TRANSPORT PROBLEMS 2025 Volume 20 Issue 1
PROBLEMY TRANSPORTU DOI: 10.20858/tp.2025.20.1.02

Keywords: ETCS; simulation; capacity; control command and signaling; railway

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SELECTED ASPECTS OF THE CONCEPT OF OPERATING TRAIN TRAFFIC UNDER THE SUPERVISION OF THE ERTMS/ETCS L2 SYSTEM ON HIGH-SPEED LINES BASED ON SIMULATION STUDIES

Summary. High-speed railway lines require the establishment of separate rules and regulations for the design and operation of traffic relative to conventional lines. These lines require the use of advanced train protection systems, such as the ERTMS/ETCS Level 2. The functionality, configuration and design capabilities of the indicated system provide opportunities for its development, including its adaptation and performance improvements. The configuration parameters are variables defined for both on-board and trackside equipment and design rules. This article presents the results of simulation studies, which made it possible to study the influence of the set parameters on system performance. In doing so, this study provides an opportunity to establish design and configuration rules for selected aspects of the ETCS.

1. INTRODUCTION

The European Train Control System (ETCS), which is being developed on the rail network of European countries, is a key foundation in pursuing a unified train control system. It is an indispensable tool for moving toward interoperability and European development.

Interoperability, in relation to the railroad system, can be understood as ensuring three aspects: safe passage, continuous passage and the maintenance of adequate performance. The development and implementation of the ETCS have made it possible to demonstrate and confirm its high level of safety assurance, which can be pointed out as the overriding goal of implementing a common rail traffic control system. Also, continuous passage, in the sense of cross-border crossings, is ensured and made possible by the ETCS. The weakest point of the system is its low effectiveness and efficiency, which is, to some extent, a consequence of ensuring a high level of safety. The challenge facing further development of the system is to improve its efficiency while maintaining the appropriate required level of security. One of the aspects cited as a weakness in the system is the control of train speed when approaching a location

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where a stop is required. The restrictiveness of the braking curves calculated by the system results in practice in forcing a train to brake significantly in advance compared to driving without ETCS.

The issues of distribution of braking forces, train braking distance and braking curves for high-speed trains based on mathematical models and conducting simulation studies on them have been the subject of previous research [1-6]. The above aspects were analyzed based on the traffic dynamics and braking process of the rolling stock itself. The lengths of the braking distances of two high-speed trains were simulated using MATLAB/Simulink software [1], which uses a braking mode curve algorithm including regenerative braking force, air braking force and stopping distance [2]. Simulations were also carried out for ETCS braking curves relating to the previous system baseline [3]. The problem of train slippage caused by the irrational distribution of braking force in the braking process of a high-speed train was addressed [4]. A simulation was also run to analyze the case of the designed Sichuan-Tibet line, whose unusual conditions pose a challenge [5]. A model was constructed to analyze braking performance in a complex environment. The article [6] describes the developed tool for predicting the braking performance of a train, with a particular focus on the accurate prediction of the braking distance, and the results obtained were compared with experimental data. Meanwhile, the present article focuses on the braking curves imposed on moving rolling stock by the on-board equipment of the ETCS on high-speed lines and its improvement.

Carrying out simulation studies using different types of models makes it possible to improve the performance and efficiency of the systems under investigation without costly and time-consuming field studies. This approach is widely used and allows the research and development of new solutions. The aspect of train smoothness was also addressed in [7], where a new original parameter characterizing a railway traffic driving smoothness indicator was analyzed. That study was based on data obtained from a neural train emulator.

A study conducted in France [8] used a similar approach to the present paper, which is based on the simulation and validation of adopted solutions. However, the approach presented in that paper covered issues at a higher level of generality, focusing on safety and compliance with ETCS specifications.

2. TRAFFIC OPERATION ON HIGH-SPEED LINES

New high-speed lines in Poland pose a multi-disciplinary challenge from the point of view of traffic guidance and train control systems. First and foremost, traditional signaling has been based on lineside signaling, which, by definition, is designed to carry traffic at a maximum speed of 160 km/h. Previous implementations of higher speeds have forced the use of cab signaling, such as on Line No. 4 (which essentially leads from Warsaw to Katowice) and Line No. 9 (Warsaw - Gdańsk). It is assumed that driver assistance is necessary at speeds higher than 160 km/h due to the difficulty in perceiving lineside signaling. Due to legal considerations and the European trend, opting for ETCS Level 2 is the natural choice. At the same time, because traffic on high-speed lines travels above 250 km/h, the movement of vehicles not equipped with cab signaling (i.e., ETCS) is undesirable. This makes it possible to consider partial or complete abandonment of trackside signals.

