MET'2015 Croatia
Trogir, October 4 - 7, 2015
12th International Conference
Modern Electrified Transport

THE INFLUENCE OF OPERATING PARAMETERS ON BRAKING PRECISION OF METRO TRAINS

Jan Anuszczyk, Andrzej Gocek
Lodz University of Technology, The Faculty of Electrical, Electronic, Computer and Control Engineering, The Institute of Electrical Power Engineering, Poland

Abstract

In the paper, the basic function of an Automatic Train Operation (ATO) called target braking has been discussed. The most important assumptions of this function have been discussed in detail. The authors' simulation model, which was developed to study the impact of the propulsion systems on the precision of train braking, has been described. The adopted model of movement of rail vehicles and the methodology of determining the braking precision of target metro trains have been described. Subsequently, simulation results of the investigation of influence of operating parameters on braking precision and braking time have been presented. The simulation model verification and the preliminary statistical elaboration of the measuring results have been presented.

Introduction

Traffic conditions present in the underground are unique because the distance between trains is short, they move with a high speed (v~90 km/h) and platforms are short. Therefore, it is required to apply specialized systems which can provide traffic safety, which in terms of speed restrictions, is ensured by Automatic Train Protection (ATP) system. Once the system has been provided with appropriate data, it can calculate safety speed for each train or all trains travelling along the same line. By executing a specified algorithm, ATP devices do not allow to exceed safety speed as it includes control of the power transmission and braking system. The ATP system is initiated only if the driver exceeds permissible speed e.g. signaled by a semaphore. Automatic Train Operation (ATO) is an example of systems which can be of help in the underground. This one is responsible for supporting the driver of the train. Target braking is one of the functions performed by an ATO system. It relies on automatic train stopping at the stations, where braking process is fully controlled by an on-board device. Precision braking is an important stage of underground train ride as it is required to stop a train in a platform with limited length. The average length of the subway train is about 100 m, length of the platform for reasons of space savings in the tunnel is very similar. At the 1st line of Warsaw underground, traffic safety provides a system commercially called SOP-2 [1]. It is a type of an ATP system which is enriched in the ATO system function – the target braking of train in the platform. The system performs its tasks by a continuous data transmission, which is achieved by using a wire loop placed between the rails. There are used two basic types of rolling stock: type "81" trains driven by a DC motor and type "Metropolis" powered by an AC motor. In the literature, there is no information about a simulation model which cooperates with a braking controller and which was developed to carry out calculation of precision braking [2, 4, 5, 6, 9, 10, 11]. Therefore, a simulation model (in the text also called the Simulator) dedicated to study the impact of the propulsion systems on the precision of train braking has been created and positively verified. The scope of research presented in this paper relies on calculation of the influence of operating parameters on target braking, for the selected type of rolling stock. The results allow for an analysis of static and dynamic parameters of the target braking process performed in subway conditions.

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 in the track, in reference to the essential resistances and additional forces of resistances counteracting the movement of the vehicle [3, 8]. 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 which forms 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 true 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 1.9),
- The kinetic energy of the component masses of the train which 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 1.7),
- It is assumed, that the underground train only moves in the tunnel, in which there are steady weather conditions (temperature, humidity, air density). As a consequence there was assumed a constant traction of the train wheels to the track surface and the omission of wheel slippage.

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 (basing on Newton's second law) can be written in the following form:

$$Fdt = mdv \tag{1.1}$$

considering that:

$$m\frac{dv}{dt} = m\frac{dv}{ds}\frac{ds}{dt} = m\frac{dv}{ds}v \tag{1.2}$$

it is given:

$$Fds = mvdv = d[m\frac{v^2}{2}] = dE_k \tag{1.3}$$

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 which 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 (1.3):

$$E_{kpoc} = E_{kpost} + E_{kobr} \tag{1.4}$$

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

$$Fvdt = vdv[m + \sum_{i=1}^{t}\frac{J_{izest}}{r_i^2} + \sum_{j=1}^{n}\frac{J_{jzest}}{r_j^2}i_{jk}^2] \tag{1.5}$$

where: J_{izest}, J_{jzest} – the mass moments of inertia corresponding to the wheelsets, $r=d_k/2$ – radius of the train wheels, i_k – kinematic shift between the rotor and the wheel set, wherein $i \in t$ and the $j \in n$.

