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TESTING OF DRIVING DYNAMICS OF AIRCRAFT RESCUE AND FIREFIGHTING VEHICLES AT THE OSTRAVA MOŠNOV AIRPORT

Ladislav JÁNOŠÍK[1], Ivana JÁNOŠÍKOVÁ[2], Radim BÜRGER[3]

Research article

Abstract: The paper briefly informs about content, procedures, and objectives of a study of driving dynamics of selected Aircraft Rescue and Firefighting (hereinafter ARFF) vehicles that have been used in practice to ensure fire safety at the Leoš Janáček Ostrava Airport. Two characteristic types of ARFF vehicles were selected for testing. Specifically, the vehicles were Mercedes-Benz 3360A 6x4.2 Actros (hereinafter M-B Buffalo) and Rosenbauer 36.705 Panther 6x6 CA5 ECE HRET (hereinafter Rosenbauer Panther). The driving dynamics testing focused on crisis braking in a straight direction, and on driving in a circle at speeds approaching the safe limit for a vehicle rollover.

Keywords: ARFF vehicles, firefighting vehicles, braking distance, braking deceleration, longitudinal acceleration, lateral acceleration, adhesion coefficient.

Introduction

The driving dynamics testing was based on some of the definitions set out in the methodology “Verification of driving characteristics of fire fighting vehicles of the Fire Rescue Service of the Czech Republic”, certification number CERO 1/2021 (Fusek et al., 2021). This methodology was approved by the Ministry of the Interior - General Directorate of the Fire Rescue Service (hereinafter FRS) of the Czech Republic on 13th September 2021. This methodology was one of the outputs of the research, development and innovation project entitled “Emergency fire-fighting vehicles’ safe driving for intervention” and identification number VH20182021035 based on the contract between the parties Czech Republic - Ministry of the Interior and the VSB - Technical University of Ostrava. The subject of the methodology was to define procedures and criteria for the evaluation of the verification of the driving characteristics of fire fighting vehicles of the FRS of the Czech Republic. The aim was to establish procedures to obtain relevant data on driving stability, frame stiffness and verification of the quality of braking systems of fire fighting vehicles.

The following two tests were performed as part of the testing.

Dry braking test with full extinguishing agent tanks at initial speeds v_0 = 50 km.h^{-1} and v_0 = 60 km.h^{-1}. In the definition of the experiment, it was specified that for each initial speed at least 5 experimental runs would be performed to eliminate any invalid experiment where the prescribed initial speed was not reached.

The test of driving in a circle in the right-hand and then left-hand direction was carried out on a dry circular track with an agreed inner radius of 25 m. The driver of the M-B Buffalo complied with this radius. For the Rosenbauer Panther occurred an opposite problem. There the inner radius was increased to approximately 26.5 m. The outer radius of the track was not defined. The vehicles were tested with full extinguishing agent tanks. The drivers were tasked to reach speeds approaching 25 km.h^{-1}. This speed limit is less than the theoretical speed for rolling over the vehicle. During the driving in a circle, the task was to gradually increase the speed to at least 30 km.h^{-1}. However, that speed increase was always dependent on the driver’s decision, which was based on his subjective feeling of reaching the safety limit of the tested fire vehicle, especially in terms of the rollover limit.

[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 Economics, Ostrava, Czech Republic, ivana.janosikova@vsb.cz

[3] Ostrava Airport, Fire Rescue Service, Mošnov, Czech Republic, radim.bur@outlook.com

The testing of the driving characteristics was carried out only on a dry road surface of the southern apron of the airport (APN SOUTH, see Figure 2). One time interval was allowed for testing on 27 October 2022 between 11:00 and 13:00 due to zero passenger and freight load on the runway. At the beginning of testing, the weather was sunny with a temperature of 15 °C. Sprinkling to provide a wet surface for testing was not permitted. In the approved methodology (Fusek et al., 2021), tests are also performed in a variant on a wet (sprinkled) road surface.

Firefighting vehicles

The first ARFF vehicle tested was the 2010 model M-B Buffalo, designation CAS 55 8000/900/250/120, registration number 6T4 4916. The year of manufacture is 2010. At the time of testing, the vehicle had a mileage of 23,344 km and an operating weight is 27,900 kg. Nominal engine power is 440 kW at 1800 rpm. The vehicle is fitted with a Telligent II automated gearbox. The vehicle is fitted with drum brakes, has a maximum speed set at 105 km.h^{-1}, and is electronically limited. Detailed tactical and technical characteristics of the vehicle are available on the web (Požáry.cz, 2010a). At the time of testing, the vehicle was fitted with Michelin XZL 365/85 R20 tyres.

