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STUDY OF THE INFLUENCE OF THE TECHNICAL LEVEL OF RAILWAY VEHICLES ON BRAKING CHARACTERISTICS

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Abstract

In the article, the traction transmission of modern STADLER KISS trains is studied. The study of the effect of the technical level of the traction transmission on the braking characteristics of the train is discussed. The application of an innovative traction reducer is proposed, which allows to increase the result indicator according to the unit consumption of the traction transmission. Taking the reduction of the mass of the proposed thrust reducer as one of the main factors shaping the effect on the braking system, the possibility of reducing the inertia coefficient of the rotating parts and the technical parameters considered in the equation of motion of the train is shown. Taking into account the method of calculating the braking distance, the braking distance in different speed ranges is calculated in a practical example, by evaluating the braking efficiency, the possibility of reducing the braking distance by 5 % and reducing the braking time in proportion is shown. As a result of the experiments carried out by the researchers, it became clear that the technical level of traction transmission, consisting of multi-stage innovative reducers, directly affects the movement of trains. Thus, increasing the value of the coefficient of inertia of the rotating parts should allow accelerating the acceleration and braking times of the trains, passing the flats quickly, reducing the braking distance and saving some fuel resources. By conducting emergency braking tests, experimental values of the train's braking distance and braking time were determined and their compliance with the reported values was confirmed. Taking into account the advantages of the proposed reducer, a comparative description of the graphs of the dependence of braking distance and braking time on speed is given.

Keywords: traction transmission, brake path, equation of motion, technical level, braking distance, reducer.

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1. Introduction

Rolling stock brakes are a type of brake used on trains and single rolling stock to control deceleration, acceleration, or to hold them stationary when stopped. Since all the useful power flow during traction and braking goes through the traction transmission, traction and braking characteristics depend on the technical level of the traction transmission [1].

One of the main economic indicators of the draft transmission and the parts that make it up is to achieve a reduction in material capacity without changing the performance criteria. To evaluate the technical level of machines and mechanisms with the same functional purpose, a quantitative parameter reflecting the ratio of the spent funds to the obtained result is used. As an objective measure of the spent funds, the mass of structural elements of the mechanical system is taken, which practically reflects the economy throughout the entire project process. As a result, the torque that characterizes the load-carrying capacity of the mechanical system, the useful work coefficient that characterizes the efficiency, and the degree of reliability that characterizes the safety are taken. It is known that the technical level of the mechanical system increases as the «result» per unit consumption (mass) increases (torque, useful work coefficient and degree of reliability). The high technical-economical and operating indicators of railway vehicles corresponding to samples with record indicators require the provision of innovative devices and equipment for their mechanical parts in parallel. At the same time, high productivity, reliability, technology, repairability, minimum dimensions and mass, ease of operation, as well as technical aesthetics are the most important factors of these mechanical systems.

In recent years, great changes have taken place in this field, all parametric standards have been developed, calculations have been improved and refined in order to ensure scientific-methodical unity in the rationalization of machines and aggregates of various purposes and the selection of their parameters; standards for their calculation methods have been developed; a new generation of machines and mechanisms used in some fields of mechanical engineering have been created, the main parameters of their load-carrying capacity have been unified; the construction of the main transmission mechanisms has been significantly changed [2–5].

Multi-stage innovative reducers developed under the leadership of the staff of the «Mechatronics and machine design» department of Azerbaijan Technical University and applied in some fields of production (for example, in the field of oil production) can be considered as one of the latest achievements of scientific progress in the field of reducers [6–9].

The advantages that innovative reducers have in comparison to traditional reducers (minimum price of dimensions and mass, simplicity of production processes, small number of organizers, high reliability, etc.) are the basis for the fact that their use in traction transmission of railway vehicles will ensure the improvement of the technical and economic efficiency of vehicles creates [10]. The scheme of the dart transmission consisting of a three-stage single-flow, two-way package reducer is shown in **Fig. 1**.

Since two-shaft cylindrical spur gear transmission multi-stage innovative reducers are a new generation of reducers, although a number of issues related to their structural and operational characteristics have been resolved, not enough research has been conducted on them in terms of construction, technology, and operation [11].