The simplified form of the train movement equation (1.5) has a following form:

$$Fvdt = mvdv(1+\alpha^o) = mvdv\alpha \tag{1.6}$$

Where in:

$$\alpha = \frac{1}{m}[\sum_{i=1}^{t}\frac{J_{izest}}{r_i^2} + \sum_{j=1}^{n}\frac{J_{jzest}}{r_j^2}i_{jk}^2] \tag{1.7}$$

The parameter α is called a total factor of mass in the progressive movement and the rotating movement.

Taking into account the relationship (1.6) in the output equation (1.1) there is obtained a final form of a general equation of a train movement equation:

$$\frac{dv}{dt} = \frac{F(v)}{m\alpha} \tag{1.8}$$

Where: α= 1+ α^o.

The total value of the force of train movement $W_o(v)$, which is implicitly in equation (1.8) – namely $F(v)=F_o(v) - W_o(v)$, is computed by using a replacement profile calculated according to equation (1.9), with the indication given in the Figure 1.

$$i_{zast}[‰] = \frac{1}{10^{-3}L}\int_{S_k}^{S_p} i(s)ds = \frac{H_p - H_k}{L}\cdot 10^{-3} \tag{1.9}$$

where: the profile $i(s)$ is expressed in parts per thousand, values s, L, H_k, H_p – in metres.

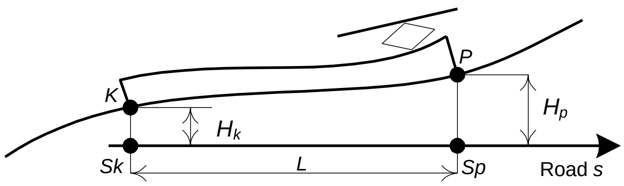

Fig.1 - A train on a facultative geodesic profile of the track - a simplified method of determining a replacement profile [3]

Methodology of determining the braking precision of target metro trains – a general braking model

The outcome of the created simulator „BRAKING", presented in the paper, relies on the implementation of the controlling system, which corresponds to an ATO layout used in the underground. The simulator 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 loops lengths, wire loops crossings, permitted line speed, restriction of 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 functional scheme of this process is shown in Figure 2. 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 on-board device embeddable on a real underground train, which cooperates with the SOP-2 system. 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 a braking system, train weight, etc. 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 $t_h=t_h+Ät$, to a train halt ($v=0$). 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 braking road s, speed v and the actual retardation a_h on the basis of 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 simulator has been developed to work together with trains powered by a DC or AC motor. The output signal from the braking regulator is the driving mode and command signals for the propulsion system (braking and driving):

- For the DC train model, permission to the movement of the shaft used to the current regulation,
- For the AC train model, the percentage of braking force.