Figure 1 Tested vehicles Rosenbauer Panther (on the left) and M-B Buffalo (on the right)

The second ARFF vehicle tested was the 2010 model Rosenbauer Panther, has the fire designation CAS 60 11800/1500/250-S2VH. The registration mark is T01 3897. The year of manufacture is 2010. At the time of testing the vehicle had a mileage of 9,186 km. Operating weight is 36,000 kg. Nominal engine power is 518 kW at 1300 rpm. The vehicle is equipped with a 6-speed automatic gearbox Twin Disc. The maximum speed of the vehicle is set at 115 km.h^{-1} and is electronically limited. The vehicle has drum brakes. Detailed tactical and technical characteristics of the vehicle are available on the web (Požáry.cz, 2010b). At the time of testing, the vehicle was fitted with Michelin XZL 24 R21 tyres. An illustrative photo of the ARFF vehicles tested is shown on Figure 1.

Leoš Janáček Ostrava Airport

The airport offers both civil and freight traffic, for which it uses a 3500 metre long runway (hereinafter RWY). A scheme of the airport is shown in Figure 2.

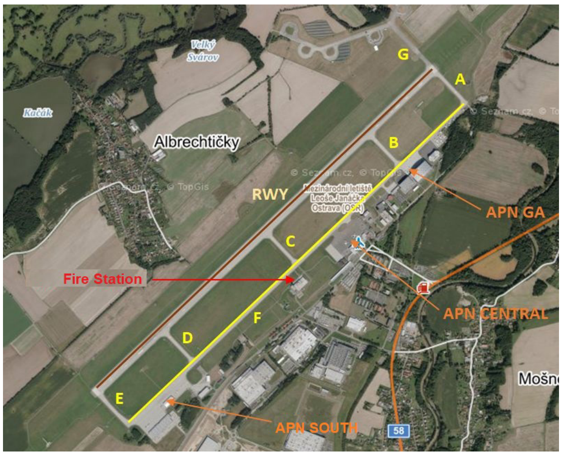

Figure 2 Screenshot of Leoš Janáček Ostrava Airport

It shows the location of the fire station, a description of the various connecting runways (A to E), taxiways (F, G) and aprons (hereinafter APN). The airport is bound by ICAO (International Civil Aviation Organization) annexes that specify a time of 180 seconds within, under normal meteorological conditions, firefighters must initiate a firefighting attack at any location of the airport area. In addition, they must arrive with another fire vehicle within 60 seconds. There must be a minimum of two fire vehicles and a firefighting team of one commander and five firefighters at the scene. The maximum distance that the intervening vehicles must travel to both runway thresholds is approximately 2.2 km. Vehicle brake testing was

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conducted on taxiway F in the direction of travel from the fire station to the APN SOUTH apron. Circle driving testing was conducted on the APN SOUTH apron.

Measuring device

A Performance Box from Racelogic Ltd, Buckingham, England, was used to measure the driving characteristics. A detailed description of the instrument is given on the manufacturer's website (Performance Box, 2022). The device is adapted to detect the absolute positioning of the vehicle in real time. The device then calculates trajectory, speed, longitudinal and lateral acceleration, and several other values. The frequency of the recordings is 10 Hz. Its accuracy is determined by real-time positioning of the vehicle using signals from the GPS and GLONASS satellite systems. An accuracy of 0.2 km.h^{-1} at a resolution of 0.01 km.h^{-1} is given for the speed measurement. An accuracy of 0.05 % (less than 50 cm per 1 km) and a resolution of 1 cm is given for distance measurements. The accuracy and resolution of the time recording is determined by the frequency of the device, i.e., 0.1 s. The device is equipped with an SD card on which the recorded data were stored and subsequently transferred to a computer and further processed in the company's VBOX Test Suite (hereafter VTS), version 1.7.55.2453 (VBOX Test Suite Software, 2020).

Methods

The procedure of an evaluation of measured data during a vehicle testing has been described in previous publications by authors (Jánošík et al., 2022a; Jánošík et al., 2022b). It is based on the fundamentals of physics (Halliday et al., 1997) and a vehicle driving dynamics (Bradáč et al., 1999; Vlk, 2003).

