Safety Engineering Series, ISSN 1805-3238 pp. 1-13, DOI: 10.35182/tses-2022-0004

EVALUATION OF RECORDS FROM DRIVING DYNAMICS TESTING ON TRAINING POLYGONS

Ladislav JÁNOŠÍK[1], Pavel POLEDŇÁK[2], Izabela ŠUDRYCHOVÁ[3], Petr VLČEK[4], Ivana JÁNOŠÍKOVÁ[5], Karolína JONOVÁ[6], Vítězslav NOVÁČEK[7]

Research article

Abstract: The paper briefly informs about the content, procedures and objectives of the student grant competition project (ID No. SP2021/58) entitled *"Verification of driving characteristics of water tender type firefighting vehicles"* (Šudrychová et al., 2022). It summarizes the results of one of the two main project objectives, namely the evaluation of records from driving dynamics testing on training polygons under emergency braking when driving in a straight line and in a circle at a speed approaching the vehicle rollover safe limit. These two tasks are essential driving skills and must be reliably mastered by firefighting vehicle drivers in critical situations on the road.

Keywords: Firefighting Vehicles, Braking Distance, Longitudinal Acceleration, Lateral Acceleration, Adhesion Coefficient.

Introduction

The driving dynamics testing task was based on some of the definitions given in the methodology *"Verification of driving characteristics of firefighting vehicles of Fire Rescue Service of the Czech Republic"*, certification number CERO 1/2021 (Fusek et al., 2021), approved by the Ministry of Interior, Directorate General of Fire Rescue Service of the Czech Republic on 13 September 2021. The methodology is one of the outputs of the research, development and innovation project entitled *"Safe ride of firefighting vehicles to an emergency"*, identification number VH20182021035, carried out under the contract between Ministry of the Interior of the Czech Republic and VSB - Technical University of Ostrava. The project period was from 1 September 2018 to 31 August 2021. The rationale of the methodology is to define procedures and criteria for the evaluation of the verification of driving characteristics of first response vehicles of Fire Rescue Service of the Czech Republic. The subject of the methodology is to establish procedures to obtain relevant data on driving stability, frame stiffness and braking system quality verification of those vehicles. The methodology is to be applied when verifying the driving characteristics of firefighting vehicles newly acquired for the Fire Rescue Service of the Czech Republic. Emphasis is placed particularly on the fact that newly acquired firefighting vehicles should have at least the same or better driving and utility characteristics than the currently used ones. This should increase operational safety and reduce the risk of damage to life, health, property and the environment.

[1] VSB - Technical University of Ostrava, Faculty of Safety Engineering, Ostrava, Czech Republic, ladislav.janosik@vsb.cz

[2] VSB - Technical University of Ostrava, Faculty of Safety Engineering, Ostrava, Czech Republic, pavel.polednak@vsb.cz

[3] VSB - Technical University of Ostrava, Faculty of Safety Engineering, Ostrava, Czech Republic, izabela.sudrychova@vsb.cz

[4] VSB - Technical University of Ostrava, Faculty of Safety Engineering, Ostrava, Czech Republic, petr.vlcek.st@vsb.cz

[5] VSB - Technical University of Ostrava, Faculty of Economics, Ostrava, Czech Republic, ivana.janosikova@vsb.cz

[6] Fire Rescue Service of the Hradec Králové Region, Hradec Králové, Czech Republic, jonova.karolina@gmail.com

[7] Fire Rescue Service of the Dukovany Nuclear Power Plant, Dukovany, Czech Republic, novajda95@gmail.com

Safety Engineering Series, ISSN 1805-3238 pp. 1-13, DOI: 10.35182/tses-2022-0004

Taking into account the research student project's limited financial and technical capacities, the driving performance testing was carried out as two tests. Both tests were planned to be conducted on a dry road surface only. According to the approved methodology (Fusek et al., 2021), the tests are also performed on wet (sprinkled) road surfaces.

- Test 1. Dry braking test with full extinguishant tanks at an initial speed of v_0 = 50 km.h^{-1} and v_0 = 60 km.h^{-1}. The definition of the experiment stipulated that for each initial speed at least five experimental runs would be performed to eliminate any invalid experiment where the prescribed initial speed was not reached.
- Test 2. Circle driving test, first in the right and then in the left turn on a dry circular track with a marked inner radius of 13 m (outer radius not defined) with full extinguishant tanks at a speed of at least 25 km.h^{-1}. This lower speed limit is less than the theoretical rollover threshold speed. During the circular run, the driver's task was to increase this speed up to 30 km.h^{-1} or even further to the safe limit. However, this increase in speed was always at the discretion of the driver, according to his subjective feeling as to whether the safe limit of the vehicle tested had been reached.

For Test 2, the team of researchers changed the task of the test compared to the methodology (Fusek et al., 2021), in which the inner radius of the circular track measures 20 m and the average speed is 33 km.h^{-1} and higher. The smaller circular track radius was chosen based on the results of previous analyses performed by the research team (Jánošík et al., 2020). The evaluation of rides to interventions in the fire districts of the Ostrava-Fifejdy and Nový Jičín fire stations revealed the highest frequency road axis radii of curvature in the group from 11 to 15 m. For the rides from the Ostrava-Fifejdy fire station, this was the highest frequency in the whole observed range of radii from 10 to 100 m. In the case of rides from the Nový Jičín fire station, this maximum frequency was exceeded only by the group of radii of 46 to 50 m, which was caused by the fact that a significant part of the rides to emergency sites took place outside urban areas.

Firefighting vehicles

Testing ran from 10 June 2021 to 5 November 2021 at two training polygons (Automotodrom Brno a.s. in Ostrovačice and LIBROS Ostrava s.r.o. (in Ostrava) and an airport (LKSLUS in Slušovice-Bílá Hlina). A total of eleven firefighting vehicles of two weight classes (medium and heavy) and two chassis designs (urban and mixed) were tested. The aim was to test at least two vehicles in one testing day due to the limited time of maximum 2 hours we could use the polygons and the vehicles for our testing.

Three testing days were held at Automotodrom Brno a.s. The first test took place on 10 June 2021. The air temperature was 16 °C, the test track surface was dry and the weather was sunny. The first firefighting vehicle tested was the SCANIA P500 4x2, designation CAS 20/3500/240-S1T, registration plate number 5B8 0972, stationed at the Brno-Lidická fire station. The vehicle was equipped with drum brakes and Continental Conti Hybrid HS3 (front axle) and HD3 (rear axle) tires. The second firefighting vehicle tested was the TATRA 815-2 4x4, designation CAS 20/4000/240-S2T, registration plate number 5B4 3503, stationed at the Pozořice fire station. The vehicle was equipped with disc brakes and Continental Scandinavia HSW2 (front axle) and HDW2 (rear axle) Winter M+S* tires.

The second test took place on 30 August 2021. The air temperature was 16 °C, the test track surface was dry and the weather was sunny. The first firefighting vehicle tested was the MAN TGM 13.240 4x4 BL, designation CAS 15/2200/135-M2Z, registration plate number 6B8 9984, stationed at the Hustopeče fire station. The vehicle was equipped with drum brakes and Matador Master FR2 (front axle) and Matador Hector DR1 M+S (rear axle) tires. The second firefighting vehicle tested was the VOLVO FL 4xR3, designation CAS 15/2500/250-M1T, registration plate number 8B0 3374, stationed at the Brno-Líšeň fire station. The vehicle was equipped with disc brakes and Continental Conti Hybrid HS3 M+S (front axle) and HD3 M+S (rear axle) tires.

