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APPLICATION OF THE BRAKE-MARKER FOR PARAMETERISATION OF THE VEHICLE BRAKING PROCESS

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Braking efficiency is one of the most important elements of a car's safety. The length of the braking distance may be influenced by many elements, including the braking system, tire condition, and suspension components, but also the state of the road surface at the braking point. Therefore, the correct determination of the braking distance measurement is one of the most essential elements in the road accident reconstruction process. This article presents a device – a marker for the beginning of the braking process called a Brake-Marker – developed at Łukasiewicz-PIMOT. The structure and operation, as well as the method of using this device in the process of testing vehicles under braking conditions are shown. This work presents the device and its research methodology, leading to the assessment of the possibility of using it to estimate the length of the braking distance at the site of a road incident. The authors of this study offer a thesis that the presented braking device can be used by experts and services to measure the braking distance in road conditions and for the process of road accident reconstruction.

Keywords: Road traffic safety, vehicle inspections, braking distance, braking delay, adhesion coefficient

1. Introduction

Stopping distance is one of the key parameters of a car that directly affects road safety. The braking distance of a car depends on many factors, including the car's initial speed, the coefficient of adhesion of the wheels to the road surface, the type and technical condition of the braking system, and the braking technique. The exact value of the adhesion coefficient is often difficult to determine. It depends on the type of road surface and its condition (Jackowski *et al.*, 2023), weather conditions, as well as the car's tires, including the type of tread pattern, tire pressure (Rievaj *et al.*, 2013), type of rubber mixture, tire age (Lorencic, 2023), and many other factors. The stiffness of tires, vehicle suspension, and the technical condition of shock absorbers also influence the braking distance (Hryciów *et al.*, 2021). Additionally, in trucks, the braking process is influenced by factors such as load distribution or the condition of the load securing devices. (Zuska *et al.*, 2023) discussed the differences in maximum deceleration values achieved by different types of vehicles that are structurally suitable for freight transport. Knowing the car's braking capabilities, apart from the obvious impact on safety, is also crucial for determining a sufficient distance between nearby vehicles, called the "assured clear distance ahead" (ACDA) (Elsagheer *et al.*, 2022), which in turn is used in the operation of driver assistance systems.

Determining the braking distance in the prevailing road conditions at a given moment is a critical element of the road accident reconstruction process. This issue is discussed in detail in the literature, among others, in (Drobiszewski *et al.*, 2015) and (Lozia *et al.*, 2010). The devices used today allow for the determination of braking distances in laboratory conditions, e.g., in accordance with braking approval regulations (Regulation No 13, 2016), with an accuracy sufficient to compare the braking effectiveness of individual vehicles, as well as the elements used in them, such as its tires, brake pads, or brake system variants.

In the process of reconstructing road accidents in Poland, services dealing with road accident reconstruction are usually limited to assessing the length of braking marks, the descriptive characteristics of the type and condition of the road surface, and the condition of tires. Based on this, the expert estimates (with some approximation) the speed of the vehicle at the moment of braking. In the future, it would be advisable to use measuring devices to increase the accuracy of vehicle speed estimation, which is often decisive in the court's decisions on accident cases. One of the key parameters influencing the measured braking distance is determining the start time of the braking process. When measuring braking distances, two methods are used to determine the beginning of braking: based on the recorded pressure on the brake pedal or changes in driving speed (exceeding a pre-defined limit).

In professional research laboratories, satellite-inertial devices are most often used to determine the parameters of the car braking process. They are characterized by high accuracy, ease of use, and adaptation to applicable standards. Unfortunately, their main disadvantage is their high price. Devices such as RT3000 (Figure 1), Vericom VC4000DAQ, or ONO SOKKI LC-8300 measure speed using the GPS/GLONASS system. Additionally, to improve its accuracy, the inertial measurement unit (IMU) system is used to complement the GPS system, especially in dense and high-rise conditions.

Devices of this type provide, among others, such functionalities as (Niekreś, 2019):

– measurement of vehicle acceleration (measurement of time, speed, and acceleration to a given speed at a set distance interval),
– the mean fully developed deceleration (MFDD) braking test,
– ABS braking test,
– fade recovery braking test (measurement of the MFDD coefficient during several consecutive braking events),
– vehicle coast down test (measures parameters during free driving of the vehicle until it stops with the power transmission system from the engine to the wheels disconnected).