The safety, reliability and efficiency of the train movement directly depends on the braking devices in the train and the principles of their efficient use. Solving the brake issue is a complex process. When studying the issue of train braking, the effects of several factors affecting the system should be taken into account: braking force, length of braking path, speed at the beginning and end of train braking, inertia coefficient of rotating parts, reported braking coefficient, braking sensitivity and reliability of brake cylinders and other braking equipment, driver's reaction time, etc. After the operator turns the crane handle to the braking position, the braking force does not occur immediately. It takes some time.

This time is spent on spreading the air flow in the brake line of the train, starting the air distributor, filling the brake cylinder with air, accelerating the assisted transmission of the brake until the brake mold touches the wheel, and increasing the compression of the mold to a certain limit [12].

In order to solve the problem, it is appropriate to conduct research in the direction of optimizing any of the above factors and determining their positive effects on the system. Optimizing such multi-factor systems first requires the study of the system as a whole, its current state, defects, interaction parameters of its elements, modeling level, etc.

The investigation of train braking issues and its factors has been of interest to researchers in our country and in many parts of the world. From them. In these [13] works, studied the structural characteristics and working principle of brake cylinders of railway vehicles in operation and proposed optimization measures to compensate for the angular inclinations of the piston at the maximum exit from the cylinder body. There is no doubt that the results of the research contribute to improving the efficiency of the train braking system, ensuring traffic safety, increasing speed, increasing reliability, etc.

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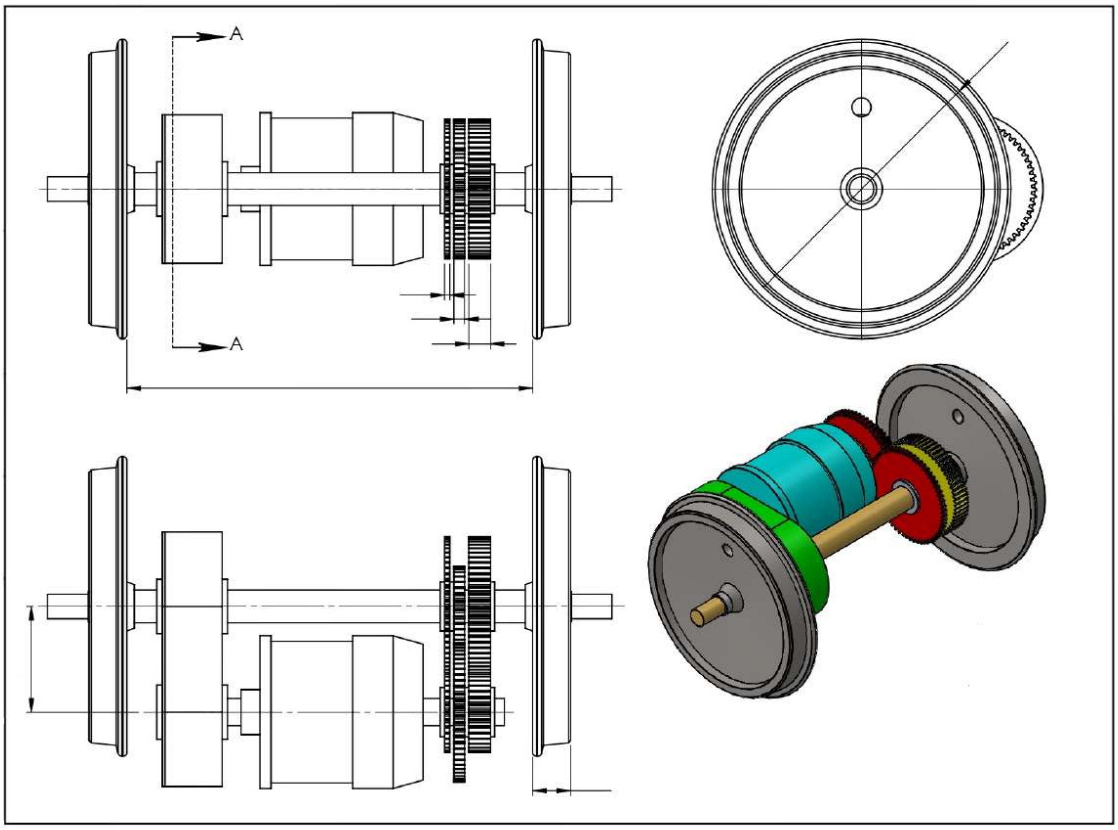

Fig. 1. Scheme of innovative dart transmission with three-stage single-flow, two-way reducer

In these [14] works in their works, they have conducted extensive research in the direction of ensuring the control of train departure time and reducing energy consumption. Using the Markov model, they proposed the benchmark professionalism strategy of the driver and the probability of reducing train delays based on statistical data of the real movement of trains and the driver's professional characteristics with the help of a program that takes into account the uncertain influence parameters of the system and determines the energy and time losses.