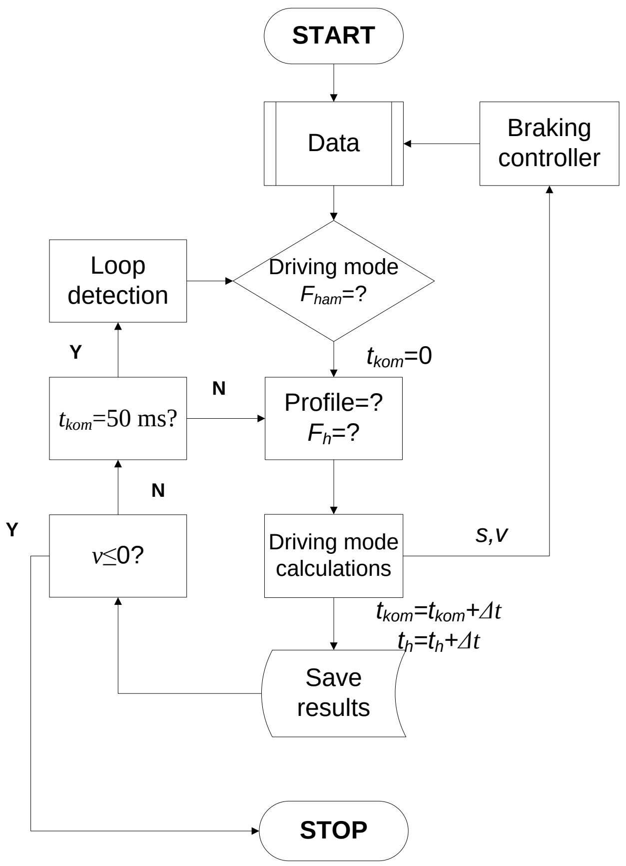

Fig.2 – A general block diagram of the simulation model – functional scheme

Target braking of the train type "81" with a DC-powered drive

The initiation of the target braking process is fixed in software. The whole process is basing on uploading four characteristics (initiation curve, calibration curve, full braking force and deceleration control curves) of the distance from the stopping point, to the vehicle microcomputer memory. The braking process starts after crossing an initiation curve. Braking takes place according to the course of a calibration curve, which was designated during a man-braking. The full braking force and deceleration control curves are responsible for the proper execution of target braking. The underground line is divided into a certain number of spacing blocks, which have been assigned with unique sequence numbers. The wired loops lengths are identical to the spacing blocks. In the area of the stations all spacing blocks are the same. The main idea of braking is based on the comparison of the coordinates of actual train position with the coordinates of the inscribed braking characteristics in the form of curves. Coordinates of the measured route from the stopping point are obtained from the number of a spacing block. The current train position and the real speed value is measured by a tachometer, thereby the actual distance from the stopping point can be counted. When the train approaches a relevant point, the system counter is positioned approximately with a constant value of the distance remaining to the stopping point. Next, the measured value of the actual driven distance is subtracted. Road calculations are similar for each subsequent wire loop during the access road. Final adjustment occurs 50 meters before the stopping point due to a wire loop crossing. Series "81" trains normal braking can be divided into three stages. The first stage concerns braking with maximum resistance of the braking resistor and smooth adjustment of motor coil excitation (48%÷100%). The second stage involves a camshaft operation, which relies on reducing the value of resistance in the braking structure. Electrodynamic braking becomes ineffective below the value of 10 km/h, therefore in the third stage, the train is stopped with the use of pneumatic brakes. The braking current of motors is in the range of 120÷420 A. The target braking force is controlled by the influence of a camshaft (through the elimination of resistances) on the current intensity of the controlling circuits. Camshafts circuits are coupled with the current adjustment block. When the voltage of camshafts circuits is disabled, in the first stage, during a regulation of motor coil excitation the current considerably decreases. In the second stage, a voltage interrupt holds the camshafts in place and the current decreases gradually to a very small value. Renewed movement of the shaft ensures emerged control voltage. The camshaft achieves subsequent adjustments, so as to the braking controlling current increases progressively. A proper control of camshafts duration times enables the realization of the calibration braking curve [1].

Target braking of the train type "Metropolis" with an AC-powered drive

The braking road consists of tracking the reference braking curve, while electrodynamic braking takes place and driving through the access road occurs (firstly with a free run and next when pneumatic braking takes place). If the train crosses the appropriate wire loop, the braking process is initiated. The road and the speed are being measured by the on-board devices. Respective braking commands are given as a result of comparison of the actual distance and the calibration curve distance from the stopping point. After crossing the drive-off curve, the drive is turned off and the braking procedure starts. The drive-off curve is calculated continuously by the braking force controller and it is based on the reference braking curve. As the train speed decreases to 10 km/h, electrodynamic braking is turned off and the trajectory tracking is finished. Finally, the train rolls free and the train stopping precision is dependent on a pneumatic braking characteristic. The pneumatic braking force operates with a constant value, until the train is stopped. The control of braking processes is performed by a drive inverter by the use of operating current. Electrodynamic braking is the basic type of braking, it operates based on the braking force reference characteristic. The operating current varies from 4 mA to 20 mA during the braking process. The current control ensures a smooth control of the deceleration. The train is braking with a delay calculated in the system or predetermined by the driver. The system is designed in such a way that it always selects a higher value of deceleration. A 8-bit operating current signal is transmitted to the encoder with an output current loop. The current signals are changed into voltage in two additional input current loops. The first is equivalent to the system deceleration value, while the second is equivalent to the deceleration predetermined by the driver [1].

