the travel time of train no. 2, which is a desirable outcome. The total travel time of both trains was not reduced once the unnecessary braking and accelerating operations had been eliminated because, as mentioned in the second paragraph of this section, the braking and accelerating distance of train no. 2 approached zero. In real-life conditions, these distances are greater than zero, meaning that eliminating unnecessary braking and accelerating operations also reduces the total travel time of both trains. This is also a positive outcome that makes it possible to reduce the time of occupancy of individual blocks.

5. CONCLUSIONS

The authors have described the assumptions adopted for the model in question as well as the simulation software developed in the Matlab and Simulink environment, used, for example, to assess:

- The time of the trains crossing the railway line segment;

- The influence of the speed profile of trains running in succession on the necessity of braking a train before a railway signal;
- The influence of the railway traffic control solution applied to the railway line segment capacity.

The results of the simulation presented in this paper also indicate that the developed model allows an appropriate time delay value to be selected for the train departure from a station relative to the *green S2* indication of the station's exit railway signal. Thus:

- Despite the application of the above-mentioned time delay, the total running time of the preceding and the following train need not be increased;
- The travel time of the next train may already be reduced. In the analysed case, the reduction in travel time was ca. 5%. Although this value may seem unimportant in practice, it should be noted that:
    - These values apply to the second train moving on the line segment, the braking of which, in turn, affects the traffic delays of subsequent trains,
    - Limiting or eliminating at least some avoidable braking on the line segment reduces the energy losses associated with braking and acceleration. Moreover, reduced braking is related to reduced brake lining wear, thus allowing the emission of their wear products into the atmosphere to be reduced.

It is assumed that further work on the model and simulation software in question will involve analyses of the effects of other factors on train travel times and consideration of the movement of trains controlled by other signalling systems (e.g., ERTMS/ETCS).

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