The evaluation of the measured data during the vehicle testing was focused on the determination of braking distances, longitudinal and lateral accelerations. Longitudinal acceleration is applied in the straight direction of travel during a vehicle start-up (a positive value) and braking (a negative value). The lateral acceleration characterises driving in a circular track. A positive value of lateral acceleration characterises driving in a left-hand curve, a negative value characterises driving in a right-hand curve.

During the braking test, the VTS software was used to evaluate the recorded data. User tests were defined there under 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 recorded data and calculated the mean (Awg) and standard deviation (Std Dev) and selected the maximum (Max) and minimum (Min) values. In this test problem, only braking time, braking distance, and longitudinal acceleration were evaluated. The results were exported to a csv file format. Next, they were processed in MS Excel environment into a publishable form.

When evaluating the circle track test, the relevant part of the test task was first selected in the VTS software. Then it was saved to disk as a new file in a vbo format (VBOX Test Suite Software, 2020). This data was already stored in a text format. After removing a part of the unnecessary header in this file using 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 values of the following variables were monitored and evaluated: velocity (v), radius (R) of the vehicle centre of gravity trajectory when passing through the circular track, longitudinal acceleration (a_x) and lateral acceleration (a_y). In the VTS software calculation results, acceleration values are given in units of multiples of the gravitational acceleration (g). The last two variables determine the basic force actions between the vehicle and the road. The longitudinal acceleration a_x is applied in the calculation of inertial forces in the longitudinal direction during starting, but mainly during braking of the vehicle according to the equation (Halliday et al., 1997):

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

where m (kg) is the mass of the vehicle. Lateral acceleration a_y is applied in the calculation of centripetal forces when driving on a circular track and is calculated analogously to the equation:

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

Lateral acceleration a_y in equation (2) for a circular path can be calculated according to the equation:

$$a_y = \frac{v^2}{R} \tag{3}$$

where v (m.s^{-1}) is the velocity and R (m) is the radius of the vehicle's centre of gravity trajectory when travelling in a circular path. For longitudinal acceleration a_x and lateral acceleration a_y in relation to the gravitational acceleration, the equation applies:

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

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where g (m.s^{-2}) is the gravitational acceleration and μ_x (-) is the adhesion coefficient in the longitudinal direction and μ_y (-) is the adhesion coefficient in the transverse direction (Bradáč et al., 1999). The designation used for the x and y directions of vehicle motion is based on definitions from the literature (Vlk, 2003). The VTS evaluation software uses the same right-handed Cartesian coordinate system. When using units of gravitational acceleration g, these values numerically represent the magnitude of the adhesion coefficient. Frequencies of occurrence of instantaneous longitudinal and lateral acceleration values were then evaluated 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 the braking test

An example of the evaluation of the Rosenbauer Panther braking test task from an initial speed of 50 km.h^{-1} in the VTS software is shown in Figure 3. Figure 4 shows a detail of the evaluation of the first braking test (Run 1) showing the change in speed, longitudinal and lateral acceleration during the braking manoeuvre.