The third test took place on 7 September 2021. The air temperature was 12 °C, the test track surface was dry and the weather was partly cloudy. The first firefighting vehicle tested was the SCANIA P480 4x4, designation CAS 20/4000/240-S2T, registration plate number 5B4 8582, stationed at the Bučovice fire station. The vehicle was equipped with drum brakes and Continental Scandinavia HSW2 Winter M+S* (front axle) and Conti Hybrid HD3 M+S (rear axle) tires. The second firefighting vehicle tested was the SCANIA P440 4x4, designation CAS 20/4000/240-S2T, registration plate number 5B8 0727, stationed at the Znojmo fire station. The vehicle was equipped with drum brakes and Continental Scandinavia HSW2 (front axle) and HDW2 (rear axle) Winter M+S* tires.

Safety Engineering Series, ISSN 1805-3238 pp. 1-13, DOI: 10.35182/tses-2022-0004

Only one testing day was held at the LIBROS Ostrava s.r.o. polygon on 9 September 2021. The air temperature was 19 °C, the test track surface was dry and the weather was sunny. The first firefighting vehicle tested was the Mercedes-Benz Econic 1833 LL 4x2, designation CAS 20/2700/200-S1T, registration plate number 8T0 6116, stationed at the Ostrava-Zábřeh central fire station. The vehicle was equipped with disc brakes and Michelin X Multi (front axle) and Michelin X Multi Way 3D (rear axle) tires. The second firefighting vehicle tested was the TATRA 815-2 4x4, designation CAS 20/4000/240-S2T, registration plate number 8T0 6180, stationed at the Opava central fire station. The vehicle was equipped with drum brakes and Michelin XZY (front axle) and Kama NR201 (rear axle) tires.

Two testing days were held at Slušovice-Bílá Hlina airport. The first test took place on 26 August 2021. The air temperature was 13 °C, the test track surface was wet after the night rain and the weather was cloudy. These adverse weather conditions significantly affected the testing results. The first firefighting vehicle tested was the MAN TGM 18.340 4x4 BB, designation CAS 20/4000/300-S2Z, registration plate number 4Z2 4898, stationed at the Zlín fire station. The vehicle was equipped with drum brakes and Continental HSC1 (front axle) and Continental HDC1 (rear axle) tires. The second firefighting vehicle tested was the Renault Midlum 270.15/14, designation CAS 24/2500/250-M1T, registration plate number 1Z7 6958, stationed at the Zlín fire station. The vehicle was equipped with disc brakes and Bridgestone M840 (front axle) and Goodyear Regional RHD II (rear axle) tires.

The second test took place on 5 November 2021. The air temperature was 6 °C, the test track surface was dry and the weather was sunny. Due to technical limitations, only the SCANIA P440 4x4, designation CAS 20/3500/210-S2T, registration plate number 3Z4 7797, stationed at the Zlín fire station, was tested. The vehicle was equipped with drum brakes and Continental Scandinavia HSW2 (front axle) and HDW2 (rear axle) Winter M+S* tires.

In the following text and description of the results, all firefighting vehicles tested will be referred to only by the chassis manufacturer's name and registration plate number shown in parentheses.

Measuring Instruments

The PerformanceBox performance meter from Racelogic Ltd, Buckingham, England, was used to measure driving characteristics. A detailed description of this device can be found on the manufacturer's website (PerformanceBox, 2022). The device is designed to detect the absolute positioning of the vehicle in real time. The device then calculates distance, speed, longitudinal acceleration, lateral acceleration and many other parameters. Its update rate is 10 Hz. The accuracy of the device is due to the real-time positioning of the vehicle using signals from the GPS and GLONASS satellite systems. The manufacturer claims an accuracy of 0.2 km.h^{-1} with a resolution of 0.01 km.h^{-1} for speed measurements and an accuracy of 0.05 % (less than 50 cm per 1 km) and a resolution of 1 cm for distance measurements. The accuracy and resolution of the time recording is determined by the update rate of the device, i.e. 0.1 s. The device is equipped with an SD card on which the recorded data were logged and then transferred to a computer to be processed in VBOX Test Suite data analysis software, version 1.7.55.2453 (VBOX Test Suite Software, 2020).

Training Polygons

The measurements at Slušovice-Bílá Hlina Airport (LKSLUS) took place on a 400 m long and 12 m wide runway. An unobstructed area of 25 m by 25 m located in front of the hangar was available for driving in a circle. An example record from the experiment evaluation in VBOX Test Suite data analysis software of the SCANIA (3Z4 7797) position on a map during the testing performed on 5 November 2021 is shown in Fig. 1.

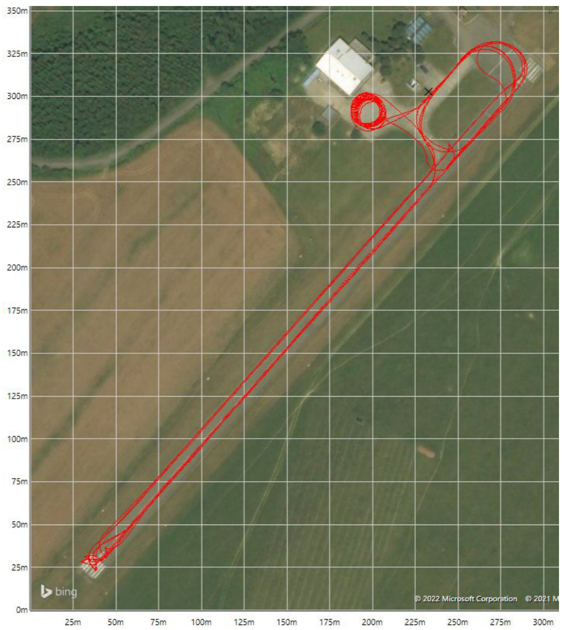

Fig. 1 Record of the SCANIA (3Z4 7797) position during testing at the airport in Slušovice

Safety Engineering Series, ISSN 1805-3238 pp. 1-13, DOI: 10.35182/tses-2022-0004

The measurements at the LIBROS polygon in Ostrava took place on a track whose straight section was 250 m long and 55 m wide. A circular area with an outer radius of 34 m was available for driving in a circle. Fig. 2 shows a record of the TATRA (8T0 6180) position during testing performed on 6 September 2021.

Fig. 2 Record of the TATRA (8T0 6180) position during testing at the LIBROS Ostrava polygon

The Automotodrom Brno polygon offered the greatest possibilities in the use of test areas. The larger test area was 238 m long and 53 m wide and was used to test driving in a circle and to accelerate vehicles for braking tests. A shorter track was connected to this area diagonally at an angle of 45°. This shorter track had a straight length of 147 m and a width of 12 m and was used for braking tests. Fig. 3 shows a record the MAN (6B8 9984) position during testing performed on 30 August 2021.

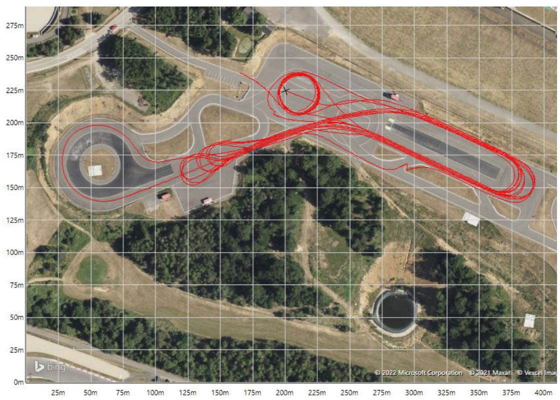

Fig. 3 Record of the MAN (6B8 9984) position during testing at the Automotodrom Brno polygon

Methods

The evaluation of the data measured during vehicle testing was focused on the determination of braking distances and longitudinal and lateral accelerations. Longitudinal acceleration is applied in the straight direction of travel when the vehicle is starting (takes on a positive value) and braking (negative value). Lateral acceleration characterizes driving in a circular curve.

