Izabela Sudrychova - Jiri Kuczaj - Ladislav Janosik - Pavel Polednak - Ivana Janosikova*

FIREFIGHTING VEHICLES BRAKING DISTANCE METERING

The paper topic is concerned with the issue of braking dynamics and adhesion coefficients of firefighting vehicles at fire rescue units. The real breaking distances at firefighting vehicles of the water tenders type are presented in the paper. The metering was made on the wet and/or dry asphalt, with different age of tires and the carload. Measured results should be used for drivers' education at fire rescue units to increase the safety during the emergency drives.

Keywords: *braking distance, braking deceleration, braking time, adhesion coefficient, firefighting vehicles*

1. Introduction

Braking on different types of road surfaces in a straight or a bend is one of the basic driving skills the driver must be able to handle in a road critical situation. To handle the critical situations is twice more important for firefighting truck drivers. Their main task is to ensure a safe and rapid transport of the fire rescue unit to an emergency site. The speed of the firefighting truck must be safe in terms of being safely stopped in a critical situation where avoiding an obstacle is impossible to be made. An analysis of Accident Statistics 2011 to 2016 showed that the speeding caused 35 traffic accidents of water tenders only (19 %) during the emergency drive. However, these accidents accounted up to 89 % of total vehicle damage (EUR 1.4 million) in the analysed period [1]. Just those facts have been the reason why the focus of this research was on that basic driving parameter of the firefighting vehicles, which is the braking distance and its change under different conditions. The metering was carried out on the firefighting vehicles deployed at the Fire Rescue Service (FRS) of the Moravian-Silesian Region. For this research, the management of the FRS of the Moravian-Silesian Region granted the firefighting vehicles with the drivers and financed the time spent on the leased training polygon of the LIBROS safe riding centre in Ostrava.

2. Firefighting vehicles

These four firefighting vehicles were used for the metering: Mercedes-Benz Econic 4×2 (Registration numbers: 5T7 9464, 6T8 9896), TATRA T815-2 TerrNo1 4×4.2 (Registration number: 9T5 2242) and TATRA T815-7 6×6.1 (Registration number: 9T5 2260).

The first tested firefighting vehicle *Mercedes-Benz Econic 1833LL 4×2* has a fire mark CAS 20/2700/200-S1T. The two-axle chassis MB Econic 1833LL 4×2 with continuous frame has been designed to operate on paved roads and has a rear axle drive that is equipped with a differential lock. The length of the vehicle is 8220 mm, the width is 2550 mm and the height reaches 3150 mm. The water tank is of a 2700 litres capacity and the foam tank is of 200 litres capacity. The operating weight is 12750 kg and the total weight is 18000 kg. The firefighting vehicle is equipped by a two-ring pressurized air system. The disc brakes are situated on both axles. The firefighting vehicle is equipped by a retarder, ABS and ASR. The front axle of the firefighting vehicle was fitted with Michelin guiding tubeless tires, X Multiway 3D 315/80 R 22.5 radial. On the dual tire rear axle, the tubeless all-season tires Michelin Grip Cold 315/80 R 22.5 radial were used. The front tires were inflated with a pressure of 750 kPa, the rear ones at 730 kPa [2]. Vehicle Registration Number 5T7 9464 tires had a DOT Code 1812 (manufactured in the 18th week of 2012) and they had a 6 mm tread depth. Tires on the second vehicle Registration Number 6T8 9896 had DOT code 1011 (manufactured in the 10th week of 2011) and they had a 5 mm tread depth.

The third tested firefighting vehicle *TATRA T815-2 Terr No1 4×4.2* has a fire marking CAS 20/4000/240-S2T. The chassis has the designation T815-231R55/411. It is a mixed two-axle chassis with an attachable front-axle gear. Both axles are equipped by a differential lock. The length of the vehicle is 7825 mm, width 2550 mm, height 3150 mm. The water tank volume is 4000 litres and the foam tank volume is 240 litres. The operating weight is 12750 kg and the total weight is 18000 kg. The car is equipped with a two-ring pressurized air system. The drum brakes are situated on both axles. The vehicle has an ABS only. The front axle of the car was fitted with Michelin, Cold 385/65 R 22.5 guiding radial tires. The rear axle with double assembly was equipped with the tubeless Barum Road Drive 315/80 R 22.5 radial tires. The front tires were inflated at 800 kPa, the rear ones at 700 kPa [3]. The tires had a DOT code 2614 (manufactured in the 26th week of 2014) and a 12 mm tread depth.

