Influence of the Head Wind on Determining Braking Performance of Zacns Tank Wagon

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Abstract: From the aspect of safety, brakes of rail vehicles are an extremely important system on the vehicle. Braking performance affects the normal functioning of vehicles and interoperability of rail vehicles in classic railway train compositions. All trains, classic and different type of motor trains must conform with the available stopping distances, which are predefined by the railway signalling, i.e. control length of a signal and depends on the maximum allowable speed for which the track section is designed. Apart from that, in classic wagons, which are combined and participate in the formation of different train compositions, mutual compatibility must be ensured from the aspect of used braking equipment and connection subassemblies, but even more important, braking performance of all wagons in the train has to be uniform within certain tolerances. This prevents weaker braked wagons from running into stronger braked ones, which can cause longitudinal jerks and may in extremes lead to a train rupture. Stopping distance during brake application depends on train braking performances, longitudinal running resistance and presence of wind and its direction. This paper deals with the influence of wind conditions on the results of slip brake tests and the estimation of a single vehicle's braking performance. Based on experimental measurements, simulations using CFD and comparison with the obtained results, this paper proposes a possibility to extract air drag resistance and wind force from the total resistance force. Presented methodology and obtained results may serve for further simulations of aerodynamic characteristics apart from braking performance, such as vehicle running resistance, energy consumption, etc. and for optimization of the wagon shape and design.

Keywords: stopping distance; slip brake tests; head wind influence; drag coefficient; numerical simulations

1 Introduction

TSI (Technical Specifications for Interoperability) and EN (European standards) define the method of determining the braking performance that is most often performed by measuring stopping distances in case of freight wagons, or by measuring deceleration of passenger coaches, motor units and high speed trains.

By keeping these parameters within the prescribed limits, uniform braking of all wagons in the classic train composition is achieved. With closed train sets, this problem is less pronounced because all units usually have the same brake system, similar or equal weight, load capacity and load level. These train sets do not separate from or connect to other vehicles during regular operation.

This paper deals with the influence of the head wind on the test results during slip tests and measured stopping distance. Depending on the wind speed, measured stopping distances may differ significantly.

The influence of wind on railway vehicles can be considered from several aspects. As an effect influencing safety and stability of vehicles [1-3] and as appearance that affects train running resistance and braking distance [4-8]. Safety and stability against overturning depend on cross wind. Head and tail wind predominantly influence running resistance and braking.

This paper focuses on the aerodynamic drag and the presence of head wind during determining the braking performance of conventional freight wagons. Wind influence is more expressed in the case of single vehicles tests and less expressed and not critical for the trains. Empty wagons vs. loaded wagon are more influenced due to smaller share of resultant force, compared to resistance force, in train motion equation. The tests with and without the presence of head wind were performed on the empty tank wagon Zacns type. The analysis included numerical simulation in the OpenFoam program and experimental measurements on the Zacns type tank wagon. According to relevant standard [9], regular atmospheric conditions for tests are described as with the minimum wind and to ride on dry rails.

This issue was treated by UIC[1] Committee in Technical & Research Report B 126/DT 422 [4] without any binding limits of wind speed, due to large number of influencing factors and inability to generalize them. Wind changes speed and direction unpredictably, so during measurements, along with other atmospheric conditions, these need to be monitored.

In this research we used both, deceleration and stopping distance measurements. Deceleration was used as the most appropriate parameter for calculation of the difference in resistance force, in the presence and without presence of wind. The paper presents how this may lead to false conclusions when expressing brake

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weight based on the braking distance measurements. Brake weight is the main and only indicator of braking performance inscripted on each passenger and freight wagon, practically used in service when forming train compositions for estimation of the whole train braking performance.

Simulation and comparison with experimental results are performed using OpenFoam software considering the air as an incompressible medium and steady state conditions of flow. Geometric model of the wagon is somewhat simplified and adapted for CFD simulations.

The results of this research are vehicle’s stopping distances measured under different wind conditions and drag force and drag coefficient, determined experimentally and numerically.

2 Braking Performance Test

Determining the braking performance of freight wagons with top speed up to 120 km/h and composite K-brake blocks requires slip tests with a single vehicle [9]. This is a full-scale test, during which the vehicle accelerates up to the required speed for braking. At this speed, an emergency (rapid) brake applies and at the same time or short time after the wagon is uncoupled from the test train composition and starts to brake until stop. The test speeds for freight wagons designed for top speed 120 km/h are 100 km/h and 120 km/h. Four valid tests need to be performed for determining the mean value of stopping distance. This value is then corrected for nominal test conditions and then braked weight percentage and brake weight is determined using assessment graphs or formulae given in [9]. Regular braking performance test methodology in the case of freight wagons assumes, among other preconditions, no wind or minimal wind during testing (no maximum wind speed is specified). Determining braking performance of one vehicle requires extensive preparation involving significant logistics, such as: locomotive, passenger coach for test team and installation of uncoupling device, closure of the test track section due to safety issues, etc.