For the dry braking test (Test 1), VBOX Test Suite data analysis software with defined custom tests was primarily used to evaluate the recorded data. In our case, the custom tests included two conditions: initial speed $v_0 = 50$ km.h^{-1} or $v_0 = 60$ km.h^{-1} and final speed $v = 0$ km.h^{-1}. The software evaluated the recorded data and calculated the mean (Awg) and standard deviation (Std Dev) and selected the maximum (Max) and minimum (Min) values. Only braking distance, longitudinal acceleration and lateral acceleration were evaluated in this test task. The results were exported to a csv file and then secondary processing of all evaluated tests was performed in MS Excel.

For the circle driving test (Test 2) evaluation, the source database (.dbn) file stored on the PerformanceBox SD card was primarily used. The file was transferred to a PC, then the respective test was run on it in VBOX Test Suite and the data was saved to disk in a new (.vbo) file. This data was now saved in text format. After a part of the redundant header was removed from the file in a suitable text editor, the data was saved as a secondary file in csv format. This data was again imported and further evaluated in MS Excel. Only the values of the following variables were investigated and evaluated: speed (v), radius of the vehicle's centre of gravity trajectory as it travels in a circular curve (R), longitudinal acceleration (a_x) and lateral acceleration (a_y). In the calculation results provided by VBOX Test Suite, acceleration values are given in units of multiples of the gravitational acceleration (g). These two quantities determine the basic force interactions between the vehicle and the road. The longitudinal acceleration a_x is applied in the calculation of inertial forces in the longitudinal direction during vehicle starting and especially braking (Halliday et al., 1997), as:

$$F_x = m \cdot a_x \tag{1}$$

where m [kg] is the mass of the vehicle. The lateral acceleration a_y is analogously applied in the calculation of centrifugal forces when driving in a circular curve, as:

$$F_y = m \cdot a_y \tag{2}$$

Safety Engineering Series, ISSN 1805-3238 pp. 1-13, DOI: 10.35182/tses-2022-0004

The lateral acceleration a_y in Equation (2) for driving in a circular curve can be calculated as:

$$a_y = \frac{v^2}{R} \quad (3)$$

where v [m.s^{-1}] is the speed and R [m] is the radius of the vehicle's centre of gravity trajectory as it travels in a circular curve. For the longitudinal acceleration a_x and the lateral acceleration a_y relative to the gravitational acceleration, the equation is:

$$\left|a_{x,y}\right| = g \cdot \mu_{x,y} \quad (4)$$

where g [m.s^{-2}] is the gravitational acceleration, μ_x [-] is the adhesion coefficient in the longitudinal direction and μ_y [-] is the adhesion coefficient in the lateral direction (Bradáč et al., 1999). The designations used for the x and y axis directions for vehicle motion are based on definitions given in the literature (Vlk, 2003). When units of gravitational acceleration g are used, these values numerically represent the magnitude of the adhesion coefficient. VBOX Test Suite data analysis software uses the right-handed Cartesian coordinate system. Then, a positive value of lateral adhesion characterizes driving in a left circular curve and a negative value characterizes driving in a right circular curve. The frequencies of instantaneous longitudinal and lateral acceleration values were then analyzed in MS Excel. Values ranging from +1.000 to -1.000 were observed and this range was divided into 20 intervals graded in 0.100 increments.

Results of Test 1 - Dry braking

The measurement and evaluation results of the braking distances for all vehicles tested are summarized in Fig. 4 and Fig. 5.

The MAN (4Z2 4898) and Renault (1Z7 6958) vehicles were included in the results shown, even though their measurements took place on a wet surface on 26 August 2021. This fact was beyond our control, as the training is planned long in advance, and resulted in different average values compared to the other vehicles tested, primarily due to the test track's surface being wet after an overnight drizzle. Another cause could have been the Continental HSC1 and Bridgestone M840 construction tires used. The specifications from the manufacturer of these tires claim increased puncture and abrasion resistance when used off paved roads. However, the practical experience of firefighter-drivers in driving them on wet paved roads is not good. The braking distances measured, especially for the MAN (4Z2 4898), confirmed their opinion.

For clarity, only the resulting average values for the defined initial speeds are shown in Fig. 6 from the cumulative results of the longitudinal acceleration values obtained during the measurement of braking distances of all tested vehicles. The standard evaluation of the longitudinal acceleration values during braking distance measurements using VBOX Test Suite produced some unexpected results. For only two vehicles these values corresponded with data reported in the literature (Bradáč et al., 1999; Vlk, 2003).

