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Simulation of The System of Provision of Target Braking of Rolling Stock

This research presents a framework simulation model that can be used to simulate target braking of rail rolling stock, with a particular focus on target braking in metro systems. The model takes into account various factors that might affect stopping accuracy, including errors in speed measurement and track sensors' positioning. The research considered the possibility to minimize the required equipment for the target braking system, with its conclusions providing insights for possible solutions that would require minimal additional equipment or infrastructure modifications. Through simulation in MATLAB®/Simulink® environment, this study investigates the individual impact of these factors on the target braking precision of rail rolling stock. By identifying these critical factors that affect braking accuracy and quantifying their impact, this research provides valuable insights into strategies for optimizing braking performance and enhancing passenger safety and comfort.
Keywords: *railway operation; urban rail transport; automatic train operation; mathematical model; uncertainty impact; time saving; traffic optimization.*

The aim of the article is to develop a technology for the selection of means of ensuring target braking of rolling stock by modelling using automated and automatic train control systems. One of the key aspects of developing such a technology is, on the one hand, the creation of reliable equipment that ensures the transmission, processing and storage of a large amount of data and knowledge, and, on the other hand, minimising resource consumption.

This area of research opens up great opportunities for improvement of train control systems, ensuring their safety and optimising their performance. The research results can be of great importance for the development of both railway and urban transport, in particular for improving the processes of target braking of rolling stock, ensuring traffic safety and reducing the risk of accidents.

Ultimately, the results of this study are intended to improve future practices in the design, maintenance and operation of automated rolling stock control systems, as well as to contribute to the safety of passengers and improve the quality of service of their demand for transportation.

Problem statement

The relevance of the study of precision braking systems is closely related to the importance of improving rail transport systems in general. The introduction of automatic train operation systems and, in particular, automatic target braking systems is possible and appropriate both on mainline railway transport and urban rail transport, in particular, on subways. The tasks that can be solved with the help of precision braking systems and the priorities for their implementation depend on many factors and the specifics of the transport system in which they are intended to be implemented. The list of tasks can include both reducing energy consumption for traction and optimising traffic schedules or increasing the system's capacity [1]. This study will focus on off-street urban railways - metros. The peculiarity of subways is their high route capacity, which reaches and exceeds the figure of 50 thousand passengers per hour per direction [2]. This high figure is achieved due to the specific nature of the metro as an urban railway.

Subway systems are separated from any street traffic and use their own right of way [2], which determines their location underground or on elevated tracks. This allows metro systems to provide high route speeds with a significant passenger capacity per unit (train) compared to other forms of urban transport.

The development and expansion of cities and the growth of their population are inevitably associated with an increase in demand for passenger transport in the city and an increase in the average distance travelled by transport. The growth of both of these values entails increased requirements for the capacity of the urban transport systems. At the same time, the reserves of the metro systems themselves for increased traffic are limited by their technical capabilities. This makes it necessary to implement such measures as increasing average operating speeds, acceleration and braking rates, etc. The introduction of targeted braking systems is the most effective measure to achieve the maximum possible deceleration rate during braking while maintaining a high level of comfort for passengers.

Analysis of recent research and publications

A number of studies have been devoted to the problems, theoretical foundations and economic basis for the introduction of automatic train operation systems, particularly in the context of integration them with rail traffic control [1, 3-6]. Much attention is paid to the problems of modelling of rolling stock dynamics [7-11].

Recognizing the high scientific and practical value of the above works, it should be noted that at the moment the problem of creating systems for automatic train operation and automatic targeted braking has not been given enough attention. It is important to use a comprehensive systematic approach to the problem, which simultaneously takes into account both the advances in the field of rolling stock dynamics and automatic operation systems and the economics of railway enterprises. The topic of automatic train operation and targeted braking requires further research and development.