In these [15] works in their research studies have evaluated the most important components of all brake systems, taking into account all the factors affecting the operation and functions of the train braking system. In this context, experimental and numerical analysis studies on the interaction of brake system components have been reviewed. Accordingly, research and development based on finite element modeling and prototype manufacturing is recommended to produce brake systems that ensure the reliability and safety of railway vehicle braking systems.

In these [16] works this paper discusses the possible options of changing the temperature to reduce the reaction time of the train's pneumatic brake system. In order to take into account the timing and characteristics of the compressed air wave traveling in the pipes, a pneumatic system, considered equivalent to the system present in a real train, was analyzed experimentally. The behavior of the present system was compared for two different air temperatures. The obtained results indicate a relevant temperature effect on pressure wave transmission, which can help to shorten the time or distance in the standard braking process.

In these [17] in his work considers the braking distance of the train as one of the main conditions of the safety of the railway system, and notes that many external factors affecting the braking distance can cause its length to change. For this purpose, an experience-based fuzzy logic system is proposed. In the paper, the authors propose a fuzzy logic system that selects the most probable control rule from a set of control rules. The input variables are speed, incline, braking force and braking equipment response. The purpose of this work is to determine the braking distance of the train and the difference between the calculated braking distance and the data obtained from the field. The main advantage of this fuzzy model over analytical and simulation models is its simple application in cases where a large number of input variables do not have a well-defined value.

In these [18] works in his work proposes a method to apply the Bellman-Ford (BF) algorithm to search for the train's braking speed trajectory in order to maximize the total regenerative braking energy in a mixed braking mode where both electrical and mechanical braking forces exist. The BF algorithm is implemented in a discretized train-state model. It is found that the sought braking speed trajectory can achieve a significant increase in the total braking time with only a slight difference compared to the constant braking speed method.

In these [19] works this paper proposed a fault diagnosis method based on multi-sensor fusion data for single fault and complex fault of train brake systems. First, a uniform mass model of the train brake is built based on the working environment. Then, pre-allocation and linear weighted aggregation criteria are proposed to combine the monitoring data. Finally, based on advanced expectation maximization, braking modes and braking parameters are determined and brake faults are diagnosed in real time.

Using the wide range of modern computer programs, researchers have proposed many issues related to the braking systems of railway vehicles and their dynamic characteristics. Improving the train braking system is a matter of achieving improvement of technical and economic indicators by conceptually implementing the principles of modeling and optimization, taking into account the interactions of all the elements that make up the system and their effects on the system as a whole. In order to solve the problem of improving the braking problem of the train, let's propose in our work to optimize the mass of the rotating parts and the value of the inertia coefficient from the factors affecting the system. As the research object, let's choose the traction transmission of STADLER KISS type electric trains [20, 21].

The purpose of the study is to study the effects of the advantages obtained during the evaluation of the technical level of traction transmission of railway vehicles consisting of multi-stage innovative reducers on the braking characteristics of the train [22, 23]. The research questions are as follows:

– by classical methods, the equation of motion of the train is derived for three modes – traction, free travel and braking modes;

– practically, the issue of train braking is solved;

– the effectiveness of the braking effect is evaluated;

– with the help of a computer program, the graph of the dependence of the braking distance on the speed is constructed, and the positive effects of the proposed transmission on the braking distance are reflected.

2. Materials and methods

The braking distance of the train is calculated using classical methods. At this time, taking the reduction of the value of the inertia coefficient of the rotating parts as an input parameter, reducing the acceleration time of the train as an output parameter, taking into account the train's equation of motion, thereby reducing the travel time between apartments, shortening the braking distance during braking, and reducing energy consumption can be achieved. One of the main factors affecting the improvement of the technical level is the reduction of the coefficient of inertia of the rotating parts.

As is known, the F generated in the locomotive to the moving train [24] F_k – traction force, B – braking force and W – resistance force of the movement, which are generated during braking of the train.

If to project the forces acting on the train along the axis of the direction of movement (OX) and replace their vectoral sum with a balancing force. The forces acting on the train are shown in **Fig. 2**. Then $F_t = F_k - B - W$ is obtained. F_t in dart's theory is called the accelerating or decelerating force.