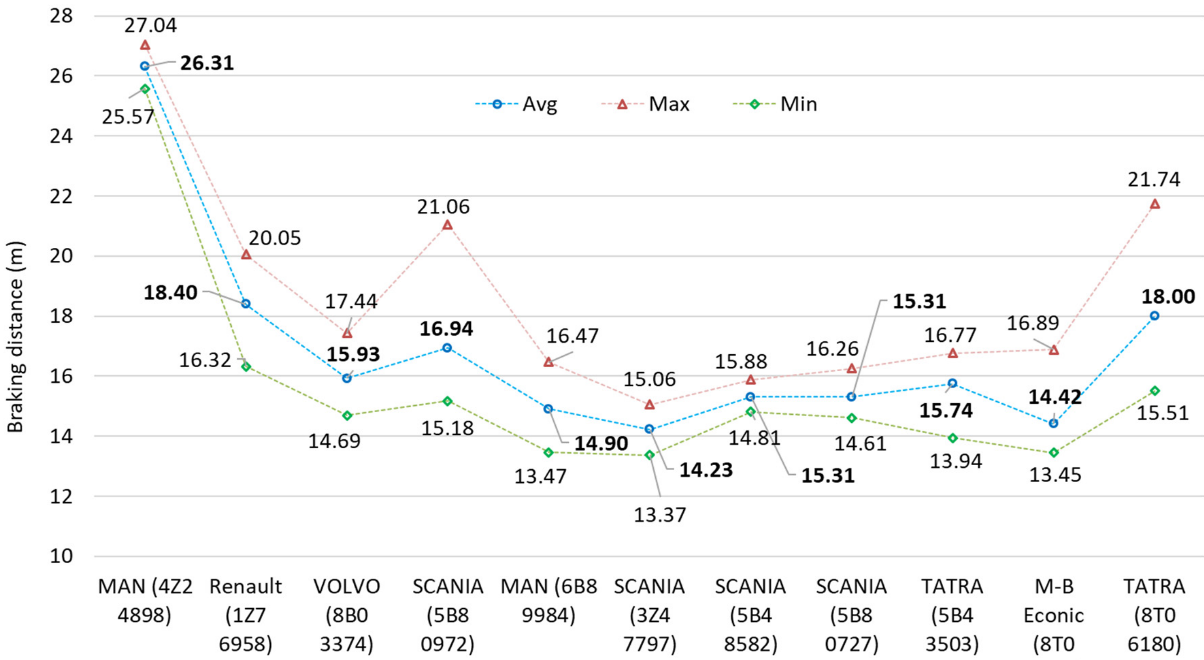

Fig. 4 Braking distance (m) for an initial speed of v_0 = 50 km.h^{-1}

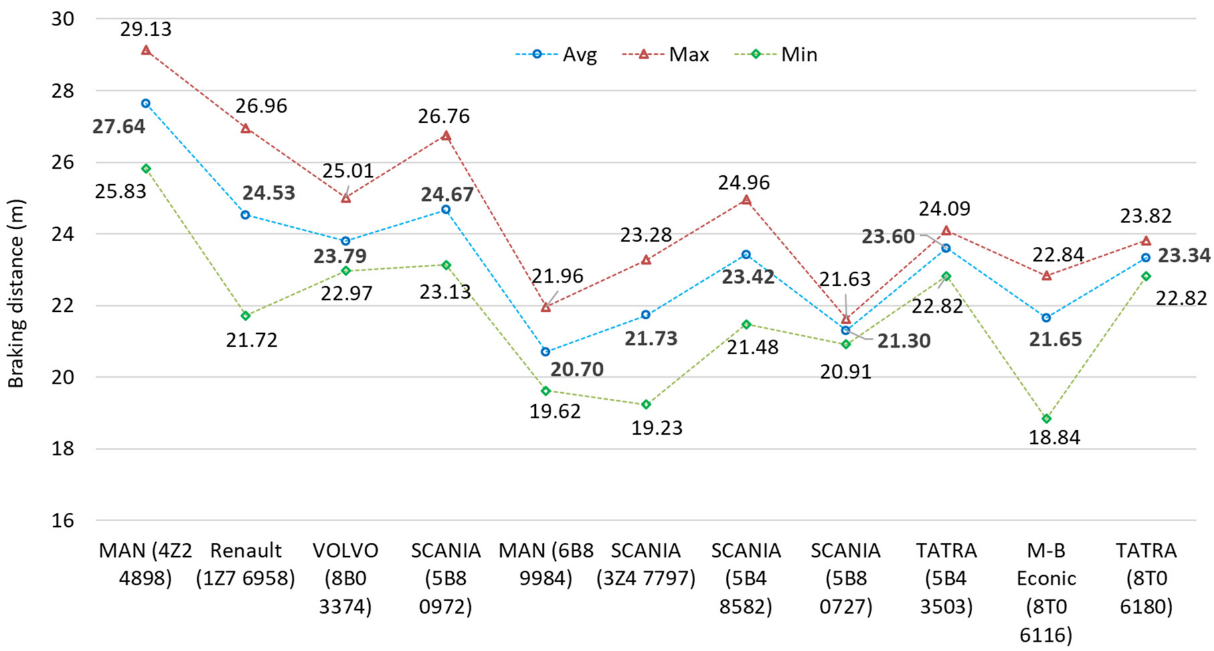

Fig. 5 Braking distance (m) for an initial speed of v_0 = 60 km.h[-1]

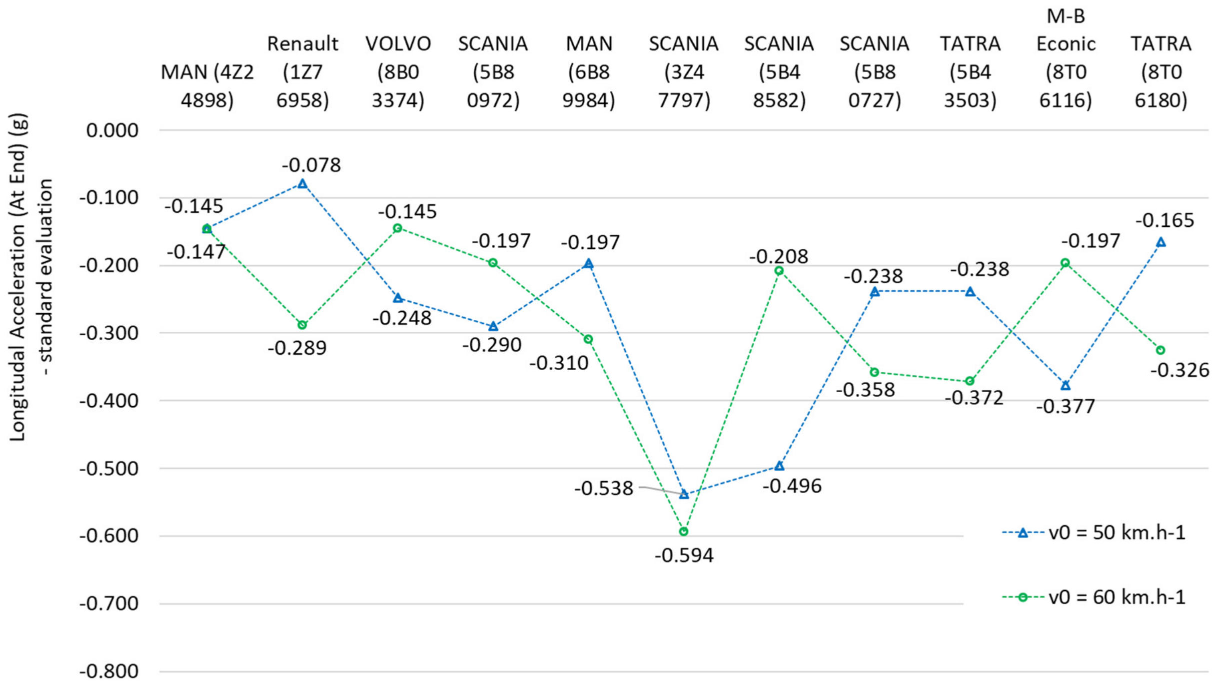

Fig. 6 Average longitudinal acceleration values after standard evaluation

Therefore, a correction was applied on the measured data using the procedure of ECE, 1958, Regulation No. 13. According to the regulation, the braking distance is evaluated only from the interval from 80 % of the initial braking speed v_0 to 10 % of the initial speed v_0. For a speed of 50 km.h[-1], for instance, the speed interval to be evaluated is from v_0 = 40 km.h[-1] to v_0 = 5 km.h[-1]. In this manner, the non-linear data are trimmed from the beginning of the braking until the braking system is fully applied and also from the end of the braking, when a suspension-equipped vehicle comes to a halt and rocks. Following the data correction, the custom test boundary conditions were re-set in VBOX Test Suite and the longitudinal acceleration values were obtained. The resulting average longitudinal acceleration values after the data correction for all tested vehicles are shown in Fig. 7. The overall average longitudinal acceleration values with the data correction applied correspond to the data

Safety Engineering Series, ISSN 1805-3238 pp. 1-13, DOI: 10.35182/tses-2022-0004

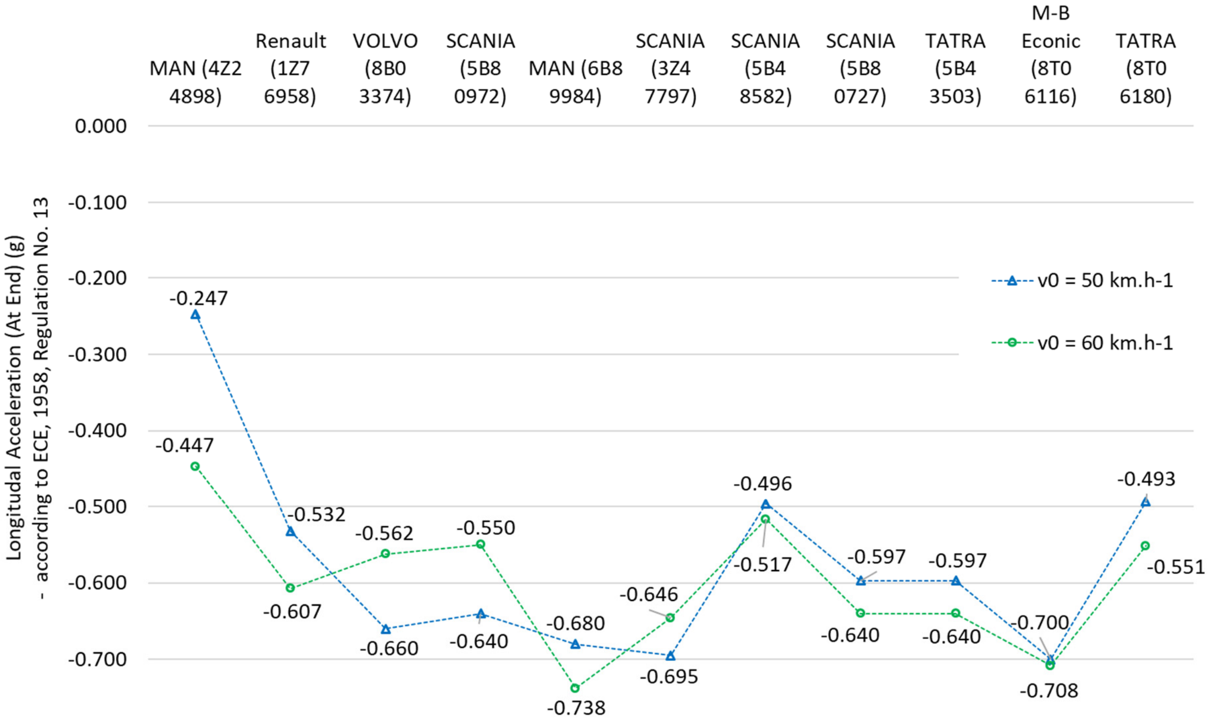

Fig. 7 Average longitudinal acceleration values after data correction according to ECE, 1958, Regulation No. 13

reported in the literature (Bradáč et al., 1999; Vlk, 2003) with the exception of the MAN (4Z2 4898) when tested with an initial speed of v_0 = 50 km.h^{-1}.