Figure 1. RT3000 satellite-inertial device

An alternative to the above-mentioned functionalities is using devices whose operation is based on measuring the vehicle's longitudinal and/or lateral acceleration. Such devices are also used in tests conducted by car inspection stations that cannot be tested on stationary inspection devices, e.g., some trucks. Devices such as XL Meter or Brake Tester LWS-2/BS enable the determination of, among others, braking duration, maximum deceleration, average deceleration (MFDD), speed of the tested vehicle at the moment of braking initiation, length of the braking distance, and pressure on the brake pedal.

Devices for non-contact measurement of speed and distance travelled by the vehicle are also used to study the dynamics of motor vehicles using the correlation-optical principle. Devices of this type (e.g., Correvit or Datron) equipped with optical sensor (Figure 2) measurement techniques dominated road research before the introduction of GPS-based devices. Despite the passage of time, due to the high measurement accuracy, they are still valuable tools for determining the travelled distance (Rievaj *et al.*, 2013).

Figure 2. Datron sensor mounted in a military vehicle

There are also other methods of measuring braking process parameters in the literature. Their common denominator is the desire to reduce equipment costs while maintaining the required measurement accuracy. They are very often developed and then used in educational institutions.

Figure 3. “Shot marker” device installed in an Opel Agila vehicle. Source: (Drobiszewski *et al.*, 2015)

To effectively mark the beginning of the braking distance, Łukasiewicz-PIMOT has developed an original solution, a marker for the beginning of the braking process known as Brake-Marker, modeled for its purposes on similar solutions available worldwide. Descriptions of similar devices and their use can be found in the literature, among others in (Luty, 2015). The main goal of the Brake-Marker authors is to develop a simple device that supports the work of services dealing with road accident reconstruction and teams testing the effectiveness of braking systems and their components.

The commercially available devices described in this chapter may be helpful in the work of car appraisers and services dealing with broadly understood road traffic issues. However, most of them are expensive, and their purchase is often economically unjustified due to the small number of applications per year and the costs of legalization. For this reason, it is advisable to fill the gap with a relatively cheap device with high operating efficiency, which will also fulfil its basic function – measuring the braking distance. On this basis, it is possible to calculate the adhesion coefficient on the tested surface or further estimate the vehicle’s initial speed at the accident scene.

The main aim of this work is to assess the accuracy of the Brake-Marker device, develop a research methodology, and determine the necessary corrections resulting from the nature of the device’s operation. An additional goal is to assess the possibility of using it when road accident experts measure the length of the braking distance at the site of a road incident and, on this basis, determine the value of the wheel adhesion coefficient to the road surface, averaged over the length of the braking distance.

In (Gogola *et al.*, 2022) and (Kolla *et al.*, 2020), the authors compared the operation of a measurement system based on a smartphone with the mSTK application with the XL Meter system. Tests performed for various surfaces showed differences of several percent when determining the braking delay. However, this measurement method makes it difficult to determine the braking distance due to the inability to register the moment of braking initiation and errors resulting from the need to integrate the acceleration course twice. (Kuchar *et al.*, 2022) compared the results of vehicle dynamic tests performed based on the XL Meter, VBox GPS, and fifth-wheel devices. The obtained results indicate the highest accuracy in measuring the distance traveled by the vehicle using the fifth wheel. Lower accuracy was obtained using the GPS system, while the largest differences (approximately 3.48%) were obtained with the XL Meter device. For this reason, systems based on acceleration measurement are not recommended for braking distance tests.

Direct measurement (e.g., using a laser rangefinder or measuring tape) is an attractive way to determine the braking distance of a vehicle. The fundamental problem, however, relates to finding the place where the driver started to brake. For this purpose, various marker designs are being developed. For example, Braker Box has developed the Shot Marker device (Figure 3). It uses a pyrotechnic launcher system to shoot markers of the starting point of braking. In the authors’ opinion, a certain drawback of this device is the electromagnetic actuator used, which is characterized by a relatively long activation delay from the moment of applying voltage (about 0.1 s (Reust, 2000)). However, the marker’s relatively high muzzle velocity resulting from using pyrotechnic materials may be an advantage. The device uses the principle of direct measurements of the braking distance using a tape measure and, assuming that the marker throwing time is consistent with the brake application time, the beginning of the braking force build-up time and the accuracy of this device may be higher than that of electronic devices using, e.g., a satellite signal. Currently, the device is used for laboratory classes with students at the Warsaw University of Technology Faculty of Transport.

