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SIMULATION STUDIES OF TARGET BRAKING ACCURACY OF AN UNDERGROUND TRAIN DRIVEN BY AN AC MOTOR

BADANIA SYMULACYJNE UKŁADU HAMOWANIA DOCELOWEGO W METRZE NAPĘDZANYM PRZEZ SILNIKI AC

A b s t r a c t

In this paper, a 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 SOP-2 system designed by the Technical University of Lodz, in cooperation with Bombardier Transportation (ZWUS), has been presented. In the text, a target braking simulation model created by the authors has been described, which was developed to study the impact of the propulsion system on the target braking accuracy. The simulation results have been presented. The average dispersion of automatic target braking provides train stopping in the most number of cases in the range of 0.53 meters. Target braking values obtained during field tests are in the range from 0.3 to 1 meter. On the basis of the obtained results of target braking, the process conclusions are as follows: rapid deceleration changes cause the so-called jerks, which are negatively perceived by the passengers; braking in a long time causes a decrease in the commercial speed. Currently, the authors have developed a simulation model that includes a DC motor drive, which is in the testing phase.

Keywords: supercapacitor storage, trolleybus, vehicle supply system, regenerative braking, energy consumption savings

S t r e s z c z e n i e

W artykule przedstawiono podstawowe funkcje Automatycznej Obsługi Pociągu. Szczegółowo omówiono najważniejsze założenia. Zaprezentowano system SOP-2 zaprojektowany przez Politechnikę Łódzką we współpracy z Bombardier Transportation (ZWUS). W tekście zasymulowano hamowanie docelowe pojazdu z dokładnym opisem układu napędowego oraz przedstawiono wyniki symulacji. Średnie odchylenie od punktu zatrzymania wyniosło 0,53 metra. Uzyskano wartości od 0,3 do 1 metra. Na podstawie otrzymanych wyników wyciągnięto następujące wnioski: gwałtowne zmiany opóźnienia nie wpływają korzystnie na pasażerów, długi czas hamowania zmniejsza prędkość handlową pojazdu. Autorzy poszerzyli model silnika DC, który zastosowano w symulacjach.

Słowa kluczowe: zasobnik superkondensatorowy, trolejbusy, energetyka trakcyjna, rekuperacja, oszczędność zużycia energii

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1. Introduction

Traffic conditions present in the underground are unique in that the distance between trains is short, they move at high speed (V~90 km/h) as well as the platforms are short. Therefore, it is required to apply specialised systems that can provide traffic safety, which in terms of speed restrictions, is ensured by the Automatic Train Protection (*ATP*) system. Once the system has been provided with appropriate data, it can calculate the 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 the safety speed, as it includes control of the power transmission and braking system. The system protects against dangerous situations, such as collision with the preceding train, failed braking before an absolute stop, falling out on curve due to excessive speed, etc. The *ATP* system is initiated only if the driver exceeds the permissible speed, e.g. signalled by a semaphore [2, 5, 7, 9, 10]. Automatic Train Operation (*ATO*) is another example of systems, which can be of help in the underground. This one is responsible for supporting the driver of the train. Both systems can cooperate, and in this case, *ATP* is a master system, while *ATO* is relative. The following functions can be implemented by an ATO system:

- Automatic train starting, riding and stopping,
- target braking,
- train doors opening/closing,
- driving for energy savings
- driving for schedule optimisation.

Target braking is one of the most important functions performed by an *ATO* system. It relies on automatic train stopping at the stations, where the braking process is fully controlled by a microprocessor device. Target braking helps to avoid dangerous situations resulting from stopping too far from the passenger transfer section of the platform. For instance, it prevents a serious injury when a passenger would fall into the gap between the platform and the train. Furthermore, the position where the train stops is very important at stations equipped with double-locked doors (the so-called closed platforms). In this case, it is required to stop the train according to the "door to door" method. Precise stopping also affects the evacuation of passengers in the event of a terrorist attack [2, 6, 9, 10].

