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GENERATING AND MODELING OF BRAKING CURVE AND THE ASSESSMENT OF THE QUALITY OF AUTOMATIC STOPPING OF THE TRAIN

Summary. This paper presents the theory about generating the braking curve and the analysis of the influence of the braking controller parameters on the generation of the braking curve of the train. In this paper, computed examples of braking quality developed using generic quality factor are shown, and on the basis of the calculations, weight components of the factor and an additional criterion for assessing the quality of braking were proposed. It has been demonstrated that the developed algorithms can be used to verify the effectiveness of the braking controller and the adjustment of the terms, and the change of these algorithms affects the shape of the generated braking curve of the train. It has been shown that the analysis of a failure of the propulsion car revealed the existence of a safe braking area. The performed statistical analysis confirmed the normal distribution of the scatter of braking results, for which the regression model fitted.

1. INTRODUCTION

Target braking (docking) is used mainly for underground lines in order to stop the train on the platform in case the length of the train and subway platform is virtually the same. Target braking may be called an automatic process of stopping the train on the station. That kind of braking is a very important part of operating the train as it requires stopping the train on a platform of a specified length. In the case of closed platforms, where the entire platform is screened from the track by a wall with automatic platform-edge doors, the train stopping at the metro station has to be very accurate and needs to implement the principle of "door to door" braking and is not allowed to open the marginal door beyond the platform area. Target braking of the train on the train stations should provide such sitting of the train (after stopping) relative to the platform, so that all the doors of the train allow passengers to get out directly on the platform. Precise train stopping is also very important from the point of view of passengers. While the train stops in the platform, the situation that the train stops in the incorrect place and a passenger could get stuck in the gap between the platform and the train cannot be allowed. Automatic braking must start at the correct distance from the stopping point and requires proper regulation of the braking force, which shall secure stopping in the required point. Target braking is one of the cases of essential braking (duty). It is based on the gradual reduction of the actual speed of the train V_{rz} to the value of allowable speed limit $V_d=0$, which shall be obtained at the point of restricting the speed x_d, without exceeding the allowable deceleration of braking a_h [1, 4, 5, 8, 9]. Automatic target braking (docking) of the train occurs during stopping the train at the platform. Stopping should be very accurate, and the actual place of stopping the train x_{rz}, on the platform, should meet the following condition:

$$x_{rz} = x_d \pm c \tag{1}$$

There is also a case, not considered during docking, when the train stops by the semaphore, where the actual train-stopping position is described by

$$x_{rz} \pm c \leq x_d \tag{2}$$

This case comes down to consider braking with an available electromagnetic braking system, which is based on the electric traction motors working as generators, and the mechanical (electropneumatic) braking.

2. THEORY OF AUTOMATIC TRAIN BRAKING

2.1. The theoretical braking curve

The theoretical braking curve should take into account the desire to provide possibly high capacity of arterial railway line, and it is advisable to brake with the maximal deceleration a_{hmax}. The limitation here is a feasible braking force F_{hmax} ensuring sufficient wheels adhesion with rails. The maximum allowable braking force is a function of the actual speed of the vehicle and the state of track and operating conditions of the line. The optimal braking process ensures a gradual increase of deceleration up to a maximum value (phase I), braking with the maximum and constant deceleration (phase II) and the gradual decrease of deceleration to zero v_g=0 (phase III). One may distinguish two basic types of theoretical braking curve: (a) Three-sector braking curve, which takes into account I, II, and III phase of braking; (b) two-sector braking curve, which takes into account I and III phase of braking.

The parameters necessary to develop a braking curve are the coordinate of a point where velocity reduction started x_g, the maximum deceleration of braking a_{hmax} and the maximum value of the derivative of deceleration of braking $|\mathring{a}|_{hmax}$. Obtaining of an appropriate braking curve, in other words, the dependency $v_h(l_h)$ may be performed substantially in three ways:

- By storing typical waveforms $v_h(l_h)$ in memory chips,
- Every-time generation of braking curve using computing devices,
- Every-time generation of braking curve for phase I and III and using of the recorded curve in phase II.

Fig. 1 shows an example of the generated theoretical curves of braking $v_h(l_h)$. Additionally for the actual speed before the braking process started where $v_{rz}(s)$ is equal to v_0=80 km/h, on this curve, three phases of the braking process are indicated, which were discussed above. At the point of overrunning the braking curve $v_0(l_{hmax})$, the process of reducing the speed to the boundary value of the speed v_g=0 km/h starts. The curve of actual speed before braking $v`_{rz}(s)$ (marked with gray) illustrates the case of starting braking from $v`_0$=40 km/h. Due to the allocation of the setup for the generation of the braking curve, one may distinguish two groups of solutions: a generation in the vehicle with the transmission to the vehicle of output data for calculations, or a generation by the trackside equipment with the transmission of the results of calculations to the vehicle.

The choice of the location for the setup for generating the braking curve depends on the range of automation of driving the vehicle, and especially depends on the amount of transmitted information and the type of data-transmission equipment. It should be emphasized that the working conditions of the data-transmission system between the track and the vehicle are very difficult, especially due to strong interference in the transmission channel. Hence the need to strive to minimize the required number of transmitted information [1, 3, 4, 10, 11, 15 - 18].