2. Methodology for determining the braking distance

Figure 4 shows a diagram of the changes in characteristic values in the braking process. It displays distance, speed, and deceleration changes in subsequent braking phases.

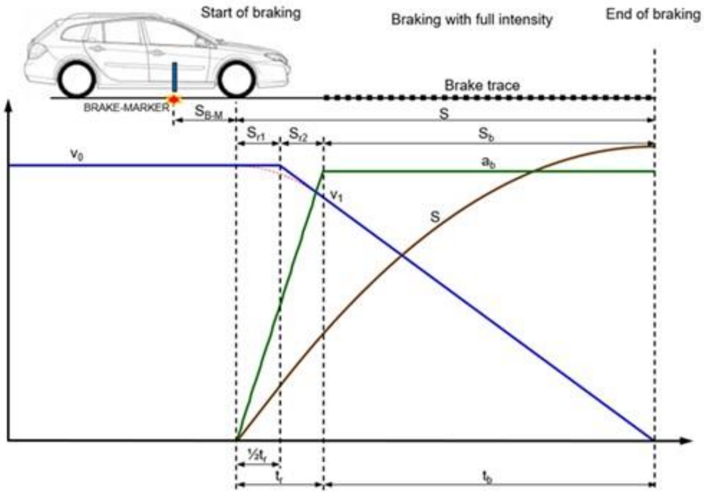

Figure 4. Diagram of the car braking process

The following symbols have been adopted in the diagram above: t_r denotes the braking force build-up (rise) time, t_b signifies the braking time with full intensity, S is the braking distance, S_r is the distance traveled during the braking force build-up, S_b is the braking distance with full intensity (length brake trace), v_0 is the initial vehicle speed, v_1 is the speed after time t_r, and a_b is the fully developed braking deceleration.

The presented diagram makes it possible to determine the characteristic values of the braking process. Individual quantities can be presented with a system of equations:

$$S = S_{\mathrm{r1}} + S_{\mathrm{r2}} + S_{\mathrm{b}} = v_0 \frac{t_{\mathrm{r}}}{2} + \frac{1}{2} a_{\mathrm{b}} (\frac{t_{\mathrm{r}}}{2})^2 + \frac{1}{2} a_{\mathrm{b}} t_{\mathrm{b}}^2, \tag{1}$$

$$a_{\mathrm{b}} = \frac{v_1}{t_{\mathrm{b}}}, \tag{2}$$

$$v_1 = v_0 - a_{\mathrm{b}} \frac{t_{\mathrm{r}}}{2}, \tag{3}$$

where the data determined as a result of the braking test are *S*, S_b, and v_0, and the searched data is given by t_b, a_b, t_r, and v_1 (Jackowski *et al.*, 2023).

Solving the system of equations enables us to find the sought values of the physical quantities characterizing the vehicle braking process, i.e., using:

$$t_{\mathrm{b}} = \frac{2S_{\mathrm{b}}\left(2+\sqrt{1+\frac{3S_{\mathrm{r}}}{S_{\mathrm{b}}}}\right)}{3\mathrm{v}_0}. \tag{4}$$

$$a_{\mathrm{b}} = \frac{2S_{\mathrm{b}}}{t_{\mathrm{b}}^2}. \tag{5}$$

$$v_1 = a_{\mathrm{b}} t_{\mathrm{b}} \tag{6}$$

$$t_{\mathrm{r}} = \frac{2(V_0 - V_1)}{a_{\mathrm{b}}} \tag{7}$$

Determining the values of these physical quantities provides measurable results. The value of the rise time t_r carries information about the technical condition of the vehicle's braking system. However, the average value of the braking deceleration a_b is approximately equal to the MFDD value. In the case of a test, the comparison makes it possible to estimate the value of the adhesion coefficient of the vehicle tire to the ground, averaged over the length of the braking distance, according to the following expression:

$$\mu \approx \frac{\mathrm{MFDD} - g\sin\alpha}{g\cos\alpha}, \tag{8}$$

where α represents the angle of longitudinal inclination of the road surface, and μ is the value of the tire adhesion coefficient to the road surface, averaged over the braking distance S_b.