If to consider the train as a material point during movement, then its acceleration is determined according to *I*. Newton's second law. The mass of the material point is m, the force acting on it is F_t – if so, then your action is urgent $a = F_t / m$ can.

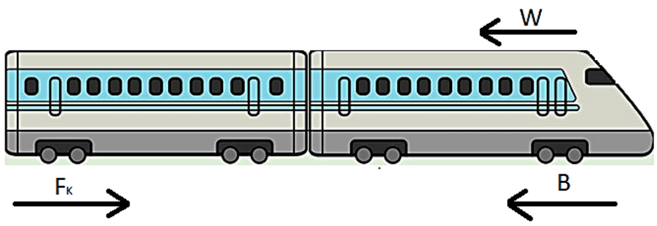

Fig. 2. Scheme of alternating forces

In addition to the force factors mentioned above, many elements of vehicles (traction motors and generators, wheel pair, gear transmission, electric motor anchor, etc.) are also subjected to rotational motion in addition to forward motion. Therefore, it is very important to take into account the inertia of the rotating parts when considering the factors affecting the movement of the train. At this time, the delivered mass of the train is calculated as follows:

$$m_g = m + m\gamma = m(1+\gamma), \tag{1}$$

here, m_g – mass of the train; m is the mass of the train, $m = m_1 + m_t$; $1+\gamma$ – is the coefficient of inertia of rotating parts. The value of this coefficient is given in **Table 1** for different vehicles. Thus, depending on the instantaneous inertia coefficient of the train, it is as follows:

$$a = 12.96\frac{F_t}{m(1+\gamma)}. \tag{2}$$

Equation (2) is called the equation of motion of the train. If to express the given equation in terms of the specific speed of the train:

$$f_t = \frac{F_t}{mg},\ a = 127\frac{f_t}{1+\gamma}. \tag{3}$$

According to the theory of traction $127/1+\gamma = \xi$ if to replace with:

$$a = \xi f. \tag{4}$$

This equation is also called the equation of motion of the train and it shows that the motion of the train depends on the instantaneous specific acceleration force and the inertia of the rotating parts. Considering the coefficient of inertia of the rotating parts. Then the equations of motion of the train for different modes of motion are obtained as follows:

$$a = \xi(f_t - \omega) \text{ – traction mode,}$$

$$a = \xi(-\omega) \text{ – free travel mode,} \tag{5}$$

$$a = \xi(-\omega - b) \text{ – braking mode.}$$

By solving the equation of motion of the train, it is possible to determine the speed and path of the train at any time and place. This is the basis of the traction theory and is considered the main factor in the performance of the entire normal work system of the traction road and ensuring the safety of movement. By solving the equation of motion of the train, it is also possible to determine the energy consumption of railway vehicles, the optimal modes of trains, etc. parameters can be calculated. As a result of the recent scientific-research works, it was determined that the problem of railway operational reliability and the issues of optimality of transportation are the same for all reporting methods of train movement and should be solved within the framework of draft reports.

According to constructive considerations and preliminary calculations carried out on the example of some dart transmissions, using a dart transmission consisting.

By reducing the mass of the rotating parts in the traction transmission of the train, it is possible to achieve an increase in the expression value of multi-stage innovative reducers up to 5 %, which characterizes the creation of a successful model of traction and braking characteristics. The Table below shows the main parameters of the train motion equation (**Table 1**).

Table 1
Analysis of indicators of typical and innovative transmission when using the equation of train motion

No.	Vehicle type and name	Coefficient of inertia of rotating parts, 1+γ		Urgent, ξ, km/sec^2	
		Available dart transmission	Innovative dart transmission	Available dart transmission	Innovative dart transmission
1	Electric locomotives (some)	1.2–1.4	1.08–1.17	106–91	118–108
2	Electric train	1.086	1.041	117	122
3	Locomotives (freight)	1.134	1.095	112	116
4	Locomotives (passenger)	1.076	1.041	118	122
5	Diesel trains	1.095	1.06	116	120

A certain amount of time is spent from turning the driver's crane to the braking position until the start of braking called time. During this period, the train goes on a preparatory or initial braking path (S_i). The path on which the train moves with working brakes is the real brake path – S_i is called then the total braking distance of the train – S_t will consist of the sum of initial and actual braking distances, S_h – true braking path:

$$S_t = S_i + S_h. \tag{6}$$

So, the brake line S_t is equal to the sum of the paths traveled by the train from the moment of braking until it stops.