Simulation results

The simulator enables an analysis of the impact of imposed parameters of target braking process (including the braking accuracy), such as initial braking speed, filling grade, mass, profile, the distribution of characteristic points in the track used to conduct the braking, elementary resistance to motion, rotating masses, train length, the dynamics of the drive system, restrictions of the retardation and braking force, delay of the system response and the electrical parameters of the braking controller. Target braking accuracy should be understood as the real stopping point in relation to the required stopping point. The results of simulation demonstrate the decrease of the road to the stopping point expressed in meters. The outcome preceded by "+" means that the front of the train has not exceeded the stopping point (located in the platform), "-" means that the front of the train has exceeded the stopping point. The braking accuracy D_{ham}[m] can be described by the following formula:

$$\mathrm{D_{ham}} = s_{rz} - s_z \; [m] \qquad (2.0)$$

Where: s_{rz} – the real braking distance [m], s_z – the distance to the predetermined stopping point [m].

Influence of operating parameters of metro trains on braking precision

Investigation of influence of operating parameters on braking precision and braking time has been carried out, below selected results are presented. The parameters adopted for considerations are as follows:

- the influence of the profile (Fig.3),
- the influence of the filling grade of the train (Fig.4),
- the influence of the reduced braking force (Fig.5),
- the influence of elementary resistance to motion (Fig.6),

on the instantaneous speed v of a train during precision braking.

Designation in the graphs below: i[‰] – a vertical profile, st[-] – a filling grade, f_h[%] – a percentage of the braking force F_h, w[-] – a proportion of resistance to motion (multiplication of W), t[s] – time, v_p[km/h] – initial braking speed. Tables 1÷4 contain the results of calculated braking accuracy (D_{ham}).

After analysing the influence of the profile, it can be stated that it affects only the braking time. The filling grade slightly acts on target braking precision. The reduction of braking force, especially for a 25-30% decrease of the available force, gives a noticeable fall down of braking precision, in this case due to a low value of braking force the train passes the stopping point.

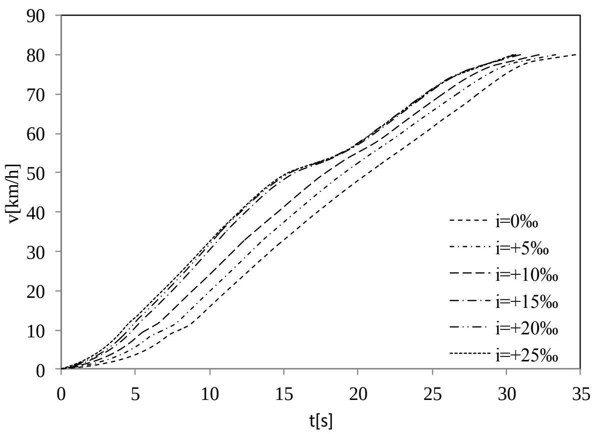

Fig.3 - The influence of the profile on the instantaneous speed of a train during target braking; st=1,0; v_p=80 km/h

Table 1 - The influence of the profile on the braking accuracy

i [‰]	+0	+5	+10	+15	+20	+25
D_{ham} [m]	0,05	0,46	1,46	-0,48	1,43	2,07

Finally, as it can be seen in Figure 6 and Table 4, there is a high influence of elementary resistance to motion on the braking accuracy. When resistances are multiplied (it rises), the braking precision significantly drops down. In this case, a large value of resistance to motion, causes stopping in a long distance before the platform.

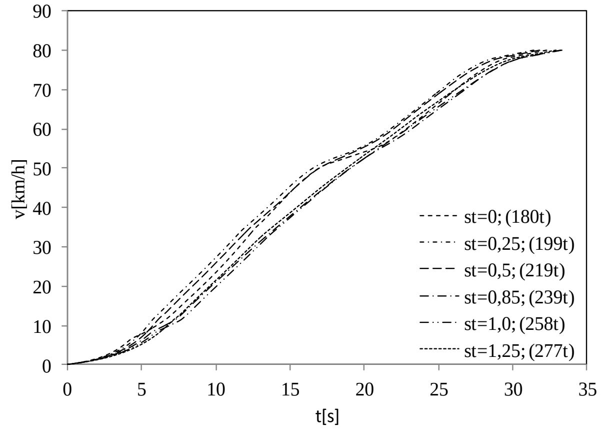

Fig.4 - The influence of the filling grade on the instantaneous speed of a train during target braking; i=+5‰; v_p=80 km/h