Statement of the problem

The main issue that will be considered in this article is the creation of a mathematical model to evaluate the technology for implementing the targeted braking system under conditions of external perturbations and imprecisions. Thus, the purpose of this work is to create a framework model that would allow testing the train precision braking system with the ability to adapt it to the specifics of any rail rolling stock, as well as with the possibility of including certain solutions for implementing the algorithm. In particular, this paper will consider the study of the accuracy of the implementation of the targeted braking algorithm under conditions of uncertainty and incomplete input information. A mathematical model created in MATLAB®/Simulink® will be used to investigate the separate influence of such factors as deviations in the location of track sensors, changes in the diameter of the wheel set with wear, and errors in speed measurement.

The main part of the material

Automatic targeted braking of rolling stock is the process of controlling the speed of trains in deceleration mode, which ensures its reduction to the required value or stopping at a given point on the track. For suburban and metro electric trains, the typical operating modes are acceleration, coasting, and braking [12]. The introduction of intense targeted braking has a significant and comprehensive effect on the performance of rolling stock. When braking manually, the electric train driver chooses the moment of braking start with a margin for his own mistake or incorrect choice of braking mode. This limits the average deceleration of the train, even if it is technically possible to apply more rapid deceleration. As optimization of driving method is one of possible ways to achieve energy savings [14], targeted braking is an effective way not only to improve the quality of passenger service and reduce the workload of the train driver, but also to increase the carrying capacity of the metro and reduce electricity consumption for rolling stock traction.

Different deceleration levels are set to regulate the braking force during targeted braking, and if only one level can be set, gradual stepped braking is used. The braking mode is selected depending on the deviation between the train's programmed speed and the actual speed, and in some systems, the derivative of this deviation. In some systems, the speed is set by a software device located along the track. In this case, the value of the set speed is determined by the distances between the elements of the ground applications or the frequency of the electrical signal. In other systems, the speed is set as a function of the measured path or is calculated based on the leading solution of the equation of train motion [5].

The calculated trajectory of the targeted braking as a function of the path is based on the value of the average deceleration rate of the train. However, the actual braking trajectory will certainly differ from the calculated one, since the train speed during braking is influenced by many factors, and they cannot always be accurately taken into account. For example, to ensure the comfort of passengers, a rapid change in braking modes is unacceptable, as it leads to unpleasant jolts during movement. Therefore, in general, it can be assumed that the train speed when braking when approaching a station is a function $V = f(V', a, j...)$, where V' is the initial speed when approaching the station, km/h; a is the deceleration value when braking, m/s^2; j is the jolt, m/s^3, etc. In turn, a train is also a complex dynamic system with a large number of nonlinear connections between structural elements [10, 15]. It should be emphasized that traction rolling stock is a very complex engineering structure and, as a result, is a complex object of simulation [16]. Therefore, in general, it is possible to raise the question of the "level of detail" of modelling of train dynamics, which will be defined as the number of factors and dependencies taken into account in the modelling of movement. In this paper, a train is considered as a material point whose movement is affected by acceleration and deceleration from the operation of traction motors and brake systems, as well as by the main resistance to movement. To determine the main resistance to movement, studies conducted on the Kharkiv metro were used [7].

The main characteristic of automatic targeted braking is the accuracy of stopping. The smallest permissible error (within ±0.3...0.45 m) is required for closed-type stations. At open-type stations, where the length of the boarding platform slightly exceeds the length of the train, the acceptable accuracy of stopping is ±1.5 m [5].

The introduction of an automatic targeted braking system requires significant capital investment, since not only the rolling stock but also the track sections are changed. The issue of reducing such capital investments is quite evident and requires a more in-depth consideration. Given the need to reduce costs, the targeted braking system proposed in the model consists of the following main elements:

1) a braking microcontroller based on fuzzy logic that makes decisions on the application of different braking modes in accordance with the deviation of the actual train trajectory from the calculated one;

2) a trajectory calculation system;

3) three track sensors that indicate the current coordinate of the train;

4) speed measurement system;

5) a system for calculating the current coordinate of the train based on the readings of the speed measurement system.