This paper presents testing of the tank wagon type Zacns [5] (Figure 1), with K-block brakes, which are composite tread brakes, rated for 120 km/h maximum speed. When empty this wagon runs at 120 km/h and in the fully loaded conditions the maximum speed is 100 km/h. During slip tests the following braking parameters vs. time were recorded: wagon speed, stopping distance, main brake pipe pressure, brake cylinder pressure and deceleration of the wagon in the longitudinal direction.

Figure 1
Tank wagon Zacns in the test train composition [5]

Wagon speed and stopping distance were measured by using OMRON optical sensor by counting wheelset revolution and by radar doppler high performance transducer Delta DRS1000, GMH Engineering, independent of the wheelset revolution speed and in that way insensitive to slip and/or micro slip during braking. The total unadjusted error of the Doppler radar sensor for the speed range up to 120 km/h is about ±0.5%. Figure 2 shows installed speed sensors on the testing wagon.

Figure 2
Speed and stopping distance sensors

Other measured parameters, pressures and deceleration in train motion direction, were measured using sensors and data acquisition system manufactured by Hottinger Baldwin Messtechnik. Based on the deceleration sensor characteristics (lateral sensitivity, linearity and hysteresis) and its calibration, expanded measurement uncertainty with a coverage factor 2 is about 1.4%.

The weather station (Figure 3) serves for checking the test conditions regularity. This station records: environmental temperature, atmospheric pressure, air humidity, wind speed and direction. It was placed on the test section in the middle of the stopping distance of the wagon.

Figure 3
Weather station position [10]

Figure 4 shows a typical measurement record when testing the brake with all the measured values shown, brake pipe pressure (BP), brake cylinder pressure (C), stopping distance (s) and vehicle speed (v), which are later used for further data processing and drawing conclusions about the braking performance.

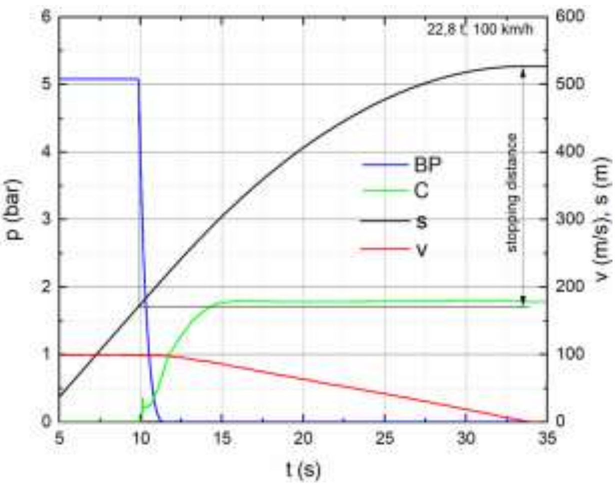

Figure 4
Typical record of measured parameters vs. time during braking of freight wagons [5]

3 Correcting the Stopping Distance

The stopping distance obtained during testing is corrected in order to take into account nominal speed in relation to the initial speed measured in the test and possible presence of gradient on the test track.

Considering that during braking process, most of the parameters are changing in a random way [11]. After determining the mean stopping distance out of four measurements (j=1..4), test validity and level of dissipation of the results are estimated by using following statistical criteria related to mean value and standard deviation:

$$\frac{\sigma_n}{\bar{s}} \leq 0.03 \tag{1}$$

$$\left| s_e - \bar{s} \right| \leq 1{,}95 \cdot \sigma_n \tag{2}$$

where:

$$\sigma_n = \sqrt{\frac{\left| s_j - \bar{s} \right|^2}{n}} \tag{3}$$

and:

s_j – stopping distance measured during test "j" [m],

n – number of valid test [-],

σ – standard deviation of test results [-],

$\bar{s}$ – mean stopping distance [m],

s_e – individual stopping distance furthest from the mean value [m].