2. A general method of target braking

Target braking is a special case of essential train braking. It consist of progressive reduction of the actual train speed V_{rz} to the permissible speed value $V_d = 0$. The permissible speed has to be obtained at the stage of speed restriction x_d. During this process, the permissible value of deceleration a_h cannot be exceeded. The automatic braking process occurs in the following situations:

- On the platform, where the train stopping has to be accurate and the actual train stopping position x_{rz} fulfils the condition of $x_{rz} = x_d \pm c$,
- by the semaphore, where the actual train stopping position is donated by $x_{rz} \pm c \leq x_d$, where:
  c – admissible stopping tolerance.

Target braking is an important stage of the underground train ride as it is required to stop a train on a platform with limited length. The average length of the subway train is about 100 m, and length of the platform for space saving reasons in the tunnel is very similar [5, 6, 12]. The process of target braking consists of two phases: motor braking phase (electrodynamic braking) and mechanical braking phase (performed by a pneumatic brake). The second stage of braking is required because of a decreasing capacity of the electrodynamic braking at low speeds. The target braking process is executed by a proper control of electric motors. However, the process is more complex than it appears. Target braking operation requires solving two problems, such as the braking has to be initiated at an appropriate distance from the stopping point and the braking process has to be properly conducted.

3. ATP system used on the no. I underground line in Warsaw

On the 1st line of the Warsaw underground, traffic safety is provided by a system commercially called SOP-2. It is a type of an ATP system, which is enriched in the ATO system function – the target braking of train on the platform. The SOP-2 performs its tasks by a continuous data transmission, which is achieved by using a wire loop placed between the tracks. There are used two basic types of rolling stock: Russian series 81 trains driven by a DC motor and Alstom Metropolis trains powered by an AC motor. Operation of the target braking structure can be divided into several phases presented in Fig. 1. The braking route consist of tracking the reference braking curve (Fig. 2), while electrodynamic braking takes place and driving trough the access road (with the impetus and next pneumatic braking) [3, 4].

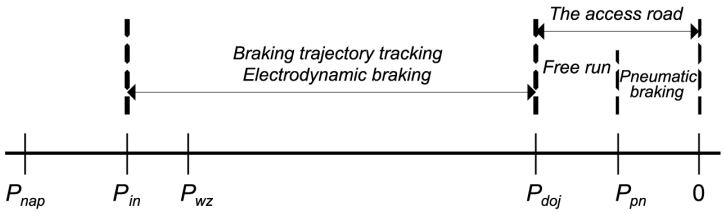


Fig. 1. Characteristic points of target braking process [3, 4]: P_{nap} – traction drives disabling, P_{in} – regulator initiation, P_{wz} – start of tracking the calibrated braking trajectory, P_{doj} – end of tracking the calibrated braking trajectory (the regulator disabling), P_{pn} – pneumatic brakes start

If the train crosses the appropriate wire loop, the braking process will be initiated. The road and the speed are measured. Respective braking commands are given as a result of a 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. At point P_{nap}, the drive is turned off. At Pin, the braking force controller starts to work; however, due to a delayed action of the controller, the trajectory tracking begins at P_{wz} point. At Pdoj, the train has to achieve a speed of 10 km/h; also, the electrodynamic braking is turned off and the trajectory tracking is finished. Afterwards, the train rolls free and the

precise train stopping is now based on the pneumatic braking characteristic. At point Ppn, the pneumatic brakes are being activated. The pneumatic braking force operates with a constant value until the train is stopped. The control of driving and braking processes is performed by the operating current. The SOP-2 units are connected with the train controlling circuits. Electrodynamic braking is the basic type of braking and takes place according to the braking force reference characteristic (Fig. 3). During the braking process, the current varies from 4 mA to 20 mA. This corresponds to the braking deceleration from 0 m/s^2 to 1,3 m/s^2. The current control ensures a smooth control of the deceleration [3, 4].