The arrangement of the track sensors (D_1, D_2 and D_3) used in the model is shown in Figure 1. Point D_4 indicates the target stopping point of the train.

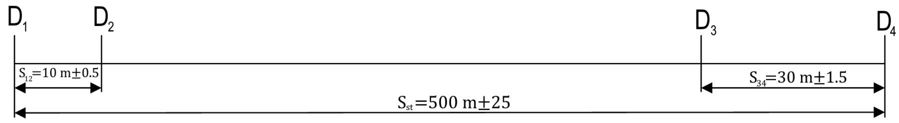

Fig. 1. Layout of track sensors

Since such a system does not use a large number of track sensors to continuously monitor and correct the current coordinate of the train's location, it is beneficial in terms of capital investments, as it minimizes the amount of equipment required. At the same time, such a system relies on the measured (using analogue axial sensors) speed of the rolling stock to calculate the current position of the train. It is sensitive both to its own internal measurement errors and to changes in the diameter of wheel sets as they wear out. In combination with the possibility of improper positioning of the track sensor that signals the current coordinate to the rolling stock, the resulting deviation of the actual stopping point from the target point can be unacceptably large.

Therefore, when calculating the distance travelled by a train, a certain measurement calibration is required. To do this, at a predetermined distance (the model assumes 10 m, which corresponds to approximately four revolutions of a normal-diameter metro car wheel set), a second track sensor D_2 is installed after the first track sensor D_1, which transmits a second, corrective coordinate to the train. The measured distance between these sensors is compared with the nominal distance between them, and then a corrective coefficient is calculated.

The third track sensor is located 30 meters from the stopping point. After this sensor is passed, the current coordinate of the train calculated by the braking system is reset to 470 meters (S_{ST} - S_{34}), while the previously calculated corrective coefficient is still used to further calculate the braking trajectory.

The flowchart of the developed simulation model is shown in Figure 2. A general view of the brake controller of the model developed in MATLAB®/Simulink® is shown in Figure 3. The brake controller used in the model is built with fuzzy logic [17] using the Fuzzy Logic Toolbox™ package of MATLAB® and uses two input parameters for control: ΔV (the difference between the set speed V' and the current measured speed V_M), and j (jolt, rate of change of acceleration). The membership functions of the linguistic terms used in the fuzzy controller for targeted braking are shown in Figure 4. The ruleset used by the controller is shown in Figure 5. The output surface of the controller is shown in Figure 6.

