

# EVALUATION OF THE INFLUENCE OF THE TRAILER MASS CENTRE POSITION ON THE STOPPING DISTANCE OF THE VEHICLE COMBINATION. EXPERIMENTAL VERIFICATION OF CALCULATIONS USING A SIMULATION MODEL

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## ABSTRACT

The paper presents the results of experimental verification of the constructed simulation model of the two-axle vehicle - single-axle unbraked trailer assembly. The model describes the effect of the trailer's centre of mass position on the braking distance. The constructed model and the assumptions adopted for its construction are described at the beginning. The acquired geometric and mass data of the vehicles used for the tests are presented. The further part of the paper describes road tests in real conditions, where the braking distance of the towing vehicle itself and the towing vehicle - loaded (in six variants) single-axle unbraked trailer assembly were assessed. The parameters of the road surface on which the tests were conducted were determined. During the tests, the distance travelled by the vehicles and the force applied to the brake pedal were recorded. The results of experimental verification of the constructed simulation model are presented, where the values of the braking distance and deceleration were assessed. The model with confirmed usefulness will be used as a software component, which will be a real effect of implementation in the workplace of the solution of one of the co-authors of this study. A utilitarian effect will also be obtained, expanding the knowledge of people dealing with the issue of road accidents (court experts and car appraisers). The summary contains conclusions and comments for further research. The research was carried out as part of the statutory work conducted at the Military Institute of Armoured and Automotive Technology.

**Keywords:** braking, road accident, braking distance of vehicle combination, trailer, coupling device.

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## INTRODUCTION

The article discusses the issues related to modelling and simulation of a moving vehicle. The main aim of this paper is to confirm the usefulness of the constructed model that enables the assessment of the impact of the value of static vertical load occurring on the coupling device, which is also a consequence of a method of how the trailer was loaded on the length of braking distance of the vehicle combination.

Braking is a very important process from a road safety standpoint that allows vehicle drivers to reduce speed or stop. The braking process and effectiveness of the operation of the braking systems are defined in the normative documents, where, inter alia, mandatory technical requirements to obtain approval and authorisation for use in road traffic were specified.

In the literature, there are numerous studies, both domestic and international, which tackle the subject of braking of vehicle with single-axle trailer [1-5]. A general review of the mentioned documents is presented in [6]. Test results included in the referenced documents clearly indicated the possible increase in length of the stopping distance of the vehicle combination referred to the vehicle itself, owing to, among others, the weight of trailer assembly, its type (with or without brake), vehicle loading or surface condition. There was no information on the results of studies, which would demonstrate an impact on the length of braking distance, position of the longitudinal and vertical centre of mass of the trailer assembly.

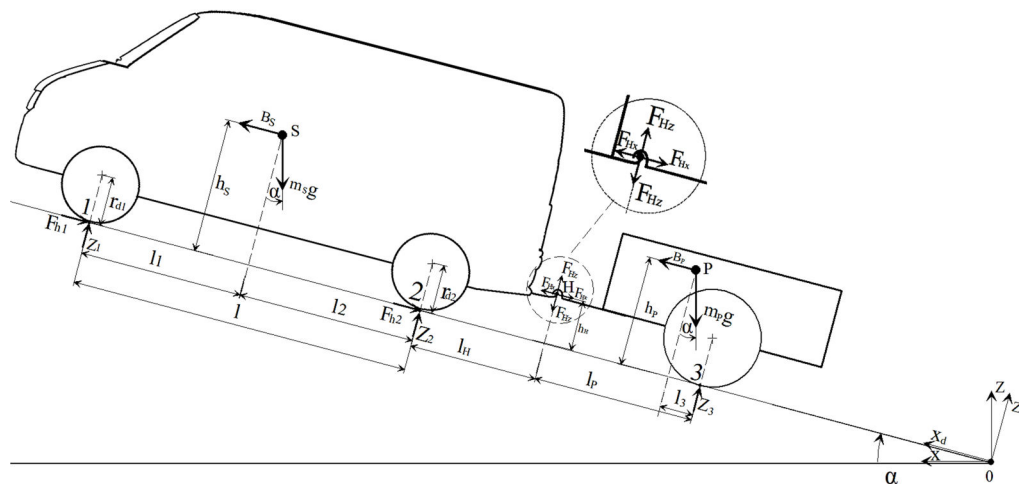
This article is a continuation of the paper [6],

where the computational model and results of simulation tests, presenting such impact, expanded with experimental verification of the constructed model were presented.

Model, dynamic balance equations and impact on the stopping distance of the towing vehicle combination (two-axle vehicle) - unbraked single-axle trailer for the case of rectilinear motion on even, horizontal and sloping road were taken from one of the co-authors [7]. The preliminary assumptions, mainly of a simplifying nature, listed below have been made:

- vehicles move on the ideally even, horizontal or sloping surface of the road;
- rectilinear motion is considered;
- frontal air resistance is negligible (such resistance is small and can be neglected, especially in the case of intense braking starting from the moderate values of speed);
- rolling resistance with the impact of masses of rotating drive wheels is negligible (impact of rotating masses cancels with the impact of rolling resistance);
- braking is performed with the engine disconnected from the drive unit.

Fig. 1 presents the assumed model of a two-axle vehicle with single-axle unbraked trailer assembly during rectilinear motion [7], which includes the used designations of coordinate systems, marked points, geometrical dimensions, weights of vehicles and forces.



Rys. 1. Model samochodu dwuosioowego z jednoosiową niehamowaną przyczepą w trakcie prostoliniowego hamowania [7] (oznaczenia opisano w [7]).

The model allows analysis of the vehicle braking process with consideration of road longitudinal slope. The braking process is divided into three stages, which include:

- stage I – response time  $t_r$  (of driver and vehicle);
- stage II - braking deceleration rise time  $t_n$ , where the deceleration begins to increase;
- stage III - time, where the speed achieved at the end of the second stage decreases linearly to zero, braking deceleration reaches maximum value.

The paper includes an analysis of part of the stopping distance called braking distance, so the response time equal to zero was assumed.

Based on the assumed model it is possible to determine the values of forces for the given longitudinal slope  $\alpha$ , and relationships describing braking deceleration of vehicles combination and length of braking distance. Below are the relationships of braking deceleration  $a$  [m/s<sup>2</sup>] and stopping distance  $S_z$  [m] and braking distance  $S_h$  [m].

$$a = \frac{m \cdot g \cdot \sin \alpha + \mu_a \cdot m_s \cdot g \cdot \cos \alpha + \mu_a \cdot m_p \cdot g \cdot \left( -\sin \alpha \frac{h_P - h_H}{l_P} + \cos \alpha \frac{l_3}{l_P} \right)}{m - m_p \cdot \mu_a \cdot \frac{h_P - h_H}{l_P}} \quad (1)$$

where:

- $m$  – weight of vehicle combination (vehicle and trailer), [kg];
- $m_s$  – vehicle weight, [kg];
- $m_p$  – trailer weight, [kg];
- $g$  – acceleration due to gravity, [m/s<sup>2</sup>];
- $\alpha$  – angle of longitudinal slope of road surface, [deg];
- $\mu_a$  – friction coefficient, [-];
- $l_P, l_3$  – distances between marked points, [m];
- $h_H, h_P$  – distances (heights) of marked points from the road surface, [m].