The overall resulting values of the investigated driving characteristics are summarized in Tab. 1 for an overview. The distribution of results is primarily by initial braking speeds. The secondary distribution of results is shown both with the inclusion of all calculated values for all tested vehicles and alternatively with the exclusion of values calculated for the MAN (4Z2 4898) vehicle.

Results of Test 2 - Circle driving

An example of the distribution of instantaneous lateral acceleration and longitudinal acceleration values recorded for the SCANIA (3Z4 7797) vehicle driving in a left turn circle is shown diagrammatically in Fig. 8, the frequency distribution of the longitudinal acceleration is shown in Fig. 9, and the frequency distribution of the lateral acceleration is shown in Fig. 10. The evaluation results of the measured lateral acceleration records for all tested vehicles are

Tab. 1 Summary of the investigated driving characteristics of vehicles under braking

		Initial speed v_0 = 50 km.h^{-1}		Initial speed v_0 = 60 km.h^{-1}	
		Calculated values	**Calculated values - without MAN (4Z2 4898) vehicle**	**Calculated values**	**Calculated values - without MAN (4Z2 4898) vehicle**
Braking distance (m)	**Avg**	16.86	15.76	23.31	22.77
	Max	27.04	21.74	29.13	26.96
	Min	13.37	13.37	18.84	18.84
Longitudal Acceleration (At End) (g) - standard evaluation	**Avg**	-0.274	-0.309	-0.286	-0.326
	Max	-0.010	-0.010	-0.010	-0.020
	Min	-0.890	-0.890	-0.760	-0.760
Longitudal Acceleration (At End) (g) - according to ECE, 1958, Regulation No. 13	**Avg**	-0.576	-0.617	-0.601	-0.619
	Max	-0.060	-0.150	-0.170	-0.330
	Min	-0.820	-0.820	-0.910	-0.910

Safety Engineering Series, ISSN 1805-3238 pp. 1-13, DOI: 10.35182/tses-2022-0004

summarized in Fig. 11. For the sake of better clarity, the negative values of lateral acceleration for driving in a right turn circle are shown as absolute values, so that they can be more easily compared with those for driving in a left turn circle.

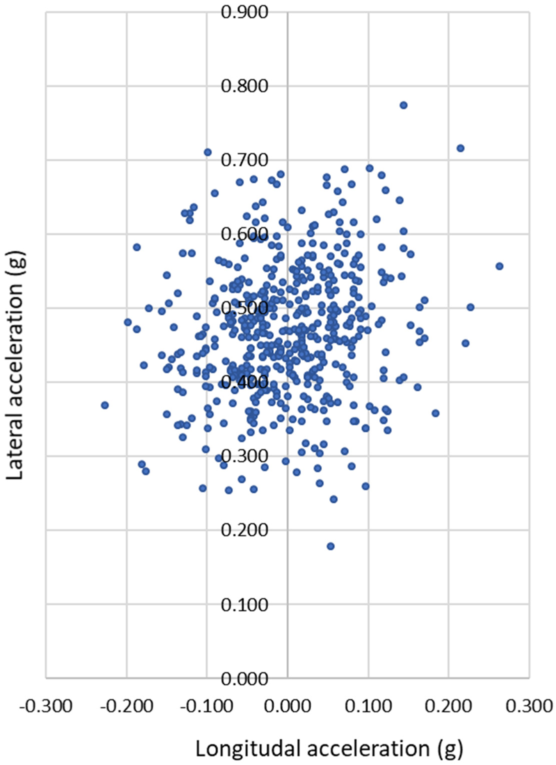

Fig. 8 Acceleration values of the SCANIA (3Z4 7797) when driving in a left turn circle

The overall resulting values of the investigated driving characteristics are summarized in Tab. 2 for an overview. The distribution of results is again shown with the inclusion of all calculated values for all vehicles tested and alternatively with the exclusion of values calculated for the MAN (4Z2 4898) vehicle.

Discussion

Evaluating the circle driving, we found that the left turn circle driving resulted in slightly higher speeds and thus lateral accelerations than the right turn circle driving, although the testing always started with the left turn circle driving so that drivers could become familiar with the designated test track and practice the agreed speed limit for the designated inner radius of the track. Two possible causes may explain this finding:

- When driving in a left curve, drivers can better see (almost directly in front of them) the delineated inner radius of the circular track they are about to pass.
- When driving in a left curve, drivers are sitting above the left front wheel, which is being weighted off, and are better able to estimate the loss of adhesion between that wheel and the road surface should the road speed approach the rollover threshold speed.

