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ANALYSIS OF BRAKING SAFETY INDICATORS BASED ON THE POSITION OF THE REAR AXLE, CONNECTION, AND GRAVITY CENTRE IN TRACTOR-SEMITRAILER SYSTEMS

PAWEŁ RADZAJEWSKI[1], MAREK GUZEK[2]

Abstract

The hazards related to the motion of heavy goods vehicles are important issues of traffic safety. The aim of this work is to show how selected deviations of geometric design parameters can impact the selected quantities that describe the safety of the braking process (braking distance, deceleration, instability indications). A quasistatic model of the rectilinear movement of the vehicle combination (tractor–semitrailer), as well as models of key subsystems (pneumatic brake system and the tangential tyre–road forces), were adopted. Before starting the actual tests, model validation was carried out in which the results of the original program were compared with the results of road tests. Then, simulations were made for the chosen tractor–semitrailer combination for different conditions – nominal and several changes in the longitudinal position of the fifth wheel. A comparison was made for mainly braking distances and forces in the connection. The presented results indicate that a considered geometric deviation, affects the measures of braking efficiency. These conditions may also significantly contribute to changes in the force in the connection, thus reducing or increasing the risk of jackknifing. It is worth emphasizing that the valuable results were obtained using a relatively simple calculation method.

Keywords: motor vehicle safety; tractor–semitrailer braking; simulation research; braking safety indicators; connection force

1 Publishing Department, Pronar Ltd., Białystok, Poland, e-mail: radzajewskilech@wp.pl, ORCID: 0000-0003-4158-5853

2 Faculty of Transport, Warsaw University of Technology, Warsaw, Poland, e-mail: marek.guzek@pw.edu.pl, ORCID: 0000-0001-9871-2230

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1. Introduction

The increasing number of motor vehicles is one of the factors influencing the level of road safety. Its primary measure is the number of fatalities. In EU countries, this number in 2021 was as much as 19.8 thousand [1, 2, 3]. Most analyses (e.g. [1, 4, 5]) show that driver errors are the main cause of road accidents. However, other factors cannot be forgotten. The report [6] indicates that about 4% of inspected heavy goods vehicles had brake system failures, and 2% had failures related to tyres, wheels and axles. In addition to the operational condition, the structure of the vehicle (construction of the braking system, geometric properties) may influence the braking process, e.g. by extending the braking distance or increasing the tendency to break the combination, and thus contribute to the occurrence or avoidance of a road accident. Road safety statistics do not usually show this; all accidents are attributed to the driver. However, in developing cargo transport safety (e.g. in the design or construction process of vehicles), efforts should be made to minimize the potential causes of road accidents.

According to statistical data, drivers of commercial vehicles (lorries) cause only a few per cent of accidents (e.g. in Poland, approx. 3% in 2023, [3]). However, due to mass, stiffness and geometric incompatibility [4, 7], the mortality rate of such accidents is much higher (e.g. according to data from [3], the mortality rate of accidents involving trucks in Poland in 2023 was approx. 8.8 deaths per 100 accidents and accidents involving trucks – approx. 15. Commercial vehicle accidents are usually associated with higher claim settlement costs.

From the point of view of active safety, the vehicle braking process plays a key role. This issue is the subject of many considerations, in which various aspects are discussed. A common thread is the influence of speed [5], vehicle weight [8, 9, 10] and its distribution on the effectiveness of the braking process [11, 12, 13]. Solid bulk [14] or liquid [15, 16] substances have a special feature. In addition to higher research areas, when designing cargo transport vehicles, attention should be paid to other aspects, e.g. the influence of braking process parameters on the durability of the vehicle structure [17]. Another important question is the influence of the braking system, e.g. optimization of such system on the delay time and motion directional stability [18]. In the works [19, 20, 21], the influence of the unbraked trailer on the braking process is considered. An important aspect is the stability of the vehicle's movement. Most often, this term refers to the movement of a vehicle on curves [22, 23, 24], but it is also used when braking vehicles on a straight road. Here, the distribution of brake forces to the individual axles of the vehicles group plays a key role. Incorrect distribution can contribute to the occurrence of the "jacknifing" effect [25] and loss of movement stability. Meeting the requirements specified in standard [26] does not guarantee preventing such an effect in widely variable operating conditions.

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Much work is devoted to the time delays when applying the brakes e.g. [27, 28]. The reaction time of the braking system is defined in normative acts, e.g. ECE [26] and should meet certain conditions. Without going into other details described in [26] – it cannot be higher than 0.6 s for towing vehicles, and 0.4 s for towed ones (e.g. semitrailers). A longer delay in the semi-trailer may lead to an excessive increase in the force in the connection and, as a result, to the effect of jackknifing.

For the purpose of simulation studies, research related to the description of tangential forces in the tyre-road contact is also essential. Such issues are addressed in many works in the context of various problems (tyre type [29], vehicle and tyre operating conditions [30, 31], road conditions [32, 33], simulation and experimental studies [34, 35]) e.g.

The above review of scientific works proves the relevance and need for research on various issues related to vehicle braking. The authors of this work focus on a specific problem – braking a combination of vehicles. The aim of the work is to show how geometric properties of the structure of selected components of the tractor-trailer vehicle combination (here, the longitudinal position of the tractor and semitrailer connection is selected) can affect selected indicators of the risk of braking safety (braking distance, deceleration, value of connection force). A relatively simple calculation method is used, which uses the model of braking a tractor-semitrailer combination. The adopted research method is justified as long as the results of simulation tests are qualitatively and quantitatively similar to field experiments with real objects. Hence, an important part was devoted to validating the simulation model.

2. Research method

2.1. Software and analyzed situations

The study used an original program simulating the braking of a vehicle combination [36, 37, 38] written in the Matlab environment. The main element is the model of straight-line braking of a combination of two vehicles supplemented with subsystem models (see Figure 1). The program includes an advanced model of the pneumatic braking system with wheel anti-lock regulator and the original model of tangential forces between the tyre and the road surface, which is a modified Burckhardt model.

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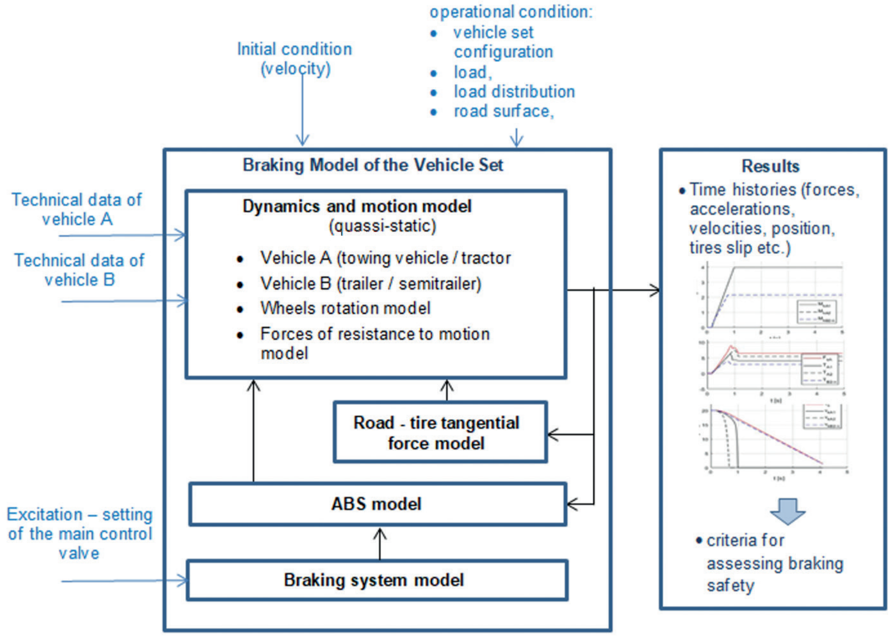

Fig. 1. Diagram of the adopted method

The study considered the braking situation of a vehicle combination consisting of a three-axle Volvo VNL tractor with a two-axle 'flatbed' semi-trailer moving at a velocity of 96,5 km/h (60 mph), on a horizontal, dry asphalt surface.