Two potential signaling configurations in Poland are currently under discussion:

- lineside signals at stations and no signals on lines between stations, ETCS marker boards and ETCS location boards,
- no lineside signaling at both stations and line between stations.

In this regard, regardless of configuration, the major challenges facing designers include:

- new design guidelines for the ETCS marker boards – ETCS top marker and ETCS location marker (called W ETCS 10 and W ETCS 11 in Poland) in connection with the possible absence of signals,
- the transition from infrastructure equipped with trackside signals to high-speed infrastructure partially or completely without trackside signals.

The abovementioned new design guidelines are necessary for both the opportunities and risks of the new signaling system. This paper describes an issue that needs to be studied to define indicator design guidelines. One of the most important challenges includes determining protective paths behind the

ETCS marker boards and, thus, defining the Supervised Location (SvL). This, in turn, translates directly into the shape of braking curves, which directly impact capacity utilization. This demonstrates the complexity of the aspect under study and the need to analyze it under multiple criteria.

3. ETCS BRAKING CURVES

The task of the ETCS is to monitor the train's position and speed at a given movement authority point. If the permitted speed or travel distance is exceeded, the on-board ETCS intervenes by sending a service or emergency braking command to the traction vehicle's braking system via a dedicated interface. For this purpose, the ETCS must use the relevant parameters characterizing the train braking process to predict the actual braking behavior of the train on a given section of infrastructure. The braking curve models used by the ETCS are based on a mathematical and physical description of the vehicle's braking behavior. Among other things, these models are based on data on railroad vehicles, such as the braking characteristics of a given rolling stock, the inertia time of the braking system, traction parameters and the length of the train.

General models for determining braking curves in the ETCS are harmonized and described in the ETCS standard [9]. In addition to rolling stock parameters, the determination of braking curves at a given point in the travel path is based on data from ETCS trackside equipment, such as the length of the movement authority, its characteristics, its longitudinal profile and speed profiles and other data characterizing the infrastructure, which is part of the received movement authority.

The length of the movement authority defined by the distance of the train front to the End of Authority (EoA) may include, but is not limited to, the following elements relevant to the dynamics of train travel:

- the length of the section at the end of which the EoA is located,
- the distance of the danger point from the EoA and the associated Release Speed,
- overlap protection route information and related parameters.

The danger point is a point on the infrastructure that a train traveling in a given permit should not be able to cross, which avoids the danger of a collision with other rolling stock. It is usually defined in the location of the end of the switch lying outside the protective path of the run for a given train.

The braking curve in the ETCS is described based on the characteristic $f(s) = v$, where s is the distance and v is the speed. Depending on the type of train set and available data, the γ model is used to calculate braking curves in the ETCS. The γ model is based on braking values for different speed intervals A_brake(v) [m/s^2], known for a specific train set (usually used for electric multiple units). It is also based on correction factors determining the difference between the nominal braking value and the guaranteed value for braking on dry and wet rails. For trainsets that can be arbitrarily set up (e.g., wagon trainsets), the λ model is used. The λ model with reference to the percentage of actual braking mass Pr specified for the train set, the train length and the type of braking system (e.g., fast-acting or slow-acting brakes), allows the A_brake(v) [m/s^2] characteristics to be determined from the conversion model.

The on-board ETCS for safe train control calculates several curves that make up the braking curve set. The most important curves are:

1. I − Indication: a curve that signals the driver that he is approaching the permitted speed.
2. P − Permitted speed: the curve of the train speed. If the driver exceeds this speed, they have a certain reaction time to apply service braking, which does not exceed the point at which the on-board ETCS will intervene.
3. SBI − Service Brake Intervention: Beyond this curve, the on-board ETCS will apply service braking if the driver fails to respond to braking initiation warnings.
4. EBI − Emergency Brake Intervention: Beyond this curve, the on-board ETCS will apply emergency braking if the effectiveness of service braking is insufficient.
5. EBD − Emergency Brake Declaration: With this curve, calculated by the on-board ETCS, it is assumed that the train will move in the event of emergency braking.