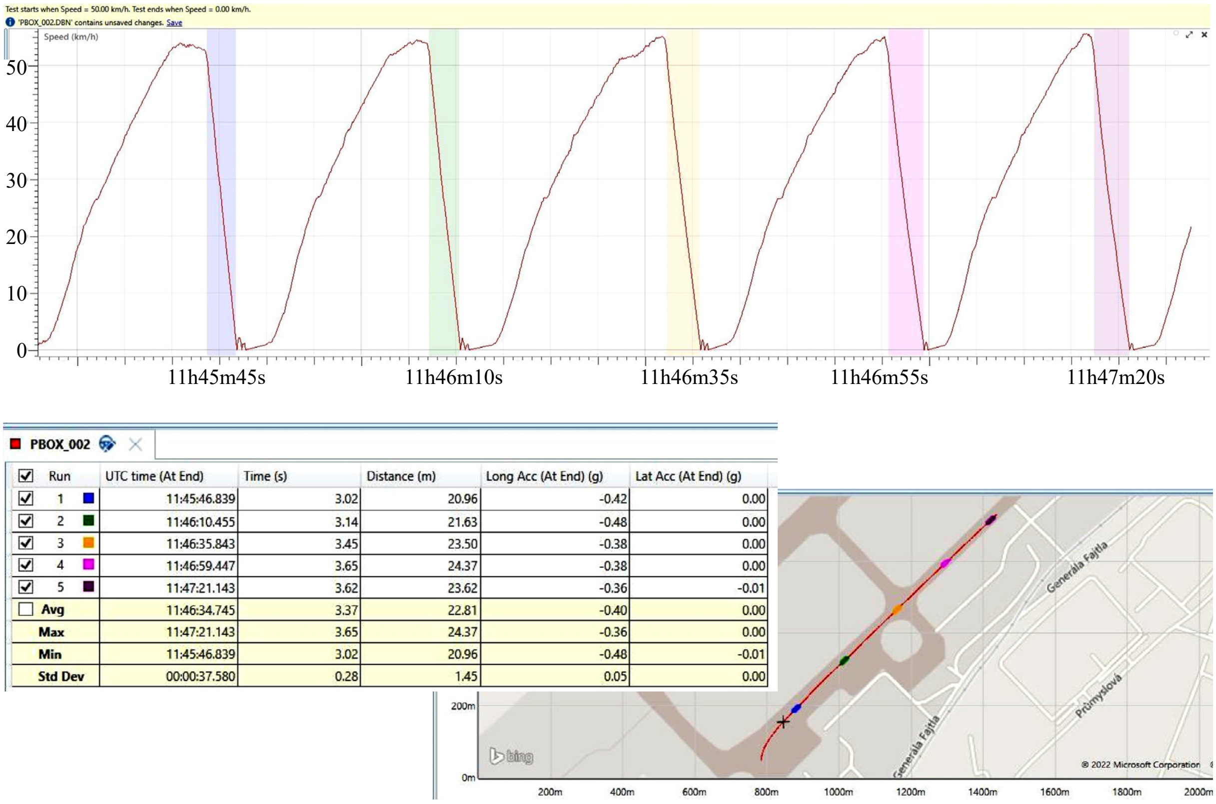

Figure 3 Speed vs. time record of the Rosenbauer Panther during braking test from an initial speed v_0 = 50 km.h^{-1}

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

Run	M-B Buffalo			Rosenbauer Panther		
	Braking time (s)	**Braking distance (m)**	**Longitudinal acceleration (g)**	**Braking time (s)**	**Braking distance (m)**	**Longitudinal acceleration (g)**
1	2.43	17.08	-0.51	3.02	20.96	-0.42
2	2.47	17.23	-0.50	3.14	21.63	-0.48
3	2.82	17.43	-0.74	3.45	23.50	-0.38
4	2.36	16.62	-0.72	3.65	24.37	-0.38
5	3.04	20.01	-0.57	3.62	23.62	-0.36
Avg	2.62	17.67	-0.61	3.38	22.82	-0.40
Max	3.04	20.01	-0.50	3.65	24.37	-0.36
Min	2.36	16.62	-0.74	3.02	20.96	-0.48
Std Dev	0.29	1.34	0.11	0.28	1.45	0.05