The study [7] includes the integration of time course  $a(t)$  formally performed two times. The following relationships for the length of stopping distance  $S_Z$ , which for the zero response time  $t_r$  becomes a braking distance, marked as  $S_h$ , were obtained as a result.

$$S_Z = \left\{ v_0 \cdot t_r - a_w \cdot \frac{t_r^2}{2} \right\} + \left\{ \left[ v_0 - (a - a_w) \cdot \frac{t_r^2}{2 \cdot t_n} \right] \cdot t_n + \frac{1}{2} \cdot \left[ -a_w \cdot \left( 1 + \frac{t_r}{t_n} \right) + a \cdot \frac{t_r}{t_n} \right] \cdot [(t_r + t_n)^2 - t_r^2] - \frac{a - a_w}{6 \cdot t_n} \cdot [(t_r + t_n)^3 - t_r^3] \right\} + \left\{ \frac{A^2}{2a} - A \cdot (t_r + t_n) + \frac{a}{2} \cdot (t_r + t_n)^2 \right\} \quad (2)$$

where:

$$A = v_0 + a_w \cdot \frac{t_r - (t_r + t_n)^2}{2 \cdot t_n} + a \cdot \left( t_r + \frac{t_n}{2} \right) \quad (3)$$

where:

- $v_0$  – initial speed, [m/s];
- $t_r$  – response time (of driver and vehicle); [s];
- $t_n$  – forces (and deceleration) rise time, [s];

- $a$  – vehicle or vehicle combination braking deceleration, [m/s<sup>2</sup>] (it is a maximum deceleration in the equation);
- $a_w$  – braking deceleration during the response time, [m/s<sup>2</sup>].

Road tests intended to verify the simulation model for the movement of a two-axle towing vehicle - single-axle unbraked trailer assembly, were based on straight-line braking at full available power from the initial speed to stop. No wheel locking took place during braking (ABS was active). The study used a heavy commercial vehicle with a gross vehicle weight of 3500 kg loaded with two people and measuring instrumentation and a light trailer with a gross vehicle weight of 720 kg, which was loaded up to the value of GVW (gross vehicle weight) six ways (variants).

## MATERIALS AND METHODS

Longitudinal and vertical positions of centres of masses for each variant of load positioning on the trailer and the vehicle itself were determined in the laboratory conditions and the specific geometrical parameters, listed in tables 1 ÷ 7, were measured. In turn, a location of the centres of mass of the trailer was shown in Figures 2 ÷ 7 on their left side, while the right side presents an actual view of the loaded trailer, which is a part of the vehicle combination, for the given variant.

Tab. 1

Data of two-axle Renault Master heavy commercial vehicle.

Parameters of vehicle model	Designation [unit]	Loading case: without load (only driver and passenger)
Vehicle weight	$m_s$ [kg]	2655
Height of centre of mass $S$	$h_s$ [m]	0.861
Axle base	$l$ [m]	4.073
Distance of centre of vehicle weight $S$ from front axle	$l_1$ [m]	1.618
Distance of centre of vehicle weight $S$ from rear axle	$l_2$ [m]	2.455
Distance of the centre of coupling hinge $H$ from rear axle	$l_H$ [m]	1.034



Data of single-axle trailer assembly loaded according to loading variant I.

Parameters of cargo trailer	Designation [unit]	Value
Trailer mass	$m_s$ [kg]	720
Height of centre of mass $P$	$h_P$ [m]	0.557
Distance of trailer driving axle from the centre of coupling hinge $H$	$l_P$ [m]	2.171
Distance of trailer driving axle from the centre of its mass $P$	$l_3$ [m]	0.522
Distance of the centre of coupling hinge $H$ from road surface	$h_H$ [m]	0.35

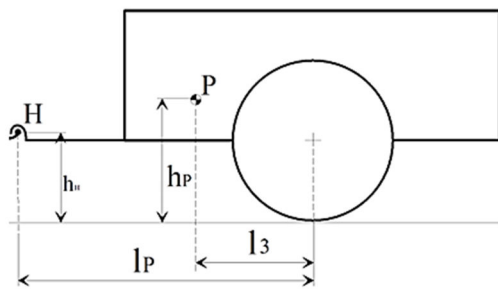


Fig. 2. View of a trailer loaded according to variant I with an indication of the position of the centre of mass.

Data of single-axle trailer assembly loaded according to loading variant II.

Parameters of cargo trailer	Designation [unit]	Value
Trailer mass	$m_s$ [kg]	720
Height of centre of mass $P$	$h_P$ [m]	0.5335
Distance of trailer driving axle from the centre of coupling hinge $H$	$l_P$ [m]	2.171
Distance of trailer driving axle from the centre of its mass $P$	$l_3$ [m]	0.067
Distance of the centre of coupling hinge $H$ from road surface	$h_H$ [m]	0.373

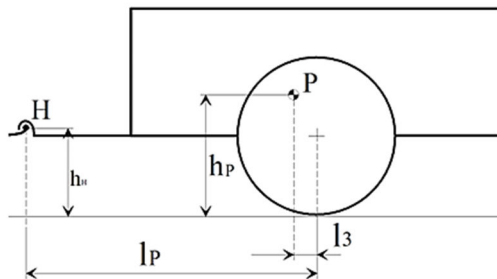


Fig. 3. View of a trailer loaded according to variant II with an indication of the position of the centre of mass.

Data of single-axle trailer assembly loaded according to loading variant III.

Parameters of cargo trailer	Designation [unit]	Value
Trailer mass	$m_s$ [kg]	720
Height of centre of mass $P$	$h_P$ [m]	0.5365
Distance of trailer driving axle from the centre of coupling hinge $H$	$l_P$ [m]	2.171
Distance of trailer driving axle from the centre of its mass $P$	$l_3$ [m]	-0.376
Distance of the centre of coupling hinge $H$ from road surface	$h_H$ [m]	0.384

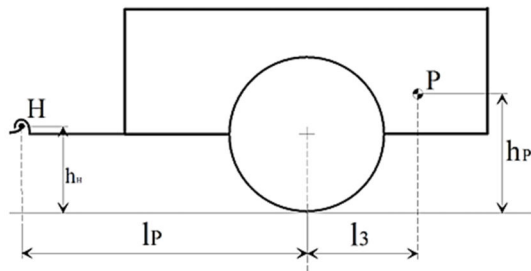


Fig. 4. View of a trailer loaded according to variant III with an indication of the position of the centre of mass.

Data of single-axle trailer assembly loaded according to loading variant IV.