2.2. Generation method of the braking curve

The primary task of a brake-control system is to obtain in the point of speed restriction x_d, permissible speed V_d with certain restrictions. To conduct this process, the following data have to be obtained: constant parameters—capacity of electrodynamic and mechanical braking a_h, coordinates of the stopping points x_z, vertical and horizontal line profile i given in promiles and variable parameters—the actual train speed V_{rz}, the actual train-stopping position x_{rz}, permissible speed V_d, train load, and any external interference z—also including elementary resistance to motion. The executing system has to perform the following tasks (in the given order):

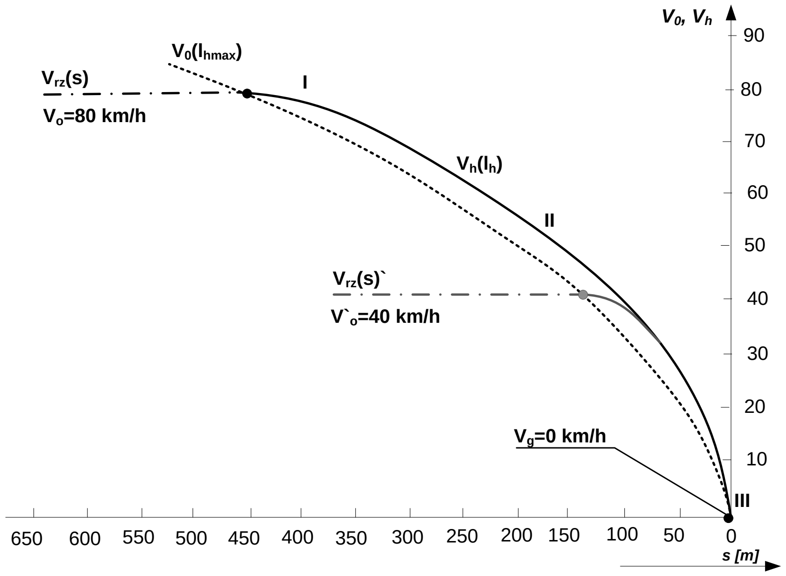

Fig. 1. The theoretical curves of braking and braking start for the speed of braking start v_0=80 and 40 km/h

1) Determine x_0 point for starting the braking process;
2) Determine the actual train position x_{rz} and begin to measure the actual train speed V_{rz};
3) Calculate the braking speed V_h;
4) Calculate in real time the braking force F_h and control the braking process.

The steps from enumeration *1 to 3* are measurement and computing operations. Therefore, these steps are not affected by the integrated train-braking system. The above-mentioned actions in no. 4 have a control-execution nature and are related to the integrated braking system [1, 4]. The structure of this system is shown in Fig. 2. The above-mentioned calculation structure may be easily calculated in a generic way in relation to a simplified computational model, and consists of the following tasks: (a) determination of the initial braking point x_0, (b) calculation of the distance l_h—between the front of the train x_{rz} and the point of speed restriction x_d, and (c) generation of the theoretical braking curve $V_h(l_h)$. The tasks of the control-execution structure are based on the calculation of the difference Δv between braking speed V_h and the actual train speed V_{rz}, next the determination of the braking force F_h, and the execution of the braking process (electrodynamic and mechanical braking phases). Braking devices are implementing the braking process with a specified value of braking deceleration a_h.

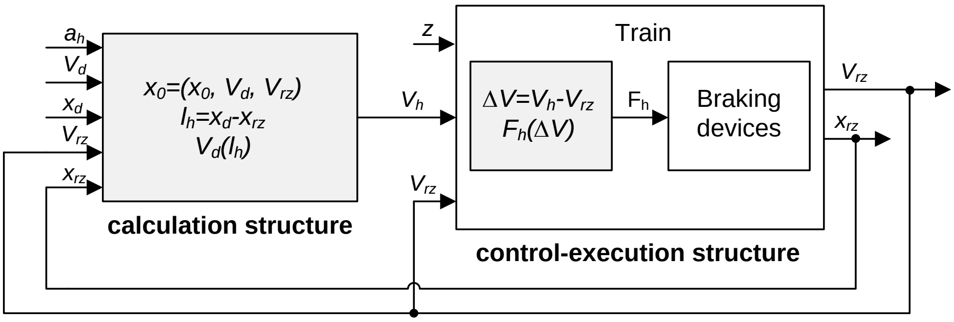

Fig. 2. Structure of the automatic braking system [1, 4]

The parameters that are permanently supplied to the system are dependent on the type of the train, the adopted braking system, and the weight of the train. Actual speed $V_{rz}(x_{rz},t)$ is a function of the place where the train is located x_{rz} and time t. The place where the train is positioned on the track $x_{rz}(t)$ is a function of time. The train is the source of the values mentioned above. The allowed speed depends on the situation of the movement and the parameters of the rail setup on the metro line, and it depends on the location of points of speed restriction x_g on the metro line as well as on time t. The source of this value is trackside equipment related to railway traffic control devices. The points of restrictions (speed change) are constant in time. The parameters required to calculate the theoretical curve of braking depend on the speed of the braking $V_h(l_h)$, which is affected by the actual –current distance between the vehicle and the point of speed limitation $l_h=x_g–x_h$ and deceleration a_{hmax}. The starting point of braking is dependent on the actual speed of the train V_{rz}, terminal speed V_g, and technical capacity of the braking train. In this step, it becomes necessary to take into account the load of the train, which is strictly dependent on the load caused by passengers. For the proper implementation of target braking, the control-executive system requires provisioning of the curve of braking speed $V_h(l_h)$, and the actual speed of the train $V_{rz}(x_{rz},t)$. The signal responsible for the implementation of the braking process is the braking force F_h, dependent on the braking speed $V_h(l_h)$ and the actual speed $V_{rz}(x_{rz}, t)$.