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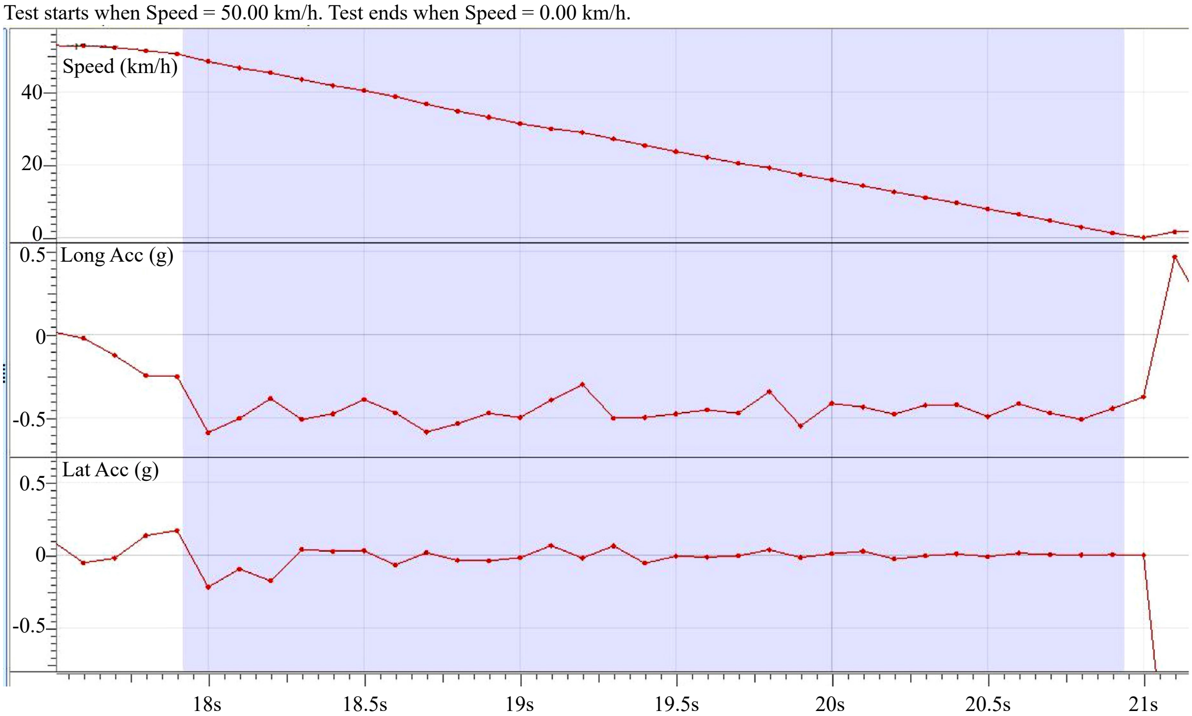

Figure 4 Detail of the evaluation of the first braking test of the Rosenbauer Panther from an initial speed of v_0 = 50 km.h^{-1}

Table 2 Braking distance (m) for an initial speed of v_0 = 60 km.h^{-1}

Run	M-B Buffalo			Rosenbauer Panther		
	Braking time (s)	**Braking distance (m)**	**Longitudinal acceleration (g)**	**Braking time (s)**	**Braking distance (m)**	**Longitudinal acceleration (g)**
1	3.20	27.74	-0.45	4.91	36.83	-0.32
2	3.46	25.49	-0.63	5.44	39.55	-0.18
3	3.18	26.93	-0.54	5.38	39.04	-0.17
4	3.33	29.02	-0.50	6.24	43.67	-0.21
5	2.99	24.66	-0.59	6.71	45.50	-0.15
6	2.94	24.88	-0.70	7.46	50.01	-0.10
7	3.11	26.33	-0.58	7.80	51.65	-0.07
8	3.58	26.36	-0.66			
Avg	3.22	26.43	-0.58	6.28	43.75	-0.17
Max	3.58	29.02	-0.45	7.80	51.65	-0.07
Min	2.94	24.66	-0.70	4.91	36.83	-0.32
Std Dev	0.22	1.47	0.08	1.10	5.66	0.08

Compendious results of the measurement and evaluation of the braking distances of the tested vehicles are summarised in Tables 1 and 2.

The evaluation of longitudinal acceleration in measurements of braking distances using VTS software produced some unexpected results in the case of the Rosenbauer Panther. For the initial speed of 50 km.h^{-1} values found close to expected values reported in the literature (Bradáč et al., 1999; Vlk, 2003). For braking from an initial speed of 60 km.h^{-1} the values were, with an exaggeration, downright cautionary. Expected longitudinal acceleration values should be at least 0.4. Therefore, a further evaluation of the measured longitudinal acceleration records was performed using the correction aligned to ECE, 1958, Regulation No. 13. According to this regulation, the mean braking deceleration is a function of the distance travelled in the speed interval v_b to v_e according to the equation:

$$d_m = \frac{v_b^2 - v_e^2}{25,92\left(s_e - s_b\right)} \qquad (5)$$

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where:

v_0 is the initial vehicle speed (km.h^{-1}),

v_b is the vehicle speed at 0.8 v_0 (km.h^{-1}),

v_e is the vehicle speed at 0.1 v_0 (km.h^{-1}),

s_b is the distance travelled by the vehicle between v_0 a v_b (m),

s_e is the distance the vehicle travels between v_0 a v_e (m).

The purpose of this calculation is to eliminate non-linearities at the beginning of braking, before the full braking effect is applied, and at the end of braking, when the vehicle's suspension cabin slides and rocks, which is recorded by the telemetry as a movement in the longitudinal direction. Results of the braking deceleration calculations (longitudinal acceleration in units of gravitational acceleration) and their comparison with the measured values from the standard test are shown in Table 3.