When the length of the braking marks has not been measured, it is possible to calculate the values of the quantities characterizing the braking process, assuming the braking force rise time t_r. This value depends, among other things, on the type and design of the braking system. It is generally assumed that passenger cars equipped with a hydraulic braking system are within the range of 0.2–0.3 s (Jánošík *et al.*, 2022) and (Kamiński *et al.*, 2019). The braking time with full intensity can be determined from the positive root of the quadratic equation, i.e.:

$$t_\mathrm{b}^2 + \left(t_\mathrm{r} - \frac{2\cdot \mathrm{S}}{\mathrm{v}_0}\right) t_\mathrm{b} + \frac{3}{4} t_\mathrm{r} - \frac{S\cdot t_\mathrm{r}}{\mathrm{v}_0} = 0 \quad (9)$$

and the braking deceleration can be found from the following:

$$a_\mathrm{b} = \frac{v_0}{t_\mathrm{b} + 0.5 t_\mathrm{r}}. \quad (10)$$

Despite the lack of exact knowledge of the braking force rise time t_r, acceptable results are obtained. Table 1 presents the results of testing the sensitivity of braking deceleration calculations depending on the determination of the initial speed v_0, the length of the braking distance S, and the assumed time t_r. The differences in the obtained results relate to the following base data: v_0 = 55 km/h, S = 19 m, and t_r = 0.25 s. The presented results show that a change in tr by 0.05 s causes only changes in the deceleration of 0.2%. The correct measurement of the braking distance and, above all, the initial speed is much more important. Its change of 2 km/h modifies the value of the calculated delay by over 7%.

Table 1. Results of the sensitivity of ab to changes in the input data

	v_0 = 55 km/h,	**v_0 = 55 km/h, S = 19 m,**		**v_0 = 55 km/h, t_r = 0.25 s**		**S = 19 m, t_r = 0.25 s**	
	S = 19 m, t_r = 0.25 s	**t_r = 0.2 s**	**t_r = 0.3 s**	**S = 18.5 m**	**S = 19.5 m**	**v_0 = 53 km/h**	**v_0 = 57 km/h**
a_b [m/s^2]	6.17	6.16	6.19	6.34	6.01	5.73	6.63
δ_{ab} [%]	–	–0.18%	0.23%	–7.17%	7.45%	2.73%	–2.59%

3. Brake-Marker device

3.1. Construction and operation

The device consists of several basic elements, as detailed in Figure 5. It is attached to the vehicle using suction cups with the barrel pointing perpendicular to the ground. The bullet containing paint is placed in the barrel. It is a ball filled with food colouring, typical of pneumatic weapons used in the military game paintball. The compressed air stored in the pressure accumulator displaces the container, eventually causing it to crash into the road surface and mark the point where the driver began pressing the brake pedal.

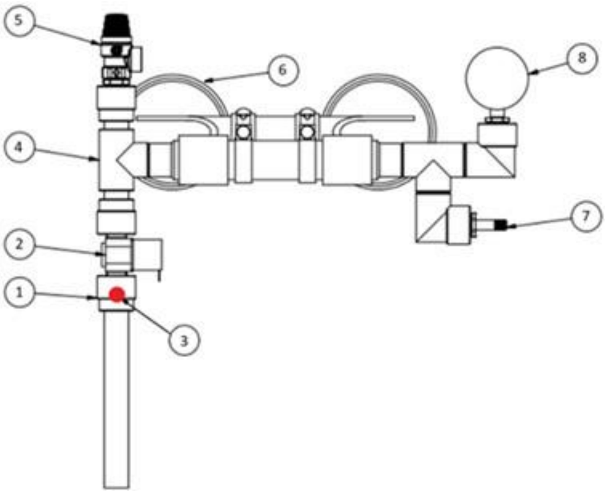

Figure 5. Depction of the Brake-Marker: 1) barrel, 2) solenoid valve, 3) paintball, 4) pressure accumulator, 5) safety valve, 6) vacuum mounting bracket, 7) pressure gauge charging valve, and 8) pressure gauge

According to the authors' concept, the device may have two alternative actuation methods: mechanical-electric and optoelectronic-electric. In the case of mechanical-electric actuation, the signal is taken from the contactor on the brake pedal pad. The contactor is activated when the driver starts pressing the brake pedal. In the case of optoelectronic triggering, the car's stop light signal is used to record the moment when the lights are turned on. The prototype of the device uses a mechanical-electric actuation variant.