The next step is correction of the mean stopping distance by the following criteria:

- basic principle - adaptation of the existing condition of the test vehicle to the actual characteristics of design series,
- additional correction - the actual filling time will be corrected in relation to the nominal value.

$$s_{\mathrm{corr}} = t_e \cdot v_{nom} + \frac{F_{test} + F_R}{F_{corr} + F_R} \cdot (\bar{s} - v_{nom} \cdot t_e) \tag{4}$$

$$t_e = t_o + \frac{t_s}{2} \tag{5}$$

$$F_{test} = M \cdot \frac{v_{nom}^2}{2(\bar{s} - v_{nom} \cdot t_e)} - F_R \tag{6}$$

$$F_{corr} = F_{test} \cdot \frac{\eta_{dyn}}{\eta_{dyn,test}} \cdot \frac{d_{test}}{d_m} \cdot \left[\frac{p_{nom} - p_{feder}}{p_{test} - p_{feder}} \right] \tag{7}$$

s_{corr} – corrected mean stopping distance [m],

$\bar{s}$ – mean stopping distance of test [m],

t_e – equivalent time for development of brake force [s],

t_s – mean measured brake cylinder filling time [s],

v_{nom} – nominal initial speed during tests [m/s] ,

F_{corr} – corrected brake force [N],

F_{test} – mean brake force during the test [N],

F_R – mean value of resistance to forward movement [N],

d_{test} – mean wheel diameter on test wagon,

d_m – diameter of semi-worn wheel [mm]; for block brakes d_m=d_{test},

η_{dyn} – mean efficiency of brake rigging during operation,

$\eta_{dyn,test}$ – efficiency of brake rigging during test,

p_{nom} – nominal brake cylinder pressure [bar],

p_{test} – brake cylinder pressure on test vehicle [bar],

p_{feder} – pressure of retaining springs relative to the effective brake cylinder piston surface area [bar],

v_o – initial braking speed [m/s],

M – mass of the vehicle including rotational inertia [kg].

4 Determination of the Drag Coefficient

Proposed methodology for determination of the drag coefficient uses differences in resistance force acting on a railway vehicle during braking, in the case of absence and presence of wind. Running resistance is a significant characteristic of all forms of transport and all transport modes [6-9, 12-15]. It is a total force acting on a vehicle against its direction of travel. In the case of a railway vehicle, it consists of several components: mechanical resistance, aerodynamic resistance and grade resistance. Mechanical resistance is mainly due to wheel rolling on the rail and increases during curves negotiation. Aerodynamic resistance is typically proportional to the square of the speed. It is additionally influenced by wind speed and its direction. Grade resistance depends on vehicle and track characteristics. During brake testing grade should be within ±3‰ [9].

The mean value of resistance to forward movement F_R is represented by a formula (8):

$$F_R = A + B \cdot v_0 + C \cdot v_0^2 \tag{8}$$

which consists of:

- one term independent of vehicle speed,
- the second term proportional to the speed, dealing mostly with the mechanical components resistance (vehicle-track),
- the third term proportional to the square of the speed (aerodynamic resistance),

where A, B, C are specific coefficients depending on vehicle type, selected according to [16] or obtained by measurements [6].

Since the creation of the Davis quadratic equation, it has been noticed that it includes the most significant factors influencing the resistance to movement, but that in some cases there are deviations that cannot be described in this equation form. Therefore, over time, a large number of authors have proposed different empirical expressions, which in specific cases better describe the dependence of resistance on different influential parameters.

Running resistance of freight trains is reported in [7]. Running resistance of passenger coaches was analyzed in ORE C179 [8]. Hara 1967 in Japan investigated influence of the aerodynamics on high-speed Shinkansen trains [12].

Running resistance is possible to be determined using different test methods:

1) Tractive effort methods,
2) Dynamometer drawbar methods,
3) Coasting methods [6].

The most suitable method, which can be used as a basis for assessment of wind drag during braking test, is adapted Coasting method. This method implies that the wagon or train accelerates to a certain speed. Then, the traction power and brakes are switched off and from that moment starts recording of speed vs. time on the track section without gradient or with known gradient along tracks. Coasting train will start to reduce speed and kinetic energy. Decelerations calculated from the speed vs. time function or directly measured by using appropriate deceleration transducer vs. vehicle speed, serves for estimation of train running resistance.

Unlike the coasting method in our case traction power is switched off, but the brakes are switched on and fully applied. Assuming that for one wagon, tested on the same track section, all test conditions are the same, the absence or presence of wind will cause a difference in deceleration, which is a consequence of wind drag force against vehicle travel direction.

The total force acting on a railway vehicle according to Newton's second law of mechanics is:

$$F_{\mathrm{T}} - F_{\mathrm{B}} - F_{\mathrm{R}} = M\,\frac{dv}{dt} \tag{9}$$

where:

F_T – traction force [N] ,

F_B – total brake force [N],

F_R – total resistance force [N],

v – vehicle speed [m/s].