To simplify the report, they conditionally assume that during the preparation period of the brake, the movement of the train takes place without brakes at a certain time and then the brakes of the whole train are activated at once. The initial braking distance depends on the average speed of the traffic and the preparation time of the brakes. During the preparation time of the brake, the speed of the train decreases along the ascent and on horizontal tracks with a slight gradient, and increases along its movement on the slope. In the reports, taking this speed as a constant, the support of the machinist crane is equal to the speed at the moment of rotation. However, the change in speed is compensated by increasing the brake preparation time on descents, and by reducing the time on uphill.

Considering the above, the initial braking path (S_i, m) is calculated by the following formula for uniform speed movement:

$$S_i = \frac{v_b \cdot 100}{3600} \cdot t_h = 0.278 v_b \cdot t_h. \tag{7}$$

Here, v_b – speed of the train at the moment of turning the support of the driver's crane to the braking position, in km/h; 0.278 – speed unit, conversion factor from km/h to m/s; t_h – the brake preparation time, calculated with the help of empirical formulas depending on the type of brake and the length of the train, sec.

For passenger trains with electropneumatic brakes:

$$t_h = 2 - \frac{3i}{b_t} = 2 - \frac{3i}{1000\varphi_{kh} \cdot \vartheta_h}. \tag{8}$$

Here, i – slope, is ‰, it is taken with «–» sign in brake reports for descents; ϑ_h – reporting braking coefficient; $\varphi_{kh} = 0.36(v+150)/(2v+150)$ – an empirical expression of the friction coefficient.

If auto-stop braking is used on vehicles, the preparation time for the brake to start moving is increased by an additional 12 seconds. This extra time is used to activate the hitch system: $t_h^i = t_h + 12$.

The actual brake line – S_h to find the start of braking of the train – v_b and the last v of the train stops speed is divided into intervals and for each interval ΔS_h – actual braking distance is calculated:

$$\Delta S_h = \frac{500\left(v_1^2 - v_2^2\right)}{\xi\left(1000\varphi_{kh}\cdot\vartheta_h + \varpi_{os} + i\right)}, \tag{9}$$

v_1, v_2 – initial and final speed of movement in each interval, km/h; ϖ_{os} – the specific resistance of the train, N/kN; ξ–1 N/kN reduction of the speed of the train due to specific resistance forces (train acceleration). The value of this coefficient is given in **Table 1.**

3. Results and discussion

3. 1. Solving train brake issues

The correct choice of braking mode plays a major role in ensuring the safety of trains. That's why special attention is paid to the solution of brake issues in draft reports. Therefore, for cases of braking on different slopes, S_t, v_b and i – the braking distance is determined according to the given parameters. The value of the brake path can be determined analytically and graphically. In the analytical method, first S_i and so on – initial and actual braking distances are determined with the help of formulas that determine the change of the speed from the starting threshold to the stop at an interval of 10 km/h is given [25].

To solve the braking problem of trains, let's calculate the braking distance of Stadler electric trains when the speed changes from 160 km/h to 0 km/h. Eş2 electric train is controlled by weight $m = 236\ t$, reported braking coefficient $\vartheta_h = 0.65$, the initial speed of braking v_b equal to 140 km/h. Braking is performed on the slope $i = -10$ ‰ (according to the railway area where the test is carried out). The report friction coefficient is taken from columns 2 to 14 for the average values of each speed interval. The main special resistance forces of the train $w_{os} = w'_{os} + w''_{os}$ is calculated in the form:

$$w'_{os} = 2.4 + 0.011v + 0.00035v^2,$$

$$w''_{os} = 0.7 + \frac{3 + 0.108v + 0.0025v^2}{m_{vo}}. \tag{10}$$

The train consists of 4-axle passenger cars, $m_{vo} = 14.7$ t.

Let's calculate the full braking distance.

For this, let's divide the full speed range from $v = 160$ to $v = 0$ into 10 km/h intervals. Now let's calculate the actual braking distance for each interval with the help of expression (9).

Thus, the actual braking distance traveled by the train with the current traction transmission at the time of braking is 670.78 m, and when the innovative traction transmission is applied, the actual braking distance traveled by the train at the moment of braking is equal to 643.28 m (**Table 2**). The initial braking distance is calculated depending on the number of braking axles or the type of brakes. however, the initial braking distance and initial braking time are not considered in the present study.