Parameters of cargo trailer	Designation [unit]	Value
Trailer mass	$m_s$ [kg]	720
Height of centre of mass $P$	$h_P$ [m]	0.8595
Distance of trailer driving axle from the centre of coupling hinge $H$	$l_P$ [m]	2.71
Distance of trailer driving axle from the centre of its mass $P$	$l_3$ [m]	0.525
Distance of the centre of coupling hinge $H$ from road surface	$h_H$ [m]	0.36

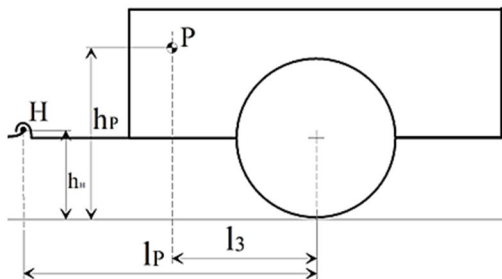


Fig. 5. View of a trailer loaded according to variant IV with an indication of the position of the centre of mass.

Data of single-axle trailer assembly loaded according to loading variant V.

Parameters of cargo trailer	Designation [unit]	Value
Trailer mass	$m_s$ [kg]	720
Height of centre of mass $P$	$h_P$ [m]	0.8635
Distance of trailer driving axle from the centre of coupling hinge $H$	$l_P$ [m]	2.171
Distance of trailer driving axle from the centre of its mass $P$	$l_3$ [m]	0.079
Distance of the centre of coupling hinge $H$ from road surface	$h_H$ [m]	0.372

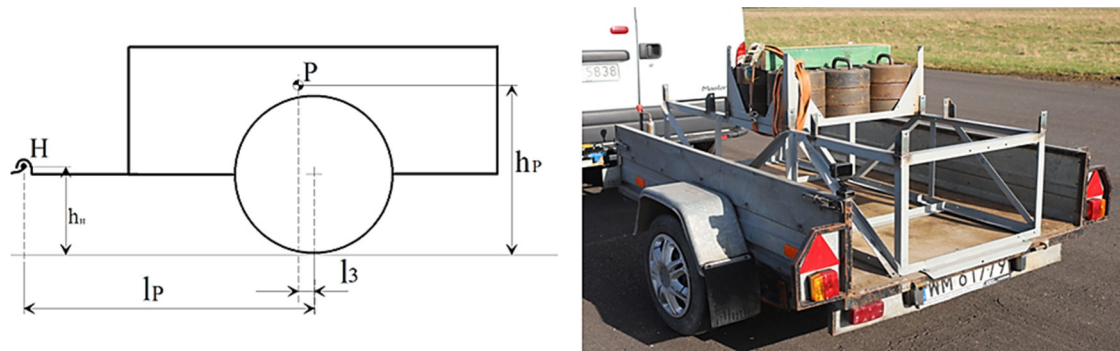


Fig. 6. View of a trailer loaded according to variant V with an indication of the position of the centre of mass.

Data of single-axle trailer assembly loaded according to loading variant VI.

Parameters of cargo trailer	Designation [unit]	Value
Trailer mass	$m_s$ [kg]	720
Height of centre of mass $P$	$h_P$ [m]	0.837
Distance of trailer driving axle from the centre of coupling hinge $H$	$l_P$ [m]	2.171
Distance of trailer driving axle from the centre of its mass $P$	$l_3$ [m]	-0.393
Distance of the centre of coupling hinge $H$ from road surface	$h_H$ [m]	0.39

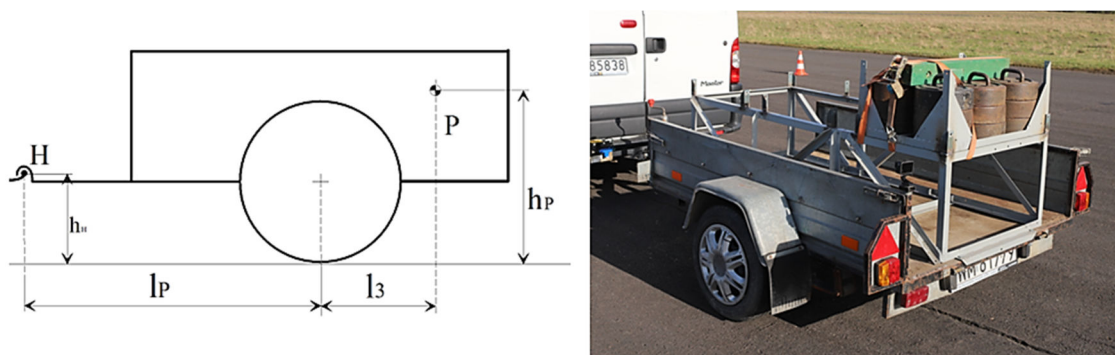


Fig. 7. View of a trailer loaded according to variant VI with an indication of the position of the centre of mass.

Experimental studies were performed on the airside of a former military airfield, with an even, hardened asphalt road surface, which was horizontal, clean and dry. Road parameters were determined using two measuring devices intended to assess the adhesion of wheels to the surface.

The first device was  $\mu$ -PW [8], whose operation is based on the measurement using a replaceable rubber sample pulled along the road surface. The sample is fixed with a holder to a two-part force sensor, which measures its ground pressure force  $F_z$  and sliding friction force  $F_x$ . The ratio of measured forces is determined by the coefficient of friction of the sample to the road surface, which allows to predict the values of coefficients of wheel adhesion to the surface [8]. As a result of measurement with  $\mu$ -PW device, a value of contact adhesion  $\mu_1 = 1.03$  and a value of slip adhesion coefficient  $\mu_2 = 0.65$  were determined.

The second device used was a Drag Sled [11],

which consists of a tyre cutout with a known weight and force gauge. Measurement is based on pulling a slice of the tyre along the surface and simultaneous reading of force value, which refers to the weight of the tyre slice, allows to determine the value of the slip friction coefficient. Measurement with Drag Sled device enabled to determine the value of friction coefficient  $\mu = 0.93$ .

A view of measuring equipment used to determine the parameters of the surface is given in Fig. 8.

A force applied on the brake pedal  $P_N$  was an extortion during road tests. The braking moments on the wheels of the towing vehicle, which were so significant that it was possible to use the action of ABS, were used as an extortion for the simulation tests. A coefficient of percent effectiveness of the ABS  $p\% = 88\%$  [6] was assumed.



Fig. 8. View of measuring equipment used to characterize the road surface.

The road travelled by the vehicle during braking was measured by two devices. The first one was an optical contactless speed measurement sensor Correvit S400 [9], which was operating with IMC Cronos recording device, creating a measurement line with a portable computer. Operation of the device is based on the illumination of the surface with a strong focused light beam and analysis of reflected rays falling on the optical receiving system. An illuminated image of the surface passes through the lens and additional diaphragm, rays reflected from the surface fall onto a prism grid, which separates them and directs them to the photocells. The frequency of the electrical signal transmits information about movement relative to the surface [9].