2.3. General factor of the quality of braking

The evaluation of the quality of target braking (docking) should primarily take into account the accuracy of stopping the vehicle at a given point and the accuracy of the theoretical implementation of the braking curve. Therefore, based on the literature research [1, 3, 4, 9, 13, 14, 15], the relationship, describing the general quality factor in the braking process, has been shown (3). Quality assessment of the braking process carried out by an automatic braking regulation system should take into account both static parameters, i.e., the accuracy of stopping the vehicle at a given point, and dynamic parameters, i.e., the accuracy of the implementation of the theoretical braking curve. Hence the formula describing the general factor of the quality of the braking process [1]

$$I_r = \alpha\left|x_{rz}(t_k) - x_g\right| + \beta\int_{t_0}^{t_k}(V_h - V_{rz})^2 dt + \gamma\int_{t_0}^{t_k}(a_h - a_{rz})^2 dt \tag{3}$$

where α, β, and γ are constant coefficients of weights of the individual components of the quality factor. The time of the braking is determined by t_0—the braking start moment and t_k—the moment of ending of braking. In the above quality factor, the static accuracy has been expressed in the form of a module of the difference between the actual stopping position of the vehicle $x_{rz}(t_k)$ and the border point x_g, where the dynamic accuracy is expressed as a squared difference between V_h (the specified braking speed) and V_{rz} (the actual speed) and a squared difference between a_h (the specified deceleration) and a_{rz} (the actual deceleration).

3. CALCULATION OF THE QUALITY OF BRAKING PROCESS

3.1. Model of movement of rail vehicles

In the theory of electric traction, a train-movement model takes into account the driving and braking forces, which occur during transient train movement on the track, in reference to the essential resistances and additional forces of resistances counteracting the movement of the vehicle [2]. The model of movement of an underground train, used for the research, has been formulated with the use of simplified assumptions, which are as follows:

- It is assumed that all cars that form the train have the same velocity along the track, which has enabled the omission of vibrations of individual cars.
- It is assumed that the mass distribution along the train is steady, which means that the focus of the mass is in the middle of the real mass.

- It is assumed that the forces acting on the train as the resultant of individual impacts are applied to the center of mass.
- Geodesic profile route has been included in a substitute manner (formula 12).
- The kinetic energy of the component masses of the train that are in a rotating motion, was taken into account in an approximate way using the factor of the rotating masses α^o=0,1 (which gives α=1.1, formula 10)
- It is assumed that the underground train only moves in the tunnel, in which there are steady weather conditions (temperature, humidity, and air density). As a consequence, a constant traction of the train wheels to the track surface and the omission of wheel slippage was assumed.

Treating the train as a material point of mass *m*, which moves with a time-dependent variable—velocity *v*—and knowing the resultant force *F* acting on it, a train-movement equation (based on Newton's second law) can be written in the following form:

$$Fdt = mdv \tag{4}$$

considering that

$$m\frac{dv}{dt} = m\frac{dv}{ds}\frac{ds}{dt} = m\frac{dv}{ds}v \tag{5}$$

It is given that

$$Fds = mvdv = d[m\frac{v^2}{2}] = dE_k \tag{6}$$

where E_k—the kinetic energy of the train.

In the train, in addition to the elements moving a progressive movement, there are rotating parts. The total kinetic energy of the train is the sum of the kinetic energy of the elements that moves in a progressive way E_{kpost} and the kinetic energy of the rotating parts of the vehicle E_{kobr}, which should be considered in equation (6):

$$E_{kpoc} = E_{kpost} + E_{kobr} \tag{7}$$

By grouping the rotating elements coupled to the drive kits in the set *n* and the rolling in the set *t*, an equation of the train movement in the following form is obtained:

$$Fvdt = vdv[m + \sum_{i=1}^{t}\frac{J_{izest}}{r_i^2} + \sum_{j=1}^{n}\frac{J_{jzest}}{r_j^2}i_{jk}^2] \tag{8}$$

where J_{izest}, J_{jzest}—the mass moments of inertia corresponding to the wheelsets, $r=d_k/2$—radius of the train wheels, and i_k—kinematic shift between the rotor and the wheel set, wherein $i \in t$ and $j \in n$.
The simplified form of the train movement equation (8) has a following form:

$$Fvdt = mvdv(1+\alpha^o) = mvdv\alpha \tag{9}$$

wherein

$$\alpha = \frac{1}{m}[\sum_{i=1}^{t}\frac{J_{izest}}{r_i^2} + \sum_{j=1}^{n}\frac{J_{jzest}}{r_j^2}i_{jk}^2]\ . \tag{10}$$

The parameter α is called a mass factor (taking account of the inertia of the rotating masses, sometimes symbolized in the literature also by "ρ").
Taking into account relationship (9) in the output equation (4), a final form of a general equation of a train-movement equation is obtained

$$\frac{dv}{dt} = \frac{F(v)}{m\alpha}\ , \tag{11}$$

where α=1+ α^o.