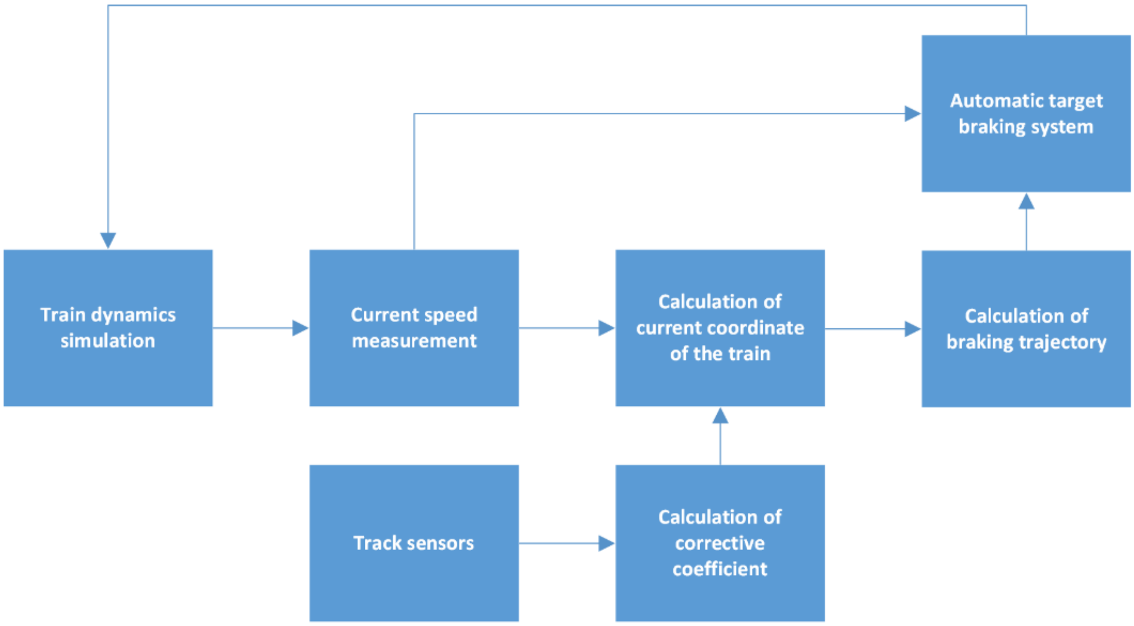

Fig. 2. Flowchart of the framework model for simulation of automatic target braking system

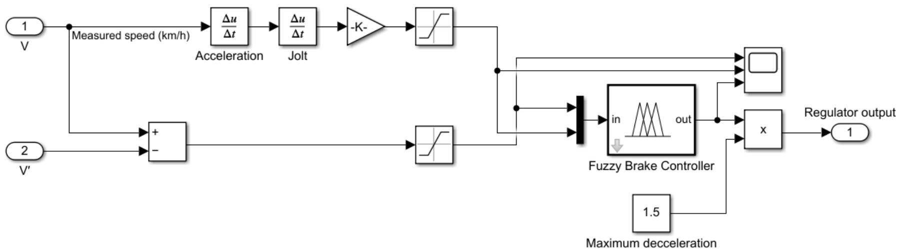

Fig. 3. Simulation of the brake controller of automatic target braking system

The stopping error is defined as:

$$\Delta S = S_{act} - S_{st} \quad (1)$$

Here S_{act} is the actual value of the distance travelled by the train after passing the first track sensor (point D_1 in Fig. 1) in metres, and S_{st} is the distance between the first track sensor D_1 and the calculated stopping point in metres (normally equal to 500 m).