During braking, traction is off and the traction force is equal to zero. Development of brake force depends on the brake system characteristics. Total resistance force depends on A, B, C coefficients, where B and C participate in the members of the equation that are a function of vehicle speed. Assuming that brake force, first and second terms of resistance force are equal or almost equal under all other same conditions, differences in measured decelerations caused by wind presence and absence, multiplied by vehicle mass, represents third term of air resistance force $C \cdot v^2$ in both cases. In that way, it is possible to compare calculated and measured drag coefficients C_D and to validate numerical model for further analysis.

5 Aerodynamic Resistance Caused by Wind

Apart from the aerodynamic resistance included in the total running resistance, additional force acting on the vehicle is induced by wind blowing on the vehicle frontal side. Head wind generally helps the braking system and decreases stopping distance. Opposite, tail wind increases stopping distance. The following formula calculates drag force [17]:

$$F_{\mathrm{D}} = \frac{1}{2}\cdot\rho\cdot A_f\cdot C_D(\beta)\cdot v_{rel}^{\;2} \tag{10}$$

In the case of direct head wind (β=0°):

$$F_{\mathrm{D}} = \frac{1}{2}\cdot\rho\cdot A_f\cdot C_D(0°)\cdot(v+v_{wind})^2 \tag{11}$$

where:

ρ – air density [kg/m^3] ,

C_D – air drag coefficient [kg/m^2],

β – yaw angle of wind [°],

A_f – drag area [m^2],

v_{rel} – relative air speed [m/s],

v_{wind} – wind speed [m/s],

v – current speed of the vehicle [m/s].

Use of this equation for additional wind resistance, requires the third term in the equation (8) to be excluded and replaced with equation (11). Minor influence of speed change exists in the second term of equation (8) depending on the speed, but it could be neglected in this analysis as of smaller order of magnitude comparing to the third term, and especially if taking into account that all other test conditions are the same or similar.

6 Test Results

This analysis focuses on pure head wind. The yaw angle β between wind direction and train travel direction during experiments was less than ±8°. The existence of this angle slightly reduces resulting head wind force and induce consequent side component of the wind force. Side wind may cause minor increase of running resistance related to mechanical components. This was neglected in this analysis since the yaw angle was quite small and better conditions in real test measurements are almost impossible to achieve. As stated above, this paper deals only with head wind component, as the worst possible scenario, considering that all other influences are known and equal during all tests. The main difference is the presence or absence of wind. One series of tests was performed without wind and one with head wind having the magnitude 7-9 m/s.

Table 1 presents test results for stopping distance in the case of wind presence and absence [10] and table 2 presents hypothetical difference in estimation of the braking performance using measured stopping distances, if the head wind influence was intentionally neglected. Test results show that in the case of Zacns tank wagon, head wind with the magnitude of v_{wind} = 7-9 m/s reduces stopping distance for about 27 m from initial speed v_0=100 km/h and from speed v_0=120 km/h for about 54 m. Consequently, determined brake weight B, if the wind was neglected, differs for 2-3 tonnes, which is unacceptably false result for assessment of the wagon braking performance.

Table 1

Measured stopping distance [9]

Initial speed (km/h)	Stopping distance (m)	
	Wind 7-9 m/s	No wind
100	337.4	370.2
	340.9	378.3
	340.0	381.2
	342.2	350.7
120	473.2	508.0
	471.4	527.0
	476.2	508.6
	479.7	515.5

Table 2

Corrected mean stopping distance, brake weight percentage and brake weight

Initial speed	Wind 7 m/s			No wind		
(km/h)	S_{corr} (m)	λ (%)	B (t)	S_{corr} (m)	λ (%)	B (t)
100	373.6	131.4	28.6	400.8	121.8	26.6
120	525.9	140.0	30.5	579.9	125.2	27.3

For determining the drag coefficient and wind force F_w, the results of measuring decelerations during braking are presented. The diagrams in Figures 5 and 6 show the records during four brakings from speeds of 100 and 120 km/h in both cases, with and without wind.