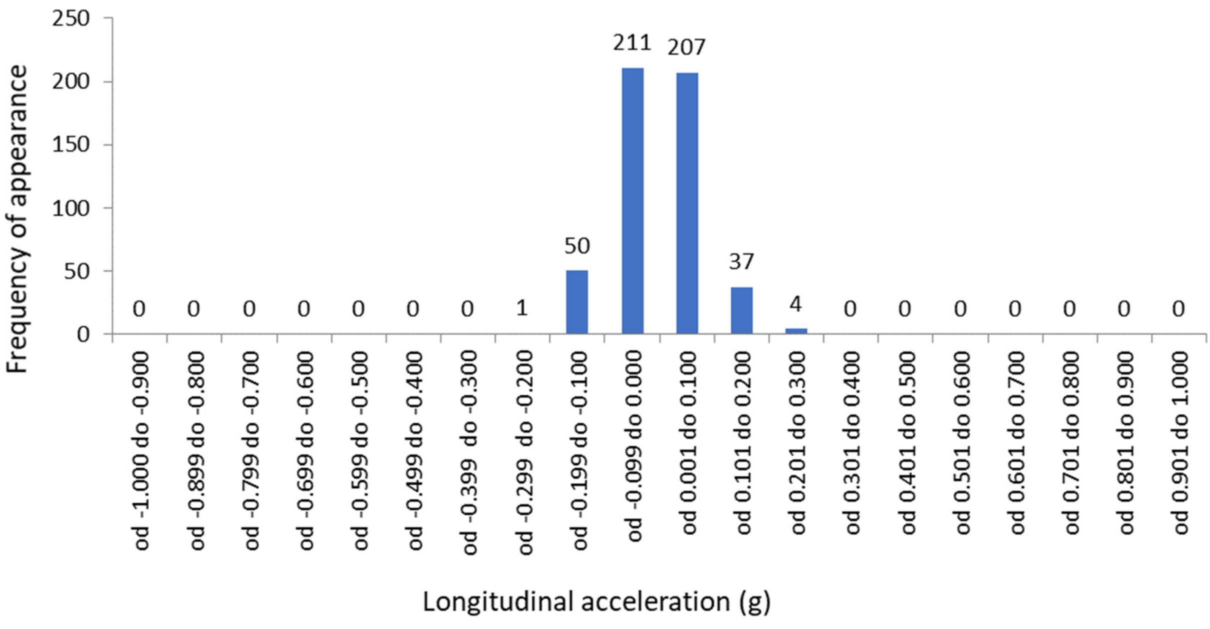

Fig. 9 Longitudinal acceleration frequency distribution

Safety Engineering Series, ISSN 1805-3238 pp. 1-13, DOI: 10.35182/tses-2022-0004

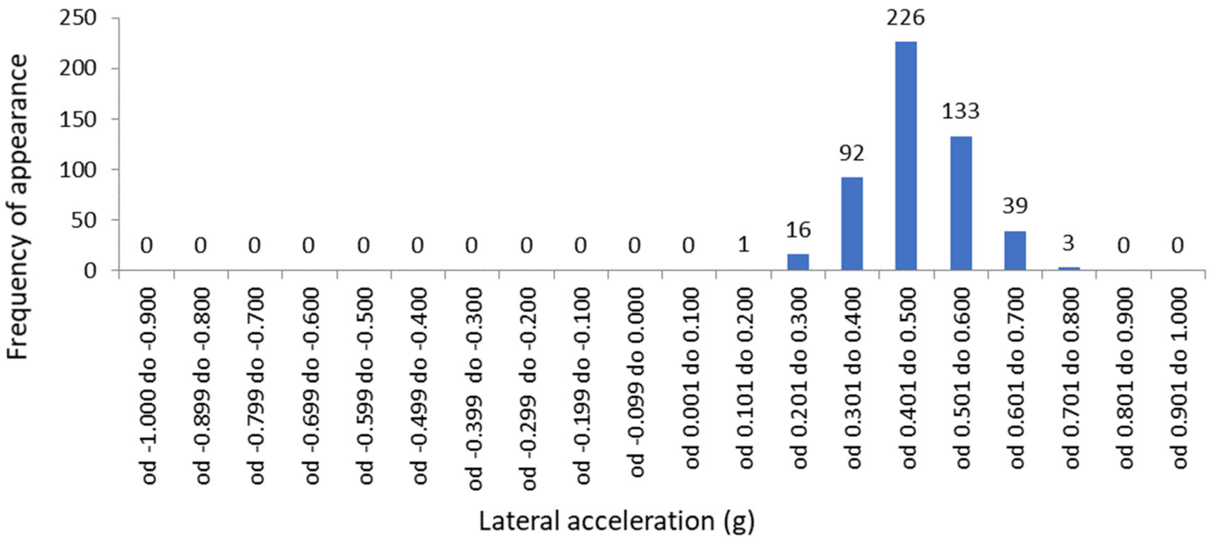

Fig. 10 Lateral acceleration frequency distribution

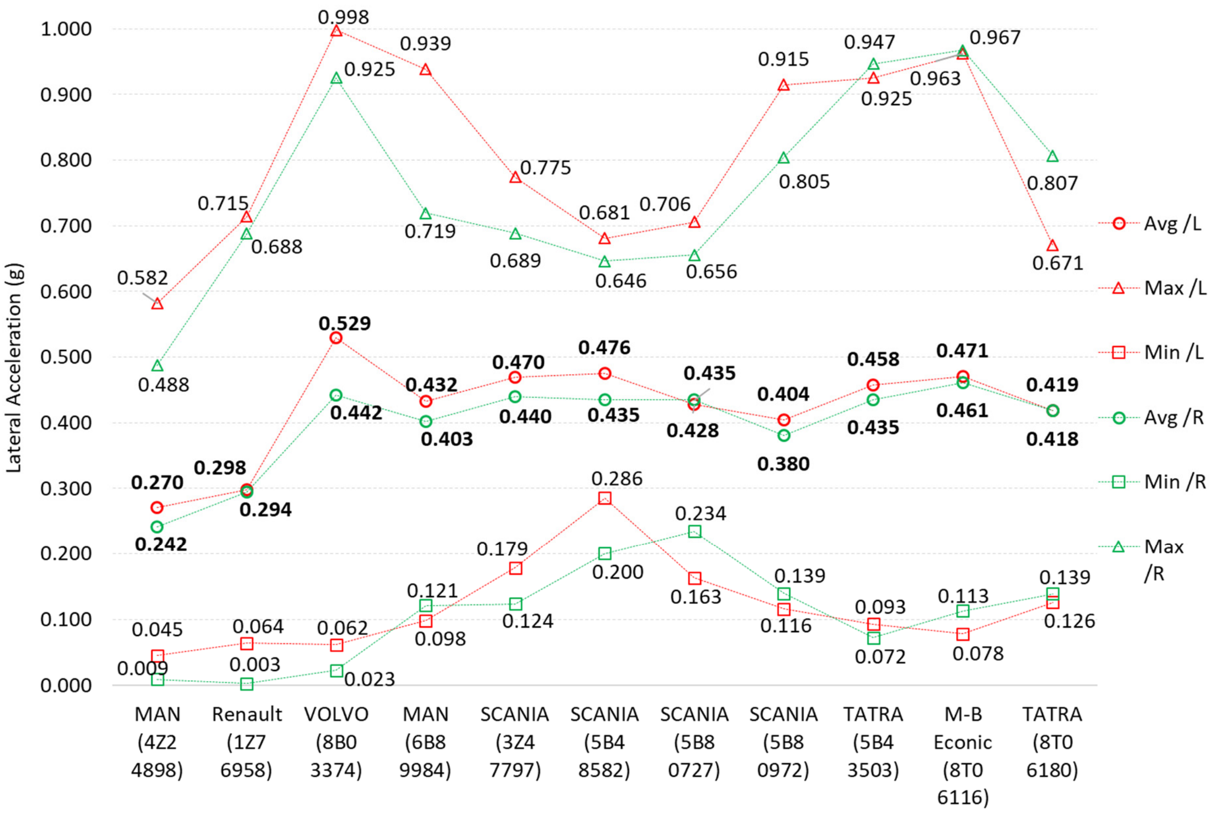

Fig. 11 Lateral acceleration evaluation results

When driving in a right turn curve, both of these causes have a negative effect on drivers' driving comfort. Drivers have to estimate the inner limit of the defined radius of the track, which (given the width of the vehicle of about 2.25 m) they do not see in front of them but rather diagonally across the front pillar of the cab. Drivers seated above the centrifugal force-compressed left wheel have an impaired estimate of the point at which the adhesion of the right front wheel is lost. As a result, they are then likely to drive slightly slower and also fail to always maintain the specified inner radius of the test track.

Safety Engineering Series, ISSN 1805-3238 pp. 1-13, DOI: 10.35182/tses-2022-0004

Tab. 2 Summary of the investigated driving characteristics of vehicles driving in a circle

		Left turn in a circle		Right turn in a circle	
		Calculated values	**Calculated values - without MAN (4Z2 4898) vehicle**	**Calculated values**	**Calculated values - without MAN (4Z2 4898) vehicle**
Lateral Acceleration (g)	**Avg**	**0.423**	**0.441**	**0.399**	**0.417**
	Min	0.045	0.062	0.234	0.234
	Max	0.998	0.998	0.488	0.646
Speed (km.h^{-1})	**Avg**	**27.80**	**27.77**	**26.42**	**26.32**
	Min	17.40	17.40	12.76	12.76
	Max	35.57	35.57	36.32	36.32
Radius of turn (m)	**Avg**	**15.01**	**14.31**	**14.41**	**13.62**
	Min	7.51	7.51	5.62	5.62
	Max	40.02	40.02	42.39	42.39

A number of factors affect the final braking distance of the firefighting vehicles tested. The main ones we investigated and evaluate their effect are:

- weather conditions,
- the gross laden mass of the vehicle,
- the type of braking system,
- type of tires.