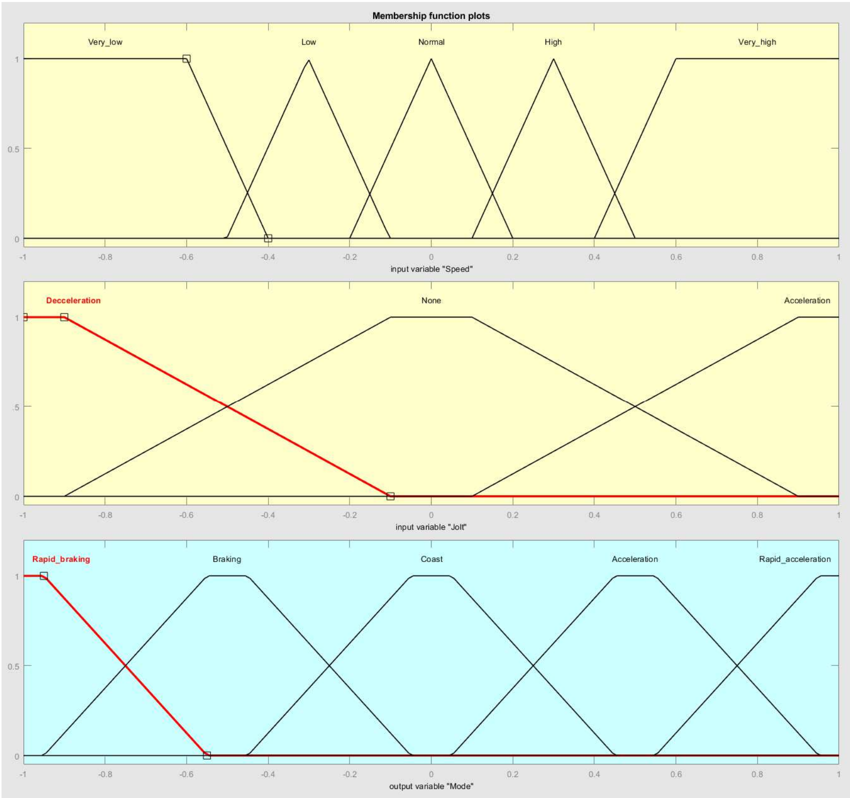

Fig. 4. Membership functions for input variables “Speed”, “Jolt” and output variable “Mode”

1. If (Speed is Very_low) and (Jolt is Decceleration) then (Mode is Coast) (1)
2. If (Speed is Very_low) and (Jolt is None) then (Mode is Coast) (1)
3. If (Speed is Very_low) and (Jolt is Acceleration) then (Mode is Coast) (1)
4. If (Speed is Low) and (Jolt is Decceleration) then (Mode is Coast) (1)
5. If (Speed is Low) and (Jolt is None) then (Mode is Coast) (1)
6. If (Speed is Low) and (Jolt is Acceleration) then (Mode is Braking) (1)
7. If (Speed is Normal) and (Jolt is Decceleration) then (Mode is Coast) (1)
8. If (Speed is Normal) and (Jolt is None) then (Mode is Braking) (1)
9. If (Speed is Normal) and (Jolt is Acceleration) then (Mode is Rapid_braking) (1)
10. If (Speed is High) and (Jolt is Decceleration) then (Mode is Braking) (1)
11. If (Speed is High) and (Jolt is None) then (Mode is Rapid_braking) (1)
12. If (Speed is High) and (Jolt is Acceleration) then (Mode is Rapid_braking) (1)
13. If (Speed is Very_high) and (Jolt is Decceleration) then (Mode is Rapid_braking) (1)
14. If (Speed is Very_high) and (Jolt is None) then (Mode is Rapid_braking) (1)
15. If (Speed is Very_high) and (Jolt is Acceleration) then (Mode is Rapid_braking) (1)

Fig. 5. Ruleset of the fuzzy controller of automatic target braking system

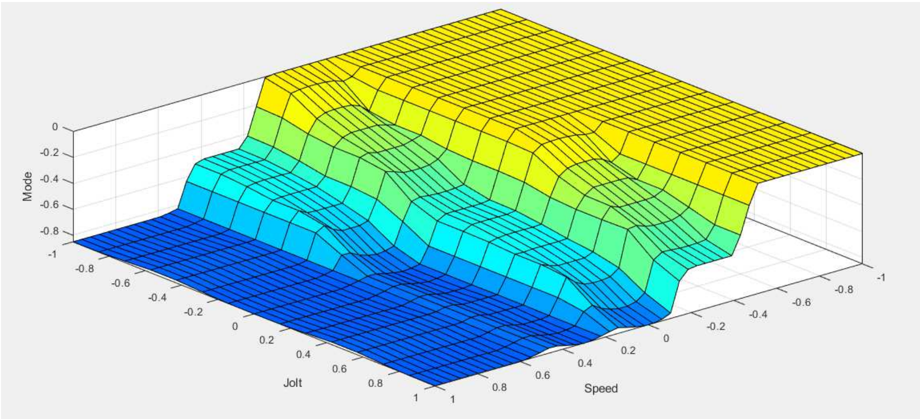

Fig. 6. Output surface of the fuzzy controller of automatic target braking system

The simulation considered the following principal factors that could affect the accuracy of the calculation of the current coordinate by the rolling stock, and as a result, the stopping error:

- variation of the wheel set diameter in the range between 790 and 725 mm (respectively for a new and a fully worn bandage);
- measurement error of the current speed value by axial sensors in the range of ±2.5 km/h;
- error of the positioning of the first (D1) and second (D2) track sensors between each other (distance S12 in Fig. 1) in the range of ±0.5 m
- error of the positioning of the third track sensor (D3) relative to the stopping point (D4) in the range of ±1.5 m;
- positioning errors of the first group of track sensors (D1 and D2) relative to the stopping point (D4) in the range of ±25 m.