3.2. Bench tests

The prototype of the Brake-Marker device (Figure 6) was subjected to bench tests using an oscilloscope and a system for recording the impact of the marker on the road surface. The research aimed to assess the possibility of using the device in road tests and preparing data for corrections when processing the results. Particular attention was paid to measuring the delay time in the activation of the device, including the accuracy and repeatability of the operation of the solenoid valve and the electric trigger system. The initial velocity of the marker at various pressures in the propellant system was also determined.

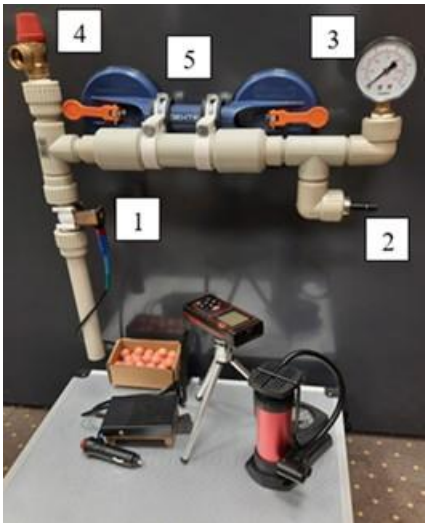

Figure 6. View of the prototype of the Brake-Marker device: 1 – solenoid valve, 2 – charging valve, 3 – pressure gauge, 4 – safety valve (at 0.6 MPa), 5 – mounting mechanism

Using an oscilloscope, the voltage waveforms in the trigger circuit that activate the solenoid valve and the voltage in the system recording the impact of the ball on the road surface were recorded (Figure 7). This made it possible to determine the delay time Δt in marking the starting point of braking and, in connection with the initial car speed, to determine the correction to the designated braking distance.

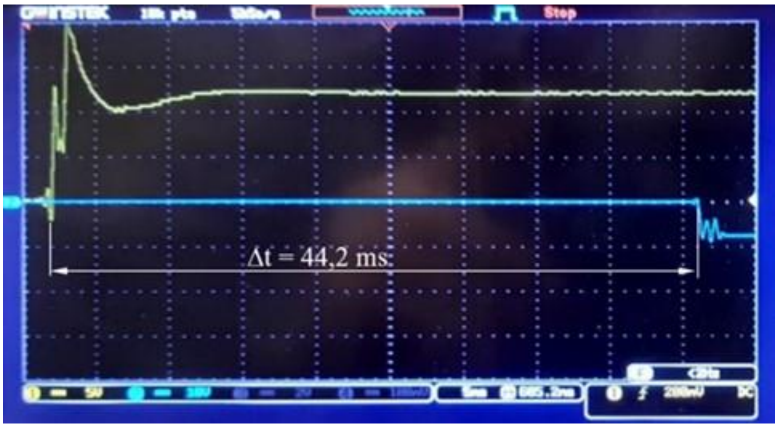

Figure 7. An example of voltage waveforms recorded on an oscilloscope: yellow – voltage on the control solenoid valve; blue color – voltage changes in the measuring system recording the impact of the ball on the road surface

During the tests, the barrel muzzle was directed vertically downwards. The tests were carried out for two values of pressure po in the propelling system (i.e., 0.25 and 0.4 MPa) and two heights ho position of the paintball in relation to the impact recording plate (0.5 and 1.5 m, respectively). For each configuration, ten repetitions were performed. Mean values and standard deviations are presented in Table 2.

Table 2. Device delay times for different altitudes and system pressures

Pressure after p_o [MPa]	**Height h_o [m]**	**Delay time Δt [ms]**	
		Mean	**Standard deviation**
0.25	0.5	43	1.4
	1.5	81	3.5
0.4	0.5	41	1.4
	1.5	74	2.1

Based on measurements and bench tests, the following operating conditions of the Brake-Marker device were assumed:

- working pressure of the device was in the range of 0.39–0.41 MPa;
- recommended height of the ball containing paint was 0.48–0.52 m (the lower edge of the barrel was 0.28–0.32 m);
- the outlet speed of the paint container was about 30 m/s;
- the delay time when marking the starting point of pressure applied on the brake pedal for the recommended heights of the lower edge of the propeller valve outlet and working pressure was 0.041 s;
- the device should be installed, if possible, halfway between the vehicle axles.