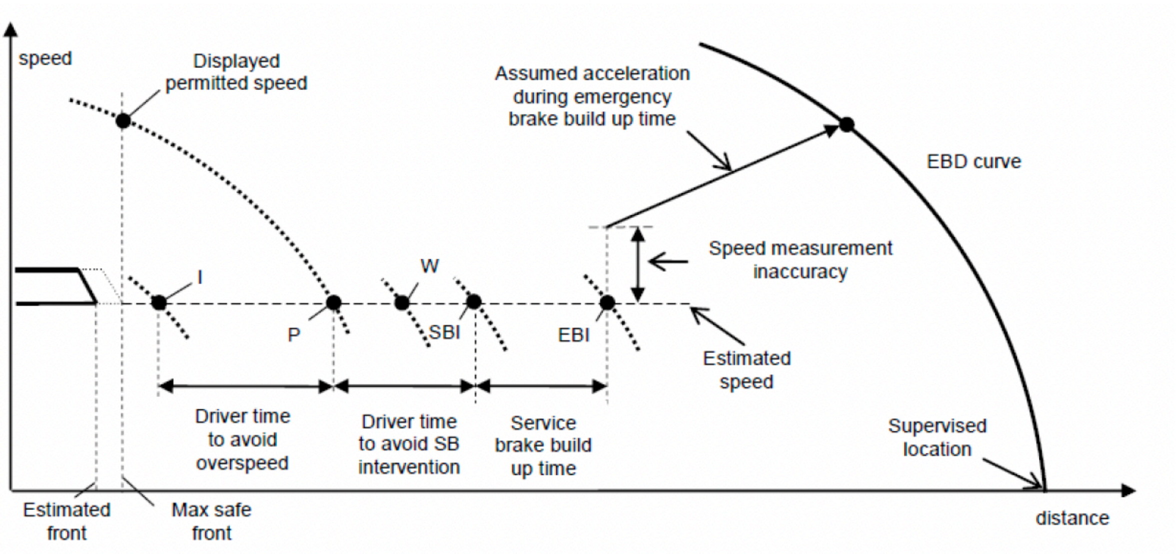

Fig. 1. ETCS braking curves (source: [9])

As part of supervising train running, the ETCS is based on the position of the train relative to the reference system, which are balises installed in the track. Odometrical measurement is subject to inaccuracy, which can result from, for example, wheel slips and slides. For this reason, in supervising the train's movement, the ETCS determines the "window" in which the front of the train may be located. The on-board ETCS, based on data from the odometry system, determines the three most prominent potential positions of the actual train front end:

1. Estimated train front end: the most likely current position of the train front.
2. Max safe front end: the most advanced position of the train front.
3. Min safe front end: the outermost position of the train front.

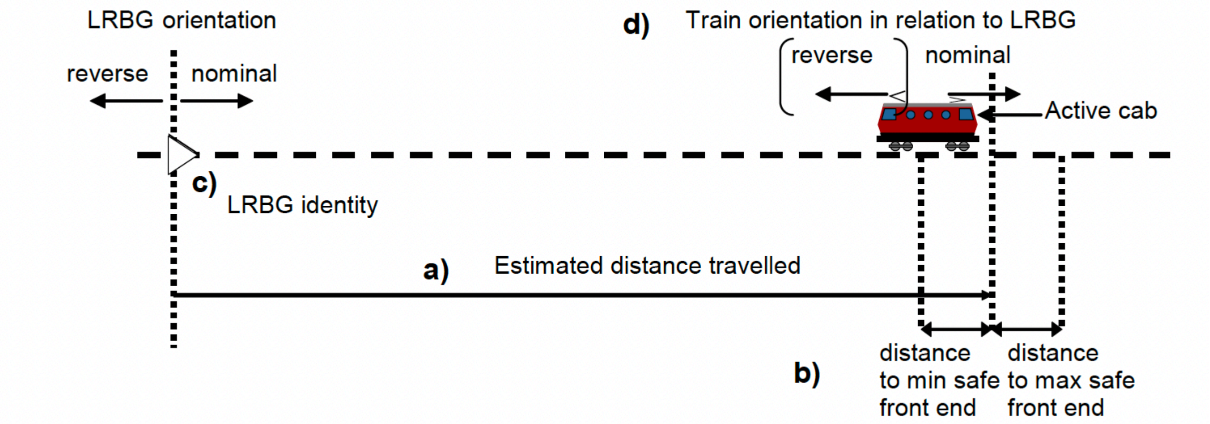

Fig. 2. The measurement of the position of the front of the train in the ETCS (source: [10])

The position of the train front and the inaccuracy of the odometry measurement substantially impact the process of train braking by the ETCS. For this reason, the ETCS can also determine the so-called Release Speed (RS), which is related to the danger point or SvL in the movement authority transmitted. The RS is a specific speed limit that applies near the EoA. It is a fixed value provided by ETCS trackside equipment or calculated by on-board ETCS equipment. After this, the SBI, W, P, and I curves are not calculated any further.