The fourth tested firefighting vehicle *TATRA T815-7 6×6.1* has a fire marking CAS 30/9000/540-S3VH. Vehicle length is 9170 mm, width 2550 mm, height 2830 mm. The water tank has a capacity of 9000 litres and the foam tank volume is 540 litres. The operating weight is 14500 kg and the total weight is 25000 kg. The car is equipped by a two-ring pressurized air system. The drum brakes are on both axles. The vehicle has an ABS only. The car is 3-axle with an all-wheel drive, a simple tire fitting and

* [1]Izabela Sudrychova, [1]Jiri Kuczaj, [1]Ladislav Janosik, [1]Pavel Polednak, [2]Ivana Janosikova
[1]Faculty of Safety Engineering, VSB - Technical University of Ostrava, Czech Republic
[2]Faculty of Economics, VSB - Technical University of Ostrava, Czech Republic
Email: ladislav.janosik@vsb.cz

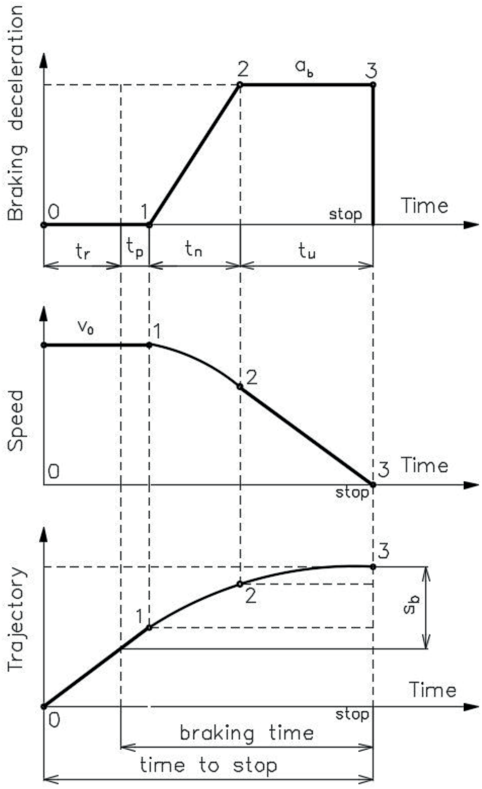

Figure 1 *The course of the braking process*

a differential lock. The front wheel drive is attachable. The car was fitted with radial year-round tires from Continental 14.00 R20 on all three axles. The tires are pressurized at 610 kPa [4]. The tires had a DOT code 0415 (manufactured in the 4th week of 2015) and a 16 mm tread depth.

3. Measuring instruments

The *Performance Box* from Racelogic Ltd, Buckingham, England, was used to measure driving characteristics. A detailed description of this device is available on the manufacturer's website [5]. The device is designed to detect the absolute positioning of the vehicle in the real time. The device then calculates the path, speed, acceleration and many other variables. The recordable frequency is 10 Hz. Its accuracy is determined by the real-time positioning of the vehicle by using signals from three satellite systems (GPS, GLONASS and a third system not identified by the manufacturer). An accuracy of 0.2 km/h at a resolution of 0.01 km/h is given for the speed measurement. An accuracy of 0.05 % (less than 50 cm per 1 km) and 1 cm resolution is given for the trajectory measurement. The accuracy and resolution of the time recording is given by the frequency of the instrument, i.e. 0.1 s. The speed, braking distance and braking deceleration of the vehicle were evaluated using this instrument. The device is equipped with an SD card to store the recorded data. The data were then transferred to the computer and further processed in the VBOX Test Suite version 1.7.55.2453.

The *MASTECH MS6520H −20 °C + 300 °C* infrared thermometer was used to measure the road surface and brakes temperatures. This contactless thermometer has an accuracy of ± 2 %, a resolution of 1 °C, an emission level of 0.95 and an optical resolution of 1:10. The thermometer has a laser pointer, it writes the minimum, maximum and average measured temperature.

4. Theoretical basis of the braking process

The theoretical course of the braking process can be depicted on three graphs (see Figure 1) that describe variations in speed, path, and acceleration over time [6]. The necessary variables are then calculated in the following Equations (1) to (3). For the calculation needs, one does not need to include driver's response time t_r. Within experiments, the driver knows the moment of braking. He only keeps a constant speed until the start of braking is indicated on the test path.