The following Table shows the results of solving the problem of train braking depending on the existing and innovative traction transmission.

As a result of the application of the proposed innovative traction drive of railway vehicles, it is possible to significantly reduce the braking distance of Esh2 type Stadler electric trains. If to compare the braking distance calculated above, it is possible to clearly see the difference.

Table 2
Train braking distance reporting results

Coefficient of friction	Specific resistance force, N/kN	Initial speed, km/h	Duration, km/h	Braking distance with available traction transmission, m	Braking distance with innovative traction transmission, m
φ_{kh}	ω_{os}	V_b	V_s	S_{Mdi}	S_{idi}
0.237	11.275	160	150	85.131	81.642
0.24	10.247	150	140	79.317	76.066
0.242	9.273	140	130	73.452	70.442
0.245	8.352	130	120	67.551	64.783
0.249	7.484	120	110	61.630	59.104
0.252	6.670	110	100	55.705	53.422
0.257	5.91	100	90	49.797	47.756
0.261	5.202	90	80	43.927	42.127
0.267	4.548	80	70	38.119	36.557
0.273	3.948	70	60	32.400	31.072
0.28	3.401	60	50	26.800	25.702
0.288	2.907	50	40	21.354	20.479
0.297	2.467	40	30	16.102	15.442
0.308	2.080	30	20	11.091	10.636
0.322	1.746	20	10	6.374	6.113
0.338	1.466	10	0	2.018	1.935
0.36	1.24	0	0	670.779	643.286

3. 2. Evaluation of the effectiveness of the braking effect

To evaluate the effectiveness of braking, the average value of the speed reduction is taken. At this time, the forces of reaction to the movement and the potential energy of the inertia of the movement component in the braking mode should be taken into account [26]:

$$\frac{1}{2}(1+\gamma)\cdot m\cdot v_b=\left[(1+\gamma)\cdot m\cdot a+m_g\cdot i_k\right]\cdot S. \tag{12}$$

Here, a – the average value of speed reduction (m/sec^2), v_b – speed at the beginning of braking, (m/sec); S_t – braking distance (m); γ – coefficient that takes into account the mass of rotating parts; $m_g i_k$ – train, i_k – its weight in parts per million.

The average value of the deceleration is determined as follows:

$$a=\frac{v_b^2}{2S}-g\cdot i_k\cdot\frac{1}{1+\gamma}. \tag{13}$$

For existing transfer trains:

$$\gamma_{mdi}=1.084,\ a_{mdi}=0.5\cdot\frac{v_b^2}{S}-9.05\cdot g\cdot i_k.$$

For innovative moving trains:

$$\gamma_{idi}=1.041,\ a_{idi}=0.5\cdot\frac{v_b^2}{S}-9.42\cdot g\cdot i_k. \tag{14}$$

The effectiveness of the braking effect is characterized by a decrease in speed (acceleration):

$$a=\frac{a_{idi}-a_{mdi}}{a_{mdi}}\cdot 100\,\%=4.01\,\%.$$

Thus, the average value of speed reduction is the kinetic energy per unit mass of railway vehicles. This energy is extinguished by means of the braking system. In modern times, the issue of increasing the speed of railway vehicles is very relevant, and the effectiveness of braking must be increased accordingly. To solve this problem, railway vehicles use composite molds, electro-pneumatic braking methods, additional electric (rheostat and recuperative) braking methods, magnetic-rail braking method, and the method of applying electrodynamic sliding clutches. However, in contrast to all these methods, in order to increase the effectiveness of braking, let's propose a method based on more fundamental principles – the method of reducing the mass of rotating parts.

It should be noted that 70–80 % of the coordinates of train collisions with vehicles, pedestrians and other external objects fall in the last 0–10 percent of the braking distance. Reducing braking distance by more than 4 % can significantly reduce accidents and fatalities.

Fig. 3 shows the difference in the braking distance of the train with the existing and innovative traction transmissions. As can be seen from the picture, the braking distance of the train can be significantly reduced if the innovative traction transmission is applied. In the figure, the red line represents the braking distance of the existing train, and the green line represents the innovative train.

Fig. 3 shows the difference between the braking distance of the existing traction transmission and the innovative traction transmission by giving a graph of the dependence of the braking distance on the speed.

