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A tool for calculating braking distances of rail vehicles

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In the article a tool for calculating the braking distance of rail vehicles developed as part of R&D project conducted at the Institute of Rail Vehicles in Poznan (Poland) was presented. The tool used high-level programming language – Python for determining the braking distance of railway vehicles in accordance with the algorithm presented in the EN 14531 standard. The developed tool takes into account the theoretical curve of pressure build-up in the brake cylinder and the variability of the friction coefficient with time during the braking process. The paper presents the results of calculating the braking distance of the electric multiple unit.

1. Introduction

Braking performance is a measure of a vehicle's ability to stop within a specified stopping distance. It can be determined on the basis of such braking criteria as e.g. braking capacity, braking distances, average vehicle deceleration, braking power, braking mass. A typical measure of the braking performance of a railway vehicles (wagons, locomotives, multiple units) is the braking mass λ (1):

$$\lambda = \frac{C}{s} - D \tag{1}$$

where: λ – brake weight percentage [%], s – braking distance [m], C,D – coefficients depending on the initial braking speed.

2. Literature review

The development of automatic train driving systems determines the necessity to develop or improve the current methods of calculating braking performance and distances of railway vehicles.

Calculation tool for obtaining braking distances of different railway vehicles was presented by Barney et al. in 2001 [1]. The authors focused mainly on describing the IBM PC® based tool.

Paukert in 2005 [4] developed three analytical models that allows to translate braked weight percentage into a function of deceleration. The author validated these three models and chose the most accurate one. This model can be used in train control system ETCS but there is still a need for testing.

A method for calculating stopping distance of freight railway vehicles was considered by Bentley and Bentley in 2007 [2].

Sicre et al. in 2008 [7] developed a tool for calculation of trains braking distance. This tool realizes iterative algorithm proposed by the authors.

Peng et al. in 2013 [5] proposed new brake calculation method for high-speed railway in China. The authors compared obtained results with real data and it occurred that a discrepancy in the results is negligible.

Pugi et al. in 2013 [6] described a tool for predicting the stopping distance of railway vehicles. The tool developed by the authors allows to calculate train braking performance with taking into account loading and operating conditions of a vehicle. The authors compared results obtained from tool with experimental data.

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Results of calculating train braking distance using Fuzzy Logic were presented by Milosavljević et al. in 2018 [3]. A created model was tested by the authors with ten different simulations of braked train's. Authors proved that results obtaining from their model are stable.

3. Algorithm

The algorithm for determining the braking distances of rail vehicles in accordance with the EN 14531 standard is shown in Fig. 1.

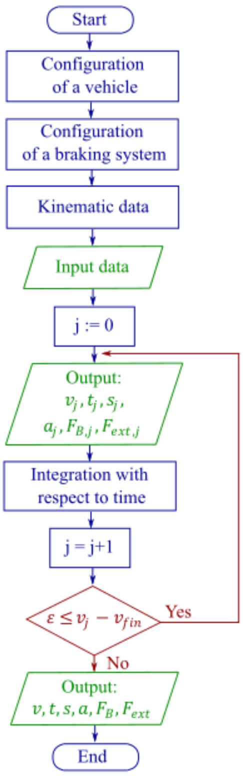

Fig. 1. Algorithm for train braking distance calculation

According to this algorithm, the calculations of braking distance should be started with determining the general characteristics of the vehicle and a braking system, i.e. mass of vehicle, the number of bogies and types of brakes with which the electrical multiple unit (EMU) is equipped. Then the kinematic data such as initial speed of vehicle, forces of brakes, external forces acting on the vehicle need to be specified.

The data prepared in this way allow in the first step to determine the delay a_j in the time instant t_j (2) [8]:

$$a_j = \frac{(\sum F_{B,i} + \sum F_{ext})}{m_{dyn}} \tag{2}$$

where: a_j – vehicle delay in time t_j [m/s^2], $F_{B,i}$ – braking force of each brake [N], F_{ext} – external forces [N], m_{dyn} – vehicle dynamic mass [kg].