Even after the braking correction from an initial speed of v_0 = 60 km.h^{-1}, the Rosenbauer Panther still had a very low braking deceleration in the speed range v_b = 48 km.h^{-1} to v_e = 6 km.h^{-1}. For vehicles of a category N3, this Regulation defines a value of mean deceleration $d_m \geq$ 5,0 m.s^{-1} for the Type 0 braking test with an engine disconnected from an initial speed of 60 km.h^{-1}. The M-B Buffalo succeeded in the service braking test as it achieved a mean value of d_m = 5,3 m.s^{-1} in our testing.

Results of the acceleration test

The recorded data were also evaluated in terms of acceleration during the start-up. The vehicle's take-off time from a fixed start to reach a 100 metre runway was evaluated according to ČSN EN 1846-2. For the heavy weight class and mixed chassis, the defined condition is that the start-up time must be less than 16 s. The results of the evaluation are shown in Table 4.

Table 3 Comparison of longitudinal accelerations (g) in tests and ECE, 1958, Regulation No. 13 correction

Initial speed (km.h^{-1})	**Final speed (km.h^{-1})**	**Mean braking deceleration (g)**	
		M-B Buffalo	**Rosenbauer Panther**
v_0 = 50	v_0 = 0	-0.61	-0.40
v_0 = 60	v_0 = 0	-0.58	-0.17
v_b = 40	v_e = 5	-0.58	-0.41
v_b = 48	v_e = 6	-0.54	-0.21

Table 4 Measured values of the start-up time according to ČSN EN 1846-2

Run	**M-B Buffalo**		**Rosenbauer Panther**	
	Time (s)	**Speed (At End) (km.h^{-1})**	**Time (s)**	**Speed (At End) (km.h^{-1})**
1	16.02	39.53	13.43	50.95
2	14.97	44.46	12.92	51.25
3	15.32	42.91	12.96	49.80
4	15.02	42.88	13.09	50.03
5	16.68	27.23	12.48	50.59
6	16.53	25.40	12.69	50.29
7	16.01	34.42	12.80	49.75
8			13.88	38.13
9			12.88	49.54
10			13.36	48.58
11			12.98	48.92
12			12.96	48.90
13			13.24	43.20
Avg	15.79	36.69	13.05	48.46
Max	16.68	44.46	13.88	51.25
Min	14.97	25.40	12.48	38.13
Std Dev	0.70	7.83	0.36	3.69

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These results show that both vehicles tested met the requirement of the standard. The Rosenbauer Panther, despite its weight, performed better than the M-B Buffalo. The specific power of the M-B Buffalo is 15.8 kW.t^{-1}, while the Rosenbauer Panther had a specific power of 14.4 kW.t^{-1}. The difference of almost 3 seconds is significant. The results are indicative of a better transmission system that transfers power to wheels. The vehicle also has larger tires in a diameter and a width. In the test, the M-B Buffalo reached an average speed of just 36.7 km.h^{-1} at the end of the 100 m track. The Rosenbauer Panther achieved a better result of an average speed of 48.5 km.h^{-1}.

Results of the driving test in a circle

An example of the distribution of recorded instantaneous values of lateral acceleration and longitudinal acceleration for the vehicle M-B Buffalo when driving in a left-hand circle is shown graphically in Figure 5. The frequency distribution of an occurrence of longitudinal acceleration is shown in Figure 6. The frequency distribution of an occurrence of lateral acceleration is shown in Figure 7.