2.2. Adopted vehicle models of the tractor-semitrailer combination

The paper deals with the analysis of the vehicle combination: tractor (vehicle A) – semitrailer (vehicle B) presented as rigid bodies in translational motion on even surface (Figure 2). The motion of the vehicles is considered only in the Ox direction vertical plane (reference system Oxz is an inertial system, where: axis x – horizontal, axis z – vertical). The motion in the direction of the z-axis, such as the displacement of the set masses due to the deflection of the suspension and tyres is omitted. The model of the vehicle bodies is created by a system of concentrated masses and weightless beams. The connection is described as a rigid articulated connection, omitting the relative motions of the vehicles. Axle assemblies (multiple axles) are modelled as a single equivalent axle on which the sums of forces act, replacing the reactions acting on individual axles concentrated at the centre of this axle. The model takes into account the air drag forces of both vehicles and the rolling resistance of the vehicle wheels. A detailed description of individual models can be found in [36, 37, 38].

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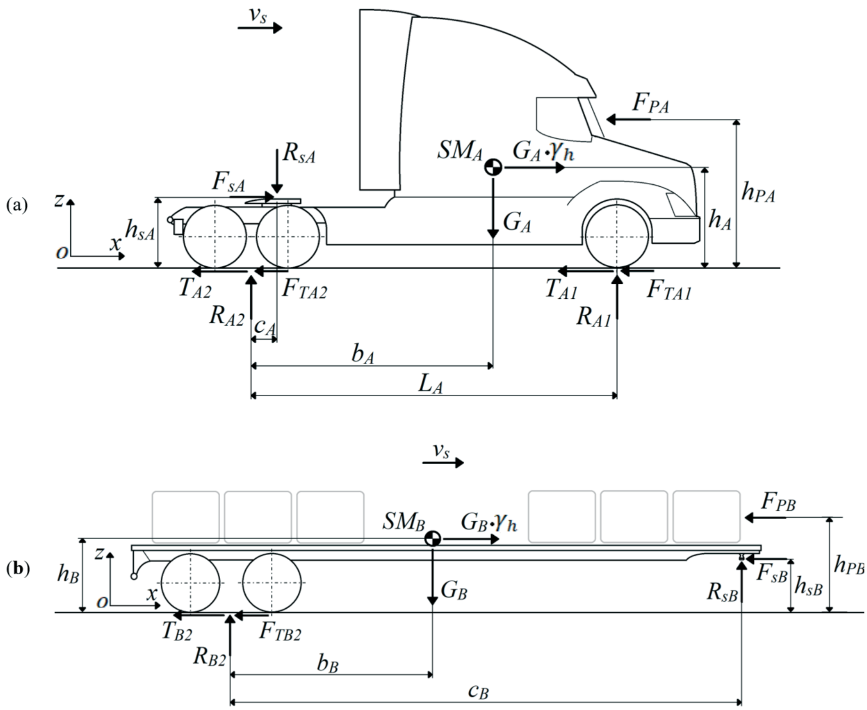

Fig. 2. Forces acting on the tractor (a) and the semitrailer (b)

In Figure 2 the symbols mean: SM – gravity centre of the vehicle, L – wheelbase, b – distance between SM and the rear axle, c – distance between the connection (fifth-wheel) and the rear axle, h – height of the vehicle's SM above the road, h_s – distance between the connection and the road, h_P – distance between point of the resultant air drag force and the road, γ_h – braking intensity (braking ratio [39]).

Forces: T – braking forces, G – gravity, R – normal reactions, F_P – air drag force, F_T – rolling resistance forces.

2.3. Nominal parameters of the model

The vehicle parameters and other values were selected to be consistent with the real vehicle described in [8] and used for validation purposes, which is described later in this work. Two cases from the loading conditions described [8] were also adopted as nominal parameters for further research. The first is a semi-loaded semi-trailer with a cargo mass of 22,600 kg, and the second is a fully loaded semi-trailer with a cargo mass of 38,800 kg. In both cases, the load was evenly distributed on the trailer. The mass and dimensional parameters of the

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vehicle and semi-trailer were taken from [40, 41, 42]. Technical data regarding the axles were taken from [43], and the structure and characteristics of the brake cylinders from [44, 45, 46]. Manufacturers of trucks, semi-trailers or braking system components do not provide all parameters and characteristics necessary to conduct simulation tests. The missing data were supplemented on the basis of similar vehicle data or indirectly based on experimental data (e.g. the coordinates of the centre of gravity were determined based on the tested axle loads from [8]). The parameters and values of individual braking system components were determined in a similar way. Detailed test data for real components could only be obtained for brake actuators. The parameters of the remaining elements of the braking system were selected from the literature [47, 48] so that the characteristics of these components were realistic. The basic parameters of the vehicles are presented in Table 1.

Tab. 1. Technical data of vehicles

property	Vehicle A	Vehicle B
name	2013 VNL64T 670	Utility Trailer 48' Flatbed
wheelbase	L_A=5.61 m	L_B= 1.24 m
Mass[1)]	m_A=8185 kg	m_B=5600 kg
CG position[1)]	b_A=3.76 m, h_A=1.13 m	b_B= 4.5 m, h_B=1.1 m
Mass[2)]	–	m_B=28200 kg / 44400 kg
CG position[2)]	–	b_B= 5.2 m, h_B=1.5 m
connection position	c_A=0.2 m, h_{sA}=0.5 m	c_B=11.88 m, h_{sB}=0.5 m
wheels[2)]	tyre: 295/70R22.5 r_{dA}=0.485 m I_{kA1}=8 kg·m^2, I_{kA2}=14 kg·m^2	tyre: 295/70R22.5 r_{dB}=0.485 m I_{kB2}=14 kg·m^2
Chamber Make/Size	Front axle: MGM 24L, Rear axles: MGM 3030L3, MGM T30L3	Haldex T3030

[1)] for empty vehicles

[2)] for semi-loaded / loaded trailer

[3)] A1 – single tyres; A2, B2 – dual tyres

The reaction times of the braking system and the braking torque depend on the design and components of the braking system. The adopted model of the braking system uses a valve that regulates the braking force depending on the axle load (LSV valve). Therefore, the final characteristic of braking torques along with actuation (reaction) and torque rise times will depend on variables describing the characteristics of the LSV valve [48]. Moreover, the maximum obtained braking torque won't be constant during the simulation depending on the braking dynamics of the vehicle combination (axle unloading/loading). However, the pressure response on the pneumatic lines were determined in such a way that the total delay times on the individual axes corresponded to the actual data from available studies in the literature [49, 50].