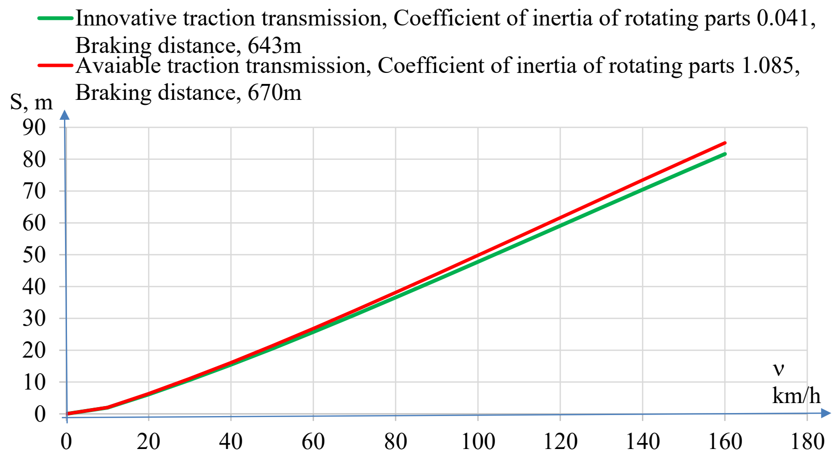

Fig. 3. Graph of the speed dependence of the braking distance of the train consisting of the existing and innovative traction reducer

In order to find the practical values of emergency braking times at different speeds during the operational period of Stadler electric trains, an experiment was conducted by applying emergency braking at several speed limits. Braking times at different speeds are recorded and graphed. Then, taking into account the positive effects of innovative reducers, a graph reflecting the dependence of the train's braking time on the speed is constructed and compared with the similar graph obtained as a result of the experiment (**Fig. 4**).

As can be seen from the graph, if the innovative reducers are applied, the braking time of the train will be significantly reduced in proportion to the braking distance.

Application of research results, consideration in future theoretical studies can be based on the participation and recommendations of the authors:

– since the proposed innovative reducers are new generation reducers, although a number of issues related to their structural and operational characteristics have been solved theoretically, not enough research has been conducted on them in terms of construction, technology, and operation;

– offered reducers can be used in all types of rail transport. It allows to significantly reduce operating costs and initial production costs, increase the level of reliability, as well as improve the technical and economic indicators of rail transport.

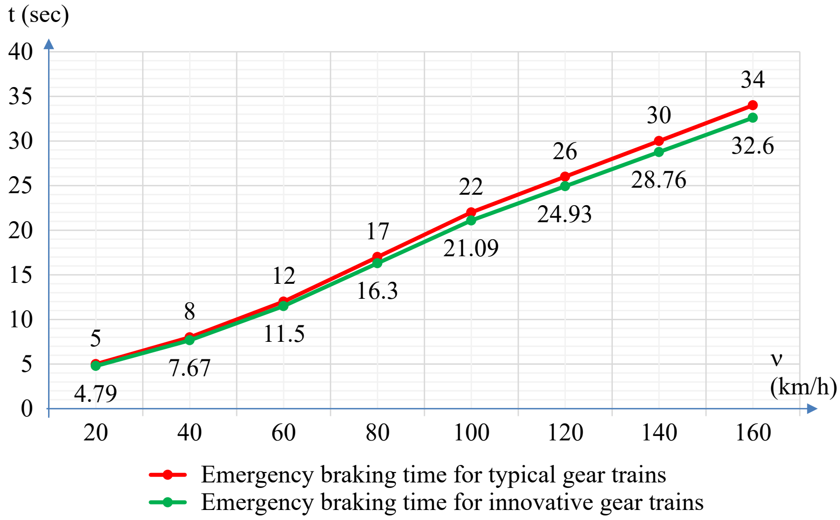

Fig. 4. Graph of dependence of train braking time on speed

4. Conclusions

1. By solving the equation of motion of the train, the influence of the advantages of the multi-stage innovative traction transmission on the braking characteristics was studied in various driving modes. Thus, due to the reduction of the mass of the rotating parts, it has been shown that it is theoretically possible to achieve an advantage of up to 5 % in traction, braking, as well as free-wheeling characteristics, which leads to fuel savings of up to 20 %.

2. With the help of a computer program, a graph of the dependence of the braking distance on the speed is constructed and the positive effects of the proposed transmission on the braking distance up to 5 % are reflected.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

Manuscript has associated data in a data repository.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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