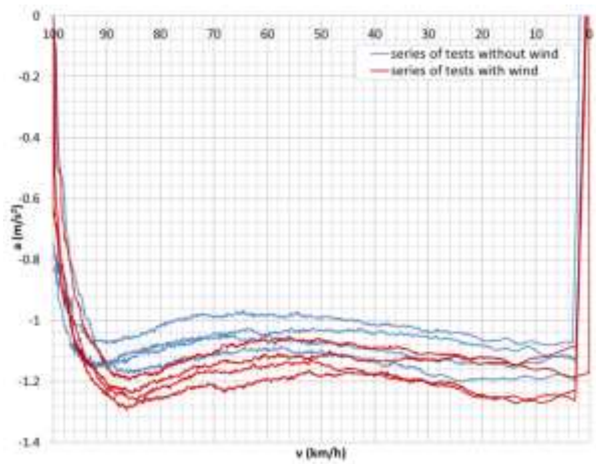

Figure 5

Series of deceleration vs. speed measurements at initial speed of braking 100 km/h

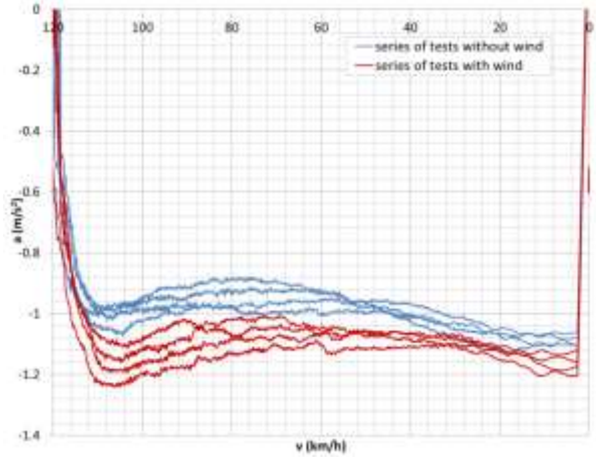

Figure 6

Series of deceleration vs. speed measurements at initial speed of braking 120 km/h

During the measurements at 100 km/h, some deviations were noticed, but the stopping distances were still within the limits according to the criteria of standard deviations. Most likely this is a consequence of insufficient bedding-in of the brake shoes during the first measurements. At 120 km/h this phenomenom was less pronounced.

For further analysis the mean values of measured decelerations were used. Figures 7 and 8 present mean values of each of the four measurements at different speeds and wind conditions.

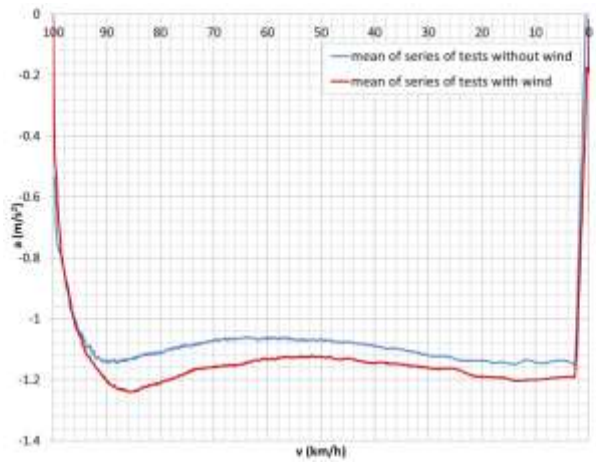

Figure 7

Mean values of deceleration vs. speed measurements at initial speed of braking 100 km/h

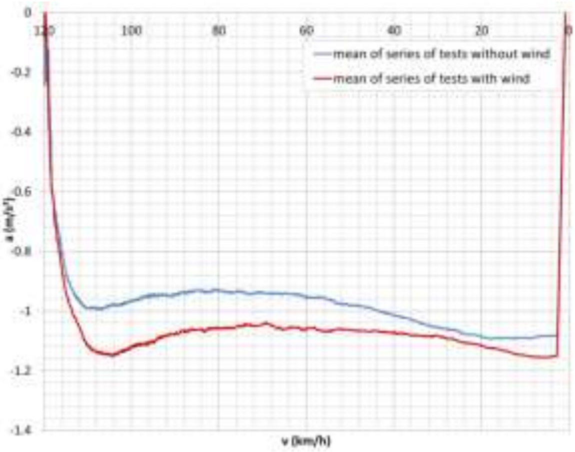

Figure 8

Mean values of deceleration vs. speed measurements at initial speed of braking 120 km/h

Based on the measured differences in decelerations Δa, it is possible to determine the share of wind force F_w in the total force, acting on the vehicle during its braking. Wind force in the longitudinal direction can be calculated as:

$$F_w = M \cdot \Delta a \tag{12}$$

By transforming expression (11), calculated drag coefficient using measured decelerations can be determined using next equation:

$$C_D = \frac{2 \cdot M \cdot \Delta a}{\rho \cdot A_f \cdot (v_{wind}^{\;2} - 2 \cdot v \cdot v_{wind})} \tag{13}$$