The breaking distance s_b is calculated according to:

$$s_b = v_0 \cdot t_{pr} + \frac{1}{2} \cdot \frac{v_0^2}{|a_b|}. \tag{1}$$

The initial speed v_0 is the speed at which the vehicle was moving before the braking started. The preparation time t_{pr} is characterized by the delay time t_p and the reaction time t_n. The delay time is the time between the moment the brake pedal is depressed and the moment of brake system starts to operate, i.e. when the brake lining abuts against the brake pad. The

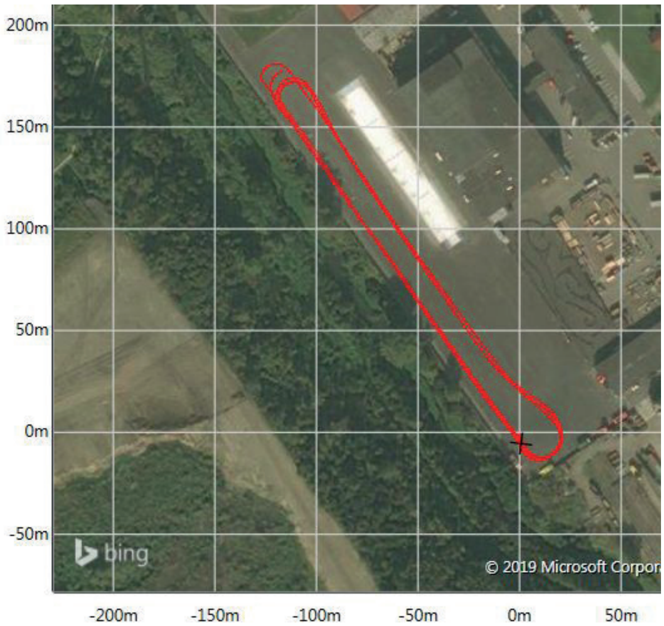

Figure 2 *Vehicle M-B Econic position record when testing*

reaction time is the time before the brakes start to work fully. The preparation time is calculated according to:

$$t_{pr} = t_p + \frac{t_n}{2}. \quad (2)$$

According to [6], the variables values are usually t_p = 0.05–0.15 s, t_n = 0.03–0.15 s. The average values used for the assessment of traffic accidents are given t_p = 0.1 s and t_n = 0.2 s [7]. Theoretically, one can calculate the braking deceleration a_b according to:

$$|a_b| = g \cdot \mu. \quad 3)$$

The coefficient of adhesion μ can be taken from the literature for a theoretical calculation, e.g. [4]. At first, it is necessary to calculate the required breaking distance for the safe execution of the experiments.

By adjusting Equation (1), one obtains the equation for calculating the real braking deceleration a_b, based on the experimentally measured values, where s_b is the braking distance, t_{pr} the preparation time and v_0 the initial velocity:

$$|a_b| = \frac{v_0^2}{2 \cdot s_b - (2 \cdot v_0 \cdot t_{pr})}. \quad (4)$$

For this calculation, the delay time t_p = 0.1 s and the reaction time t_n = 0.02 s were calculated. The same values were used for all the three vehicle types as they were determined by the same design type of the braking system. After adjusting the Equation (3), one can calculate the adhesion coefficient μ.

5. Methods

The experimental measurement of braking distances took place at the training centre of the LIBROS Safety Centre in Ostrava, Palacky 1114 Street, in 2018, March 14. The surface of the experimental track was dry asphalt (bituminous, weathered, 8 years old). The first measuring started at 7:00 a.m. and the experimental driving was completed at 3:00 p.m. The air temperature was 10 °C at the beginning of the experiment. At 9:10, started to rain and the air gradually cooled to 5.5 °C. An example of a M-B Econic (registration mark 6T8 9896) vehicle position recording in the orthophoto map when evaluating the first set of experiments in the VBOX Test Suite software is shown in Figure 2. The vehicle's starting position is marked with a cross in the figure.

To determine the real adhesion coefficients μ according to Equations (3) and (4), it was necessary to determine the breaking distance of a vehicle s_b. The breaking distance is given by the point of change (decrease) in its initial velocity v_0, at which the driver started to brake until the moment of stopping the vehicle. The braking time was also found from the graphs.