RS may be necessary for two main reasons:

1. Approaching the EoA: The train must be able to approach the EoA where the permitted speed reaches zero. In the absence of RS, the braking curve may be too restrictive and make it impossible to

approach the EoA due to inaccurate odometry (the ETCS considers the inaccuracy of odometry measurement).

2. For ETCS Level 1: In Level 1 applications, a train must be able to pass over a balise when the signal box connected to that balise displays a proceed signal.

The RS allows the train to approach the EoA since the on-board ETCS equipment supervises the EoA by the min safe front end (instead of the max safe front end, as is the case in the absence of a defined RS). Thus, the issue of defining the danger point and the value of the RS becomes important from a safety point of view. When the driver fails to properly stop the front end of the train before EoA, the system must be able to stop the train before the danger point when the system's intervention may occur when the actual front end of the train is already past EoA.

Previous in-own research [13] has shown that, in certain situations, the ETCS Level 2 can increase the gap occupation time compared to the averaged gap occupation values taken into account in the timetable's construction. This is due to the system's more restrictive approach to braking compared to the behavior of a driver driving based on trackside signaling. Longer braking times increase block occupancy and headway times for the following train. Since timetables are based on traditional braking distances, using ETCS may sometimes lead to deviations from the schedule [13]. Eliminating this phenomenon with applications of the ETCS Level 2 implemented on existing infrastructure equipped with classic trackside signaling, and therefore, classic sections and lengths of protection routes can be difficult.

Previous research by the authors on increasing capacity through the overlay of ETCS L2 on existing conventional signaling schemes proposes using additional block divisions with sub-sections [13]. This solution was analyzed through simulation methods to assess ETCS braking curves, followed by analytical methods to determine the minimal headway time [13]. The issue of capacity assessment was also addressed in the article [11], which analyzed the use of another configuration of ETCS. This paper also assumes additional block divisions by using virtual block sections through the hybrid ETCS Level 3. Another study on simulation and implementation of ETCS is presented in the paper [12]. This article also addresses the issue of ETCS performance and evaluates it using a numerical solution of the non-Markovian model.

When analyzing the implementation of ETCS Level 2 on high-speed lines, where, in principle, traffic will be based on the ETCS only without classical trackside signaling and the relations can be simplified, the following aspects, among others, should be considered:

- section lengths adapted to driving under ETCS supervision considering equal occupation time
- layout of balises limiting the inaccuracy of odometry measurement
- implementation of danger point offset from EoA depending on the protection route of the train route (including dynamic offset if the protection route is not occupied)
- extension of protection routes
- use of calculation of RS by on-board equipment or definition of a fixed value depending on the distance of danger point from EoA
- ETCS national values that impact the values calculated by on-board ETCS braking curves.

The first aspect was addressed in [14], where a methodology was presented to calculate optimal section lengths and indicator locations with as little signaling equipment as possible. Moreover, in [15], the design of a signaling system was analyzed. A design approach is presented to identify a signaling layout that minimizes investment and management costs while maintaining the required capacity level. The current study focuses on the last three aspects related to determining the length of the protection route and the RS on it.

4. SIMULATION METHODOLOGY

The simulation studies were conducted based on the mathematical model of braking curves in the ETCS, which is harmonized and described in the ETCS standard [6]. Parameters describing a representative model of the train were assumed to be invariant throughout the simulation study. These include basic data such as the type of train and its length, as well as the values of variables and coefficients modeling braking curves in on-board equipment for a given vehicle. The basic parameters adopted for the train are shown in Table 1. The detailed vehicle parameters, which primarily concern braking performance, represent a basic vehicle with average braking performance. The study focuses on a group of vehicles that present poorer parameters, as they represent the group of vehicles that degrade driving efficiency.

Table 1

Parameters of the train under study

Parameter Name	**Value**
Train type	Gamma Train
Brake position	Passenger train in P
Speed inaccuracy	According to Subset-041
Position inaccuracy	According to Subset-041
Train length [m]	20
Nominal rotating mass [%]	10
Maximum deceleration value under reduced adhesion conditions [m/s^2]	0.45
Weighting factor for available wheel/rail adhesion	0
Confidence level for emergency brake safe deceleration on dry rails [%]	99.99
Initial speed [km/h]	250

Another group of adopted parameters was the trackside data of the ETCS, whose constant values that did not change during the tests were adopted according to Table 2. As shown below, the value of the gradient of the track and the positioning of the balises were not the subject of study in the simulations.