The total value of the traction force F(v) of train movement, which is implicitly given in equation (11)—namely $F(v)=F_o(v) \pm W_o(v)$ (where $F_o(v)$ represents only the traction force from the drive and

$W_o(v)$ is the resistance to movement), is computed by using an equivalent line gradient calculated according to equation (12), with the indication given in Fig. 3.

$$i_{zast}[‰] = \frac{1}{10^{-3} L} \int_{S_k}^{S_p} i(s)ds = \frac{H_p - H_k}{L} \cdot 10^{-3} \tag{12}$$

where the profile $i(s)$ is expressed in parts per thousand, values s, L, H_k, and H_p—in meters.

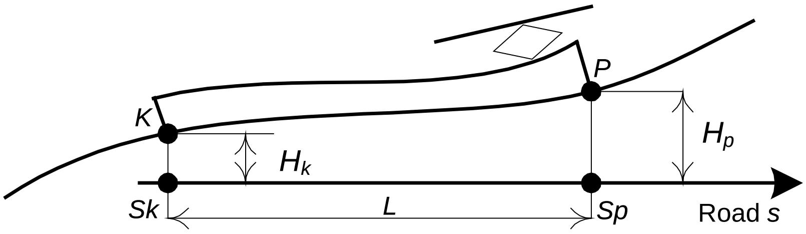

Fig. 3. A train on a facultative geodesic profile of the track—a simplified method of determining a replacement profile

3.2. Methodology of determining the braking precision—a general braking model

The outcome of the created simulator relies on the implementation of the controlling system, which corresponds to a layout used in the underground to generate the docking stage. The simulator has been widely discussed in ref. [2], it takes into account the train-movement equations, profile i, resistance to motion W, the combination of the traction characteristics $F_{ham}(v)$, delay of the controller, line spacing, wire loop lengths, wire loop crossings, permitted line speed, restriction of the increase of braking deceleration, the derivative of acceleration with respect to time, weight of the train, train filling, and electrical controlling signals used in the process of precision braking. The simulation model communicates with a braking controller, which is based on a PID regulator, in a connection time t_{kom}= 50 ms. The braking controller reflects the operations of the onboard device embeddable on a real underground train, which cooperates with the system that realizes docking. Depending on the signal from the controller, the simulator implements one of the available driving modes (steady ride, free run, or braking). Next, the program checks the initial parameters of train physics, line profiles, the drive characteristics (F_{ham}—the braking force of traction machines), parameters of the braking system, train weight, and so on. The algorithm of the software detects the number of a wire loop (*loop detection*) and sets the value of the distance to the stopping point. Depending on the selected driving mode, the script performs calculations of resistance to motion, profile, and the road during braking. The calculations are performed with a time step $t_h=t_h+\Delta t$, to a train stop ($v=0$). The value of the total braking force $F_h=F_{ham}+W$ is being calculated during the braking process. For the following steps, the program calculates the actual stopping distance s, speed v, and the actual deceleration a_h on the basis of the total braking force F_h, resistance to motion W, and profile i. The actual train speed v and the road s are the input data supplied to the regulator. The functional scheme of this process is shown in Fig. 4.

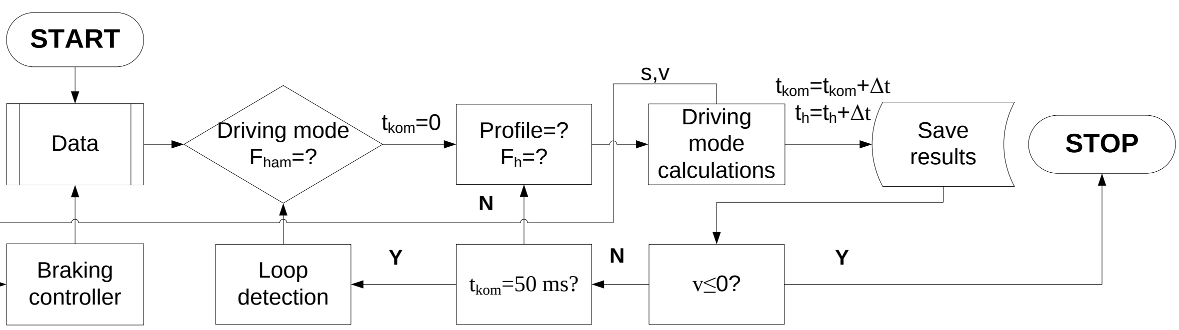

Fig. 4. A general block diagram of the simulation model—functional scheme

3.3. The influence of coefficients for the PID terms of a controller on generation of the braking curve

The description of the authorial tool developed to perform the objective research and the applied target-braking steering systems of the train with AC and DC drive were extensively discussed in papers [2, 3, 6]. The developed simulator cooperating with the braking control system PID, which is reflecting the influence of braking function of the applied system used in the subway, has been analyzed in terms of the impact of the parameters on the generation of the braking curve. In particular, the effect of changing parameters of the terms of a controller to offset the braking distance was analyzed. For this purpose, four sets with values of the terms of parameters of the controller were tested—K_p, T_i, and T_d. Considering the proposed sets of terms of parameters of the controller, using the developed target-braking simulator, the calculations were carried out for several theoretical rides of a train, for which an infringe of stopping distance was scheduled. The results of calculations are presented in Table 1, where the accuracy of stopping (D_{ham}) is given from the point of the required stop. In a situation where the train passes by a stopping point the result has the sign "minus".