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There are many models to define unit tangential force $\mu=T/R$ in the tyre-road contact. The most popular ones in the motor vehicle dynamics simulation research field belong to the so-called semi-empirical class. These are, for example: Magic Formula [51] and its modifications [52], Dugoff, Fancher, Segel model [53], TM-Easy model [54], UniTire [55], Fastsim, Polach [56] or Burckhardt model [39, 57]. They are characterized by varying degrees of complexity and input values that do not always correspond to the assumed vehicle model. In the presented calculations, the Burckhardt model modified by the article's authors was used. The unit longitudinal tangential force μ is described as:

$$\mu(s) = \left[c_1(1 - e^{-s \cdot c_2}) - s \cdot c_3 \cdot G_p\right] \cdot G_s \cdot (1 - c_5 \cdot F_z^2) \tag{1}$$

The G_p and G_s coefficients are described as follows:

$$G_p = \frac{e^{-c_{p3} \cdot v}}{c_{p2}} \tag{2}$$

$$G_s = c_{p1} \cdot v - 0.5 \cdot arctan\left(-c_{p4} \cdot s \cdot v\right) + 1 \tag{3}$$

c_1, c_2, c_3 –coefficients describing the influence of the road surface and the tyre,
c_5 – an additional factor that makes the longitudinal force dependent on the reaction R,
c_{p1}, c_{p2}, c_{p3}, c_{p4} –coefficients describing the influence of the vehicle velocity,
s –wheel slip ratio,
v – vehicle velocity, m/s.

Table 2 contains the adopted values of the coefficients of this model. They have been adjusted so that the peak and sliding values of adhesion obtained from their characteristics as a function of the values of the slip ratio corresponded to the values found, for example, in [58] for the discussed condition of the road surface: dry asphalt surface. The unit longitudinal force curves for several velocities and different loads are shown in Figure 3.

Tab. 2. Parameters of the author's tire-road model (dry asphalt surface)

c_1	c_2	c_3	c_5	c_{p1}	c_{p2}	c_{p3}	c_{p4}
0.97	26.5	0.19	10^{-11}	-0.006	1.1	0.016	0.004

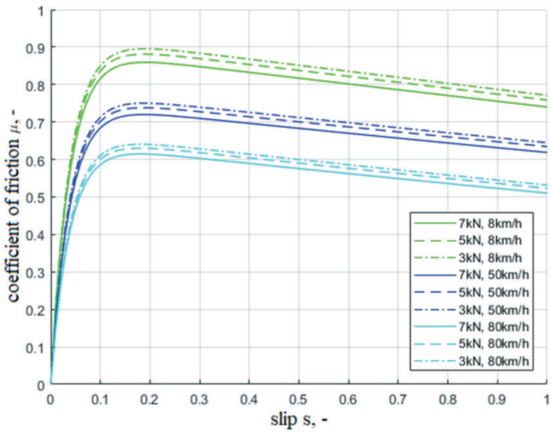

Fig. 3. Tyre-road unit tangential force curves depending on the axle load and vehicle velocity

2.4. Variable parameters and indicators of the risk of braking safety

As mentioned, the work focused on the impact of changing vehicle design parameters on braking safety indicators. Selected geometric changes in the vehicle structure will affect the static gravity forces distribution on the axles and, during the braking phase, the relief or load individual of axles/axle combinations. The variable parameters included the position of the vertical plane passing through the centre of the semi-trailer axle assembly c_B and the position in the horizontal plane of the connection in the tractor c_A. In the first case, the position of the gravity centres of the semi-trailer with the load b_B relative to the substitute axle and the position of the forces (marked with index B2) acting on this axis will also change – see Figure 2.

The values of the above-mentioned parameters in the case of the position of the substitute axle were changed to the extent probable for such a configuration of a road vehicle (design enabling the change of the position of the axle combination in operating conditions), and for the position of the tractor connection – theoretical, but technically achievable (dimensional aspect), i.e.:
c_B – from 12 m to 9 m, in 0.5 m steps,
c_A – from −0.2 m to 0.3 m, in 0.05 m steps.

To obtain a wider range of possibilities for assessing the risk of braking safety, simulations for the above variable parameters were also carried out in three configurations of the centre of gravity position and two braking system configurations. Due to the fact that the location of the centre of gravity is an operational property (distribution of the load on the trailer), the influence of the adopted variable parameters on the braking safety indicators was checked in the event of shifting the centre of gravity of the trailer with the load by 2 m backwards

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and forwards. Tests were also carried out for the braking system with nominal parameters (reflecting the actual vehicle also used in the validation) and without a Load Sensing Valve (LSV). This is to obtain an idea of the influence of the correction valve on the test results.

The braking distance s, the horizontal force in the fifth wheel (tractor-semitrailer connection) F_{sB} in the fully developed braking phase and the average deceleration a in this phase were taken as indicators of the risk to braking safety for the analysis of the results.

3. Validation

Before starting the actual tests, it was decided to compare the program created by the authors with the results of road tests of a comparable vehicle. The experimental results for comparison were taken from [8]. Technical data and other parameters in both validation and actual simulations correspond to the vehicle from road tests (see section 2.3). The first stage of work before starting the comparative tests was to determine the missing data of the vehicles and braking system. The positions of the vehicles' gravity centres and the position of the tractor connection were determined based on the tested axle loads for each tested load. As described in section 2.3, components of the actuation mechanism, brake actuators and axles are taken from vehicle component catalogs or their equivalents. Only the valuesdefining the characteristics of the automatic Load Sensing Valve (LSV valve) were selected iteratively.

The biggest unknown vehicle parameter for the authors was the characteristics of the LSV valve. In the initial validation tests with the omission of this valve, the simulation results did not coincide with the road ones in any case. The tested real vehicle [8] has the same size and type of brake cylinders on the rear axles of the tractor and semi-trailer. The axles system (wheels, tires) is also the same. Additionally, measurements [8] of the distribution of gravity forces on the axles show that the load values of the above-mentioned axle combinations are similar. This means that without pressure correction on both axle combinations, the braking moments would be close to their maximum value. However, road test results with turning off the brakes of one of the tractor's rear axles, show a greater increase in braking distance than turning off one of the semi-trailer axles (see Table 3). The above suggests that the tested vehicles used a Load Sensing Valve. The model simulated the simplified operation of a mechanical LSV valve, in which the dependence of the valve characteristic value on the load on the axle/axle combination was determined. The above values were selected using an iterative experimental method, carrying out subsequent simulation tests for various valve settings. In a similar way, the initially assumed parameters of the F_S force model of the tire-surface model were corrected, ultimately obtaining the values given in Table 2.

The validation results focused on the impact of the weight of the load on the trailer and the lack of braking of some axles of the vehicles on the braking safety indicators such as braking distance, acceleration and braking time (such comparative data could be found in [8]).

A comparison of the results of actual road and simulation tests for various load values and failures is presented in Table 3, where: s is the total braking distance, p is the control pressure on the braking valve, a is the deceleration for fully developed braking, and the $avg.\ a$ is the average deceleration over the entire run, t is the total braking time. The graphical interpretation of selected results is presented in Figure 4 and Figure 5.

Tab. 3. Comparison of the results of road tests (taken from [8]) and simulation tests