The exact speed of the vehicle was checked by the driver using the Performance Box, which was attached to the vehicle's windscreen in driver's field of view. For the M-B Econic, the initial speed before starting braking was determined at v_0 = 60 km/h. For TATRA vehicles, the initial speed v_0 = 50 km/h was determined.

The procedure for each experiment was as follows. The Performance Box was placed in the car. The driver started the vehicle after activating the device and establishing a satellite connection and then began to accelerate to the agreed initial speed v_0. The driver started to brake as much as possible after reaching and stabilizing that speed. This experimental drive was carried out 5 times on a defined circuit. One measured run on a test circuit lasted about 80 seconds. The Performance Box was moved to the next vehicle after finishing of each measured series. These experiments were conducted for each of the 4 vehicles tested.

Realized experiments on the training polygon were divided into the following three stages from the perspective of the load and the state of the road surface:

***Table 1** Input driving characteristics with full water tank on dry asphalt*

Vehicle (registration mark) Parameter	MB Econic (6T8 9896)	TATRA 815-7 (9T5 2260)	TATRA 815-2 (9T5 2242)	MB Econic (5T7 9464)
Test time [hh:mm]	07:00	07:42	08:10	08:22
Air temperature [°C]	10.0	10.0	10.0	10.0
Road surface temperature [°C]	6.6	6.6	6.0	6.7
Initial speed [km/h]	60	50	50	60
Front brake temperature [°C]	192	150	78	195

***Table 2** Input driving characteristics with full water tank on wet asphalt*

Vehicle (registration mark) Parameter	MB Econic (5T7 9464)	MB Econic (6T8 9896)	TATRA 815-2 (9T5 2242)	TATRA 815-7 (9T5 2260)
Test time [hh:mm]	09:22	09:41	10:05	10:20
Air temperature [°C]	6.0	6.0	7.0	6.0
Road surface temperature [°C]	6.5	5.7	5.5	5.8
Initial speed [km/h]	60	60	50	50
Front brake temperature [°C]	243	241	87	94

***Table 3** Input driving characteristics with empty water tank on wet asphalt*

Vehicle (registration mark) Parameter	MB Econic (6T8 9896)	MB Econic (5T7 9464)	TATRA 815-2 (9T5 2242)	TATRA 815-7 (9T5 2260)
Test time [hh:mm]	13:45	14:05	14:20	14:40
Air temperature [°C]	7.0	9.0	8.0	9.0
Road surface temperature [°C]	5.6	5.9	6.1	6.2
Initial speed [km/h]	60	60	50	50
Front brake temperature [°C]	186	183	70	47

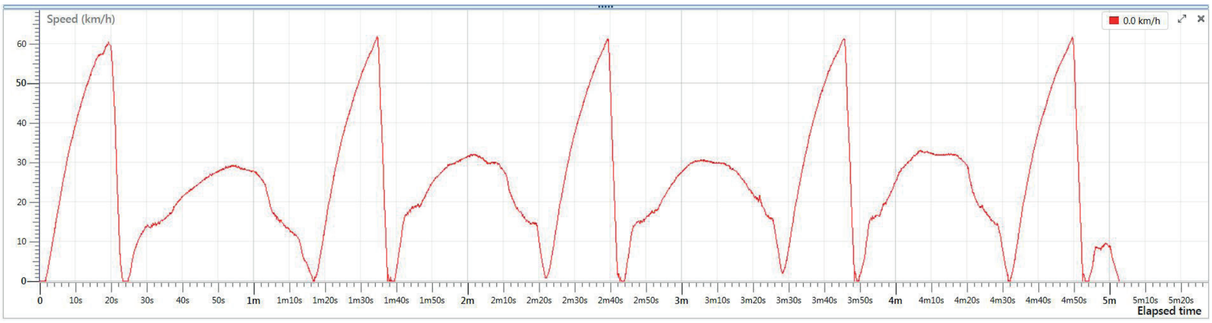

***Figure 3** Speed record based on M-B Econic vehicle time during testing*

- driving with a full water tank on dry asphalt (see Table 1),
- driving with a full water tank on wet asphalt (see Table 2),
- driving with drained water tank on wet asphalt (see Table 3).

The fourth stage of experiments with a drained water tank on dry asphalt fell out from the original plan due to the change of weather.

The outside air temperature was recorded by the thermometers installed in the vehicles before each measurement. The contactless thermometer was used to measure the surface temperature of the road on which the vehicle was moving. The measurement start time was also recorded. At the end of the 5 measurements the brake temperature was measured by a contactless thermometer. In the following Tables 1 to 3, all of these recorded environmental and vehicle data are summarized.