Table 2

Parameters of the track under study

Parameter Name	**Value**
Target type	EoA/SvL
Distance origin [m]	10,000
Gradient [‰]	0
Distance between relocation balises [m]	650

The data presented in Table 1 and Table 2 should be considered inputs in the model under study. The values taken as variables in the simulation study are shown in Table 3.

Table 3

Variables examined in simulation studies

Variable Name	**Tested values**
Distance between EoA and SvL	0, 25, 50, 75, 100, 150, 200, 250, 300, 350, 400, 450, 500, 1000, 1500, 2000, 2500, 3000, 3500, 4500, 5000
RS	40, 30, 20, 10, 5, calculated on-board

The above variables were successively tested iteratively. Whenever the value of one variable subject to analysis was changed, this constituted one test case. The results were then compiled in a database, whose analysis and compilation of each test case made it possible to draw relevant conclusions. The database includes the results from the test of each case concerning the following parameters:

- the distance between successive relocation balises;
- the analyzed distance EoA-SvL;
- the distance to the end of the permit in which the train reached the braking curve I, P, W, SBI, EBI;

- the value of the RS;
- the distance to the end of the movement authority in which the train reached the RS value.

The results for each test case are also presented in a graph of the dependence of speed on the travel distance covered V(s) for the braking curves: W, I, P, SBI, EBI, EBD.

The simulation study was conducted to determine the effect of the variables presented in Table 3 on the braking curves of a train moving under the supervision of the ETCS on high-speed lines. The purpose of registering these relations was to determine the acceptable values of each variable separately and in relation to each other for use on high-speed railways.

5. THE RESULTS OF SIMULATION STUDIES

The appropriate selection and configuration of the trackside data responsible for determining the RS value for a given train route, as well as appropriate SvL determination, make the ETCS more efficient and useful. Strict braking curves forcing irrationally early train speed loss are the source of many negative voices and perceptions of ETCS use. More importantly, the configuration of the ETCS may, for example, not allow precise arrival at a stopping point by making it impossible to stop a train in the platform area.

Various inconveniences adversely affect the capacity of railroad lines or the efficiency of driving; on high-speed lines, the effects will be more pronounced. This study attempted to prevent these negative outcomes by examining variants of configuration data and their possible optimization to increase the efficiency of running railroad traffic. The conclusions and summary in this regard are included below.

The conclusions obtained relate to vehicles with poor braking performance, since such vehicles were the subject of the analyses conducted, as the weakest point causing a reduction in the efficiency of running traffic. When using a vehicle with better braking performance, the conclusions and differences in braking curves indicated below do not apply. Vehicles with other braking parameters are the subject of ongoing further studies.

5.1. The impact of the distance between EoA and SvL

By studying the braking curves affected by the distance from the EoA to the supervised location, it can be determined whether and by how much we can improve the braking curves by providing a sufficiently long protection route. Improving the braking curves to allow a later start of braking will improve the functional perception of the ETCS and line capacity without reducing safety. Acceptable configurations of ETCS parameters should have a safety level not less than that of current implementations.

Table 4 shows the distance to the EoA at which the train reached a given braking curve for a distance between relocation balises of 650 m and a RS of 40 km/h. Figure 3 shows a linear increase in the distance of achieving a given braking curve, the end of which can be indicated in the 2500 m value of the EoA-SvL distance. This means that, above this value, we do not benefit from the distance of the SvL from the EoA in the formation of braking curves. Moreover, at values above 3000, there is no further gain in the shift of braking curves.

Moving the SvL away from the EoA allows braking curves to reach later than the current configuration when the EoA and SvL are at the same point. In the case of unoccupied consecutive sections and non-reflection of conflicting runs, the SvL can be selected dynamically to delay the train braking by the ETCS as much as possible.

5.2. The impact of RS

The first purpose of the analysis was to examine at what point the train would be in a curve, allowing it to move further with RS depending on the value adopted. The results were then compared with the values obtained for a configuration in which the RS value is calculated by on-board equipment. Table 5 summarizes the results of these simulations, which show the values of the distance from the EoA when the train enters the RS area in relation to the value of this speed and the offset of the SvL from the EoA. A comparison of the above data resulting from simulation studies made it possible to draw several conclusions related to the configuration of trackside data and their influence on train braking curves.