The marker of the beginning of vehicle stopping distance "Shot Marker" [10] was used as a second device. This is a marking gun. The device is installed on the vehicle body so that the barrel is directed downwards, perpendicular to the surface. The contact force sensor is placed directly on the brake pedal and the device is supplied from the electrical system of the vehicle. Before braking, the barrel of the marking gun is charged with a portion of chalk, and a blank cartridge is placed from the top. An electric signal, activating the electromagnetic of the lock trigger, is released at the moment of pressing the

braking pedal. The released needle hits the primer cap of the cartridge, which initiates a shot and launches the chalk from the barrel downwards. It leaves a mark on the surface being a reference point determining the position of the vehicle at the beginning of braking distance [10].

A contact force on the brake pedal during braking was recorded using a sensor. The registration was performed with a sampling frequency of 500 Hz. An overview of the vehicle prepared for tests with installed test equipment is given in Fig. 9.



Fig. 9. View of measuring equipment used for the measurement of braking distance: Correvit S400 head on the left, Shot Marker on the right.

### RESULTS

In the course of the experimental studies, braking processes were performed with the engine disconnected from the drive unit, which allowed to avoid the action of a negative pressure device supporting the braking system. Tests were started by braking the vehicle without a trailer, whose initial speed was within the range of 19.02÷19.97 m/s (68.5÷71.9 km/h). Braking was performed until the stop of the vehicle. Five braking procedures were performed in total.

A selected averaged (moving average for 101 points) time course for deceleration for straight-line

braking of a vehicle from an initial speed of 19.78 m/s (71.2 km/h), the time course of the speed of the translational motion and longitudinal movement of the vehicle is shown in fig. 8. Rise time for braking deceleration  $t_n$ , average value of braking deceleration and value of mean fully developed braking deceleration MFDD were marked.

Figure 11 presents (for the same braking) a time course for a force applied to the brake pedal  $P_n$  and a time course of averaged deceleration for straight-line braking.

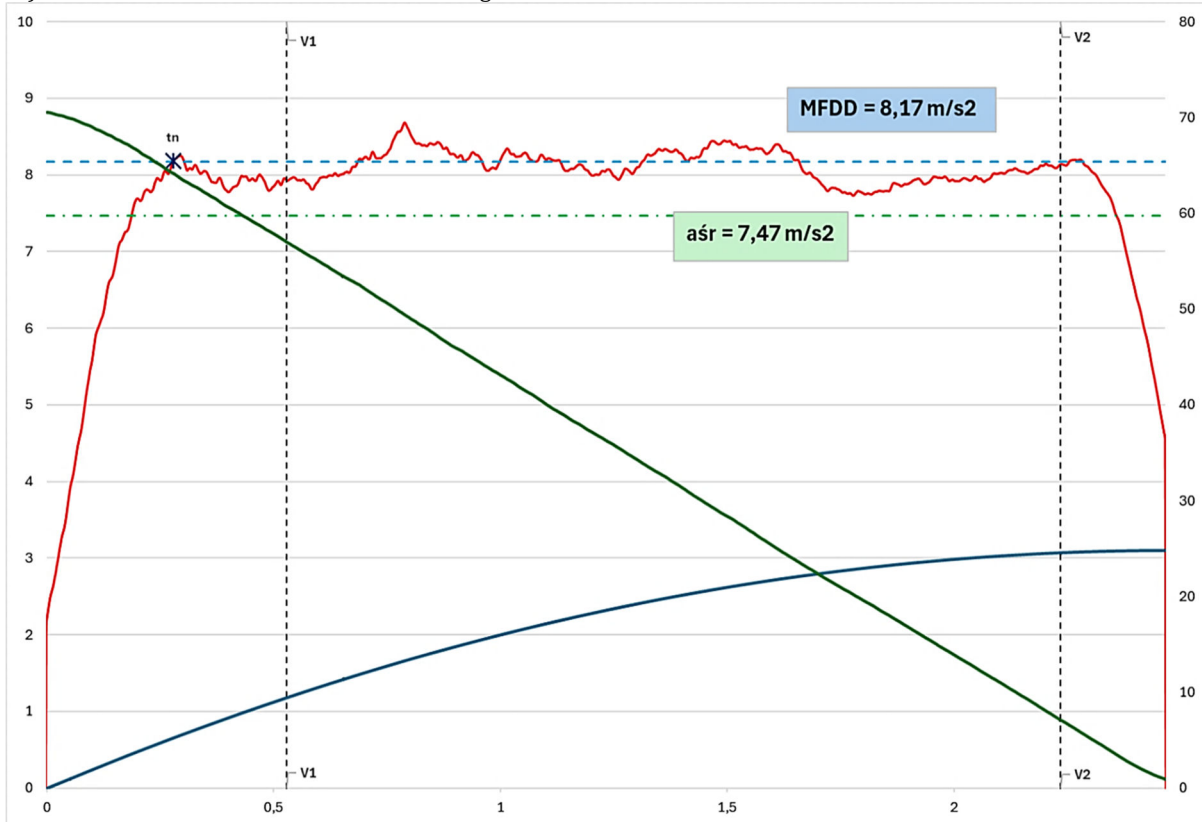


Fig. 10. Straight-line braking of vehicle from  $V_0 = 71.2$  km/h to zero. Time courses for braking deceleration, speed of translational motion, and longitudinal movement.  
 Left axis: Deceleration on subgrade  $V(t)$  (average of 101 points) [m/s<sup>2</sup>].  
 Right axis: distance [m], speed [km/h].  
 Bottom axis: time [s].