Weather conditions

At the beginning of the project, it was planned that testing would take place on a dry road surface to eliminate the effect of weather conditions. However, on the days of testing the weather conditions and therefore their effect on the road surface were beyond our control. In our case, the effect of weather conditions unfortunately played a significant negative role on one testing day on 26 August 2021 at Slušovice Airport. On the wet test track, the MAN (4Z2 4898) vehicle had the longest average braking distance of 26.3 m at an initial speed of 50 km.h^{-1}. Moreover, doubts were raised about the effectiveness of the braking system of the vehicle during the testing. In the evaluation of the results, a variant was therefore elaborated where this vehicle was not included in the calculation of the results (see Tab. 1 and Tab. 2).

With this exception, the scheduled tests were performed on a dry surface at temperatures between +6 °C and +19 °C. According to the results obtained at the different temperatures, this range of air temperatures had no demonstrable effect on the braking distance. For example, the best average braking distance of 14.2 m at an initial speed of 50 km.h^{-1} was achieved by the SCANIA (3Z4 7797) at an ambient air temperature of only +6 °C on a dry road surface (see Fig. 4).

Gross laden mass of the firefighting vehicles

The effect of the gross laden mass of the vehicles could not be conclusively demonstrated given the small sample of firefighting vehicles tested. Only three vehicles out of the eleven tested had a gross laden mass of less than 16 t: the Renault (1Z7 6958), VOLVO (8B0 3374) and MAN (6B8 9984). The Renault (1Z7 6958) was tested at an air temperature of +13 °C on a track that was wet after an overnight rain. The average braking distance of this vehicle was 18.4 m at an initial speed of 50 km.h^{-1}, which was the second longest braking distance (see Fig. 4). Thus, in this case, the effect of the wet road surface had a demonstrable and negative effect. The braking distance of this firefighting vehicle was approximately 2.5 m longer compared to the other two vehicles that were tested on a dry road at an air temperature of +16 °C. In order to reliably assess the effect of the gross laden mass of the vehicles, it would have been necessary to carry out the testing on a larger sample of vehicles and under comparable weather conditions.

Type of braking system

Before our testing began, we had expected the type of braking system to have a significant effect on braking distance. This was not conclusively demonstrated in our experiments. Of the eleven firefighting vehicles tested, seven were equipped with drum brakes and only four were equipped with disc brakes on both axles: the Renault (1Z7 6958), VOLVO (8B0 3374), TATRA (5B4 3503) and M-B Econic (8T0 6116).

Safety Engineering Series, ISSN 1805-3238 pp. 1-13, DOI: 10.35182/tses-2022-0004

The theoretical assumption was that vehicles with disc brakes would achieve better braking performance and thus shorter stopping distances. Drum brakes, which are cooled by the air flow less efficiently, tend to overheat during repeated braking and the increased temperature causes a braking performance decrease. This is caused by a smaller coefficient of friction between the brake linings and the drum at high temperatures. In contrast, disc brakes are open and therefore directly exposed to the cooling effect of the air flow.

The testing results for the first two fire trucks have been described above. In this group of vehicles, the M-B Econic (8T0 6116), with a gross laden mass of 18 t, achieved the best average braking distance of 14.4 m at an initial speed of 50 km.h^{-1}. The worst results were recorded for the Renault (1Z7 6958) with disc brakes, which had an average braking distance of 18.4 m on a wet road, and for the TATRA (8T0 6180) with drum brakes, which had an average braking distance of 18.0 m on a dry road. With some exaggeration one can say that the wet surface reduced the expected higher braking performance of disc brakes to the level of drum brakes.

Type of tires

Before we started our testing, we had assumed that the type of tires used would have a decisive effect on the test results. Unfortunately, we could not completely control that the different types of tires were evenly represented on the test vehicles. The firefighting vehicles tested were predominantly (in seven cases) equipped with tires from Continental AG. Of these, four vehicles were fitted with Scandinavia Winter HSW2/HDW2, M+S tires, for which the manufacturer declares high driving stability due to the tread pattern adapted for winter use. Two vehicles were fitted with Conti Hybrid HS3/HD3 M+S tires, for which the manufacturer declares excellent wet mileage throughout the lifetime with lower fuel consumption. These tires are particularly suitable for regional transport. One vehicle was fitted with the summer version of HSC1/HDC1 tires. These tires are mainly intended for use on construction sites. Another non-negligible influencing factor was that four firefighting vehicles had winter tires with the designation 3PMSF (Three-Peak Mountain SnowFlake), two vehicles had

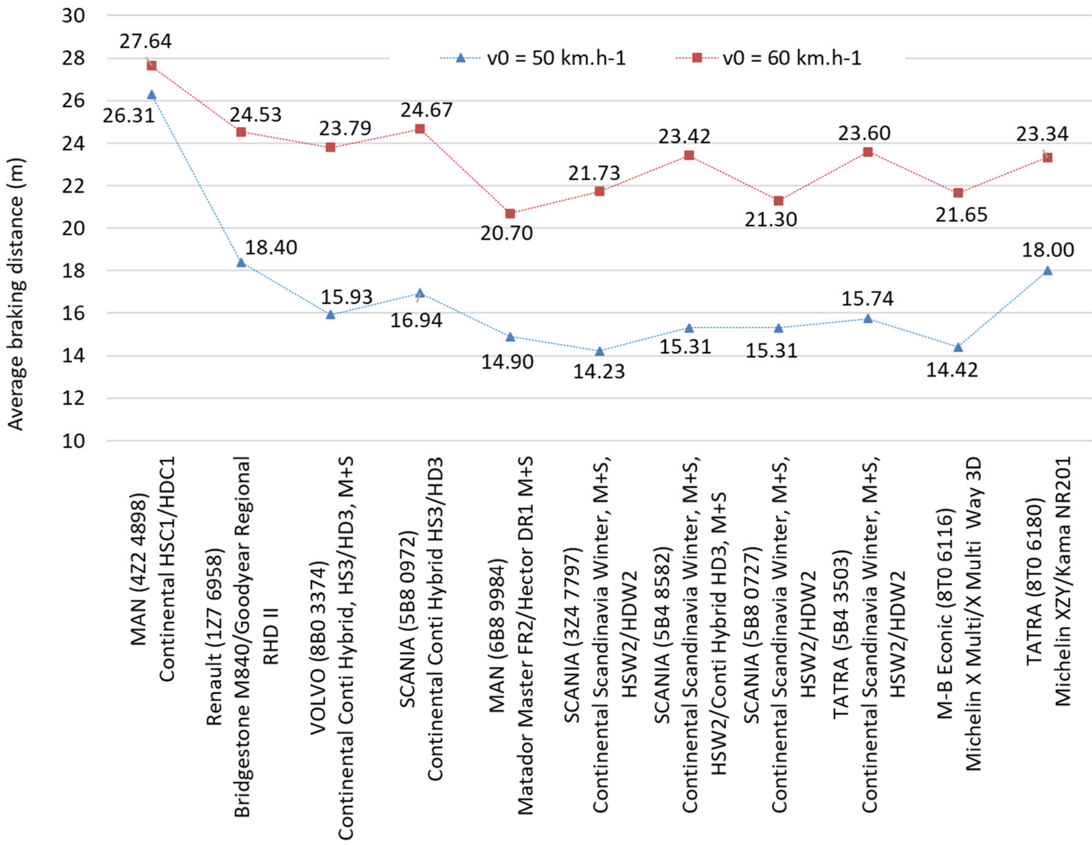

Fig. 12 Effect of tire type on average braking distance

Note: The first two tires on the far left of the graph were tested on a wet road surface at an air temperature of +13 °C. All other tires were tested on a dry surface at air temperatures between +6 °C and +19 °C.

all-season tires with the designation M+S (mud and snow), and the rest of the vehicles had summer tires.