Table 4

The distance to the end of the movement authority in which the train has reached a given braking curve [m]

Braking Curve / EoA-SvL Value [m]	0	100	200	300	400	500	1000	1500	2000	2500	3000
Permitted	7295	7199	7104	7009	6914	6818	6311	5804	5297	4821	4742
Emergency Brake Intervention	7017	6922	6826	6731	6636	6541	6033	5526	5019	4543	4014

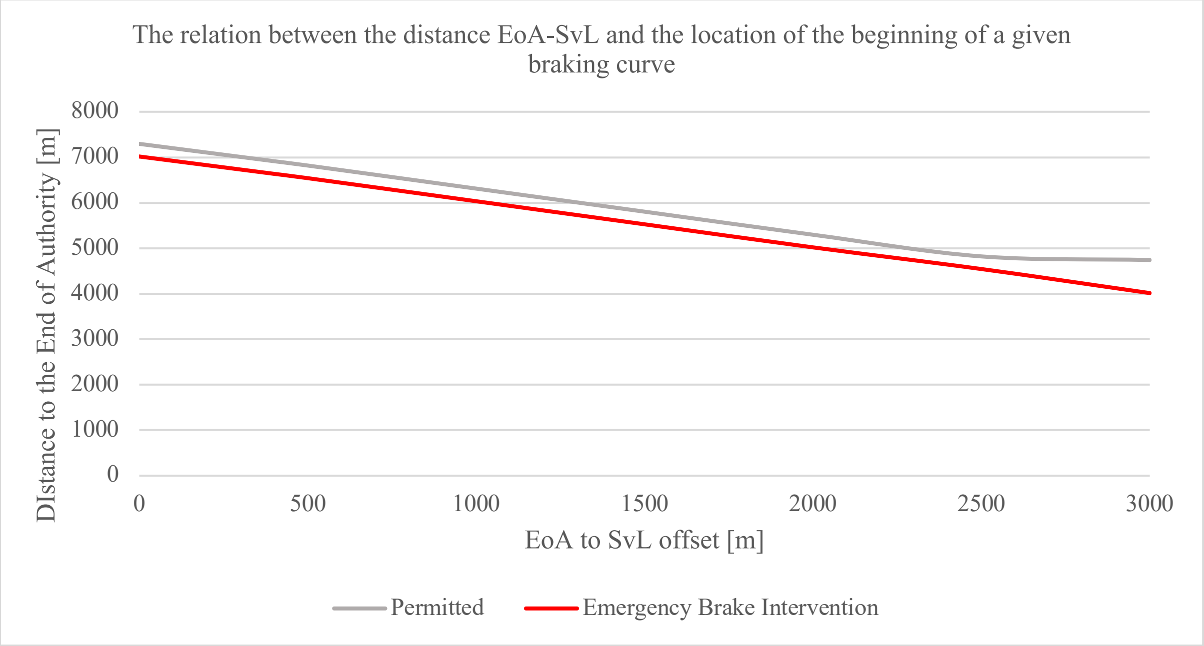

Fig. 3. Relation of end of authority to supervised location offset and braking curves (source: own study)

The value of RS, according to the specification in [10], can be a fixed value ranging from 0–600 km/h in increments of 5 km/h, or it can be dynamically calculated by on-board equipment. The above values allow us to determine the minimum RS values that have practical applications. The use of values of 5 or 10 km/h in practice will be felt analogously to the use of RS = 0 since the train will be so late in its area of operation. The braking of the train in such a configuration can be as rigorous as it is currently when SvL=EoA.

In addition, calculating RS using on-board equipment is not an optimal solution from the point of view of the driver. The driver cannot predict the moment or the value of RS that will be calculated by the on-board equipment, and consequently, the vehicle will be driven close to this limit. On the other hand, it is reasonable to use RS calculation by on-board above a certain EoA-SvL distance if only because of the time-consuming preparation of the ETCS application data distinguishing the adopted RS value for each successive value of SvL offset from EoA. For large values of SvL offset from EoA, it seems reasonable to use on-board RS calculations. By specifying a single fixed value for the RS, the on-board equipment should be enabled to calculate the RS for an SvL-EoA offset above which the RS will be less strict than the specified fixed value.