Table 1

The results of calculation of an infringe of stopping distance of a train for different controller parameters

	Set 1	Set 2	Set 3	Set 4
The accuracy of stopping the train D_{ham} (infringe of stopping distance) [m]	–1,10	–3,41	1,34	0,38

The conclusions of the analysis are as follows:

– The developed simulator [2, 3, 6] enables modeling the shape of the computational curve of braking speed, through the ability to change electrical parameters of the controller operating in the system of target braking, which is illustrated by characteristics shown in Fig. 5. As can be seen in Fig. 6, which presents the trajectories of the braking curve f(t)=Δv during the braking process, the smallest oscillations of the concerned sets of terms of parameters of the regulator are for Set 4. All trajectories are characterized by suppressed oscillations. From simulation calculations, it may be noticed that the change of terms of parameters of a controller affects the course of the target-braking process, and consequently the value of the infringe of the train's stopping distance.
– The developed simulator [2, 3, 6] cooperating with the brake-adjustment block can be used to study the influence of electrical parameters on the process of target braking and may be used for selection and verification of parameters for the braking controller.

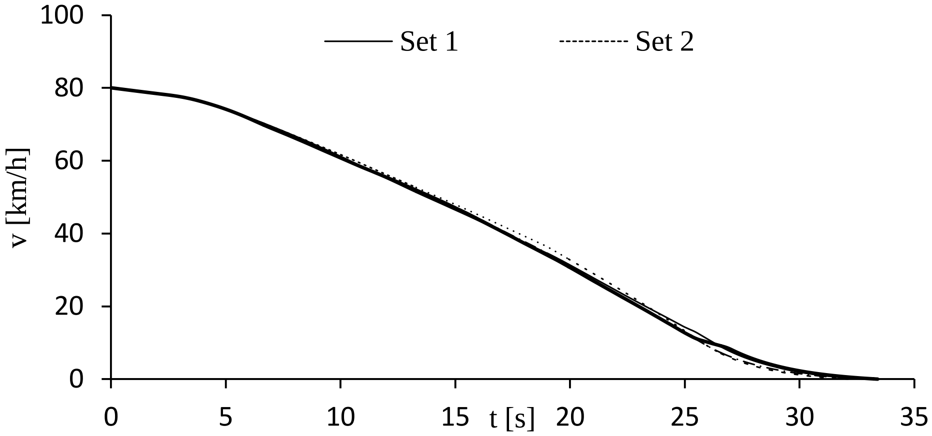

Fig. 5. Trajectories of braking speed depending on the adopted controller parameters (parameters of terms of a controller); the degree of filling st=1,0; speed of initiation of braking v_p=80 km/h, and the complex route profile

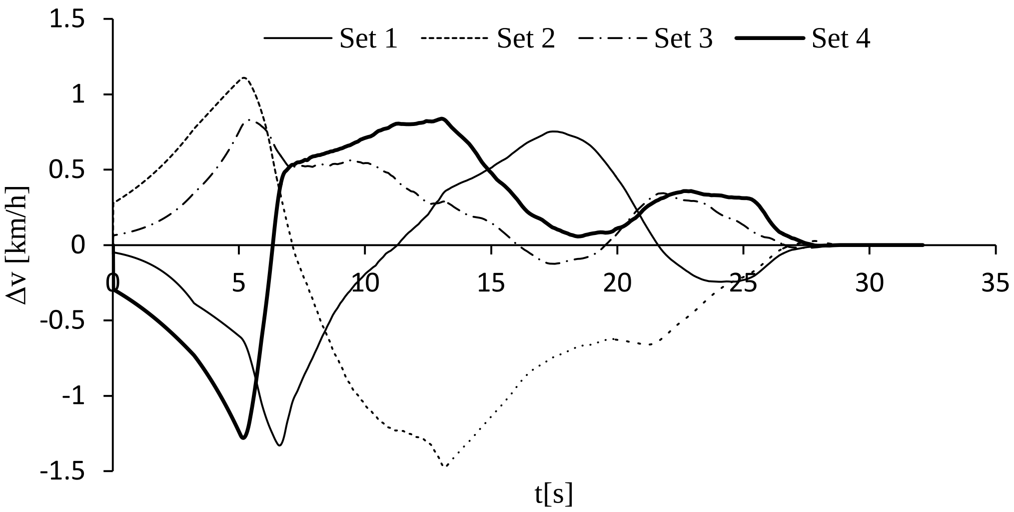

Fig. 6. The suppressed oscillatory course for adopted sets of terms of controller parameters; the degree of filling st=1,0; speed of initiation of braking v_p=80 km/h, and the complex route profile