By gradually changing each of these factors within the specified limits, their individual impact on the accuracy of targeted braking is determined. Thus, in the course of the research, it was found that the diameter of the wheel set (Fig. 7) and the error of the speed measurement system (Fig. 8) do not have a significant effect on the stopping error. Variation of the wheelset diameter in the entire possible range of its values did not lead to a significant deviation of the actual stopping point of the train from the calculated one as it remained within ±0.1 m. Similar error margins were observed when changing the error of speed measurement.

Regarding the change of the relative position of the track sensors among themselves, it was found that the stopping error is directly proportional to the error of their positioning. This is true both for the relative position of sensors D1 and D2 (Fig. 9) and for the positioning error of sensor D3 relative to the stopping point (Fig. 10), with the positioning accuracy of sensor D3 having a slightly greater impact on the accuracy of targeted braking. At the same time, due to the use of the third sensor D3, which updates the coordinate of the train while it is moving within the station, even very significant disturbances in the location of the first group of track sensors (D1 and D2) relative to the station are compensated. Thus, a variation of their placement within ±15 meters (3%) did not lead to unacceptable deviations from the stopping point (Fig. 10); it should also be noted that a deviation of the location of the first group of sensors towards the station leads to a more rapid increase in the stopping error than a deviation in the other direction.

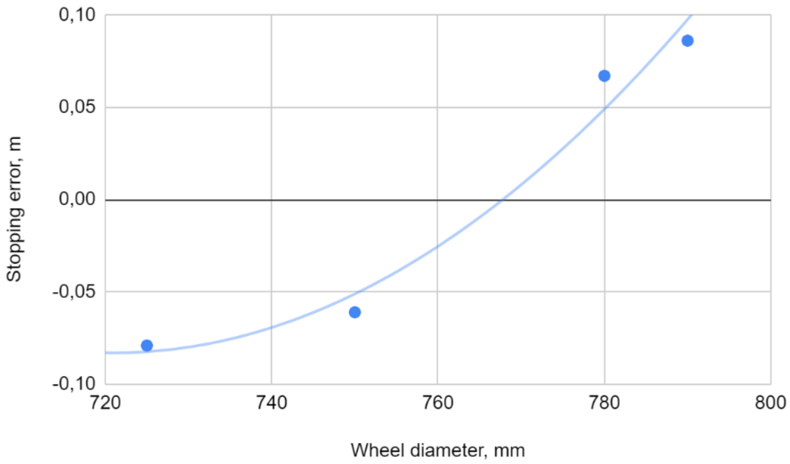

Fig. 7. Impact of the wheelset diameter on the precision of automatic target braking

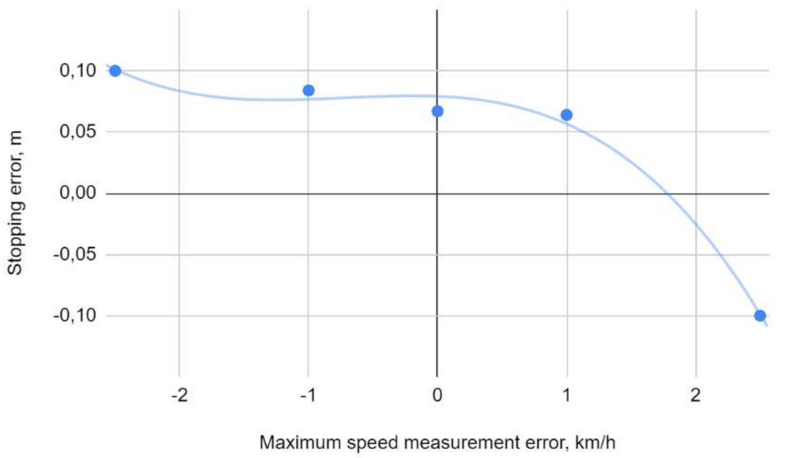

Fig. 8. Impact of the speed measurement error on the precision of automatic target braking