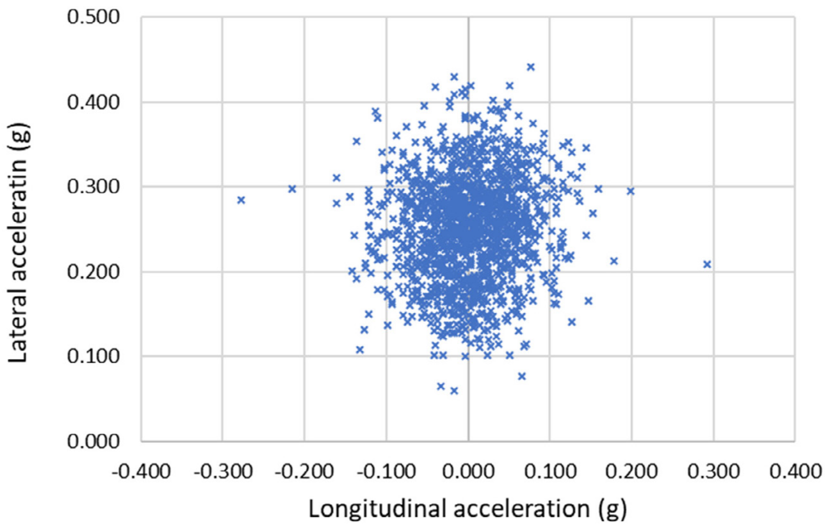

Figure 5 Recorded acceleration of the M-B Buffalo in a left-hand circle

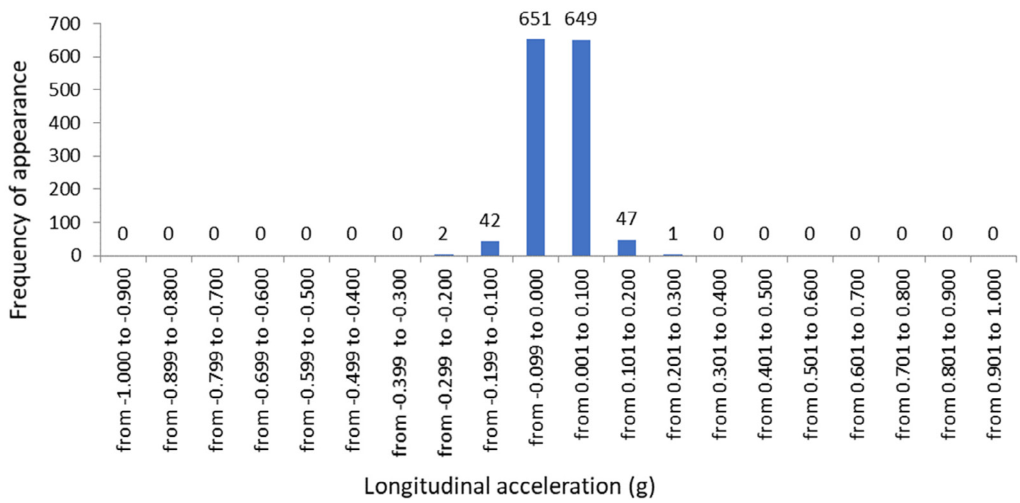

Figure 6 Frequency distribution of longitudinal acceleration of the M-B Buffalo in a left-hand circle

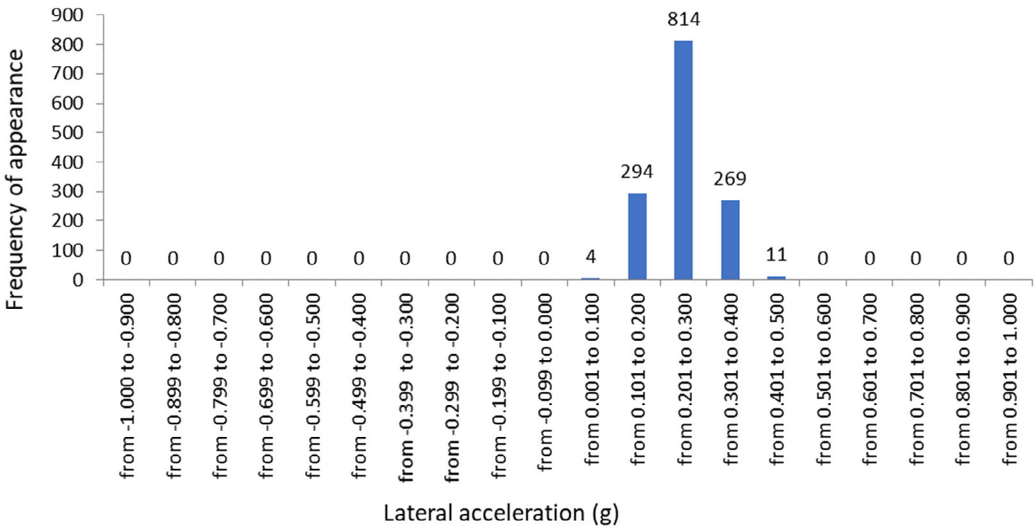

Figure 7 Frequency distribution of lateral acceleration of the M-B Buffalo in a left-hand circle