		Road tests				Simulation tests				
Vehicles combination weight (kg/lb)	Failures from the nominal state	s (m)	p (bar)	a (m/s²)	t (s)	s (m)	p (bar)	a (m/s²)	avg.a (m/s²)	t (s)
27 216 / 60 000		67.5 68.7 73.1	6.8 7.0 7.1	5.9 6.0 5.7	4.7 4.7 4.9	71.1	7.0	5.9	5.5	4.9
27 216 / 60 000	No braking of the first driving axle	90.0 95.4 91.1	7.2 7.2 7.2	4.3 4.1 4.2	6.3 6.7 6.4	91.0	7.0	4.4	4.1	6.4
27 216 / 60 000	No braking of the rear axle of the semi-trailer	75.0 77.4 78.3	7.2 7.1 7.0	5.3 5.2 5.2	5.2 5.3 5.4	75.4	7.0	5.5	5.1	5.2
36 287 / 80 000		66.4 69.5 71.3	6.9 6.8 6.6	5.9 5.8 5.6	4.7 4.8 4.9	69.9	7.0	6	5.5	4.8
36 287 / 80 000	No braking of the first driving axle	97.4 95.2 93.4	6.9 6.9 6.8	3.9 4.0 4.0	6.9 6.7 6.7	89.2	7.0	4.5	4.3	6.3
36 287 / 80 000	No braking of the rear axle of the semi-trailer	80.5 79.3 78.3	6.8 6.7 6.7	4.8 4.9 4.9	5.6 5.6 5.5	78.2	7.0	5.3	4.9	5.4
36 287 80 000	Shifting the centre of gravity forward	69.1 68.1 70.0	6.8 6.9 6.9	5.9 5.9 5.7	4.8 4.7 4.8	70.8	7.0	5.9	5.4	4.9
36 287 / 80 000	No braking of the first driving axle Shifting the centre of gravity forward	99.1 100.3 98.9	6.9 6.8 6.7	3.8 3.8 3.8	7.0 7.1 7.1	94.4	7.0	4.2	4	6.6
36 287 / 80 000	No braking of the rear axle of the semi-trailer Shifting the centre of gravity forward	75.3 77.4 76.7	6.8 6.8 6.8	5.2 5.1 5.2	5.3 5.4 5.3	75.7	7.0	5.4	5.1	5.3
43 998 / 97 000		75.1 72.0 76.0	6.8 6.8 6.8	5.4 5.5 5.3	5.1 5.0 5.2	70.3	7.0	6.0	5.5	4.8

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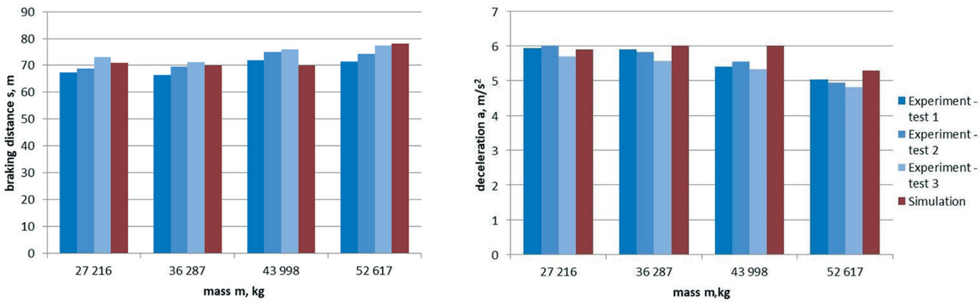
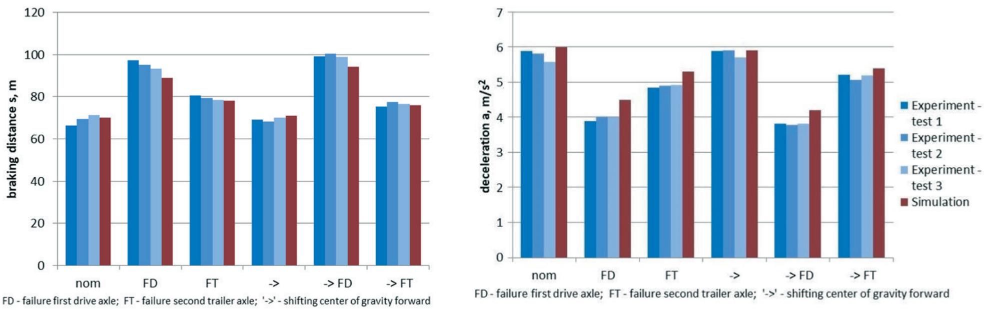
		Road tests				Simulation tests				
Vehicles combination weight [kg/lb]	Failures from the nominal state	s [m]	p [bar]	a [m/s²]	t [s]	s [m]	p [bar]	a [m/s²]	avg.a [m/s²]	t [s]
43 998 / 97 000	No braking of the first driving axle	102.5 103.8 101.2	6.8 6.8 6.8	3.8 3.6 3.8	7.2 7.4 7.2	86.3	7.0	4.7	4.4	6.1
52 617 / 116 000		71.5 74.2 77.4	7.1 6.9 7.0	5.0 4.9 4.8	5.2 5.4 5.5	77.8	7.0	5.3	4.9	5.5
52 617 / 116 000	No braking of the first driving axle	101.7 100.6 99.8	7.2 7.2 7.1	3.5 3.6 3.6	7.5 7.4 7.3	97.0	7.0	4.1	3.9	6.9
52 617 / 116 000	No braking of the rear axle of the semi-trailer	95.5 94.1 94.0	7.0 7.0 7.1	3.8 3.8 3.9	7.0 6.9 6.9	91.4	7.0	4.4	4.1	6.5



(a) (b)

Fig. 4. Braking parameters for different weights of the trailer with load; (a) braking distances, (b) decelerations



(a) (b)

Fig. 5. Braking parameters for different braking system failures or CG positions. Set total mass 36 287 kg; (a) braking distances, (b) decelerations

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Based on the above results, it can be concluded that both qualitatively and quantitatively, the simulation program shows similar results of the experiment. The main differences may result from not knowing the exact values of all vehicle and braking system data. In particular, we can emphasize the characteristics of the automatic Load Sensing Valve (LSV valve), the response times of individual axles and the μ curves of the tire-road interaction. Variable brake control pressure and unknown characteristics between this pressure and the operating pressure at the brake actuators in the actual vehicle may also affect the results.

The braking safety indicators listed (see section 2.4) also include the connection force. Unfortunately, due to the scarcity of road tests on this topic, the authors of this article were unable to match similar vehicles for validation purposes. However, previously comparative studies on this topic were carried out in [37] for a vehicle combination with slightly different parameters. The F_S force was compared there based on the available literature [59]. In the mentioned tests, the deceleration of the vehicles was (0.53–0.63) m/s^2, and the F_S force was (1.2–13.7) kN, depending on the brake cylinders pressure on individual vehicle axles. The mass of the vehicle combination and its distribution on the axles was similar to the simulation of a loaded vehicle described by the authors in [37]. With a similar pressure ratio in the braking system and an average deceleration of 0.57 m/s^2, the F_S value in the experiment was 10.9 kN [59], and in the simulation it was 14 kN [37]. However, in the case of no braking of the semi-trailer axle, the experiment achieved a force of 13.7 kN with an average deceleration of 0.63 m/s^2, and in the simulation in an analogous case with a similar deceleration, the horizontal force in the clutch was 16 kN. The list of ranges of Fs force values obtained in simulation and experimental tests for the given range of deceleration of the vehicle combination is presented in Table 4.

Tab. 4. Comparison of the results of simulation tests and the results of experimental studies taken from the literature – couple horizontal force

Case	Deceleration [m/s^2]	F_S [kN] (experiment)	F_S [kN] (simulation)
Nominal vehicle combination	0.57–0.63	9.7–13.7	12–15
Semi-trailer brakes not working	0.56–0.63	12.6–13.7	13–16

Bearing in mind that the vehicles mentioned in [37, 59] differ in design and the range of tested deceleration values is small (which is associated with a large impact of external factors on the results), based on Table 4 it can be concluded that qualitatively and to some extent quantitatively simulation results reflect the real situation.

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4. Research Results and Discussion

The results of simulation calculations of the basic braking safety indicators of the tested vehicle combination for the adopted test scope are presented below. Figures 6–7 show the test results for the shift of the vertical plane passing through the centre of the c_B semi-trailer axle assembly. The solid line shows the results for the nominal braking system (with the LSV valve) and the dashed line for the situation when the LSV valve is not working. Three cases of the location of the gravity centre of a semi-trailer with a load b_B were considered: nom – nominal, *b+2* – shifted forward by 2 m (compared to the nominal position), and *b-2* shifted backwards by 2 m.