In Fig. 12, the resulting average braking distances depending on the type of tires used for the two defined initial braking speeds of v_0 = 50 km.h^{-1} and v_0 = 60 km.h^{-1} are plotted from the values in Fig. 4 and Fig. 5.

The best results were achieved by four firefighting vehicles with Continental Scandinavia Winter HSW2/HDW2 M+S tires, which produced an average braking distance of 15.15 m at an initial speed of v_0 = 50 km.h^{-1}. If we evaluate all seven tires of the Continental AG Group, which includes the Matador brand, when tested on a dry road surface (third to ninth tires in the graph in Fig. 12), the average braking distance is 15.48 m at an initial speed of v_0 = 50 km.h^{-1}. The second best result was achieved with Michelin X Multi tires on the M-B Econic (8T0 6116) equipped with disc brakes. In contrast, tires from the same manufacturer on the TATRA (8T0 6180) equipped with drum brakes had the longest braking distance of 18 m on a dry road surface at an initial speed of v_0 = 50 km.h^{-1}.

Evaluating all seven Continental AG tires tested at an initial speed of v_0 = 60 km.h^{-1} gives us an average braking distance of 22.75 m. If we select only the four firefighting vehicles that were equipped with Continental Scandinavia Winter HSW2/HDW2 M+S tires, the average braking distance is 22.51 m.

These results are in relation with the results of previous measurements performed in 2019 (Jánošík et al., 2022). These measurements were carried out in the months of October, November and December. Testing was always conducted on dry roads at temperatures ranging from +23 °C to +11 °C. The average braking distances achieved during that testing are shown in Tab. 3. The resulting average braking distances for all vehicles tested were 15.6 m at an initial speed of v_0 = 50 km.h^{-1} and 22.4 m at an initial speed of v_0 = 60 km.h^{-1}.

Conclusion

The resulting braking distance of vehicles is primarily affected by the tires used. Somewhat unexpectedly, the best average braking distances were achieved in our measurements with three Scania firefighting vehicles equipped with winter tires and drum brakes. At the beginning of the testing it was sunny and the air temperature was between +12 and +16 °C. At these air temperatures one would expect the winter tires to be softer and therefore the braking distance to be longer. This was not confirmed. The Scania (5B8 0972) firefighting vehicle was fitted with summer tires and yet its average braking distance at an initial speed of v_0 = 50 km.h^{-1} was 2.7 m longer than the best result obtained (see Fig. 12).

When evaluating the longitudinal adhesion coefficient μ_x during braking, clearly more accurate results corresponding to the literature data (Vlk, 2003) were obtained when data correction (ECE, 1958, Regulation No. 13) was applied. In a standard evaluation of the results of the test vehicles with the exclusion of the MAN (4Z2 4898) vehicle, for initial speeds of v_0 = 50 km.h^{-1}, the average longitudinal adhesion coefficient μ_x was calculated to be 0.309 when no data correction was applied and 0.617 when data correction was applied. For initial speeds of v_0 = 60 km.h^{-1}, the average μ_x was 0.326 when no data correction was applied and 0.619 when data correction was applied.

Acknowledgments

This paper was supported by the internal research grant *"SP2021/58 - Validation of the driving characteristics of water tender type firefighting vehicles"*. The project team and the authors of the paper would like to thank all collaborators in fire units of Fire Rescue Service of the Czech Republic

Tab. 3 Average braking distances of vehicles tested in 2019 (Jánošík et al., 2022)

v_0 (km.h^{-1})	**50**	**60**	**Vehicle/Dislocation (Registration number)**	**Tires**
Average braking distance (m)	14.90	20.51	CAS 20 - MAN TGM/FS Zlin (4Z2 4898)	Continental HSC1, M+S
	14.65	22.02	CAS 24 - Renault Midlum/FS Zlin (2Z7 8478)	Michelin XZY
	16.22	23.89	CAS 20 - Scania P480/FS Marianske Lazne (3K5 1139)	Continental Scandinavia Winter M+S*, HSW2
	16.55	25.00	CAS 20 - TATRA 815-2/FS Hlucin (8T8 6180)	Michelin Cold
	15.74	20.72	CAS 24 - MAN TGM/FS Hlucin (4T3 4949)	Continental HDR 11

Safety Engineering Series, ISSN 1805-3238 pp. 1-13, DOI: 10.35182/tses-2022-0004

in the Moravian-Silesian, South Moravian and Zlín Regions. Without their active and gratuitous help beyond the call of duty, this project would have been impossible to accomplish successfully. They provided expert consultations, but most importantly they actively helped us and arranged for us free testing of selected vehicles during trainings on polygons. Our thanks go to the following people in particular: Mr. Jiří Kuczaj, mechanical service technician of the Regional Directorate of Fire Rescue Service of the Moravian-Silesian Region, for arranging testing within the training at the LIBROS s.r.o. Ostrava polygon; Mr. Bohuslav Ježek and Mr. Ladislav Dobeš, mechanical service technicians of the Regional Directorate of Fire Rescue Service of the South Moravian Region, for arranging testing within the training at the Automotodrom Brno a.s. polygon; Mr. Vlastimil Balcárek, mechanical service technician of the Regional Directorate of Fire Rescue Service of the Zlín Region, for expert consultations; and Mr. Pavel Koňařík, commander of the central fire station in Zlín, for arranging testing within the training at Slušovice-Bílá Hlina airport.

References

Bradáč, A., Krejčíř, P., Lukašík, L., Ošlejšek, J., Plch, J., Kledus, M., Vémola, A. 1999. Forensic Engineering. 1st edit. Brno: Academic publishing CERM. (in Czech).

ECE, 1958, Regulation No. 13. Uniform Provisions Concerning the Approval of Vehicles of Categories M, N and O with regard to Braking, Economic Commission for Europe, Geneva, Switzerland.

Fusek, M., Famfulík, J., Šmiraus, J., Richtář, M., Šofer, M. 2021. Verification of Driving Characteristics of Emergency Fire Trucks of Fire Rescue Service of the Czech Republic. Certification number CERO 1/2021. Ostrava: VSB - Technical University of Ostrava. (in Czech).

Halliday, D., Resnick, R., Walker, J. 1997. Fundamentals of Physics. Fifth Editon Extended. Hoboken: John Wiley and Sons.

Jánošík, L., Jánošíková, I., Poledňák, P., Šudrychová, I. 2020. Driving Dynamics Comparison of Firefighting Vehicles in Urban Agglomeration Ostrava and District Town Nový Jičín. Krízový manažment, 19(2): 14-20. DOI: 10.26552/krm.J.2020.2. (in Czech).

Jánošík, L., Jánošíková, I., Kuczaj, J., Poledňák, P., Šudrychová, I., Tomášek, M., Vlček, J. 2022. Measuring of Braking Distances of Firefighting Trucks. Communications - Scientific Letters of the University of Zilina, 24(2): F1-F13. DOI: 10.26552/com.C.2022.2.F1-F13.

Performance Box [on-line]. VBOXMotorsport, 2022 [cit 2022-01-18]. Available at: https://vboxmotorsport.co.uk/index.php/en/products/performance-meters/performancebox.

Software VBOX Test Suite [on-line]. Racelogic Support Centre, 2020 [cit 2020-10-16]. Available at: https://en.racelogic.support/01VBOX_Automotive/03Software_applications/VBOX_Test_Suite.

Šudrychová, I., Poledňák, P., Jánošík, L., Jánošíková, I., Jonová, K., Tomášek, M., Nováček, V. 2022. Verification of Driving Characteristics of Firefighting Vehicles. Final report of the student grant project. ID number SP2021/58. Ostrava: VSB - Technical University of Ostrava. (in Czech).

Vlk, F. 2003. Dynamics of Motor Vehicles. Brno: Vlk Publishing. (in Czech).