Then the speed of the vehicle should be determined in the next moment of time t_{j+1} (3) [8]:

$$v_{j+1} = v_j - a_j \cdot \Delta t \tag{3}$$

where: v_{j+1} – vehicle speed in time t_{j+1} [m/s], v_j – vehicle speed in time t_j [m/s], a_j – vehicle deceleration [m/s^2], Δt – time step [s].

In the third step, the braking distance at the time instant is calculated t_{j+1} (4) [8]:

$$s_{j+1} = s_j - v_j \cdot \Delta t - \frac{1}{2} \cdot a_j \cdot \Delta t^2 \tag{4}$$

where: s_{j+1} – vehicle braking distance in time t_{j+1} [m], s_j – vehicle braking distance in time t_j [m], v_j – vehicle speed in time t_j [m/s], a_j – vehicle deceleration [m/s^2], Δt – time step [s].

The last step of the calculations is to determine the deceleration in time step t_{j+1} (5) [8]:

$$a_{j+1} = \frac{(\sum F_{B,i} + \sum F_{ext})_{j+1}}{m_{dyn}} \tag{5}$$

where: a_{j+1} – vehicle deceleration in time step t_{j+1} [m/s^2], $F_{B,i}$ – braking force of each brake [N], F_{ext} – external forces [N], m_{dyn} – vehicle dynamic mass [kg].

The above calculations are repeated until the difference of the final vehicle speed v_k and the instantaneous speed v_{j+1} is smaller than the assumed value of ε. This criterion is expressed by the inequality (6) [8]:

$$\varepsilon \geq v_k - v_{j+1} \tag{6}$$

where: ε – assumed accuracy of calculations, v_k – vehicle final speed [m/s], v_{j+1} – vehicle speed in time step t_{j+1} [m/s].

The presented calculation algorithm has been implemented in the Python programming language in the form of a calculation script in order to perform analyzes of the braking distances of a rail vehicle.

3. Analysis of braking distance of selected railway vehicle

As part of R&D project, an analysis of the braking distances of a traction unit with the axle configuration 2'Bo '+ Bo'2' was performed (Fig. 2).

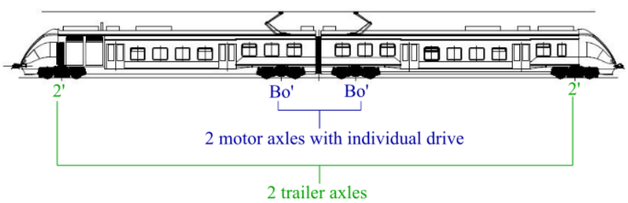

Fig. 2. Configuration of the analyzed EMU

The braking system of the considered trainset consists of the following types of brakes (Fig. 3):

- electrodynamic (ED),
- direct/indirect brake (DB),
- magnetic track brake (MG),
- parking brake (PB).

Fig. 3. Braking system of the analyzed EMU

The analyzed braking cases of the EMU are summarized in Table 1.

Table 1. Braking cases – R mode

No.	Wheels condition	Coefficient of friction	Active brakes TB1	MB1	MB2	TB2
1	new	0.35	Direct brake	Direct brake	Direct brake	Direct brake
2		≠const				
3		–15%				
4		–30%				
5	half-worn	0.35				
6		≠const				
7		–15%				
8		–30%				
9	worn	0.35				
10		≠const				
11		–15%				
12		–30%				

Table 2. Braking cases – R+Mg mode

No.	Wheels condition	Coefficient of friction	Active brakes TB1	MB1	MB2	TB2
13	new	0.35	Direct brake + Magnetic track brake	Direct brake	Direct brake	Direct brake + Magnetic track brake
14		≠const				
15		–15%				
16		–30%				
17	half-worn	0.35				
18		≠const				
19		–15%				
20		–30%				
21	worn	0.35				
22		≠const				
23		–15%				
24		–30%				

The cases presented in tables differ in the type of active brakes, the value of the friction coefficient and the diameter of the wheels. For each case of braking, calculations were made for three different wheel conditions: new, half-worn and worn.