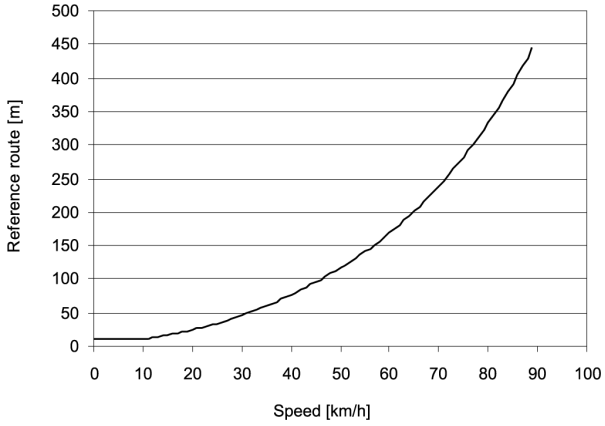


Fig. 2. Reference braking curve [3, 4]

The train is braking with a delay calculated in the system or predetermined by the driver. The system is designed to always select a higher value of deceleration. With an output current loop, an 8-bit control current signal is transmitted to the encoder. In two additional input current loops, the current signals are changed into voltage. The first is equivalent to the system deceleration value, while the second to the deceleration predetermined by the driver [3, 4].

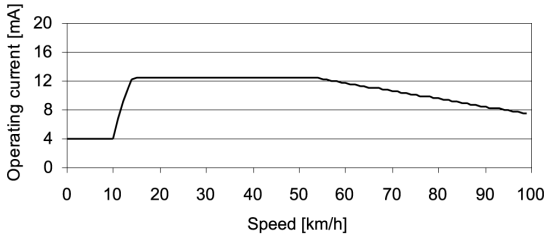


Fig. 3. Braking force reference characteristic [3, 4]

4. Simulation model

In order to assess the impact of the target braking accuracy, a simulation model has been created. The simulation model has been developed by using the C++ programming language. The model has been created to simulate a train driven by an AC electric motor, which is

controlled by an inverter. The concept of the script consists of calculations of the access road. Access road is understood through the nearest section to the platform including the division into wire loops and track circuits (line spacing). The general operations of the script have been presented on a block diagram (Fig. 4). The created simulation model takes into account such parameters as: movement resistance, vertical line profile, delay in relation to the function of the controller, line spacing, wire loops lengths, wire loops crossings, permitted line speed, restriction of increase of braking deceleration, weight of the train and train filling. A general block diagram is presented beneath. The simulation model includes a physical representation of the train movement. This model has been created to conduct studies of an automatic target train braking; therefore, it realises the primary train movement phases used during train braking, such as: braking, determined mode and freewheel. This model does not perform train starting. To implement the calculations of train physics, the below formulas were applied.

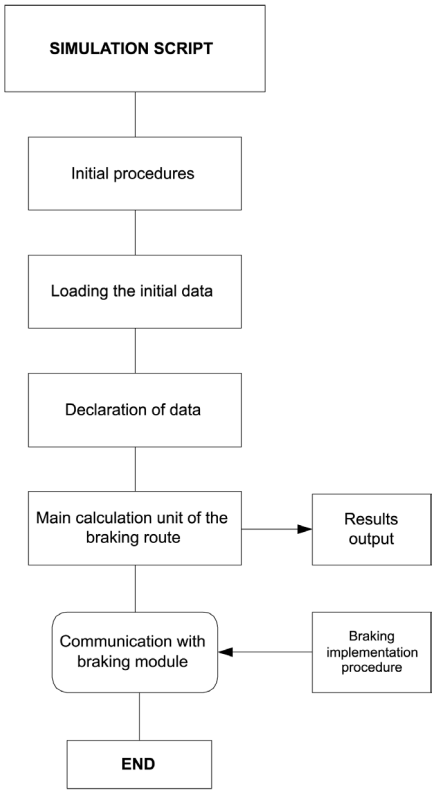


Fig. 4. A block diagram of the simulation script

Movement resistance W[N]. Unconsolidated movement resistance was computed from the Jaworski formula [11]:

$$W = w_0 + \frac{1}{k}\left(\frac{V}{10}\right)^2 \left[\frac{\mathrm{N}}{\mathrm{kN}}\right] = [\text{promile}] \tag{1}$$

where:

k – factor depending on the type of train,

w_0 – essential resistance.