6. Results

The presentation of individual experiments results is summarized in the following sections in the time sequence in which they were carried out. Figure 3 shows the M-B Econic's speed record (6T8 9896) during the first stage of the experiment. The record shows the continuous course of all the five measured rides.

Figure 4 shows a detail of the first run processing of the above record. The vehicle speed is presented here in two graphs depending on time and distance. The marked limits can be visually checked on the upper graph for a braking time of about 3.3 s and a braking distance of 26.3 m. The resulting values were determined by the VBOX Test Suite to evaluate all the measurements by specifying that the initial velocity is equal to v_0

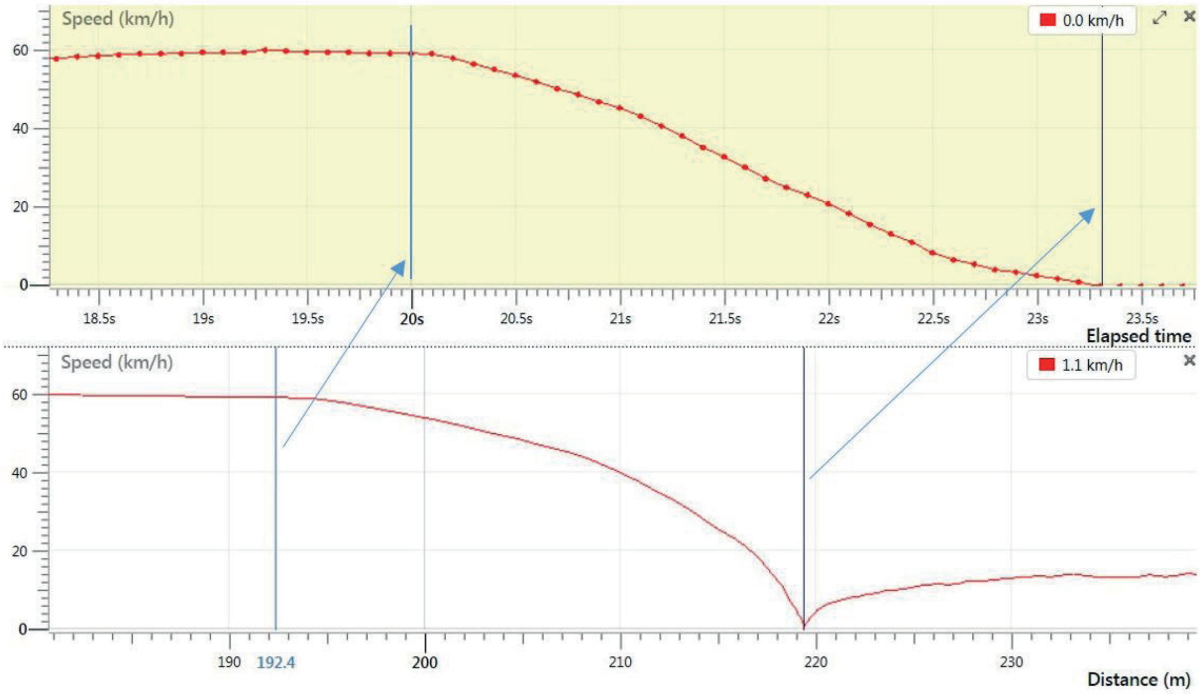

***Figure 4** Detail of the first run processing*

***Table 4** Results of braking distances measuring on dry asphalt with full water tank*

order	MB Econic (6T8 9896)		TATRA 815-7 (9T5 2260)		TATRA 815-2 (9T5 2242)		MB Econic (5T7 9464)	
	time (s)	breaking distance (m)	time (s)	breaking distance (m)	time (s)	breaking distance (m)	time (s)	breaking distance (m)
1	3.26	26.30	2.61	18.86	2.83	16.88	2.92	25.02
2	2.58	21.82	2.88	18.02	2.40	17.39	3.27	25.34
3	3.08	21.37	2.71	16.03	2.37	16.74	3.35	24.57
4	2.58	21.97	2.41	17.10	2.36	17.15	3.20	26.70
5	2.64	21.69	2.46	17.32	2.82	17.50	2.77	23.58