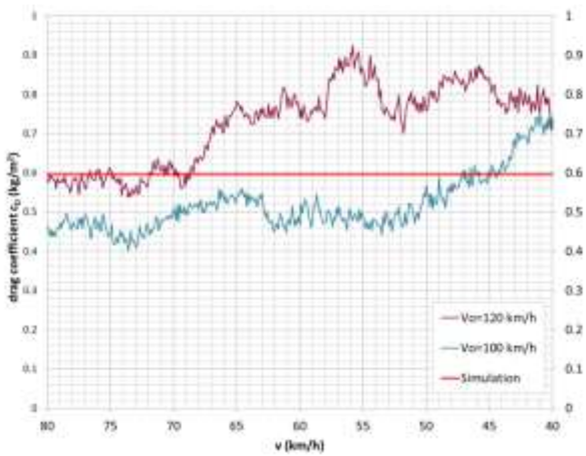

Figure 9

Calculated drag coefficient based on the measured wind influence on braking

The diagram in Figure 9 shows the drag coefficient C_D obtained by experimental measurements in the speed range in which the braking force reached the maximum value and became approximately constant, assuming that during braking the wind blew in the range of 7-9 m/s i.e. by using its mean value 8 m/s. C_D values obtained experimentally are relatively close to cca 0.6 kg/m^2 that was obtained by using numerical simulations presented below.

7 Numerical Simulations

There are many computer programs around the world dealing with train resistance simulations. They are power tools, serving for estimation of the energy consumption, for determining trains running time, etc. The computer programs specialized for running resistance including aerodynamic forces, use CFD and include wind magnitude, wind yaw angle, wind speed distribution, flow around the vehicle [1, 6, 12]. These programs may help solve different problems and performance of a vast number of simulations. In this paper, we use OpenFoam for comparison and widening possible conclusions about wind influence on braking performance test.

For numerical simulations of air flow around a rail tank wagon, the Reynolds averaged Navier-Stokes (RANS) approach is sufficiently accurate for this research [1]. Considering that maximal speed value is 120 km/h (33.3 m/s) and maximal Mach number less than 0.1, it is justified to assume that the flow is incompressible. During braking, vehicle speed changes almost uniformly, so with some approximations, it is possible to use assumptions of flow steadiness.

The main challenge in this type of simulation is to optimize computational mesh and to select computational method and turbulence modelling. The mesh is created with automated algorithm starting from triangulated surface geometries in Stereolithography (STL) format. After mesh independence test, it appeared that the optimum number of cells is about 5,700,000. The cells are generally hexagonal shape. For modelling turbulence, viscosity k-ω SST turbulence model is used and SIMPLE algorithm was used for solving system of discretized equations. Figure 10 shows air pressure distribution at 100 km/h. Figures 11 and 12 show air flow lines and air speed distribution.

The pressure distribution and the change in flow depend on the shape of the vehicle, but also on the boundary conditions of the modeled space, which include track geometry and its mechanical characteristics. The surface of the wagon is treated as no-slip walls. The ground is modeled as moving flat surface. Additionally, there is an impact of the equipment installed under the vehicle on flow characteristics, so it can be expected that real resistance to movement is a bit greater and actual drag coefficient is slightly higher compared to the one obtained in the simulations. This impact will be the subject of further research, in order to improve the model itself and the simulations accuracy.