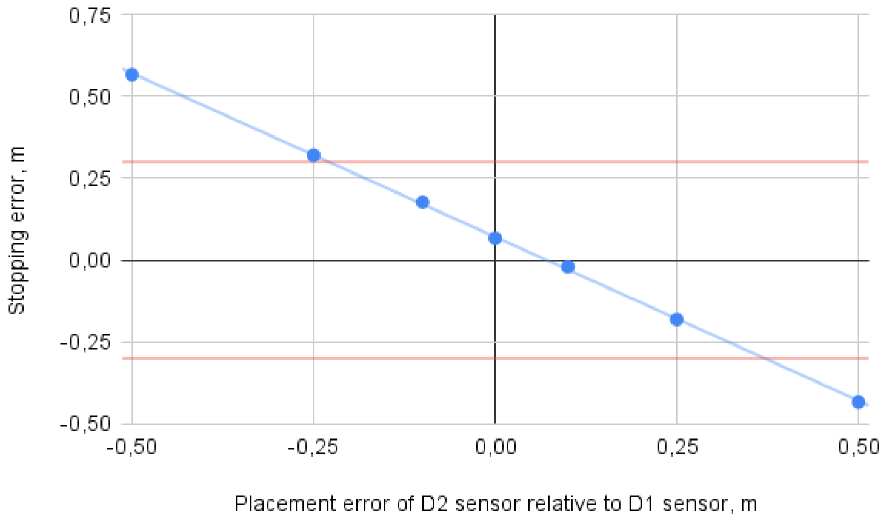

Fig. 9. Impact of error of positioning of corrective sensor D_2 relative to initial sensor D_1 on the precision of automatic target braking

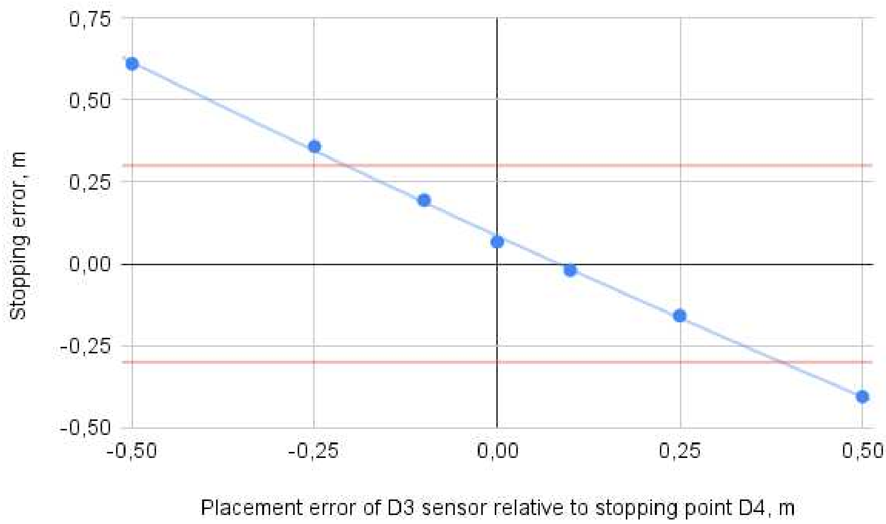

Fig. 10. Impact of error of positioning of corrective sensor D_3 relative to the stopping point D_4 on the precision of automatic target braking