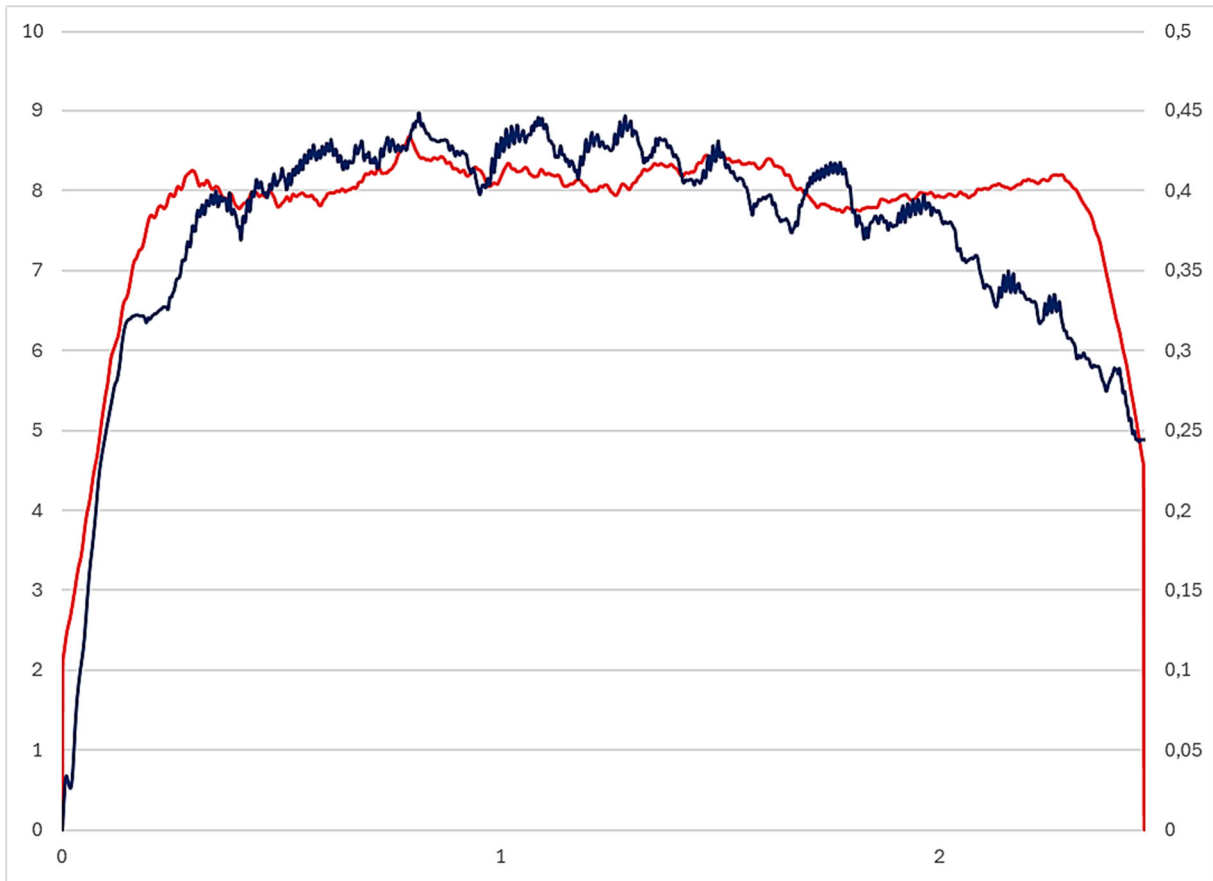


Fig. 11. Straight-line braking of vehicle from  $V_0 = 71.2$  km/h to zero. Time courses for a force applied to brake pedal  $P_n$  and braking deceleration.  
 Left axis: Deceleration based on  $V(t)$  (average from 101 points)  
 Right axis: Force applied on brake pedal –  $P_n$  [kN]  
 Bottom axis: czas [s]

Table 8 presents a listing of values of lengths of braking distance  $S_h$  for braking from the initial speed within the range  $19.02 \div 19.97$  m/s ( $68.5 \div 71.9$  km/h), measured during the experiment (E) using the Correvit S400 (Corr, five braking procedures) and Shot Marker (Shot-M, three braking procedures) devices and

calculated using simulation model (S), with road parameters determined as a result of measurement using Drag Sled device. The value of the coefficient of percent effectiveness of the ABS  $p\% = 88\%$  was assumed.

Tab.8

Lengths of braking distance  $S_h$  for the assumed variants of braking.

Comparison of test results (experiment (E)/simulation(S)) - Drag Sled

Test no.	Initial speed $V_0$ [km/h]	Initial speed $v_0$ [m/s]	Rise time of braking deceleration $t_n$ [s]	Braking distance (E - Correvit) $S_h$ [m]	Braking distance (E - Shot Marker) $S_h$ [m]	Braking distance (S) $S_h$ [m]	Relative difference (E-Corr S)/S [%]	Relative difference (E-Shot M - S)/S [%]
1	71.2	19.780	0.280	24.79	23.16	24.10	2.9	-3.9
2	70.6	19.610	0.260	25.04	23.70	23.52	6.5	0.8
3	71.9	19.970	0.219	25.20	23.40	23.94	5.3	-2.2
4	71.9	19.960	0.203	26.05		23.76	9.6	
5	68.5	19.020	0.283	23.87		22.41	6.5	



Lengths of braking distances measured using the Correvit S400 device were within 23.87÷26.05 m (average value of the length of braking distance 24.99 m, the difference between minimum and maximum value of the length of braking distance 2.18 m). Lengths of braking distances measured using the Shot Marker device were within 23.16÷23.70 m (average value of length of braking distance 23.42 m, the difference between minimum and maximum value of length of braking distance 0.54 m).

Lengths of braking distances measured on the basis of the simulation model with parameters of the surface determined using Drag Sled were within 22.41÷24.10 m (average value of length of braking distance 23.54 m, difference between the minimum and maximum value of length of braking distance 1.69 m).

While comparing the lengths of braking distances measured using the Correvit S400 device and the lengths of braking distances calculated using the simulation model it is clear that the differences ranged from 2.9% to 9.6%. For the lengths of braking distances measured with

the Shot Marker device, a comparison with the simulation results indicates that the differences were from 0.8% to 3.9%. It should be noted that the average length of braking distance calculated during simulation for surface parameters determined based on the measurements using Drag Sled ( $S_{h(S) sr} = 23.54$  m) was between the average values of braking distances measured during the experiment ( $S_{h(Ec) sr} = 24.99$  m,  $S_{h(Em) sr} = 23.42$  m).

Table 9 presents a listing of values of lengths of braking distance  $S_h$  for the initial speed within the range 19.02÷19.97 m/s (68.5÷71.9 km/h) measured during the experiment (E) using the Correvit S400 and Shot Marker devices. Also, the values calculated using the simulation model (S), with road parameters determined as a result of measurement using  $\mu$ -PW device are given. A percent coefficient of effectiveness of the ABS of  $p\% = 88\%$  was assumed.

Tab. 9

Lengths of braking distance  $S_h$ . Symbol E indicates the results of experimental tests, symbol S indicates the results of the simulation.

Comparison of test results (experiment(E)/simulation(S)) -  $\mu$ -PW

Test no.	Initial speed $V_0$ [km/h]	Initial speed $v_0$ [m/s]	Rise time of braking deceleration $t_n$ [s]	Braking distance (E - Correvit) $S_h$ [m]	Braking distance (E - Shot Marker) $S_h$ [m]	Braking distance (S) $S_h$ [m]	Relative difference (E-Corr S)/S [%]	Relative difference (E-Shot M - S)/S [%]
	71.2	19.780	0.280	24.79	23.16	21.51	15.2	7.7
2	70.6	19.610	0.260	25.04	23.70	20.97	19.4	13.0
3	71.9	19.970	0.219	25.20	23.40	21.30	18.3	9.8
4	71.9	19.960	0.203	26.05		21.13	23.3	
5	68.5	19.020	0.283	23.87		20.16	18,4	

Lengths of braking distances measured on the basis of the simulation model with parameters of the surface determined using  $\mu$ -PW were within 20.16÷21.51 m Average value of the length of braking distance amounted to 21.01 m and it was shorter by 2.53 m (that is by approx. 10.7%) than the average value of length of braking distance calculated for the parameters of surface determined based on the measurement using Drag Sled. The difference between the minimum and maximum value of the length of braking distance for this case was 1.35 m.