Table 2 - The influence of the filling grade on the braking accuracy

st [-]	0	0,25	0,5	0,85	1,0	1,25
D_{ham} [m]	1,35	1,45	1,82	0,46	0,46	1,35

Considering the examined operating parameters, the reduction of available braking force and the value of resistance to motion have the greatest impact on the target braking process. As can be seen, the simulator allows calculating the results under variable conditions, which enables the assessment of general braking parameters including the braking accuracy.

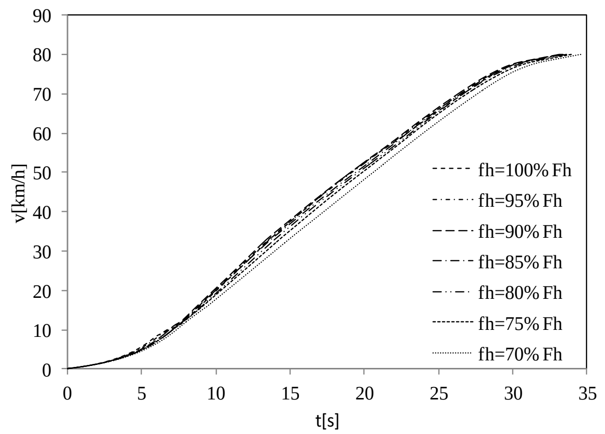

Fig.5 - The influence of the reduced braking force on the instantaneous speed of a train during target braking; i=+5‰; st=1,0; v_p=80 km/h

Table 3 - The influence of the reduced braking force on the braking accuracy

f_h [%]	70	75	80	85	90	95	100
D_{ham}	-4,7	-	-1,06	0,62	0,86	0,61	0,46

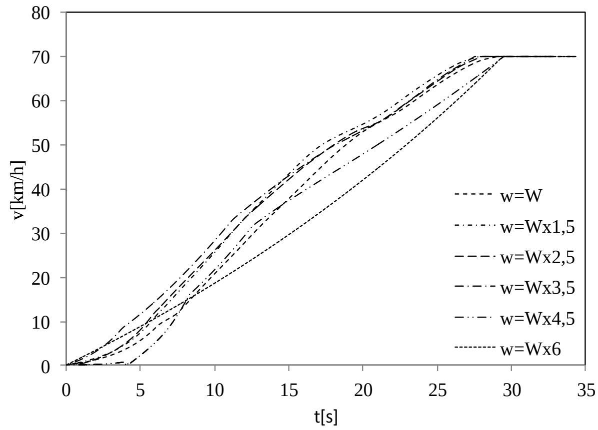

Fig.6 - The influence of resistance to motion on the instantaneous speed of a train during target braking; i=+5‰; st=1,0; v_p=70 km/h

Table 4 - The influence of resistance to motion on the braking accuracy

w [-]	x1	x1,5	x2,5	x3,5	x4,5	x6
D_{ham}	0,48	1,27	2,18	2,40	8,80	30,00

Verification of the simulation model

Conducted studies have enabled the assessment of precision braking and determined the influence of a number of parameters which affect braking. However, in order to confirm the correct functioning of the simulator, a verification of the model compliance was performed, including the check of dynamic (Fig. 7÷8) and static (Fig. 9) outcomes. Using the simulator, for each type of train, points of the velocity curves $v_p=f(s)$ were obtained. At subsequent graphs, the results of measuring points obtained during a real train braking were presented. Furthermore, on each of the graph, the results of software calculations in a form of an approximating function were presented.