Table 5

The distance of the beginning of monitoring the RS value [m]

RS Value [km/h] / EoA-SvL Value [m]	**0**	**100**	**200**	**300**	**400**	**500**
40	156.88	76.21	76.21	76.21	76.21	76.21
30	101.04	42.87	42.87	42.87	42.87	42.87
20	60.58	19.05	19.05	19.05	19.05	19.05
10	32.85	4.67	4.67	4.67	4.67	4.67
5	23.77	1.19	1.19	1.19	1.19	1.19
Calculated on-board	0	28.36 (for RS=24.4 km/h)	85 (for RS=42 km/h)	145.57 (for RS=53.8 km/h)	207.90 (for RS=63.7 km/h)	241.55 (for RS=72.3 km/h)

It is necessary to determine the RS values to be applied when selecting the configuration data of the trackside ETCS depending on the dynamically changing EoA-SvL distance. It is also necessary to determine the limit value from which the RS calculation will be the on-board's task. A sample determination of these values is proposed below in Table 6.

Table 6

RS values dependent on EoA-SvL distance

Distance between EoA-SvL [m]	**RS value [km/h]**
Less than 100	40
100–200	40 or more
More than 200	Calculated on-board

The above is based on the analysis of the data obtained during the simulation tests. At the RS values considered above, for the offset of SvL from EoA by less than 200 m, the benefit of calculating the braking curve on board relative to the highest adopted constant value (40 km/h) was negated.

5.3. Comparison to current solutions

The graph of braking curves in Figure 4 shows the solution based on the currently adopted design assumptions, where the RS is 20 kph and EoA=SvL, while Fig. 5 shows the braking curves with the adoption of rules in line with the above proposal, where the RS is calculated by on-board equipment as a dynamic offset of SvL from EoA of 500 m.

The above illustrates the data showing that the solution shown in Fig. 5 allowed the train to be in the braking curve corresponding to the implementation of the brakes 476.2 m farther than in the case shown in Fig. 4. The train will not be forced to reduce speed earlier and travel longer distances with reduced speed. In addition, the moment the permitted curve meets the RS curve, the train can continue moving at a maximum speed equal to the value of the RS, which will occur at a distance of 241.55 m from the end of the movement authority, where the RS will have a value of 72.3 km/h, and this will allow the driver to effectively operate the train's speed when braking. This results in an increase in the efficiency of the ETCS. It also makes running the train closer to the driving dynamics without ETCS while preserving all the safety advantages offered by the system. A braking delay of a few hundred meters should significantly impact the railway line's capacity.

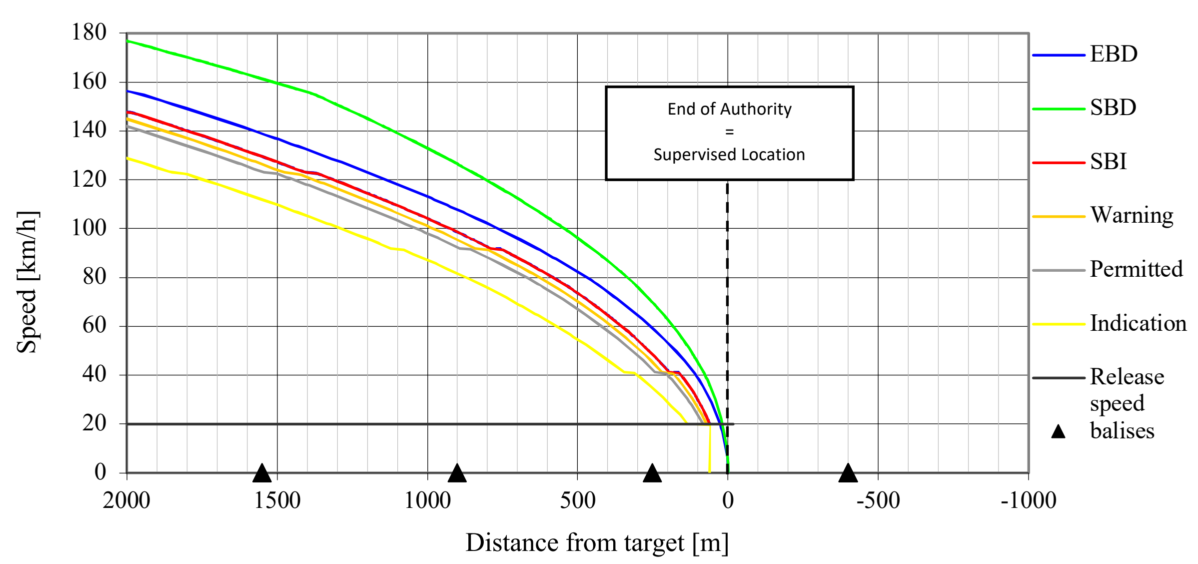

Fig. 4. Braking curves in accordance with current design rules (source: own study)