3.4. The impact of the propulsion-car failure on the accuracy of target braking

A case of damaging the propulsion car during braking was analyzed to determine the impact of failure states of the rolling stock equipped with a system using target-braking function on the target-braking accuracy. This case comes down to braking with one damaged car (no electromagnetic braking is available, which is based on the electric traction motors working as generators) in such a way that, in the final stage only the mechanical (electropneumatic) braking is realized. A simulation of a case was performed where the damage occurs to the propulsion car in a six-car train. The available braking force is reduced as a result of that damage. Software recreation of this case has been done due to reducing the braking force of the train. As shown in Fig. 7, the tests were carried out on the approaching section of the chosen station for various distance *X* to the stopping point. Fig. 8a shows the results of calculating of braking accuracy value D_{ham} for the described failure condition. The given conditions of movement of a train over the section approaching the station are taken into consideration, with a complex profile for different load of the train and the same initial braking speed v_p=80 km/h.

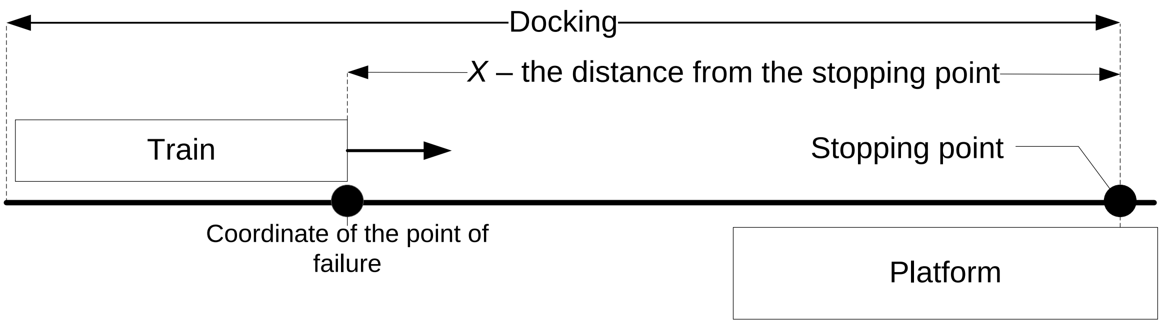

Fig. 7. Approaching section of the selected station in front of which the failure of the propulsion system of one car occurs

The conclusions from the conducted analysis are as follows:

- In the event of a failure state of the propulsion car, for the majority of events, the train passes a stopping point. This occurs due to a decrease of the available braking force as a result of damage of the propulsion car. The conclusions of the simulation of the failure state of the car are in accordance with the results of calculations regarding the influence of limiting the braking force F_h on the accuracy of train braking presented in paper [2].

- A significant reduction of the precision of braking occurs when the train is fully loaded, which is the most unfavorable of all considered cases. For the distance to the stopping point at which there occurs failure of the car in the range of 50–175 m, the greatest deterioration in the precision of stopping can be seen. Damage to the propulsion car decreases the accuracy of target braking, particularly if it occurs close to the stopping point.
- In the opposite case, when the failure of the propulsion car occurs at a distance of about 25 m to the stopping point, when the train speed is low (~24 km/h), there is a slight decrease in the accuracy of braking, because in the last few meters of braking, the train is stopped by means of pneumatic brakes. These brakes operate independently of the propulsion system. At a distance of about 5.5 m from the stopping point, pneumatic braking is initiated, which corresponds to a speed close to 10 km/h.
- If a fault condition occurs within a larger distance, i.e. 200÷250 m from the stopping point, the controller corrects with satisfactory results the error of tracking the benchmark braking curve.

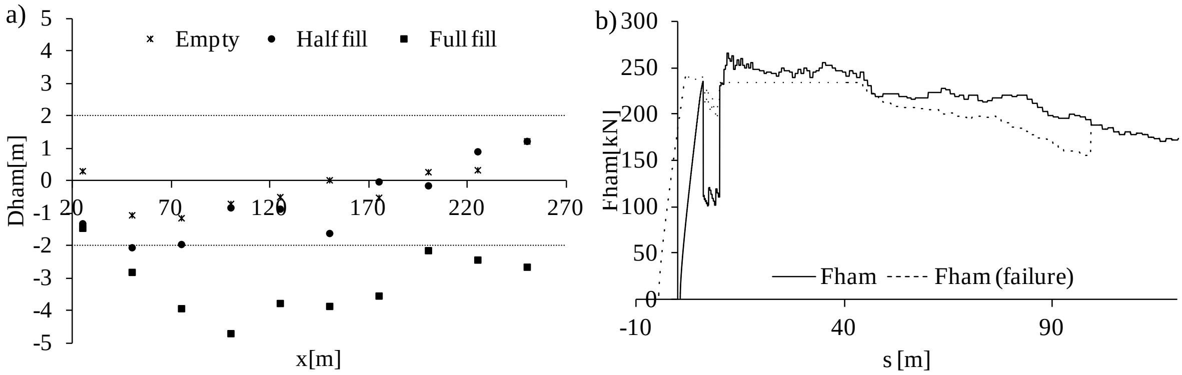

Fig. 8. a) Scattering of stopping points as the distance to the stopping point at which the state of failure and the impact on the accuracy of train have occurred (±2 is the stopping tolerance); b) mapping the braking force during the failure of a propulsion car ($F_{ham\ failure}$) and the standard activity of braking during docking (F_{ham})

A selected failure situation, which occurred 100 m before the stopping point, is shown in Fig. 8b. The figure shows a decrease in the braking force as a function of the road of braking F_{ham}. The dotted line shows the braking force for the case of failure, while the solid line shows the braking force for normal target-braking occurrence. One may conclude that the developed simulator enables the analysis of the accuracy of the stopping distance for a failure of the propulsion car (constituting a damage to the electric drive), which allows for a more complete assessment of the target-braking process.