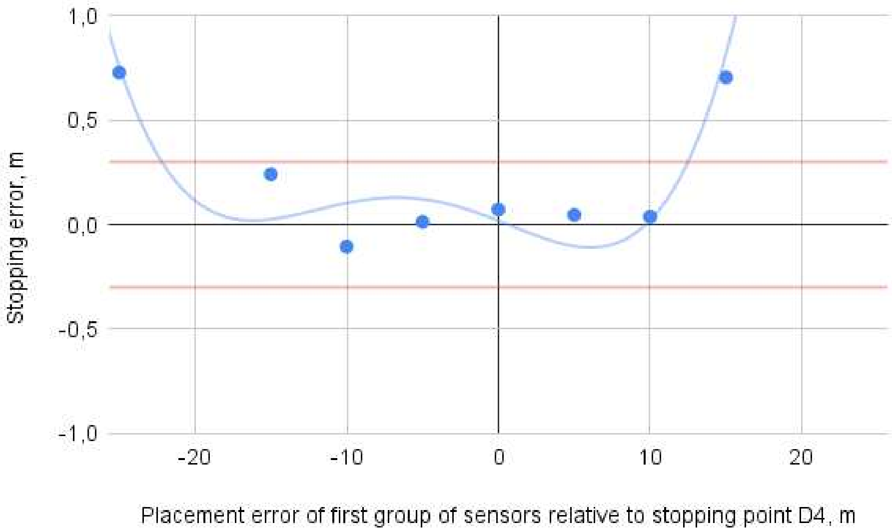

Fig. 11. Impact of error of positioning of the first group of track sensors (D_1 and D_2 combined) relative to the stopping point D_4 on the precision of automatic target braking

Conclusions

As part of the study, a mathematical framework model was created for the development and testing of an automatic targeted braking systems. As an example, this paper considered a system based on a fuzzy controller with the Mamdani algorithm. Modelling with the consecutive addition of input deviations that may occur during the use of the system made it possible to track the influence of each individual factor on the resulting braking precision. The modelling showed the following:

- rolling stock elements, such as wheel set diameter or speed measurement system error, can be accounted for by using a corrective coefficient and do not have a significant impact on braking accuracy. This means that the rolling stock itself does not necessarily need to implement new speed measurement systems and can use existing devices;
- even with significant deviations (up to 3-5%) in the installation of track sensors, the train stopping position remains within acceptable limits. This makes it possible to use a lower accuracy rating when placing track sensors.

The conclusions from the modelling are particularly relevant in the context of reducing capital investment in the implementation of train control systems in general and automatic targeted braking in particular.

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Ляшенко В. М., Яцько С. І., Ващенко Я. В., Хворост М. В. Моделювання системи забезпечення прицільного гальмування рухомого складу.

Анотація. У даному дослідженні представлено структурну імітаційну модель, яка може бути використана для моделювання прицільного гальмування залізничного рухомого складу, зокрема, прицільного гальмування в системах метрополітену. Модель враховує різні фактори, які можуть вплинути на точність зупинки, включаючи похибки вимірювання швидкості та позиціонування колійних датчиків. У дослідженні розглянуто можливість мінімізації необхідного обладнання для системи прицільного гальмування, а його висновки дають уявлення про можливі рішення, які потребують найменшого додаткового обладнання або модифікацій інфраструктури. За допомогою моделювання в середовищі MATLAB®/Simulink® в цьому дослідженні вивчається індивідуальний вплив цих факторів на точність цільового гальмування залізничного рухомого складу. Визначивши ці критичні фактори, що впливають на точність гальмування, і кількісно оцінивши їх вплив, це дослідження дає уявлення про стратегії оптимізації гальмівних характеристик і підвищення безпеки та комфорту пасажирів.

Ключові слова: експлуатація залізниць; міський залізничний транспорт; автоматичне керування рухом поїздів; математична модель; вплив невизначеності; економія часу; оптимізація руху.

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