While comparing the lengths of braking distances measured using Correvit S400 with lengths of braking distances calculated using the simulation model it can be seen that the differences ranged from 15.2% to 23.3%. Comparison of the lengths of braking distances measured using Shot Marker device with the lengths of braking distances calculated by a simulation model indicates that the differences were in the range from 7.7% to 13.0%. Results of lengths of braking distances obtained in a simulation with road surface parameters determined based on the  $\mu$ -PW device were each time smaller than the length of braking distances measured during the experiment.

An averaged value of braking deceleration for a vehicle without a trailer, which amounted to 8.13 m/s<sup>2</sup>, was determined on the basis of the recorded (during five braking procedures) characteristics of braking deceleration as a function of force applied to the brake pedal, for the braking period with mean fully developed deceleration (MFDD). Figure 12 presents braking decelerations as a function of the force applied to the brake pedal for the mentioned braking period recorded during five braking procedures.

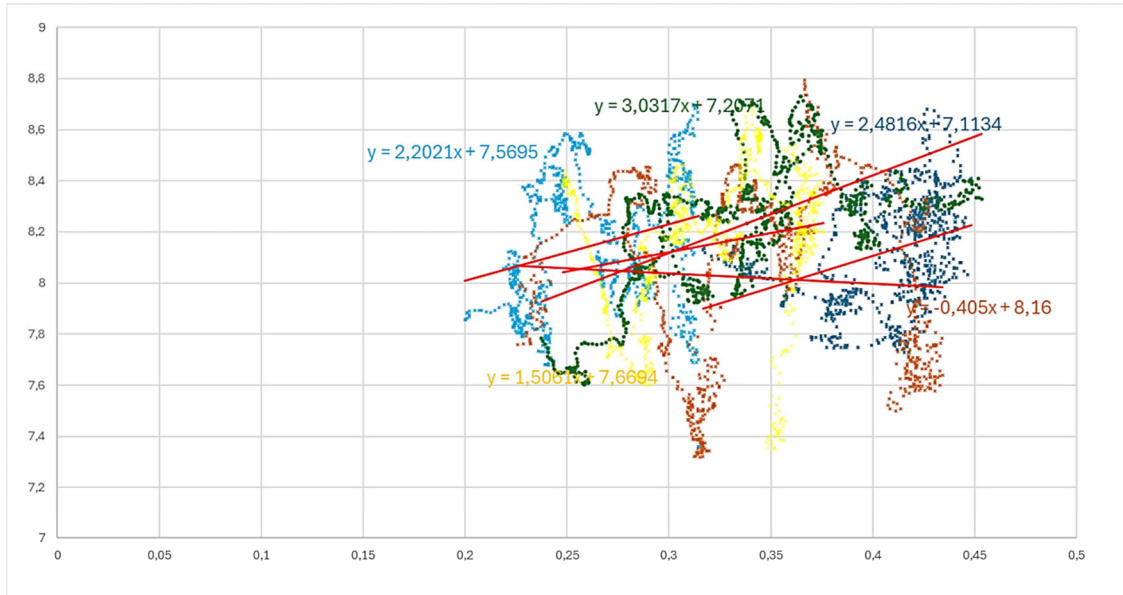


Fig. 12. Characteristics of braking deceleration as a function of the force applied to the brake pedal recorded during five braking procedures.  
 Left axis: Braking deceleration [m/s<sup>2</sup>]  
 Bottom axis: Force applied on brake pedal [kN]

An averaged characteristics of braking deceleration, from five tests, as a function of the force applied to the brake pedal is given in Figure 13.

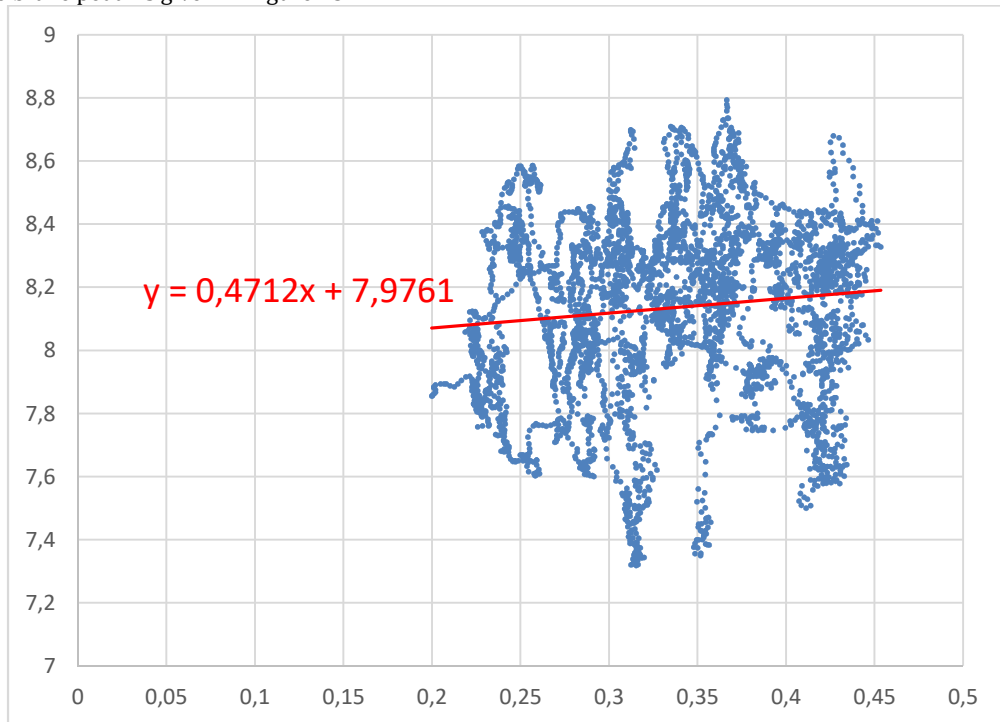


Fig. 13. Characteristics of braking deceleration as a function of the force applied to brake pedal averaged for five braking procedures.  
 Left axis: Braking deceleration [m/s<sup>2</sup>]  
 Bottom axis: Force applied on brake pedal [kN]

On this basis, it was concluded that the value of inertia force during braking of a vehicle with of weight of 2655 kg amounted to 21595.24 N and was approximately equal to the braking force of a towing vehicle (aerodynamic drag, rolling resistances and action of rotating masses are neglected). After connecting a trailer of a weight of 720 kg to the vehicle, loaded in a way that does not change the pressure forces of the individual axles of towing vehicle on the surface, it should be possible to obtain a braking deceleration of vehicle

combination at the level of 6.40 m/s<sup>2</sup> (for the assumed percent effectiveness of the ABS),

Tables 10 ÷ 15 present results of the measurements of the length of braking distance of the vehicle combination for six methods of trailer loading already described in the article (variants from I to VI). Five braking tests from the initial speed of approx. 70 km/h until a stop was performed for each trailer loading variant. The force applied to the brake pedal, distance and speed were recorded during braking.

Tab. 10

Distances of braking distance of combination of vehicle with trailer loaded according to variant I.