3.5. Quality calculations in the braking process

In order to determine the general quality factor, using the developed simulator of target braking, a few exemplary calculations were performed for implementation of the benchmark braking curve for the selected station and for the changeable initial speed in the range of v_p=(80÷30) km/h. The results of calculations of I_r factor are presented in Table 2. At the current stage of research, the following coefficients of weights of the individual components of the quality factor in the braking process were adopted arbitrarily: (a) coefficients of weights are equal, i.e., $\alpha=\beta=\gamma=0,33$; (b) considering the safety of the passengers on the platform, it is assumed that the most important criterion for assessing the quality of target braking is the accuracy of stopping the train at a given point. The quality factor will fulfill this assumption, when the coefficients of weights will take, for example, the following values: $\alpha=0,9$; $\beta=0,05$; and $\gamma=0,05$.

In formula (3), the static component of the factor expressed in [m] constitutes the absolute value of the accuracy of stopping $|x_{rz}-x_g|$ at a given point. Speed dynamic component of a factor takes into account the difference between the value of the given speed v_h [km/h] (benchmark curve of developed braking) and actual speed values v_{rz} [km/h] (actual braking curve determined using the simulator at a specific time t). It is similar for acceleration values a_h [m/s^2] and a_{rz} [m/s^2]. The values of braking quality factor I_r are counted from the moment t_0—the start of braking (decelerating), until t_k—the end of braking (reaching speed equal to 0 km/h from the initial braking speed v_p). Among the considered examples, in Fig. 9, a chosen braking curve presented in a time domain of benchmark-braking speed curves $v_h(t_h)$ and the actual braking speed curves is shown $v_p(t_h)$.

Table 2

The results of calculations of the individual components of the I_r factor for the selected examples of target-braking process

v_p [km/h]	80	75	70	65	60	55	50	45	40	35	30
	Quality factor I_r [–]										
α=β=γ =0,33	65676	65517	51746	34867	34981	30088	143765	119629	79506	260576	254079
α=0,9; β=0,05 ; γ=0,05	9951	9927	7841	5284	5302	4560	21785	18128	12046	39481	38497

The trajectory of benchmark-braking curve reference $v_h(t_h)$—to stop the train of a certain type is identical. The trajectory of the actual braking curve $v_p(t_h)$—illustrates the implementation of a benchmark curve by the devices of an automatic braking target system. Basic conclusions of the calculations for I_r factor are as follows:

- The calculation examples confirm that the representation of the actual deceleration curve relative to the benchmark-braking curve influences the values of components of the factor I_r. It can be concluded that with the approach of the actual velocity curve to the benchmark curve, the value of the quadratic quality factor decreases.
- The increase of dynamic components v_h and a_h for speed in the range v_p=(30–50) km/h, can be explained so that a benchmark braking curve, which starts from speed v_p=90 km/h, was introduced to the calculations.
- The difficulty in interpretation of the value of the presented braking quality factor occurs due to lack of broader studies regarding the selection of weight to its components. The issue of choosing the weights can be partially solved by using the Harrington function of compliance (desirability function) [7] or by developing an algorithm of choosing the weights of braking quality factors, i.e., simplex method.
- The developed simulator [2,3] enables to change the terms of the target-braking regulator and allows to model the shape of the computational braking curve, which in turn affects the quality factor I_r.
- The values of the quality factor show the following regularity for the spread of accuracy of braking D_{ham}: I_r=(4500÷5300) for D_{ham}=(0,8÷1,65 m); I_r=(7000÷10000) for D_{ham}=(0÷0,80 m); and I_r=(12000÷21000) for D_{ham}>2 m.

4. SUMMARY

An outcome of a statistical analysis of the obtained simulation results is summarized in the next illustration in Fig. 10a. The distribution of the dispersion of braking accuracy D_{ham} passed four tests for normality. A description of the gained values as the random variables according to the normal distribution, can be regarded as suitable. To investigate the mechanism of interrelationships between the variables to simulate, an attempt to fit the regression model was made. The regression function is an analytical expression of the assignment of the average values of the dependent variable to the specific values of the independent variable. Speed v_p was taken as a random independent variable, and load of the train *st* was taken as the dependent variable. The obtained square models explained less than 10% of the alternation of the phenomenon. Fig. 10b shows an example of a regression model for the considered functions [12].