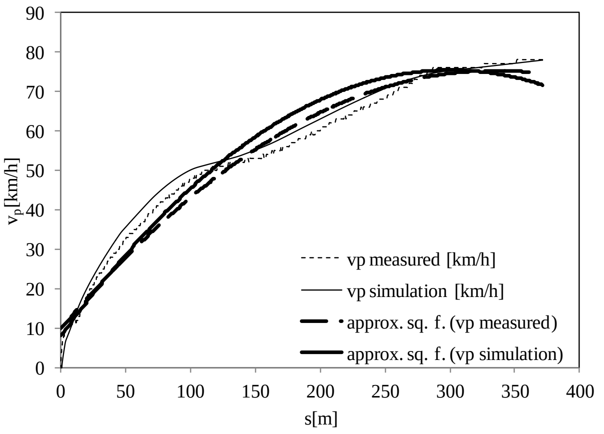

Fig.7 – The comparison of braking curve for train type “AC” calculated with the use of the simulator – $v_{p\ simulation}$=f(s) with curve obtained during measurements – $v_{p\ measured}$=f(s); st=0; v_p=78 km/h; s - road

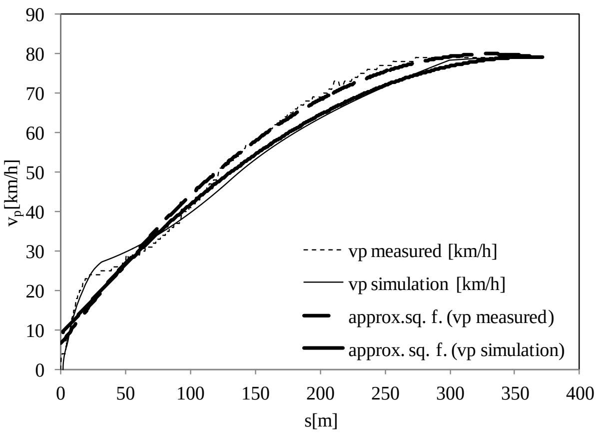

Fig.8 – The comparison of braking curve for train type “DC” calculated with the use of the simulator – $v_{p\ simulation}$=f(s) with curve obtained during measurements – $v_{p\ measured}$=f(s); st=0; v_p=78 km/h; s - road

On the basis of the results it may be considered, with a high degree of certainty, that the developed simulator performs correctly the target braking process. Thereby, the simulator models properly a real object. There have been performed hundreds of simulations, which have given the expected, satisfactory results.

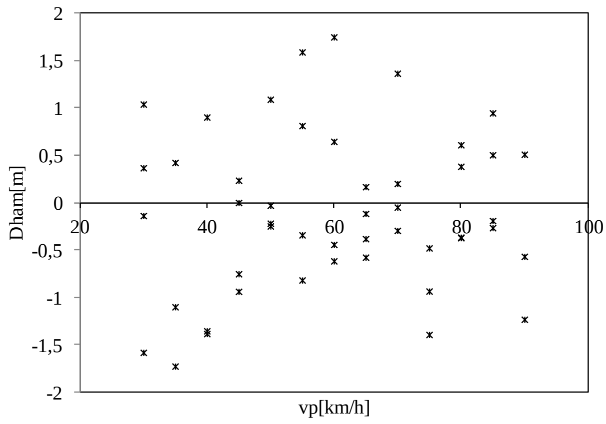

Fig.9 – The dispersion of braking accuracy tests as a function of initial speed D_{ham}=f(v_p); complex profile; various wire loops distribution; st=1.0; v_p=(30÷90) km/h

According to the manufacturer of the SOP-2 system, as a criterion for validation of a target braking function, the stopping of a train should take place in the distance of 2 meters from the stopping point. As it can be seen in Figure 9, in a significant number of cases the train is being stopped in the range from –1.0 to +1.0 meters. Thus, it has been proven that a software recreation of target braking is possible.

Preliminary statistical analysis of simulation results

An outcome of a statistical analysis of the obtained simulation results – shown in Figure 9, is summarized in the next illustration (Fig. 10). The distribution of the dispersion of braking accuracy D_{ham} passed 4 tests for normality [7]. A description of the gained values as the random variables according to the normal distribution, can be regarded as suitable.