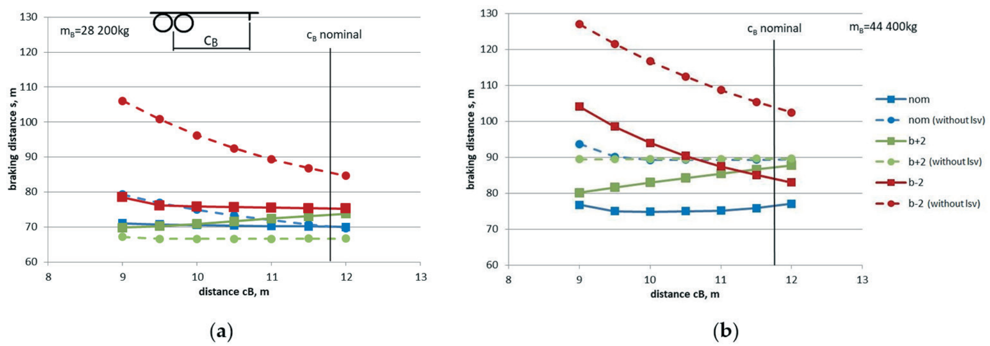

Fig. 6. Braking distances depending on the position of the semitrailer axle assembly, taking into account the position of the semitrailer SM_B and the operation of the LSV valve; (a) with a semitrailer mass of 28 200 kg, (b) with a semitrailer mass of 44 400 kg

Based on the results, it can be said that the trends in the variability of the braking distance and deceleration from the adopted variables are very similar. Therefore, the discussion of the results will be presented only on the example of the braking distance. Analyzing charts of this size, it can be concluded that for a combination of vehicles with a nominal braking system and a mass of 28 200 kg, changing the location of the rear axle combination in relation to the connection does not significantly affect the braking distance. For the nominal position of the gravity centre, the difference in s value is approximately 1 m between the extreme positions of the semi-trailer axle assembly. The largest difference in braking distance – 4 m – was achieved when the SM_B of the semi-trailer with the position of the gravity centre was shifted forward. A small influence of the location of the c_B semi-trailer axle assembly on the length of the braking distance is ensured by a valve that regulates the braking torque depending on the axle load distribution. This thesis is confirmed by the results of testing a combination of vehicles with a braking system without an LSV valve. Here, in the extreme case, the difference in braking distance between the marginal positions of the axle assembly is approximately 21 m (visible for the case of *b-2* without LSV)

After increasing the weight of the semi-trailer with a load of 44 400 kg, the differences in s value between the marginal positions of the axle assembly are greater, even with a nominal braking system with an LSV valve. When the SM_B of the semi-trailer is moved to the rear, this difference is 21 m, with the nominal position of the gravity centre it is approximately 2 m, and when the centre of gravity is moved forward – 9 m.

For both loading conditions, as the distance between the semi-trailer axle assembly and the connection increases (shifting the axle backwards), the braking distance increases or decreases depending on the SMB position of the semi-trailer with the load. The s value decreases when the gravity centre b of the loaded semi-trailer is located closer to the semi-trailer axle assembly and increases when the gravity centre is located closer to the semi-trailer connection.

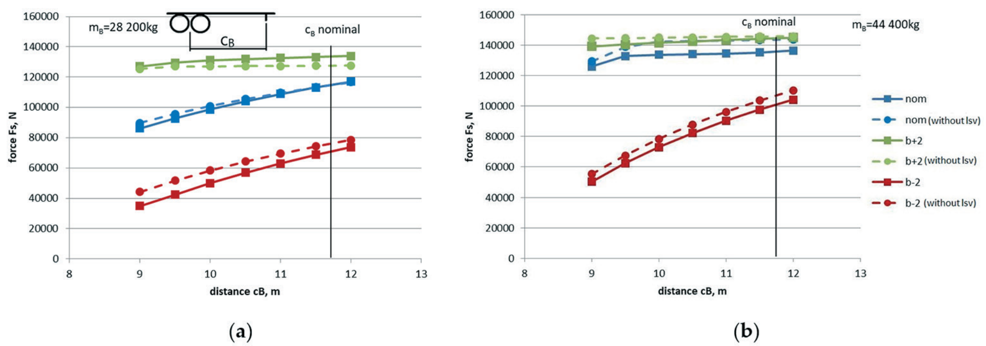

Fig. 7. Horizontal forces in the fifth wheel depending on the position of the semitrailer axle assembly, taking into account the position of the semitrailer SM_B and the operation of the LSV valve; (a) with a semitrailer mass of 28 200 kg, (b) with a semitrailer mass of 44 400 kg

Contrary to the braking distance in the F_s curves (Figure 7), the results of the group of vehicles with the nominal system and without the LSV valve are quantitatively similar and qualitatively can be assumed to be the same. The graph shows a tendency that the more the gravity centre of the loaded semi-trailer is shifted backwards, the greater the influence of the location of the semi-trailer axle assembly on the Fs force (the greater the slope of the trend). This force itself increases as the c_B value increases (shifting the axle assembly rearward). For shifting the gravity centre by 2 m backwards, the difference in the F_s force between the peripheral location of the semi-trailer axle assembly is approximately 34 kN for the mass of the semi-trailer with a load of 28 000 kg and 54 kN for 44 400 kg, and for shifting the gravity centre 2 m forward only approx. 7 kN for both loading states.

It is also worth paying attention to the fact that for a fully loaded semi-trailer (44 400 kg), the characteristics of the F_s force due to the location of the axle assembly for the nominal

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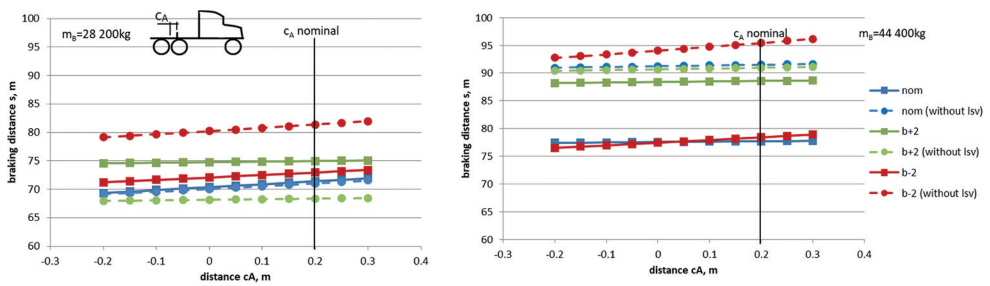
position of the gravity centre became 'flattened' at high values of this force (approximately 130–140 kN). This suggests a reduction in the ability to reduce the Fs force by appropriately positioning the axle assembly and gravity centre positioning. In this loading condition, this is only possible when the SM_B is positioned 2 m backwards - case *b-2* (then the smallest value of the F_s force is approximately 55 kN). However, for a medium-loaded semi-trailer, this was also possible for the nominal gravity centre position.

The direct impact of the SM_B shift and the operation of the LSV valve on braking safety indicators is not the main topic of research. However, it can be mentioned that in the absence of LSV valve operation, as the distance of the gravity centre from the rear axle b_B decreases, the braking distance increases. In extreme cases, even by 40 m (see Figure 6a). After using the LSV valve, the difference in the braking distance narrowed to a maximum of 8 m. In the case of F_s force, its value decreases with the reduction of the distance b_B, regardless of the use of the LSV valve or not.

Figures 8–9 show the test results for the shift in the horizontal plane of the connection position relative to the rear axle of the tractor c_A.