As part of the work, the following general conclusions can be proposed:

The use of the proposed generic quality factor of braking allows the evaluation of the implementation process of stopping (static component), and evaluation of the implementation of the benchmark braking curve by automatic train operation system devices. The second evaluation leads to comparison of the benchmark curve and the actual braking curve. In the case of ideal realization of the benchmark curve, the presented dynamic square component of the quality factor will approach zero. Initially proposed values of coefficients of weights of the individual components of the quality factor of I_r, as well as the importance level (hierarchy) of evaluation criteria for quality presented in paper [4], were proposed and require further research.

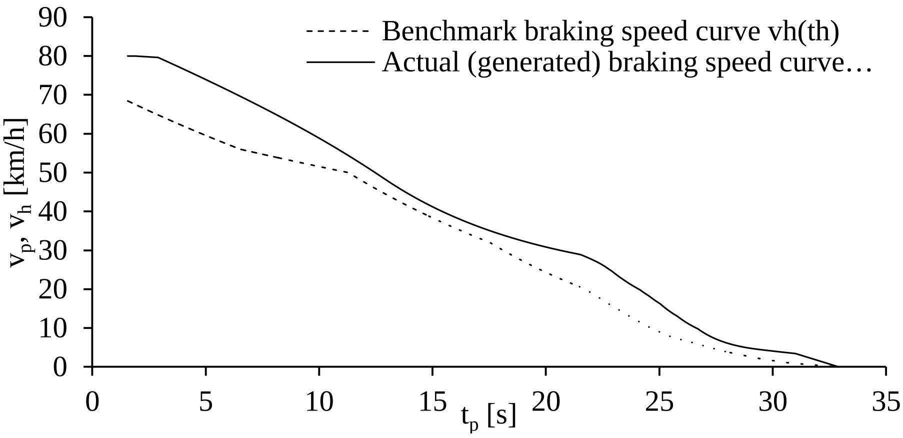

Fig. 9. Implementation of the braking curve for the selected station for initial braking speed v_p=80 km/h

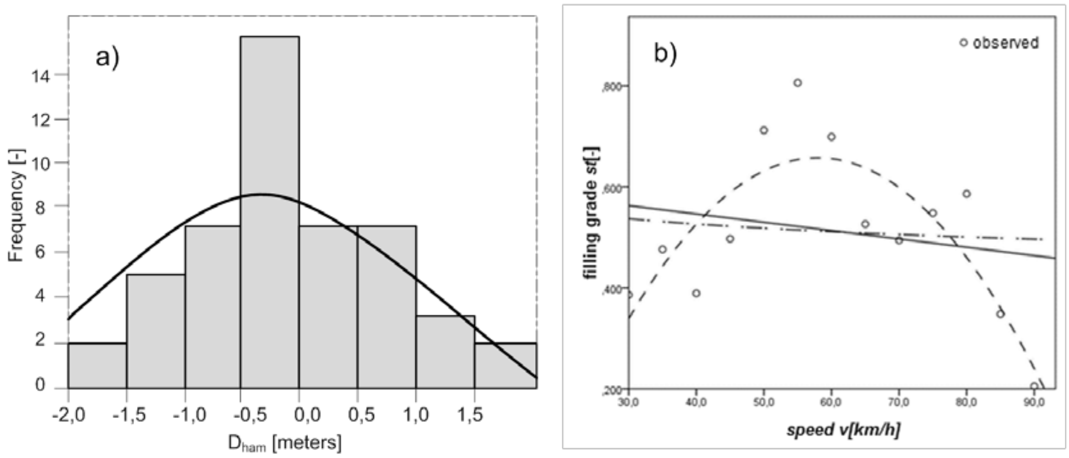

Fig. 10. a) A histogram of simulation outcomes of braking precision D_{ham} with a normal distribution curve; b) adjusting of the regression model for D_{ham} developed for the results of simulation (solid line—linear- regression function, the dotted line—logarithmic function, and intermittent line—the quadratic function)

As an extension of the criteria proposed in paper [4], it is proposed, as a criterion for assessing the quality of target braking, to assume the efficiency of regenerative braking energy utilization. In this case, it is possible to achieve by adopting the following technical and organizational solution: an appropriate way of controlling traffic should be adopted, to enable the possibility to harmonize the moments of start-up and braking, which would enable obtaining much better efficiency of energy recovery. The introduction of railway traffic management for energy savings through the introduction of dynamic control system, which would enable to adjust the startup period of vehicles to the period of recuperative braking of other vehicles, would ensure the efficient use of recuperation energy. Due to sectioning of power supply, fixed time intervals even with appropriate time delay would not allow in any case to reach by recuperating trains the startups of other trains in the vicinity, particularly with less traffic.

The analysis deduces that changing the electrical parameters of the regulator affects the process of target braking, and consequently influences the value of infringe of the stopping distance of the train and that the developed algorithms can be used to verify the effectiveness of the braking regulator. An analysis of the precision of braking for failure train operation related to a failure of one propulsion car has revealed the existence of a safe braking area.

The created simulation model allows the analysis of the impact of imposed target-braking parameters, such as the initial braking speed, load of the train, the distribution of points in a track characterizing the braking distance, profiles, rudimentary friction, reducing the braking force, and failure states and terms of parameters of the braking regulator as shown in paper [2]. The accuracy of stopping the train at a given point changes together with the change of the target-braking parameters.

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