While the propeller is equal to 0 (freewheel), the essential resistances can be computed by using:

$$w_0 = 2 * \left(1 + \frac{G_l}{G}\right) \tag{2}$$

where:

G_1 – weight of empty train,

G – weight of train with passengers.

The relationship between the resistance movement and the essential resistance unit is as follows:

$$W = w * G = w * m * g \tag{3}$$

where:

m – train and passengers mass expressed in tones.

Total movement resistance W_c can be given by:

$$W_c = w_c * G \tag{4}$$

$$w_c = W \pm i \tag{5}$$

where:

W – movement resistance,

i – movement resistance arising from vertical profile.

Braking force F_{ham}

$$F_{ham} = F + W_c \text{ [N]} \tag{6}$$

where:

F – braking force on the train wheels,

W_c – total movement resistance.

Braking deceleration a can be equal to:

$$a = \frac{F_{ham}}{m * \alpha} \left[\frac{\text{m}}{\text{s}^2}\right] \tag{7}$$

where:

F_{ham} – braking force,

m – train and passengers mass expressed in [kg],

α – rotating masses factor.

The braking road S[m] and the speed in the course of braking mode V[km/h] can be defined as follow:

$$S = S_0 - V_0 * t + \frac{a * t^2}{2} \tag{8}$$

$$V = V_0 - a * t \tag{9}$$

In order to improve the reality of the target braking model, which has been developed on the basis of an Automatic Train Protection system called SOP-2, the authors applied movement resistance supplied by the fleet manufacturer for the Warsaw 1st underground line. Also, the braking force characteristic (supporting an electrodynamic braking stage) supplied by the fleet manufacturer was implemented in the model. The program uses such characteristic to calculate the braking force enlarged with total movement resistance and to calculate the retardation. A simplified functional diagram of the target braking simulation model has been presented in Fig. 5.

The braking implementation procedure reflects the operation of the braking controller embeddable on a real underground train. It gets information about the momentary speed of the train and the route coordinate including the driven distance by the train. Next, it performs the actions described in Section 3 of this paper, which particularly consists of working out the value of the braking force – given as a percentage of available braking force value.

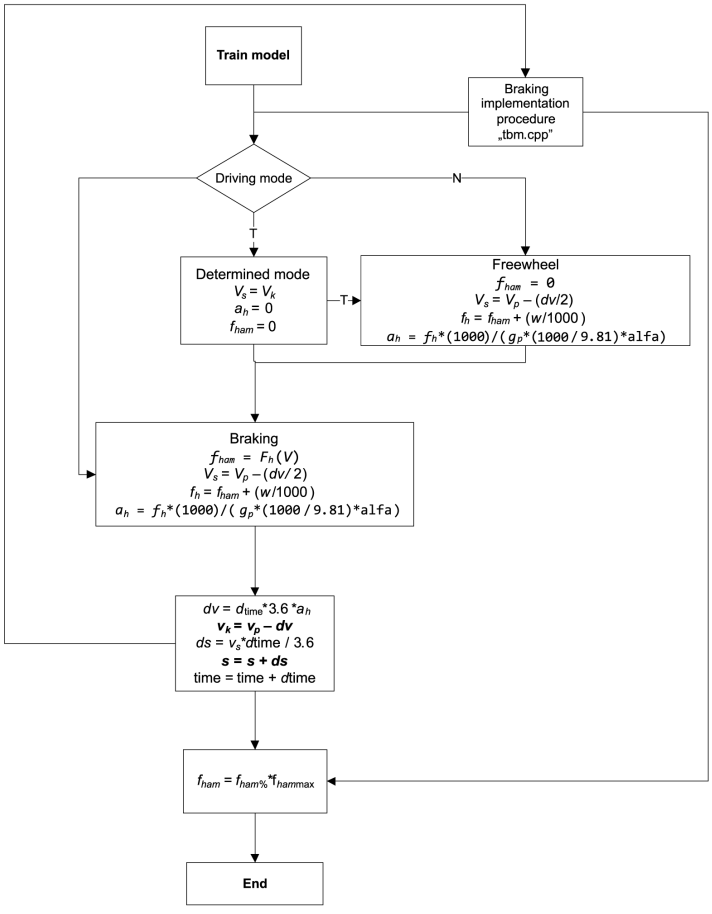


Fig. 5. Simplified functioning diagram of the target braking simulation model

5. Simulation research of the target braking accuracy realised on the access road to a platform

For the purpose of assessing the accuracy of a train target braking (AC driven) executed by an ATP system, computer research has been carried out. The authors have investigated the target braking process with the following assumptions:

- simulation time step = 10 ms,
- communication with the braking implementation procedure = 50 ms,
- braking deceleration restriction = 1.3 m/s^2,
- initiation speed of the braking process (in the range 85–10 km/h),
- variable filling of the train (empty, half fill, full fill by the passengers),
- given distance to the stopping point – complete access road set by the last beginning of transmission loop = 369 m,
- access road tested with the assumption of vertical profile equal to 0,
- a real distribution of wire loops and crossings of wire loops on the access road, in this case 5 wire loops (including 1 crossing used for the last road coordinate setting) on the access road. The lengths of loops have real values and defined starting points.

Target braking accuracy [m] should be understood as that real stopping point in relation to the required stopping point.

Table 1

Results of braking accuracy tests

No.	Braking initiation speed [km/h]	Target braking accuracy [m]			Average braking time [s]
		Empty = 0 [–]	Half fill = ½ [–]	Full fill = 1 [–]	
1	85	1.98	2.14	–0.10	32.56
2	80	2.44	1.23	0.30	32.60
3	75	2.48	1.21	–0.17	33.20
4	70	0.77	1.51	0.29	33.83
5	65	1.03	2.12	–1.12	34.30
6	60	–0.31	0.19	1.13	36.10
7	55	–0.26	–0.53	0.44	37.53
8	50	0.99	0.63	–0.07	38.43
9	45	0.91	1.17	–1.59	40.46
10	40	0.99	0.80	–2.59	43.30
11	35	1.28	0.48	–2.34	47.53
12	30	–0.14	1.38	–1.12	53.63
13	25	0.03	0.00	–0.10	62.56
14	20	0.39	–0.36	–0.87	75.63
15	15	0.55	–0.09	–0.76	96.80
16	10	0.80	0.26	–0.27	139.50

The results show 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 on the platform), "–" means that the front of the train has exceeded the stopping point. The results are presented in Table 1.

6. Conclusions

The average dispersion of automatic target braking provides train stopping in the most number of cases in the range of 0.53 meters. In some cases (4 cases), the train runs over the stopping point around 1.12–2.34 meters. The train does not reach the stopping point in 11 cases with values around 1.51–2.48 meters (22% of conducted tests of target braking). Target braking values obtained during field tests are in the range from 0.3 to 1 meter. In reality, there are single situations in which the accuracy of target braking reaches a value higher than 1 meter (which also has been obtained in the simulation test). The several derogations between values of the target braking accuracy conducted the during field test and received during computer simulations arise from the differences between the real and computed movement resistances and the characteristic of the braking force applied in the simulation program. The braking force characteristic obtained from the fleet manufacturer provides only the electrodynamics stage of braking – with its use, these samples were conducted. To generate more exact target braking data, it is necessary to use a combined characteristic, which also includes a stage of pneumatic braking. The authors have not been able to obtain such characteristic from the carrier, and instead, a combined electro–pneumatic characteristic has been determined experimentally. It has substantially improved the results of target braking. After confirmation of the combined electro–pneumatic characteristic, the