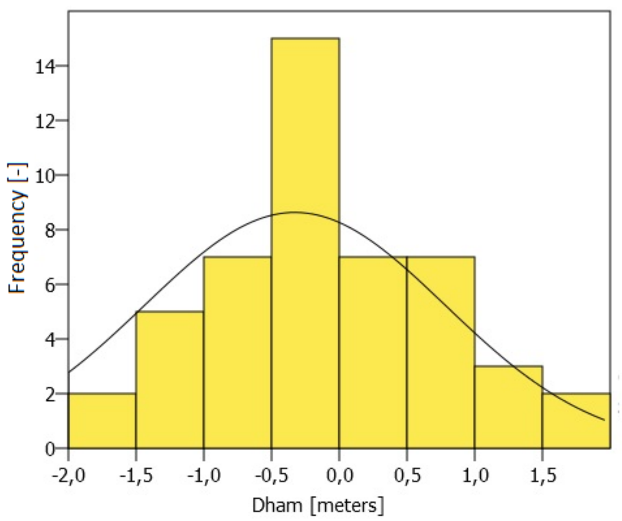

Fig.10 – A histogram of simulation outcomes of braking precision D_{ham} with a normal distribution curve

Conclusions

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

- From the examined operating parameters, the reduction of available braking force and the addition of resistance to motion have the greatest impact on the precision of braking. The obtained outcomes can be generalized to most kinds of rolling stock operating with an ATO system,
- Supreme precision has been obtained for the initial braking speed v_p in the range of 50÷90 km/h (mean values of the train speed),
- Conducted studies can support existing ATO systems by improving the accuracy of automatic train stopping on the platform. The increase of accuracy of target braking improves the safety of passengers e.g. by minimizing the risk of falling on the tracks. For platforms with double doors (so-called closed platforms), exact stopping of the train will play a key role in the evacuation of passengers in case of fire or a terrorist attack,
- **The created tool can be used to support the process of designing automatic train operation systems,**
- **A software recreation of target braking is possible,**
- **The major effect of the work is the developed target braking model. The model allows for performance in dynamic conditions the target braking process and it provides the ability to calculate braking accuracy,**
- The research results of braking accuracy are consistent with a normal distribution.
- The simulator allows calculating the quality factor, which makes possible the assessment of generated braking curve, which is an additional research interest.

References

[1] A. Gocek, M. Steczek *Simulation studies of target braking accuracy of an underground train driven by an AC motor.* The Conference Proceedings of XVI Scientific Conference of the Electric Traction Semtrak 2014. Zakopane, Poland, 2014.

[2] H. Kawashima, F. Komura, K. Honma., A. Iwasaki, T. Takaoka, K. Tashiro, N. Monma *A Total Railway System Simulator and its Application to the Evaluation of Energy Saving Train Operation*. Wessex Institute of Technology Conference, COMPRAIL 92, Washington, 1992.

[3] J. Madej *The theory of movement of rail vehicles.* Publishing House at The Warsaw University of Technology. Warsaw, Poland, 2004 (in Polish).

[4] R. Mincardi, S. Savio, G. Sciutto *Models and tools for simulation and analysis of metrorail transit systems.* COMPRAIL 94. Computers in Railways – Fourth Int. Conference on Computer Aided Design. Rome, Italy, 1994.

[5] Mohammad Ali Sandidzadeh, Babak Shamszadeh *Improvement of Automatic Train Operation Using Enhanced Predictive Fuzzy Control Method*. InTech. Iran. 2012.

[6] Neha Deotale, Manish Katkar, S.P. Khandait *Automatic Train Operation, Scheduling, Simulation And Anti-Collision System With Terminal's Station Backup of Train's Schedule - A Review.* IOSR Journal of Computer Science (IOSR-JCE). India, 2014.

[7] B.L. Nelson *Statistical Analysis of Simulation Results.* Handbook of Industrial Engineering: Technology and Operations Management, USA, 2001.

[8] B. Pniewska *Controlling the slave traction unit at a given timetable.* Dissertation. The Warsaw University of Technology, Faculty of Electrical Engineering. Warsaw, Poland,1995 (in Polish).

[9] A. Szeląg *The influence of the voltage in the 3kV DC traction network on the energy and traction parameters of supplied vehicles.* The Institute of Scientific Publishing Spatium. Radom, Poland, 2013 (in Polish).

[10] Q. Wen, S. Kingsley, R. A. Smith *Energy Simulation of Hybrid Inter-city Trains*. Proceedings of the Institution of Civil Engineers, United Kingdom, 2007.

[11] S. Yasunobu, S. Miyamoto *Automatic Train Operation System by Predictive Fuzzy Control.* Industrial Applications of Fuzzy Control, North Holland, 1985.