Test no.	Rise time of braking deceleration $t_n$ [s]	Initial speed $v_0$ [m/s]	Braking distance - E (Correvit) $S_h$ [m]	Braking distance - E (Shot Marker) $S_h$ [m]
1	0.185	19.298	27.870	26.290
2	0.223	20.190	30.649	27.140
3	0.257	19.930	29.940	27.939
4	0.235	19.526	28.064	
5	0.149	19.274	27.662	

Tab. 11

Distances of braking distance of combination of vehicle with trailer loaded according to variant II.

Test no.	Rise time of braking deceleration $t_n$ [s]	Initial speed $v_0$ [m/s]	Braking distance - E (Correvit) $S_h$ [m]	Braking distance - E (Shot Marker) $S_h$ [m]
1	0.169	20.064	31.734	30.120
2	0.221	19.430	29.541	29.050
3	0.233	19.606	30.800	30.000
4	0.109	19.828	30.988	
5	0.139	18.932	27.662	

Tab. 12

Distances of braking distance of combination of vehicle with trailer loaded according to variant III.

Test no.	Rise time of braking deceleration $t_n$ [s]	Initial speed $v_0$ [m/s]	Braking distance - E (Correvit) $S_h$ [m]	Braking distance - E (Shot Marker) $S_h$ [m]
1	0.145	19.358	30.988	30.030
2	0.169	19.616	31.981	29.740
3	0.197	19.536	31.822	30.710
4	0.163	19.930	33.290	
5	0.225	19.550	31.460	

Distances of braking distance of combination of vehicle with trailer loaded according to variant IV.

Test no.	Rise time of braking deceleration $t_n$ [s]	Initial speed $v_0$ [m/s]	Braking distance - E (Correvit) $S_h$ [m]	Braking distance - E (Shot Marker) $S_h$ [m]
1	0.109	19.964	28.487	27.750
2	0.163	19.888	28.660	28.150
3	0.207	19.488	28.606	27.540
4	0.223	19.746	28.285	
5	0.215	18.942	26.185	

Tab. 14

Distances of braking distance of combination of vehicle with trailer loaded according to variant V.

Test no.	Rise time of braking deceleration $t_n$ [s]	Initial speed $v_0$ [m/s]	Braking distance - E (Correvit) $S_h$ [m]	Braking distance - E (Shot Marker) $S_h$ [m]
1	0.121	18.804	26.950	26.670
2	0.157	19.166	27.997	27.640
3	0.177	19.096	28.973	28.150
4	0.133	19.638	29.000	
5	0.173	19.734	29.430	

Tab. 15

Distances of braking distance of combination of vehicle with trailer loaded according to variant VI.

Test no.	Rise time of braking deceleration $t_n$ [s]	Initial speed $v_0$ [m/s]	Braking distance - E (Correvit) $S_h$ [m]	Braking distance - E (Shot Marker) $S_h$ [m]
1	0.209	19.532	31.840	30.620
2	0.191	19.358	30.357	29.470
3	0.171	19.406	30.587	29.760
4	0.195	20.052	32.529	
5	0.155	19.178	29.592	

Tables 16 and 17 present a listing of values of initial speed  $v_0$ , the rise time of braking deceleration  $t_n$  and length of braking distance  $S_h$  for the given variant of trailer loading obtained in the course of the experiment (average values from five brakings performed for each variant of trailer loading) and results of simulation

calculations of the length of braking distance  $S_h$ , referenced to them, taking into account the road parameters determined by the Drag Sled and  $\mu$ -PW.

Length of braking distance - comparison of experiment results with simulation calculations (road parameters based on Drag Sled).

Variant of trailer loading	Average value of speed $v_0$ [m/s]	Average value of speed $V_0$ [km/h]	Average value of deceleration rise $tn$ [s]	Average value of braking time	Average braking distance (Correvit) [m]	Average braking distance (Shot Marker) $S_h$ [m]	Braking distance - simulation $S_h$ [m]	Relative difference (E-Corr S)/S [%]	Relative difference (E-Shot M - S)/S [%]
I	19.64	70.72	0.210		28.84	27.12	31.97	9.8	15.2
II	19.57	70.46	0.174		30.15	29.72	31.51	4.3	5.7
III	19.59	70.52	0.180		31.91	30.16	31.67	0.8	4.8
IV	19.61	70.58	0.183		28.05	27.81	30.89	9.2	10.0
V	19.29	69.44	0.152		28.47	27.49	29.64	3.9	7.3
VI	19.51	70.22	0.184		30.98	29.95	30.72	0.9	2.5

The smallest differences between the values of lengths of braking distances obtained in the experiment and simulation for parameters of the surface determined using Drag Sled were found for variants no. III and VI of load positioning method on the trailer. In the case of measurement of the length of braking distance using Correvit S400, these differences amounted to 0.8÷0.9%, while for measurement of the length of braking distance using Shot Marker, these differences were in the range of 2.5÷4.8%. For variants no. II and V the differences in lengths of braking distances ranged from 3.9% to 4.3% when braking distance during the experiment was measured using Correvit and from 5.7% to 7.3%, for

measurements with Shot Marker. For variants no. I and IV, the differences in length of braking distance were the biggest and ranged from 9.2% to 9.8% for the distance measured using Correvit and from 10.0% to 15.2% for the measurement performed using Shot Marker.

When the centre of mass of the trailer was shifted to the back, there was a noticeable increase in convergence of results of the experiment and simulation for both methods of braking distance measurement. Differences between the experiment and simulation did not exceed 15.2%. Figure 14 presents a graphic comparison of differences in the length of braking distance for the experiment and simulation.

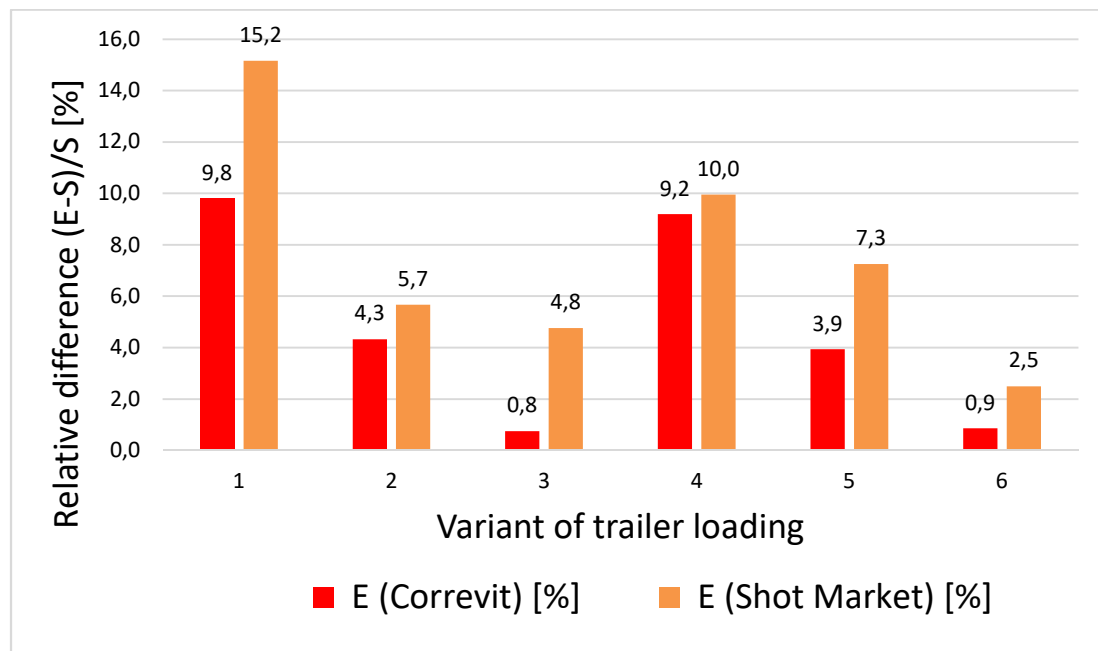


Fig. 14. Comparison of length of braking distance obtained during the experiment (E) and simulation (S), when the parameters of the surface were determined using Drag Sled.