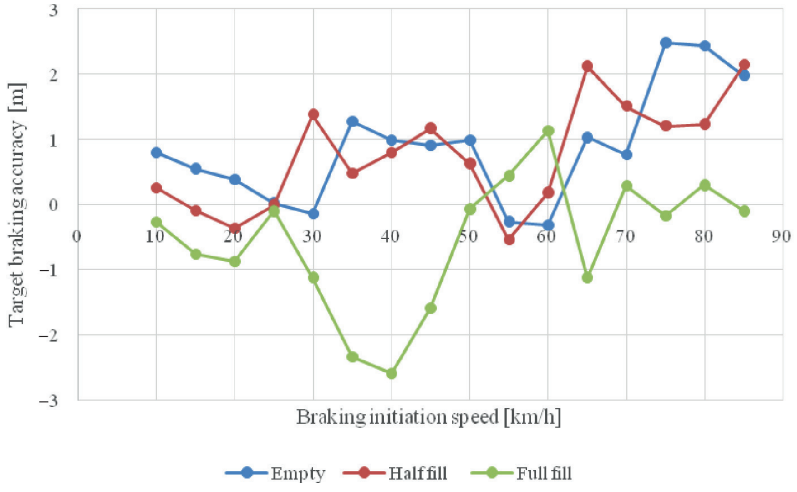


Fig. 6. Target braking accuracy depending on the braking initiation speed

results will be presented one more time.On the basis of the obtained results, the target braking process has to be carried out in the following manner:

- rapid deceleration changes cause jerks, which are negatively perceived by the passengers e.g. passengers are falling down,
- as short as possible, braking for a long time causes a decrease in the commercial speed.

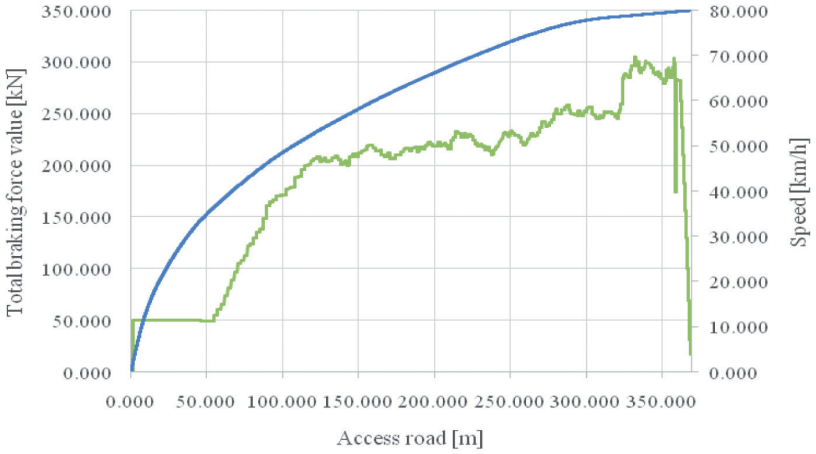


Fig. 7. An example of an access road ride, the graph shows one of most important parameters computed during target braking – braking force

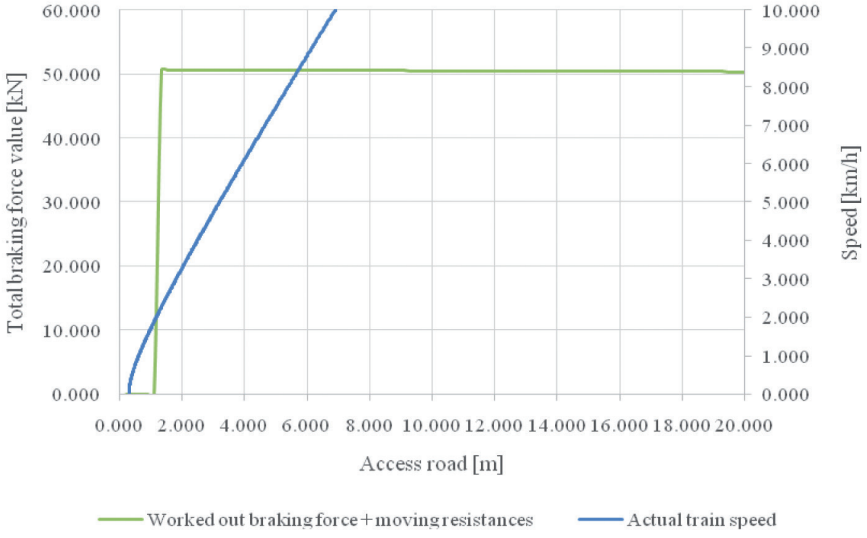


Fig. 8. An example of an access road ride – enlarged course of the ending of access road calculated during target braking

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