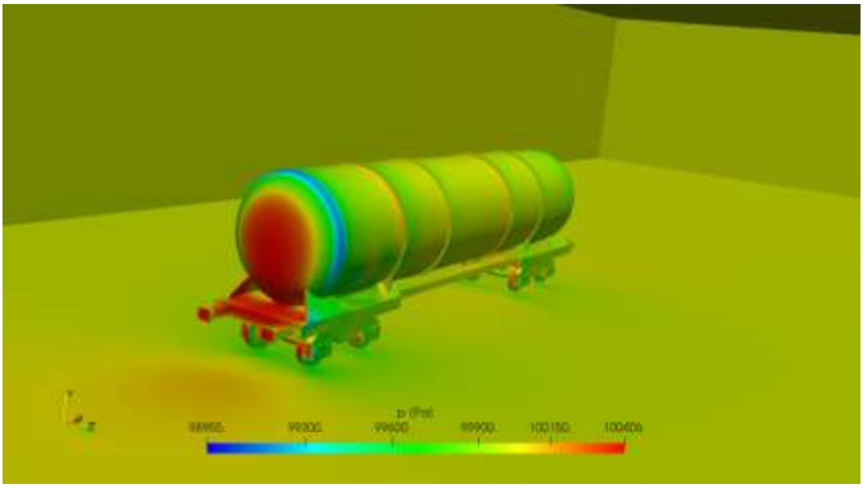

Figure 10
Air pressure distribution at 100 km/h

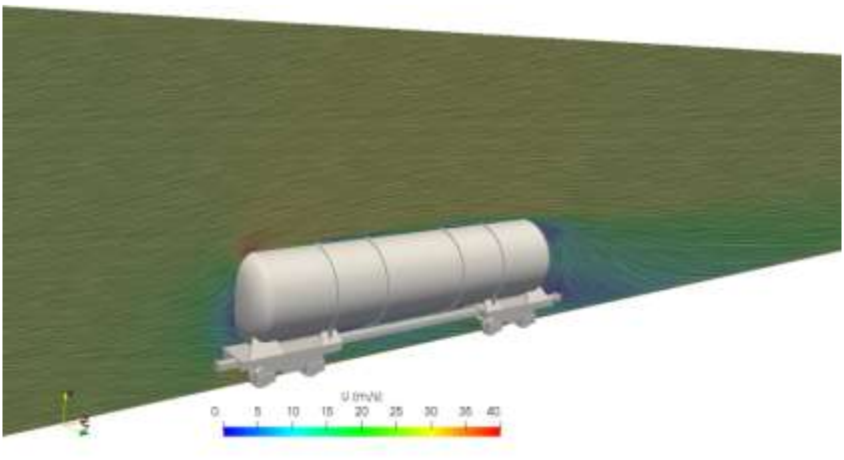

Figure 11
Air flow lines and air velocity distribution around the vehicle at 100 km/h

Computations were performed with air speed values in the range from 20 km/h to 120 km/h (Table 3), with the goal to calculate air drag force F_D and drag coefficient C_D. The total drag force generally consists of two parts: the pressure drag force that depends on the pressure distribution on the body surface and the viscous drag force that results from the friction between the air and the surface. The values of these forces obtained by simulations are presented in Table 3.

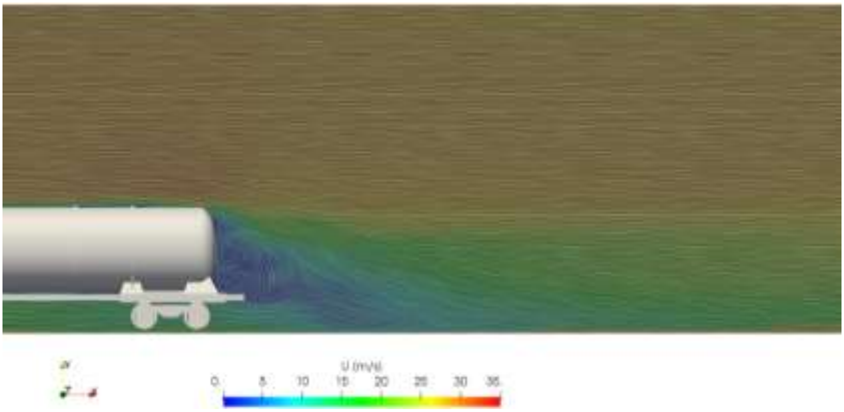

Figure 12
Air flow lines and air velocity distribution at rear of the vehicle at 100 km/h

Table 3
Review of the simulations results

U [m/s]	U [km/h]	C_D [kg/m^2]	Drag force [N]	Pressure force [N]	Viscous force [N]
5.56	20	0.593	102	81	21
8.33	30	0.595	231	183	47
11.1	40	0.596	411	330	81
13.9	50	0.592	637	500	137
16.7	60	0.592	918	738	180
19.4	70	0.593	1251	1018	233
22.2	80	0.596	1643	1312	331
25.0	90	0.594	2073	1661	412
27.8	100	0.601	2588	2105	483
30.6	110	0.601	3131	2481	650
33.3	120	0.600	3720	2909	811

It is noticed that drag coefficient changes very slightly when the Re changes. This independence is typical of all bodies of a similar shape to the shape of tank wagon, at high values of Re [19]. Typical value for the dimensionless wall distance y+ for the first cell layer used in this analysis was 30.

Conclusions

As required by the relevant European standards and as stated in UIC Technical Reports [4, 9, 16], when testing braking performance, the influence of wind should be excluded, by choosing test site and time of the test without presence of wind. The presence of wind will further complicate an already complex procedure for correcting measured stopping distance and reduce reliability of measurements.

Wind causes additional running resistance force that acts on the vehicle and the train compositions. Based on the available information from the railway practice and service, significant problems related to wind influence on braking process are not reported, however the test results show that in the case slip test of Zacns tank wagon, the head wind of magnitude 7 to 9 m/s reduces stopping distance for about 54 m during braking from initial speed 120 km/h. Consequently, this may lead to unacceptably false concluding and assessment of the vehicle's braking performance.