***Table 5** Results of braking distances measuring on wet asphalt with full water tank*

order	MB Econic (5T7 9464)		MB Econic (6T8 9896)		TATRA 815-2 (9T5 2242)		TATRA 815-7 (9T5 2260)	
	time (s)	breaking distance (m)	time (s)	breaking distance (m)	time (s)	breaking distance (m)	time (s)	breaking distance (m)
1	2.86	23.70	2.89	23.89	3.39	29.38	2.78	20.12
2	2.71	23.23	2.62	22.74	2.66	19.09	2.57	18.19
3	2.87	23.86	3.17	24.15	3.05	18.74	2.95	17.79
4	3.33	23.64	3.54	25.29	2.61	18.35	2.87	22.74
5	7.68	28.27	3.28	25.59	2.52	17.84	2.43	17.32

and the final velocity is zero. The program-determined parameters are shown in Tables 4 to 6, divided into individual measurement stages and according to vehicles in the time sequence of the experiments.

The CAS 20 TATRA 815-2 4×4 (9T5 2242) exceeded the agreed initial speed v_0 = 50 km/h before braking during the first measurement on the wet asphalt with a full tank and repeatedly with an empty tank on the wet asphalt. This distorted the evaluation results. Therefore, these values were not included in the resulting average of the measured braking distances.

At CAS 20 MB Econic 4×2 (5T7 9464) vehicle, when measured on the wet asphalt with a full tank, the driver relieved the brakes. Subsequently, the vehicle was not completely stopped and the stopping distance was therefore distorted. For this reason, this experiment is not included in the resulting average of the measured values. On the same vehicle, when measured on the wet asphalt with an empty tank, a brief momentary release of the power supply occurred at 14:09 during the fourth run on the circuit. There is only a part of the record available with the vehicle starting, the record ended at reaching the speed of 56 km/h. After a quick

Table 6 *Results of braking distances measuring on wet asphalt with empty water tank*

order	MB Econic (6T8 9896)		MB Econic (5T7 9464)		TATRA 815-2 (9T5 2242)		TATRA 815-7 (9T5 2260)	
	time (s)	breaking distance (m)	time (s)	breaking distance (m)	time (s)	breaking distance (m)	time (s)	breaking distance (m)
1	2.56	21.28	2.54	21.62	3.09	26.86	2.36	17.32
2	2.74	23.56	2.67	22.79	2.29	15.72	2.51	16.11
3	2.61	21.82	2.70	23.12	2.36	16.23	2.42	15.94
4	2.65	22.38	-	*power failure*	2.42	17.02	2.47	16.05
5	2.70	22.60	2.71	23.99	2.46	17.13	2.56	16.30

Table 7 *Resulting breaking deceleration a_b [m/s^2]*

Vehicle (registration mark)	TATRA 815-2 (9T5 2242)	TATRA 815-7 (9T5 2260)	MB Econic (5T7 9464)	MB Econic (6T8 9896)
Dry asphalt surface, full water tank	6.18	6.05	5.98	6.68
Wet asphalt surface, full water tank	5.68	5.45	6.38	6.17
Wet asphalt surface, empty water tank	6.43	6.51	6.60	6.78

Table 8 *Resulting adhesion coefficient μ [-]*

Vehicle (registration mark)	TATRA 815-2 (9T5 2242)	TATRA 815-7 (9T5 2260)	MB Econic (5T7 9464)	MB Econic (6T8 9896)
Dry asphalt surface, full water tank	0.63	0.62	0.61	0.68
Wet asphalt surface, full water tank	0.58	0.56	0.65	0.63
Wet asphalt surface, empty water tank	0.66	0.66	0.67	0.69

Table 9 *Comparison of the coefficients of adhesion*

Road surface	Theoretical coefficients of adhesion	Calculated coefficient of adhesion
dry asphalt	0.6-0.9	0.61-0.68
wet asphalt	0.3-0.8	0.58-0.65

check by the driver, the power was restored during the ride to the starting position for the fifth run.

The measured braking distances were averaged and the average braking deceleration a_b and the adhesion coefficient μ were calculated according to Equations (3) and (4). The results are shown in Tables 7 and 8.

The resulting values may be distorted by the ABS function. The ABS was activated with the different effect while testing and the wheels were not always blocked, which would probably lead to greater braking deceleration and hence greater coefficient of adhesion.