The device is additionally equipped with a pneumatic pump, a laser rangefinder with a range finder of 100 m, and a transport case that also serves as a board to mark the place where the paint container hits the road surface.

4. Results of road tests

A Renault Laguna 3 Grandtour vehicle was used for road tests. The vehicle was instrumented (depicted in Figure 8) in accordance with the assumptions indicated above. The tests were conducted on the Łukasiewicz-PIMOT road training ground with a smooth concrete surface. The surface condition was wet, there was light rainfall during the tests, and the air temperature was approximately 3 °C.

The braking parameters were recorded using the RT 3000 satellite-inertial device mounted and positioned on the vehicle in accordance with the manufacturer’s requirements. During the tests, ten braking actions were performed, during which the driver rapidly pressed the brake pedal and kept it pressed until the car stopped completely.

Figure 8. A prototype of the Brake-Marker device mounted on a vehicle

As a result of braking, measurement results were obtained from the RT 3000 device (in accordance with ECE Regulation 13), and braking distance measurement results were based on the markings of the Brake-Marker device. The results of the braking distance measured using the two independent methods are summarized in Table 3. Based on the analysis of the results, it can be concluded that the Brake-Marker device has a relatively high accuracy. The average difference in braking distances measured with the two devices did not exceed 0.36 m (which is less than 2% of the average braking distance).

Table 3. Braking distance measurement results

Measurement no.	RT 3000			Brake-Marker	Difference	
	Speed		Distance	Distance	Absolute	Relative
	V [km/h]	*V* [m/s]	S_1 [m]	S_2 [m]	[m]	[%]
1	54.1	15.03	18.5	18.20	0.30	1.62
2	50.4	14.00	16.1	16.62	–0.52	3.23
3	48.4	13.44	15.7	15.23	0.47	2.99
4	55.3	15.36	18.3	18.53	–0.23	1.26
5	53.1	14.75	16.9	16.98	–0.08	0.47
6	57.1	15.86	18.8	18.89	–0.09	0.48
7	55.4	15.39	19.2	18.37	0.83	4.32
8	55.8	15.50	19.8	19.35	0.45	2.27
9	55.8	15.50	19.9	19.45	0.45	2.26
10	58.1	16.14	22.20	21.99	0.21	0.95
Mean absolute measurement difference					0.36 m	
Average relative measurement difference					1.98%	
Standard deviation					0.23 m	

The waveforms of the braking deceleration as a function of time, recorded by the RT 3000 satellite-inertial device, for three braking tests (no. 7, 8, and 9) at which the speeds of the beginning of braking are most similar are shown in Figure 9. Accordingly, in Figures 10 and 11, the changes in speed and distance traveled during these tests are summarized. In these graphs, vertical lines mark the beginning of braking (0.5 s was assumed in all graphs) and the moment when the Brake-Marker device marks the beginning of braking (delay of 41 ms – the vehicle moves approximately 60 cm during this time). Based on the analysis of the graphs, the braking deceleration rise time can be determined. A fully developed braking force is achieved approximately 0.25 seconds after pressing the brake pedal.

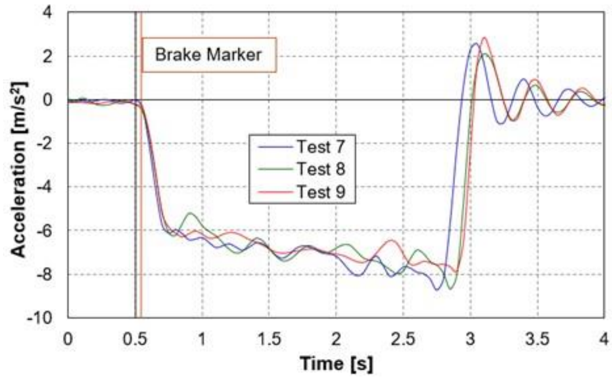

Figure 9. Decelerations recorded by the RT 3000 satellite-inertial device, for three selected braking tests (no. 7, 8, and 9)

Based on the analysis of speed changes, it can be concluded that, in test no. 7, a higher braking intensity was achieved, which resulted in a shorter braking distance (by approximately 0.6–0.7 m compared to tests no. 8 and 9).