The calculations were made for three types of vehicle load:

- AW0 – empty vehicle,
- AW1 – vehicle with sitting passengers and crew,
- AW4 – vehicle with sitting and standing passengers and crew.

The emergency braking in R mode shown in Table 1 means braking with the direct brake only. The braking force growth curve with this brake is shown in Fig. 4.

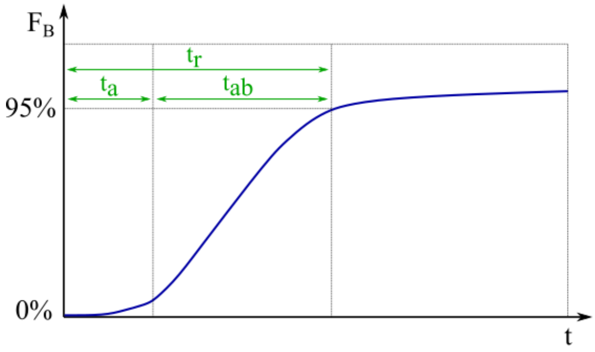

Fig. 4. The curve of building-up braking force

The brake force build-up time marked as t_{ab} is the time from the start of braking to the brake reaching 95% of the braking force.

The phenomenon of pressure build-up in the brake cylinder was described in the calculation tool by the assumed function given by the equation (7), which models this curve well.

$$p(t) = p_{max} \cdot \left(1 - e^{\frac{-3 \cdot t}{t_{ab}}}\right) \tag{7}$$

where: p – pressure in a brake cylinder [bar], p_{max} – nominal pressure in a brake cylinder [bar], t – real time [s], t_{ab} – brake force build-up time [s].

Each of the braking case was performed assuming a constant and variable friction coefficient as a function of velocity. The coefficient of friction (COF) of brake pads depends on many variables such as speed, temperature, humidity and dissipated energy.

On the basis of the actual characteristics of the friction coefficient obtained from the tests, the theoretical curve of the friction coefficient value was adopted in the calculation tool (Fig. 4). Thus the COF was modelled as a function of the instantaneous vehicle speed.

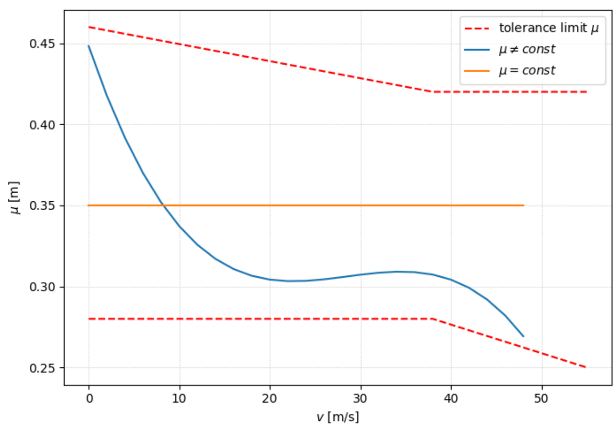

Fig. 4. The theoretical COF curve

This curve was described by a third degree polynomial, and the equation (8) was implemented in the developed calculation tool.

$$\mu(v) = -7 \cdot 10^{-6} \cdot v^3 + 6 \cdot 10^{-4} \cdot v^2 - 0.0164 \cdot v + 0.5 \quad (8)$$

where: μ – friction coefficient, v – instantaneous vehicle speed [m/s].

4. Results

Figure 5 shows the obtained values of the braking distances in the R mode (only the direct brake activated), assuming different values of the friction coefficient and wheel wear conditions. The diagram also shows the tolerance field of the braking distances in the R mode, which were specified as required in EN 16185 standard.