(a) (b)

Fig. 8. Braking distances depending on the horizontal position of the tractor connection, taking into account the position of the semitrailer SM_B and the operation of the LSV valve; (a) with a semitrailer mass of 28 200 kg, (b) with a semitrailer mass of 44 400 kg

Analyzing the graphs of the braking distance depending on the distance c_A, it can be concluded that for a combination of vehicles with a nominal braking system and without an LSV valve and for both loading states, changing the position of the tractor connection towards the front of the vehicle (an increase in the c_A value) results in an increase in the total braking distance of the vehicle combination. Additionally, this increase is greater the closer the SM_B of the trailer with the load is to the rear axle combination (case *b-2*), equally for the nominal brake system and the case without the LSV valve.

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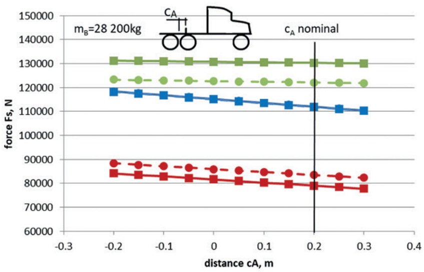
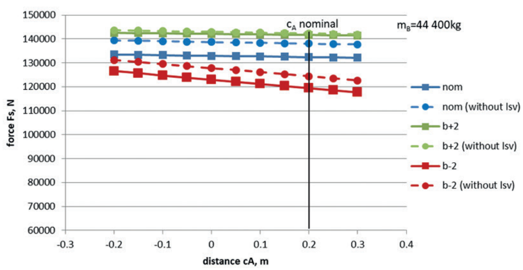
For a semi-trailer with an average load (28 200 kg), with the gravity centre at the nominal position and shifted backwards by 2 m, the difference in s value for peripheral values of c_A is up to 3 m. If the gravity centre is shifted forward by 2 m, this difference is up to 0.5 m.

For the maximum trailer load (44 400 kg), the difference s value for peripheral c_A values is up to 3.5 m only in the case of shifting the gravity centre by 2 m rearward. In other cases, this difference does not exceed 0.7 m.

It is worth noting that most tractor-trailer vehicles have a connection located in positive c_A values. However, the smallest braking distances are obtained for negative values of the connection position. However, the differences in the braking distance between the peripheral values of the connection position are not significantly large (max. 3.5 m), and a greater threat is caused by incorrect load distribution, lack of a properly adjusted LSV valve or the position of the semi-trailer axle assembly (see analysis for Figures 6, and 7).



(a)



(b)

Fig. 9. Horizontal forces in the fifth wheel depending on the horizontal position of the tractor connection, taking into account the position of the semitrailer SM_B and the operation of the LSV valve; (a) with a semitrailer mass of 28 200 kg, (b) with a semitrailer mass of 44 400 kg

The analysis of the characteristics of the F_s force in the fifth wheel depending on its position in the horizontal plane shows that as the connection is shifted forward of the tractor (an increase in the c_A value), the value of the F_s force decreases. This is even more visible when the SM_B of the trailer with load is closer to the rear of the vehicle – case *b-2*. This characteristic is visible both for the average and maximum trailer load and for both variants of the braking system.

Contrary to the braking distance, the lowest values of the connection force are obtained for positive c_A values. The differences in the F_s force between the peripheral values of c_A are up to 9 kN. From this analysis of the results, it seems more advantageous to shift the connection towards the front of the tractor. This also has a positive effect on the axle load distribution (part of the weight of the loaded semi-trailer will weigh both axles of the tractor to a greater extent).

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It should also be noted that for a higher semi-trailer mass (and for the nominal gravity centre location), as well as for shifting the position of the semi-trailer axle assembly c_B (see the analysis for Figure 7), the horizontal force characteristics depend only slightly on the location of this connection c_A. Therefore, we can say that for both experiments (changing c_B and c_A), the greater mass reduces the possibility of reducing the Fs force by appropriately positioning the axle assembly and the position of the connection.

However, based on the analysis of the results shown in Figures 6–9, it can be concluded that the simultaneous combination of design parameters (position of the axle assembly) and operational parameters (load distribution – position of the gravity centre) of the semitrailer has a greater influence on the braking safety indicators than the position of the connection relative to the tractor axle. For example, the largest difference in s value and F_s force between the peripheral positions of the axle assembly in tests with shifting the position of the semi-trailer axle assembly was 21 m and 54 kN (case *b-2* for a mass of 44 400 kg), and for tests with shifting the position of the connection relative to tractor 3 m and 9 kN.

5. Conclusion

Simulation research allows for a broad understanding of the impact of various design and operational parameters of vehicles and their deviations on various movement characteristics in various conditions. This article analyzes the influence of the position of the axle/axle assembly relative to the connection in a tractor-trailer road combination on selected braking safety indicators: braking distance, deceleration and horizontal force in the connection. An important element of this analysis was the validation of the computational model, which showed that this model reflects well qualitatively and quantitatively enough the actual object in the considered motion for the selected braking indicators.

The main conclusions from the calculations are:

- As the distance of the semi-trailer axle assembly from the connection increases (shifting the axle backwards), the braking distance may increase or decrease depending on operational parameters such as the loading status of the semi-trailer (it decreases when the centre of gravity of the loaded semi-trailer is closer to the axle assembly and increases in the opposite situation).
- The influence of the position of the semi-trailer axle assembly on the braking distance depends on the mass and position of the gravity centre of the semi-trailer with the load. Due to proper load distribution and low weight, it is practically negligible.
- A valve that regulates the braking torque on the wheels depending on the axle load is able to minimize the impact of the position of the semi-trailer axle assembly on the braking distance, but only for low trailer loads.

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- As the distance between the trailer axle assembly and the connection increases (shifting the axle rearward), the F_S force increases.
- The more the gravity centre of the semi-trailer with the load is shifted backwards, the greater the influence of the position of the semi-trailer axle assembly on the F_S force.
- The F_S force can be reduced by properly positioning the trailer axle assembly and distributing the load.
- Changing the position of the tractor connection towards the front of the vehicle (increase in the c_A value) causes an increase in the braking distance of the vehicle combination and a decrease of the F_S force in the fifth wheel.
- The influence of the position of the tractor connection on the braking distance and the fifth wheel force (F_S) depends on the mass and position of the gravity centre of the loaded semitrailer. The closer the gravity centre is to the front of the trailer, and the greater the mass, the smaller this influence is.
- For large loads, the F_S force is reduced by appropriately positioning the axle assembly, the position of the semi-trailer load and the tractor connection.
- The position of the tractor connection has a smaller impact on the risk indicators for braking safety than the design parameters (position of the axle assembly) and operational parameters (load distribution – position of the gravity centre) of the semitrailer.

The results of simulation tests can be used to design vehicles. They can also become the first stage of research, before road tests, which will help shorten the time, reduce the costs of such tests and help focus on the main threats to braking safety and the proper purpose of the research. The presented simulations showed that even the use of relatively simple vehicle dynamics models can provide interesting and non-obvious information.

6. References

[1] European Road Safety Observatory. European Commission (2024) Annual statistical report on road safety in the EU, 2024. Brussels: European Commission, Directorate General for Transport, 2024. https://road-safety.transport.ec.europa.eu/document/download/b30e9840-4c22-4056-9dab-0231a98e7356_en?filename=ERSOnext_AnnualReport_20240229.pdf (accessed on 4 Nov 2024).

[2] European Road Safety Observatory. European Commission (2024) Facts and Figures Buses and Heavy Goods Vehicles. Brussels: European Commission, Directorate General for Transport, 2024. https://road-safety.transport.ec.europa.eu/document/download/d8610fe4-cb96-48bf-99b3-544a384c6f93_en?filename=ff_buses_hgv_20240326.pdf (accessed on 13 Dec 2024).

[3] Wypadki drogowe w Polsce w 2023 roku (Road accidents in Poland in 2023). Report of the Police Headquarters and similar reports from previous years. Polish Police, Warsaw, Poland, 2023. https://statystyka.policja.pl/st/ruch-drogowy/76562,Wypadki-drogowe-raporty-roczne.html (accessed on 20 May 2024).