7. Discussion

The age of the tire counts among many factors that affect the adhesion and thus the resulting braking distance of the vehicle. It is generally believed that the age of the tire affects the adhesion factor. In these experiments with M-B Econic vehicles, the tires produced in March 2011 were used on one vehicle and those produced in May 2012 were used on the second vehicle. The results for specifically tested vehicles did not directly confirm the influence of the tire age on the braking distance.

The expectation that a vehicle with a drained water tank would have a shorter breaking distance has been confirmed.

In Table 9, the theoretical coefficients of adhesion [6] are compared to the measured values. On the wet asphalt, the measured coefficients of adhesion are within the theoretical interval [6]. On dry asphalt, the measured values are closer to the lower limit of the reported interval. The results are likely to be affected by the repeated multiple braking of the vehicles and thus the warming of the brakes.

8. Conclusion

Measurements and calculations found that the coefficient of adhesion between the dry and wet asphalt did not differ significantly. The biggest difference was at the vehicle T815-7, where the full water tank adhesion coefficient was 0.62 on the dry asphalt and 0.56 on wet asphalt (the difference is 0.06).

Another point of interest resulted from the comparison of two M-B Econic cars, when the coefficient of adhesion in two of the three measurements was better for a vehicle with older tires with a more worn out pattern. For a vehicle with the newer tires, the adhesion coefficient was better only with a full water tank and on the wet asphalt. To confirm whether this is caused by tires, more measurements on other vehicles would be required. So far, it can only be said that tires on vehicles parked in garages, where they are not exposed to direct sunlight, do not have significantly different properties compared to younger tires.

A surprising finding was a significant improvement in adhesion on wet asphalt tests, where the water tank was discharged for all the vehicles. If the adhesion theoretically does not depend on the weight of the vehicle, then the ABS must be the cause. This system limits the efficiency of the brake system as the brake temperature does. Each brake system has a certain temperature at which it is the most efficient. The breaking efficiency is not optimal if the brake is at a low temperature or vice versa, then the braking effect is noticeably weakened.

The front brakes temperature was ascertained after each measurement series. A much greater increase in disc brakes on the M-B Econic cars was noticed. They cannot be compared directly to the other two TATRA cars in obtained results. These vehicles had a lower starting speed v_0 due to the limitation of the runway length (approximately 200 m) available to the vehicles for testing. The second aspect is another design of drum brakes on these vehicles.

Acknowledgments

This research was realized within the project of specific research *„Safe ride of fire fighting vehicles to an emergency"*, project registration number SP2017/51 and under the support of the FRS of the Moravian-Silesian Region based on the *„Agreement of the Cooperation"*with the Faculty of Safety Engineering, VSB – Technical University of Ostrava.

References

[1] JANOSIK, L., JANOSIKOVA, I., COCHLAR, M., JEMELIK, S. economic aspects of firefighting vehicles safe driving within EU civil protection. 4th International Conference on European Integration 2018: ICEI 2018: proceedings 1st part. Ostrava: VSB – Technical University of Ostrava, 2018. ISBN 978-80-248-4169-4, p. 556–565.
[2] THT. Water tender: CAS 20/2700/200-S1T Mercedes-Benz Econic 4×2 [online]. Policka: THT Policka, s.r.o., 2016. [Viewed 2019–02–18]. Available from: https://www.tht.cz/en/water-tenders/cas–20-s–1-t-mercedes-benz-econic–4×2
[3] THT. Water tender: CAS 20/4000/240-S2T T815–2 4×4.2 [online]. Policka: THT Policka, s.r.o., 2016. [Viewed 2019–02–18]. Available from: https://www.tht.cz/en/water-tenders/cas–20-t815-2–4×4
[4] THT. Water tender: CAS 30/9000/540 – S 3 VH T815–7 6×6.1. THT [online]. Policka: THT Policka, s.r.o., 2016. [Viewed 2019–02–18]. Available from: https://www.tht.cz/en/water-tenders/cas30-s3r-t815–7
[5] VBOX Motorsport. Products [online]. Racelogic Ltd. [Viewed 2019–02–18]. Available from: https://www.vboxmotorsport.co.uk/index.php/en/products/performance-meters/performancebox
[6] VLK, F. *Dynamics of motor vehicles* (in Czech). Brno: Frantisek Vlk publishing, 2003. ISBN 80–239–0024–2.
[7] VLK, F. *Working on dynamics of motor vehicles* (in Czech). Brno: Frantisek Vlk publishing, 2001. ISBN 80–238–6574–9.