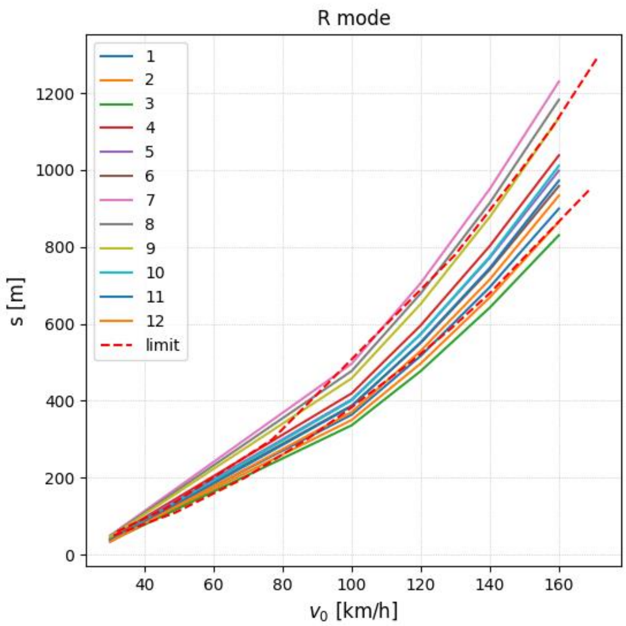

Fig. 5. Braking distances in R mode

It was noticed that only one curve (no. 12) does not fall within the lower limit values of the braking distances. It represents braking under degraded friction conditions i.e. when μ = 0.25. This means that the brake system with which the unit under consideration is equipped allows the vehicle to brake effectively in the R mode, but in the conditions of a reduced coefficient of friction, its braking distance is extended. Such situation can be caused by e.g. phenomenon of aquaplaning or very high temperature of the brake disc. Moreover, one can notice that the difference of the calculated braking distances assuming a constant and variable coefficient of friction is around 10%.

Figure 6 shows the obtained values of the braking distances in the R+MG mode (active direct brake and magnetic track brake). One can observe that two curves do not fall within the lower limit. These curves represent the situations of braking in degraded COF conditions.

The differences between braking distance with a constant and variable COF value are around 8%.

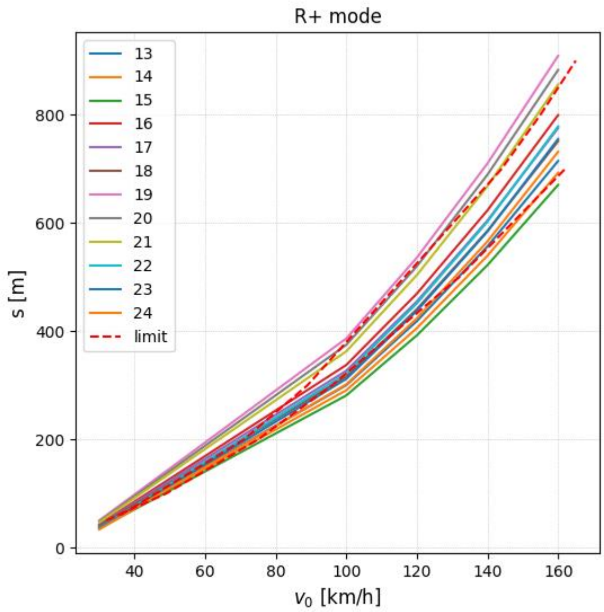

Fig. 6. Braking distances in R+ mode

5. Summary

Braking performance is a measure of the ability of the braking system to slow or stop the rail vehicle.

As part of the R&D project, the "Tabor" Railway Vehicle Institute developed a tool for calculating the braking distance of rail vehicles, taking into account the variability of the friction coefficient as a function of speed and the rate of pressure increase in the brake cylinder. This tool makes it possible to evaluate the braking performance of a train at the stage of designing its braking system.

Nomenclature

EMU	electrical multiple unit
TB	trailer boogie
MB	motor boogie
F_B	braking force
F_{ext}	external force
COF	coefficient of friction

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