[4] Global status report on road safety 2023. WHO. https://www.who.int/publications/i/item/9789240086517 (accessed on 1 Feb 2025).

[5] Stan bezpieczeństwa ruchu drogowego oraz działania realizowane w tym zakresie w 2023 r (The state of road traffic safety and actions taken in this area in 2023). https://www.krbrd.gov.pl/baza-wiedzy/raporty-o-stanie-brd/ (accessed on 4 Nov 2024).

[6] Kupiec A, Kupiec J, Jęsiek Ł. Analiza przyczyn niesprawności pojazdów ciężarowych [Analysis of the causes of failures in trucks]. Autobusy: technika, eksploatacja, systemy transportowe. 2018;19(12):115–120. https://doi.org/10.24136/atest.2018.366.

[7] Road traffic injures. WHO. https://www.who.int/health-topics/road-safety#tab=tab_1 (accessed on 6 Oct 2022).

[8] Lascurain MB, Capps G, Franzese O. Heavy and Overweight Vehicle Brake Testing: Combination Five-Axle Tractor-Flatbed Final Report. U.S. Department of Transportation Federal Motor Carrier Safety Administration. USA. 2017. https://doi.org/10.21949/1502942.

[9] Luty W. Simulation-based analysis of the impact of vehicle mass on stopping distance. Eksploatacja i Niezawodnosc – Maintenance and Reliability. 2018;20(2):182–189. http://dx.doi.org/10.17531/ein.2018.2.03.

[10] Ondrus J, Vrabel J, Kolla E. The influence of the vehicle weight on the selected vehicle braking characteristics. In: Transport Means – Proceedings of the International Conference. 2018:384–390.

[11] Skrucany T, Vrabel J, Kazimir P. The influence of the cargo weight and its position on the braking characteristics of light commercial vehicles. Open Engineering. 2020;10(1):154–165. https://doi.org/10.1515/eng-2020-0024.

[12] Dižo J, Blatnický M, Droździel P, Melnik R, Caban J, Kafrik A. Investigation of Driving Stability of a Vehicle–Trailer Combination Depending on the Load's Position Within the Trailer. Acta Mechanica et Automatica. 2023;17(1):60–67. https://doi.org/10.2478/ama-2023-0007.

[13] Šarkan B, Jaśkiewicz M, Kiktová M. The impact of the truck loads on the braking efficiency assessment. Open Engineering. 2020;10(1):105–112. https://doi.org/10.1515/eng-2020-0014.

[14] Vrabel J, Jagelcak J, Zamecnik J, Caban J. Influence of Emergency Braking on Changes of the Axle Load of Vehicles Transporting Solid Bulk Substrates. Procedia Engineering. 2017;187:89–99. https://doi.org/10.1016/j.proeng.2017.04.354.

[15] Otremba F, Navarrete JAR, Guzmán AAL. Modelling of a Partially Loaded Road Tanker during a Braking-in-a-Turn Maneuver. Actuators. 2018;7(3):45. https://doi.org/10.3390/act7030045.

[16] Ibrahim RA, Singh B. Assessment of ground vehicle tankers interacting with liquid sloshing dynamics. International Journal of Heavy Vehicle Systems. 2018;25(1):23–112. https://doi.org/10.1504/IJHVS.2018.089894.

[17] Kovalchuk S, Goryk O, Burlaka O, Kelemesh A. Evaluation of the strength of the truck tractor's frame under emergency braking conditions. The Archives of Automotive Engineering – Archiwum Motoryzacji. 2024;105(3):74–87. https://doi.org/10.14669/AM/192345

[18] He R, Jing Z. Study on braking stability of commercial vehicles: An optimized air brake system. Advances in Mechanical Engineering, 2019;11(5):1–10. http://dx.doi.org/10.1177/1687814019848593.

[19] Marienka P, Frančák M, Jagelčák J, Synáka, F. Comparison of Braking Characteristics of Solo Vehicle and Selected Types of Vehicle Combinations. Transportation Research Procedia. 2020;44:40–46. https://doi.org/10.1016/j.trpro.2020.02.007.

[20] Świder P, Bułka D. Hamowanie samochodu z przyczepą bez hamulców [Braking a car with a trailer without brakes]. X International science-technical conference. Kielce – Ameliówka, 2016 February 22–24. Poland.

[21] Kąkol M, Kuśnierz D, Lozia Z. Wpływ niehamowanej przyczepy jednoosiowej na długość drogi zatrzymania samochodu dwuosiowego. (The influence of an unbraked single-axle trailer on the stopping distance of a two-axle car). Paragraf na Drodze, Prawne i kryminalistyczne problemy ruchu drogowego. Wydawnictwo Instytutu Ekspertyz Sądowych, Kraków. 2021;2023(1):55–73. https://doi.org/10.4467/15053520PnD.23.004.17720.

[22] Xu J, Xin T, Gao C, Sun, Z. Study on the Maximum Safe Instantaneous Input of the Steering Wheel against Rollover for Trucks on Horizontal Curves. International Journal of Environmental Research and Public Health. 2022;19(4),2025. https://doi.org/10.3390/ijerph19042025.

[23] Tang Y, Cai Y, Liu Z, Sun X, Chen L, Wang H, et al. Research on Active Trailer Steering Control Strategy of Tractor Semitrailer under Medium-/High-Speed Conditions. Actuators. 2024;13(9):360. https://doi.org/10.3390/act13090360.

[24] Bai Z, Lu Y, Li Y. Method of Improving Lateral Stability by Using Additional Yaw Moment of Semi-Trailer. Energies. 2020;13(23),6317. https://doi.org/10.3390/en13236317.

[25] Leng Z, Wang Y, Xin, M, Minor MA. The Effect of Sideslip on Jackknife Limits during Low Speed Trailer Operation. Robotics. 2022;11(6),133. https://doi.org/10.3390/robotics11060133

[26] Regulation No 13 of the Economic Commission for Europe of the United Nations (UN/ECE) — Uniform provisions concerning the approval of vehicles of categories M, N and O with regard to braking [2016/194]. Belgium. 2016. http://data.europa.eu/eli/reg/2016/194/oj) (accessed on 20 May 2024).

[27] Janczur R, Zawałeń J. Parametry hamowania pojazdów ciężarowych i autobusów w rekonstrukcji i analizie wypadków drogowych. (Braking parameters of trucks and buses in the reconstruction and analysis of road accidents). Paragraf na Drodze, Prawne i kryminalistyczne problemy ruchu drogowego. Wydawnictwo Instytutu Ekspertyz Sądowych, Kraków. Special Issue 2021:105–120.

[28] Cięþka P, Wolak S. Czas narastania opóźnienia hamowania w motocyklach – wyniki badań poligonowych. (Braking Deceleration Rise Time in Motorcycles – Field Test Results). Proceedings of X International Science-Technical Conference „AUTOMOTIVE SAFETY 2016". Kielce – Ameliówka, 2016 February 22-24; Poland.

[29] Lorenčič V. The Effect of Tire Age and Anti-Lock Braking System on the Coefficient of Friction and Braking Distance. Sustainability. 2023;15(8):16. https://doi.org/10.3390/su15086945.

[30] Du X, Wang G. Analysis of Operating Safety of Tractor-Trailer under Crosswind in Cold Mountainous Areas. Applied Sciences. 2022;12(24),12755. https://doi.org/10.3390/app122412755.

[31] Zuska A, Kurczynski D, Jackowski JT. Study of Loads Acting on the Load during the Sudden Braking of a Vehicle. Applied Sciences. 2023;13(3),1559. https://doi.org/10.3390/app13031559.