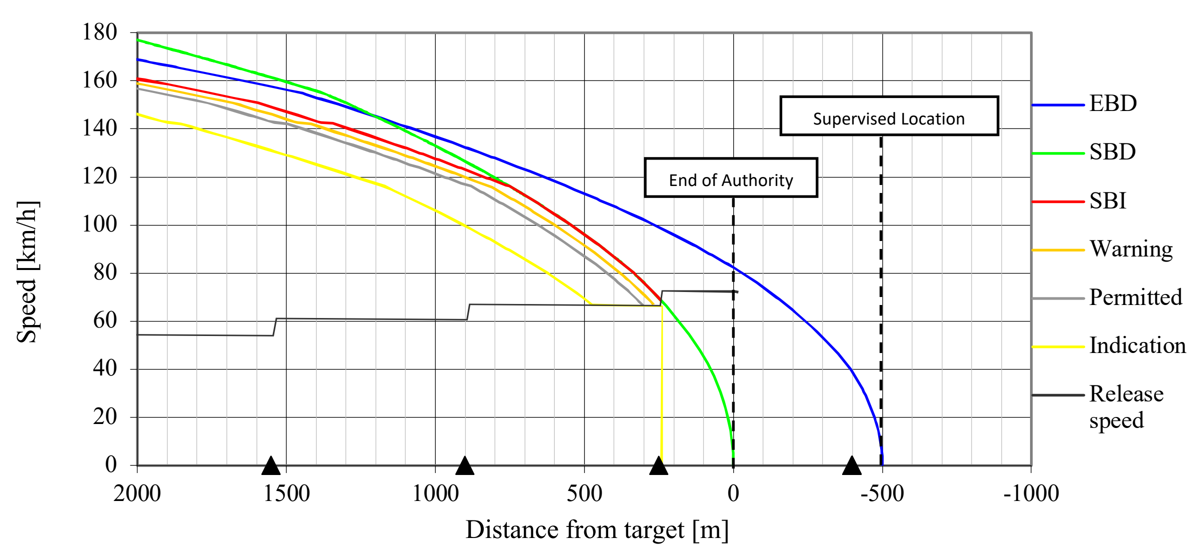

Fig. 5. Braking curves in accordance with the proposed approach (source: own study)

However, the length of the protection route and the value of the RS must be determined on a case-by-case basis. Depending on the layout of the balises and the danger points, the value of the protection route must be such that, at high RSs, it is possible to stop the train before reaching the supervised location. This prevents situations where the driver passes the end of movement authority, commonly referred to as signal passed at danger (SPAD). Wheel-rail adhesion must also be considered. As long as the ETCS supervises train movement based on braking curves, correction factors for reduced adhesion conditions, among other things, are considered. This factor is determined individually for each train on an experimental basis according to the EN 15595 standard [16]. When moving within the limits of the RS, the braking process to the point of the EoA is entirely the responsibility of the driver. In this case, wheel slide protection (WSP) systems should be considered. An analysis of their operation and testing methods have been described in scientific studies [17][18] using hardware-in-the-loop simulation. Those systems are widely used in many fields for verification and testing before a certain system is built [18]. It is advisable to carry out analogous tests for the planned Polish high-speed rail network, especially because the WSP system can test various hazardous braking conditions that cannot be tested under real conditions.

6. CONCLUSIONS

The purpose of this research was to develop and analyze a new approach to the configuration of the trackside part of the ETCS and to study its effect on the braking curves calculated by the on-board equipment of this system. This approach was intended to improve the efficiency of rail traffic operation under the supervision of the ETCS.

Based on the simulation studies carried out in this paper, the following conclusions can be drawn:

- Both the overlap (protection route) and the RS in the ETCS must be configured to enable precise arrival at a target location.
- Extending protection routes allows a train under ETCS supervision to delay braking.
- The value of the RS should depend on the dynamically changing protective path or the protective path selected according to a constant specified RS.
- The value of the RS and the length of the safety clearance must enable the train to be stopped safely if the end of the movement authority is passed at the RS.

The current results make it possible to confirm the positive effect of the proposed solution on the formation of train braking curves. The goal of reducing the restrictiveness of the braking curves and enabling the train to reach the end of the running permit more efficiently has been achieved. Therefore, it is reasonable to further develop the proposed solution.

The presented solution requires further simulation studies considering more variables and their possible values. There is also a need to analyze the impact of the presented solution on throughput.

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Received 25.01.2024; accepted in revised form 07.03.2025