Length of braking distance - comparison of experiment results with simulation calculations (road parameters based on  $\mu$ -PW).

Variant of trailer loading	Average value of speed $v_0$ [m/s]	Average value of speed $V_0$ [km/h]	Average value of deceleration rise $t_n$ [s]	Average value of braking time	Average braking distance (Correvit) [m]	Average braking distance - E <sub>Sh</sub> (Shot Marker) [m]	Braking distance - S <sub>Sh</sub> simulation [m]	Relative difference (E-Corr S)/S [%]	Relative difference (E-Shot M - S)/S [%]
I	19.64	70.72	0.210		28.84	27.12	29.07	0.8	6.7
II	19.57	70.46	0.174		30.15	29.72	28.63	5.3	3.8
III	19.60	70.55	0.180		31.91	30.16	28.78	10.9	4.8
IV	19.61	70.58	0.183		28.04	27.81	27.99	0.2	0.6
V	19.29	69.44	0.152		28.47	27.49	26.84	6.1	2.4
VI	19.51	70.22	0.184		30.98	29.95	27.85	11.2	7.5

The smallest differences between the values of lengths of braking distances obtained in the experiment and in simulation for the road parameters determined using  $\mu$ -PW were found for variants no. I and IV of load position method on the trailer, when the distance was measured using Correvit and they amounted to 0.2÷0.8%. When the distance was measured using Shot Marker, the smallest differences between the experiment and the simulation were achieved for variant IV and were equal to 0.6%.

For variants no. III and VI, the differences in length of braking distance were the biggest and ranged from 10.9% to 11.2% for the distance measured with Correvit. For the braking distance measured using Shot

Marker, the differences between the experiment and simulation were the biggest for variants no. I and VI and ranged from 6.7% to 7.5%. The diverging results for the experiment and simulation with shifting of the centre of mass of the trailer to the back were observed when braking distance during the experiment was measured using Correvit. Such effect was not visible when the braking distance was determined using Shot Marker for variants from I to III and it was visible for the variants from IV to VI. Differences between the experiment and simulation did not exceed 11.2%. Figure 12 presents a graphic comparison of differences in the length of braking distance for the experiment and simulation.

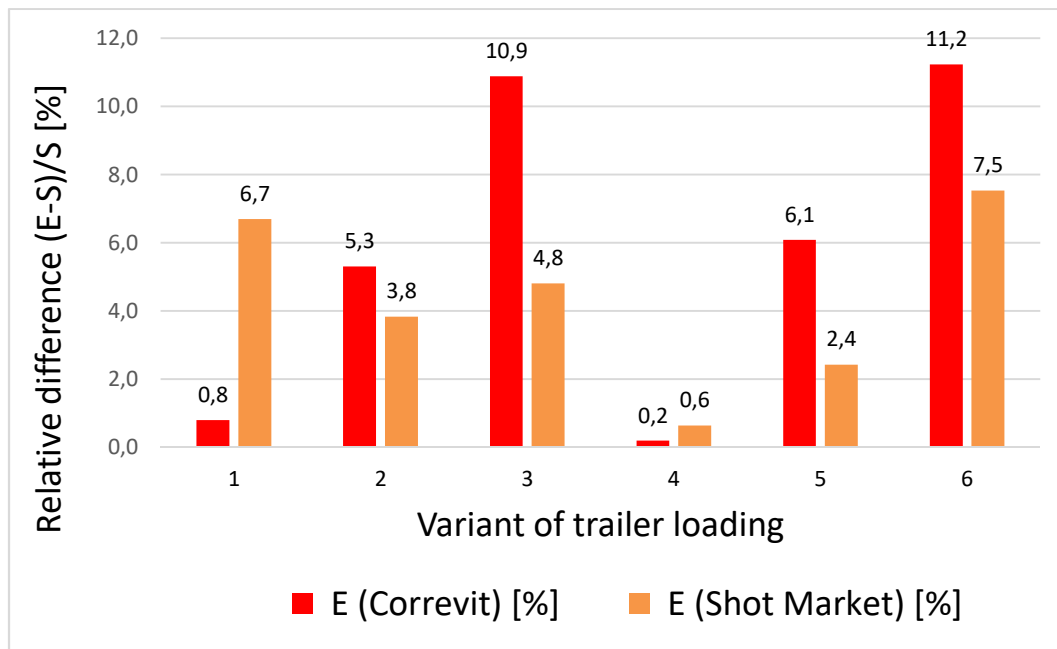


Fig. 15. Comparison of length of braking distance obtained during the experiment and simulation when the parameters of the surface were determined using  $\mu$ -PW.

## CONCLUSIONS

Experimental verification of results of calculations of the motion model of the two-axle vehicle with single-axle unbraked trailer assembly indicates its quantitative and qualitative conformity with the properties of the real object in the discussed braking process.

Comparison of results of simulation calculations and experimental studies presented in the article gave rise to the state that the simulation model well reflects the properties of the real object during braking.

If the surface parameters were determined using the Drag Sled device it gave a smaller divergence of the results of simulation and experiment, when the braking distance was measured using the Correvit S400 device in comparison to the case when the braking distance was measured using the Shot Marker device.

If the surface parameters were determined using  $\mu$ -PW, then the obtained divergence of results of simulation and the experiment was smaller when the braking distance was measured using the Shot Marker device as compared to the situation when the braking distance was measured using the Correvit S400 device, while these differences were small.

## SUMMARY, EVALUATION OF OBTAINED RESULTS

Results of tests of braking distance of the vehicle combination consisting of a two-axle towing vehicle and single-axle unbraked trailer, taking into account the impact of the position of the centre of mass of the trailer, presented in the article, were rarely described in the available literature sources so far. They did not present a comparison of the results of model and simulation tests combined with the results of experimental studies.

As a result of the comparison of the results of the experiment and simulation for the various cases of trailer loading, it was possible to demonstrate the usefulness of the constructed model for testing of impact of the position of the centre of mass of the trailer assembly and coupling point on the length of braking distance.

Differences between the results of the experiment and simulation did not exceed 15.2%, which was considered a satisfactory result.

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