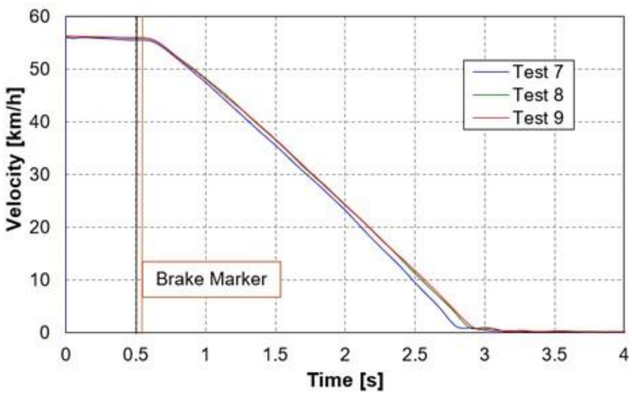

Figure 10. Changes in car speed, recorded by the RT 3000 satellite-inertial device, for three selected braking tests (no. 7, 8, and 9)

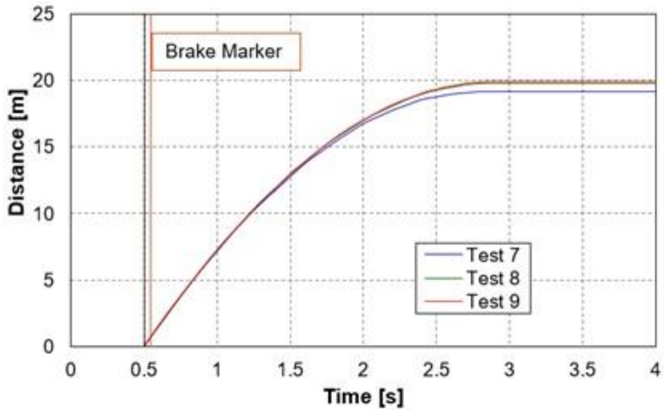

Figure 11. Graphs of the distance traveled during the braking test

Based on the collected emergency braking data, the values of the tire adhesion coefficient to the road surface averaged over the braking distance S_b are calculated based on the relationships presented in Chapter 2. The obtained results are very similar. The maximum difference between the values of the μ coefficient, determined based on two independent braking distance measurements, does not exceed 5%. The average value obtained from the RT 3000 device measurements is 0.633, and the Brake-Marker is 0.639.

Table 4. Values of the adhesion coefficient of wheels to the road surface

Measurement no.	**Adhesion coefficient *μ***		**Relative difference [%]**
	RT 3000	**Brake-Marker**	
1	0.627	0.637	–1.67
2	0.626	0.606	3.18
3	0.592	0.610	–3.14
4	0.662	0.654	1.26
5	0.662	0.659	0.48
6	0.688	0.684	0.48
7	0.633	0.662	–4.59
8	0.623	0.637	–2.36
9	0.620	0.634	–2.35
10	0.602	0.607	–0.97
Average value	0.633	0.639	
Standard deviation	0.029	0.026	

5. Conclusions

The presented test methodology enables the determination of the average value of braking deceleration and then the adhesion coefficient on the tested surface. Sensitivity analysis showed that the accuracy of the initial speed measurement and the braking distance have the most significant impact on the accuracy of the results.

The presented road test results indicate a high repeatability of the results obtained using the Brake-Marker device and compliance with the results from the RT 3000 system. The average value of the adhesion coefficient was 0.639, and its difference (between two independent systems) did not exceed 1%. To increase the accuracy when determining the braking distance and then calculating the braking deceleration and the adhesion coefficient, it is advisable to account for the delay resulting from the time from pressing the brake pedal to marking the position on the road. As a result of the bench tests, the determined delay value was 41 ms.

Bench tests confirmed the correct operation of the Brake-Marker device. The device has the intended functionality and is characterized by the repeatability of measurements, which was confirmed by tests using the certified RT 3000 satellite-inertial device.

The features of the Brake-Marker indicate its usefulness in the process of reconstructing road accidents (for estimating road grip and vehicle speed before the accident). The device is also expected to be widely used as a preliminary assessment of the efficiency of vehicle braking systems without the need to visit a vehicle inspection station for comparative measurements of braking effectiveness on various types of surfaces, tires, and friction elements of braking systems, as well as to conduct laboratory classes with students in the fields of transport and the construction and operation of motor vehicles.

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