Recent editions of valid European standards [1, 6, 16] for any further analyses related to railway vehicles aerodynamics, suggest the use of CFD and experimentally determined resistance coefficients for each vehicle and not using general coefficients from the databases for similar vehicles, given in [18].

In order to obtain reliable indicators of the validity of applied analytical expressions and numerical simulations, further analyses should include more experimental tests under different wind magnitudes and directions of blowing. More realistic boundary characteristics and more detailed vehicle model will additionally increase simulations accuracy.

In addition to the main goal of this research, the paper proposes a way to separate the influence of the wind and air drag from the total resistance force acting on the vehicle. This allows us to determine drag coefficient of the tested vehicle based on the measurements of stopping distances during braking of a wagon, in the presence and absence of head wind of known wind speed.

Acknowledgement

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References

[1] EN 14067-6:2018+A1:2020 : Railway applications - Aerodynamics - Part 6: Requirements and test procedures for cross wind assessment

[2] M. Yu, R. Jiang, Q. Zhang, *et al.*, Crosswind Stability Evaluation of High-Speed Train Using Different Wind Models. *Chin. J. Mech. Eng.* **32,** 40 (2019) https://doi.org/10.1186/s10033-019-0353-7

[3] C. Baker, F. Chelli, A. Orellano, N. Paradot, C. Proppe, D. Rocchi, Cross-wind effects on road and rail vehicles, *Vehicle System Dynamics* 47(8), 2009, pp. 983-1022

[4] UIC B 126/DT 422 : Influence of head and tail wind on the braking distance of trains and single vehicles, Paris, December 2011

[5] D. Milković, Brake performance test of Zacns wagon, No. LSV-I-7/20, Technical Report, University of Belgrade, Faculty of Mechanical Engineering, Laboratory of rail vehicles, Belgrade 2020

[6] EN 14067-4:2013+A1:2018 : Railway applications - Aerodynamics - Part 4: Requirements and test procedures for aerodynamics on open track

[7] ERRI A168.2/RP8 : Line tests with a view to reducing the aerodynamic drag of freight vehicles, Utrecht, 1992

[8] ORE C179/RP2 : Determination of train resistance in the open air over typical track, using coasting method - BR analysis, Utrecht, 1991

[9] EN 16834:2019: Railway applications - Braking – Brake performance

[10] D. Milković, S. Radulović, G. Simić, J. Tanasković, Influence of head wind on the braking distance of single railway vehicle, Proc. of XIX International Scientific-expert Conference on Railway Railcon '20, October 15-16, 2020, Niš, Serbia, pp.13-16, ISBN: 978-86-6055-134-6

[11] S. Koch, E. Köppen, N. Gräbner and U. von Wagner, On the influence of multiple equilibrium positions on brake nose, *Facta Universitatis, Series: Mechanical Engineering*, 2021, https://doi.org/10.22190/FUME210106020K

[12] T. Hara, J. Ohkushi, B. Nishimura, Aerodynamic drag of trains QR of *RTRI*, 8 (4), 1967

[13] Z. Nunić, M. Ajanović, D. Miletić, R. Lojić, Determination of the rolling resistance coefficient under different traffic conditions, *Facta Universitatis Series: Mechanical Engineering*, Vol. 18, No. 4, 2020, pp. 653-664

[14] R. Tarakka, N. Salam, Jalaluddin, M. Ihsan, Effect of Blowing Flow Control and Front Geometry Towards the Reduction of Aerodynamic Drag on Vehicle Models, *FME Transactions*, Vol. 47, No. 3, 2019, pp. 552-559

[15] H. S. Hansen, M. U. Nawaz, N. Olsson, Using operational data to estimate the running resistance of trains. Estimation of the resistance in a set of Norwegian tunnels, *Journal of Rail Transport Planning & Management*, Vol. 7, Issues 1-2, 2017, pp. 62-76, ISSN 2210-9706

[16] EN 14531-1:2015 : Railway applications - Methods for calculation of stopping and slowing distances and immobilization braking - Part 1: General algorithms utilizing mean mean value calculation for train sets or single vehicles

[17] P. Lukaszewicz, Energy consumption and running time for trains, Royal Institute of Technology, Stockholm, Doctoral Thesis, 2001

[18] EN 14531-1:2005: Railway applications - Methods for calculation of stopping and slowing distances and immobilization braking - Part 1: General algorithms utilizing mean value calculation for train sets or single vehicles (withdrawn)

[19] J. J. Kim, L. Sangseung, M. Kim, M., D. You, S. J. Lee, Salient drag reduction of heavy vehicle using modified cab-roof fairings, *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 164, 2017, pp. 138-151