[32] Liu X, Wang H, Cao Q, Chen J, Huang X. Evaluation of Vehicle Braking Performance on Wet Pavement Surface using an Integrated Tire-Vehicle Modeling Approach. Transportation Research Record. 2019;2673(3):295–307. http://dx.doi.org/10.1177/0361198119832886.

[33] Zhang Y, Gao J, Li Q. Experimental study on friction coefficients between tire tread rubber and ice. AIP Advances. 2018;8(7). https://doi.org/10.1063/1.5041049.

[34] Luty W. Nieustalone stany bocznego znoszenia ogumienia. (Transient conditions of tire sideslip. Experimental and model research). Publishing House of the Warsaw University of Technology. Warsaw, 2017.

[35] Wang Y, Hu J, Wang F, Dong H, Yan Y, Ren Y, et al. Tire Road Friction Coefficient Estimation: Review and Research Perspectives. Chinese Journal of Mechanical Engineering. 2022;35(1). https://doi.org/10.1186/s10033-021-00675-z.

[36] Radzajewski P, Guzek M. Symulacyjna ocena bezpieczeństwa hamowania zestawu drogowego. Problemy transportu - wyzwania XXI wieku. Oficyna Wydawnicza Politechniki Warszawskiej. Warszawa. 2022:321–338.

[37] Radzajewski P, Guzek M. Assessment of the Impact of Selected Parameters of Tractor-Semitrailer Set on the Braking Safety Indicators. Applied Sciences. 2023;13(9):5336. https://doi.org/10.3390/app13095336.

[38] Radzajewski P, Guzek M. Braking of the tractor-semitrailer set in a rectilinear motion. WUT Jour-nal of Transportation Engineering. 2021;133:39–58. https://doi.org/10.5604/01.3001.0015.6499.

[39] Vieira D, Orjuela R, Spisser M, Basset M. An adapted Burckhardt tire model for off-road vehicle applications. Journal of Terramechanics. 2022;104:15–24. https://doi.org/10.1016/j.jterra.2022.08.001.

[40] 2011 Volvo VNL64T 670 specifications. https://www.pensketruckleasing.com/pdfs/Volvo_VNL-64T-670.pdf (accessed on 24 May 2024).

https://doi.org/10.14669/AM/204097

[41] Volvo Trucks USA – VNL760 specifications. Volvo trucks US. https://www.volvotrucks.us/trucks/vnl/specifications/ (cited 24 May 2024).

[42] Utility flatbeds trailer specifications. https://www.utilitytrailer.com/flatbeds/specifications/ (accessed on 24 May 2024).

[43] MERITOR TN4671L4516 – AY-TRAILER AXLE. FinditParts. https://www.finditparts.com/products/8082162/meritor-tn4671l4516 (accessed on 17 Nov 2023).

[44] Technical Report: Optival. UNECE Regulation No. 13, Annex 19, 30/30" Diaphragm Diaphragm S-Cam Brake Chamber. Turkey: Optival Belgelendirme Hizmetleri. 2022. https://www.haldex.com/globalassets/europe/3.-trailer-application-guide/trailer-guide/actuators/346-range/oph-t-01532-00.3_optival_haldex_34630300xx_e.pdf (accessed on 4 Nov 2024).

[45] Technical Report: Optival. UNECE Regulation No. 13, Annex 19, 24/30" Diaphragm Diaphragm S-Cam Brake Chamber. Turkey: Optival Belgelendirme Hizmetleri. 2022 https://www.haldex.com/globalassets/europe/3.-trailer-application-guide/trailer-guide/actuators/346-range/oph-t-01531-00.3_optival_haldex_34624300xx_e.pdf (accessed on 4 Nov 2024).

[46] MGM Brakes Technical Bulletin EB 06-003. MGM Brakes. https://mgmbrakes.com/files/7314/6972/9045/5059-16.pdf (accessed on 22 May 2024).

[47] Dousti M, Baslamısli SC, Onder ET, Solmaz S. Design of a multiple-model switching controller for ABS braking dynamics. Transactions of the Institute of Measurement and Control. 2015;37(5):582–595. https://doi.org/10.1177/0142331214546522.

[48] Pneumatic brake equipment for trailer vehicles. Product catalogue. Europe. Edition 4. Belgium, Wabco. 2021. https://www.wabco-customercentre.com/catalog/docs/8150100343.pdf (accessed on 4 Nov 2024).

[49] Zhang Z, Sun N, Chen Y, Ahmadian M. Detailed Modeling of Pneumatic Braking in Long Combination Vehicles. SAE International Journal of Commercial Vehicles. 2021;14(3):245–258. https://doi.org/10.4271/02-14-03-0020.

[50] Zhang L, Feng S, Shan H, Wang G. Tractor-trailer-train braking time sequence detection based on monocular vision. Advances in Mechanical Engineering. 2021;13(12). https://doi.org/10.1177/16878140211067045

[51] Mi T, Stepan G, Takacs D, Chen N. Vehicle Shimmy Modeling With Pacejka's Magic Formula and the Delayed Tire Model. ASME. Journal of Computational and Nonlinear Dynamics. 2020;15(3):031005. https://doi.org/10.1115/1.4045943.

[52] Singh KB, Sivaramakrishnan S. Extended Pacejka Tire Model for Enhanced Vehicle Stability Control. arXiv:2305.18422 [eess.SY]. 2023. https://doi.org/10.48550/arXiv.2305.18422.

[53] Bhoraskar A, Sakthivel P. A review and a comparison of Dugoff and modified Dugoff formula with Magic formula. International Conference on Nascent Technologies in Engineering (ICNTE). 2017 January 27–28, Vashi, India. https://doi.org/10.1109/ICNTE.2017.7947898.

[54] Rill G. An engineer's guess on tyre parameter made possible with TMeasy. Proceedings of the 4th International Tyre Colloquium: Tyre Models for Vehicle Dynamics Analysis. 2015:49–58.

[55] Gong C, Zong C, Lu D, Kaku C, Zhang D. Estimation of Tire-Road Friction Coefficient Based on the Unitire Model. 2022 6th CAA International Conference on Vehicular Control and Intelligence (CVCI), Nanjing, China, 2022 October 28–30. https://doi.org/10.1109/CVCI56766.2022.9964825.

[56] Bosso N, Zampieri N. A Novel Analytical Method to Calculate Wheel-Rail Tangential Forces and Validation on a Scaled Roller-Rig. Advances in Tribology. 2018;2018:7298236. https://doi.org/10.1155/2018/7298236.

[57] Sider A, Amiri A, Hassan MK, Mohd Radzi MA, Toha SF. Mathematical design and analysis of anti-lock brake system for electric vehicle based on brake-by-wire technology. International Journal of Electric and Hybrid Vehicles. 2015;7(4):303–322. http://dx.doi.org/10.1504/IJEHV.2015.074668.

https://doi.org/10.14669/AM/204097

[58] Janczur R, Zawałeń J. Dynamika ruchu pojazdów ciężarowych po wystrzale opony. Analiza śladów powstałych na miejscach wypadków drogowych i próba komputerowej symulacji ruchu pojazdów w programie V-SIM. (Dynamics of heavy duty vehicles motion after tyre blow out. Analysis of traces of traffic accidents and attempt of computer simulation of vehicle motion in V-SIM program). Paragraf na Drodze. Prawne i kryminalistyczne problemy ruchu drogowego. 2017; 2017:115–127.

[59] Main reports. UNECE. https://unece.org/DAM/trans/main/wp29/wp29wgs/wp29grrf/grrfinf/49/49-inf02text-of-main-report.pdf (accessed on 7 Feb 2023).