Table 5 Summary of resulting values of the monitored driving characteristics

Vehicle	**M-B Buffalo**		**Rosenbauer Panther**	
Driving in a circle	**left turn**	**right turn**	**left turn**	**right turn**
Lateral Acceleration (g)				
Avg Max Min	0.251 0.441 0.060	-0.255 0.007 -0.475	0.267 0.574 -0.003	-0.261 -0.025 -0.694
Velocity (km.h^{-1})				
Avg Max Min	28.35 32.36 21.57	28.57 32.37 24.62	30.75 33.92 24.72	30.01 33.35 25.05
Radius of turn (m)				
Avg Max Min	25.45 30.92 21.09	25.33 29.46 21.79	28.08 33.36 23.80	27.48 30.99 25.01

Compendious results of the evaluation of measured records and the overall resulting values of monitored driving characteristics of the tested vehicles when driving in a circle are summarized in Table 5.

Discussion

Evaluation of driving in a circle

In the evaluation of driving in a circle, our test of vehicles did not confirm findings of the previous research (Jánošík et al., 2022a; Jánošík et al., 2022b). Slightly higher speeds and thus lateral accelerations were achieved when driving in a left-hand circle than in a right-hand circle. There, the calculated mean, and maximum measured values for both left- and right-hand driving were recorded with very little differences (see Table 3). When testing the fire fighting vehicles at the units of the FRS of the Czech Republic, these observed values were different. Here, the fact that the airport specials were driven by the same driver, on the same day, with a minimal delay in changing vehicles, probably played a role. While each tested vehicle of the FRS of the Czech Republic was driven by a different driver, on different days, under different climatic conditions.

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Stopping distances

Several factors can influence resulting stopping distances of the fire trucks tested. The main ones are weather conditions and a tire type. At the outset of the measurement preparation, it was determined by the airport operator that testing would be conducted on the current road surface condition and only one test morning between 11:00 am and 1:00 pm was allowed. The reason was that the runway was not used by both passenger, and air freight traffic in a circumscribed time. That fact precluded testing under various weather conditions. On the test day, the temperature was sunny at +15 °C.

Tire influence

The effect of tires could not be compared, too. Both fire vehicles tested had the same type of Michelin XZL. It is a heavy-duty tire designed for an all-year-round use (M+S). According to the manufacturer, the tire was designed for all types of road surfaces and off-road surfaces. The tires differed only in their dimensions. For the M-B Buffalo, the tires were marked as 365/85 R20, an outer diameter measured on the vehicle was about 1150 mm, a width of a tire was about 310 mm. The Panther vehicle had tires marked as 24 R21, which, measured on the vehicle, had an outer diameter of about 1340 mm and a width of about 530 mm. The only two factors that could be observe and could influence the braking track length were:

- a gross vehicle weight,
- a design of a braking system.

The gross weight of the vehicle

The influence of the gross vehicle weight was evident in the measurement results. There was a difference in operating weight of 8000 kg between the fire vehicles tested, to the disadvantage of the Rosenbauer Panther. This is 29 % more than the M-B Buffalo. However, with this higher weight, the Rosenbauer Panther can carry up to 49 % more liquid extinguishing agents (water and foam). From a tactical point of view, this fact clearly leads to its choice. As a result, this weight difference was reflected in the longer stopping distances of the Rosenbauer Panther in the tests. The Rosenbauer Panther's average braking distance from an initial speed of 50 km.h^{-1} was only 5.1 m longer than that of the M-B Buffalo. However, at the 60 km.h^{-1} initial speed, the difference was already 17.3 m. According to the laws of physics for calculating the kinetic energy of a material body which is directly proportional to its mass and the square of its speed it is reasonable to expect that the differences in braking distance between vehicles will increase at higher speeds.

The design of the braking system

Both vehicles tested were fitted with drum brakes. Similar results could therefore be expected. However, that result was not confirmed with the test. The effect of the design of brake components on the length of the braking distance was evident in experiments. It is a well-known fact that drum brakes are cooled less efficiently by the flowing air. During repeated braking, the drum brakes overheated after 5 braking cycles in a short succession. Increasing the brake lining temperature to 300 °C caused a decrease in the friction coefficient for some brake linings (Jánošík et al., 2022c).

When measuring the size of the brake drums on the tested vehicles (measuring the external dimensions from the inside of the chassis), the following was found. The M-B Buffalo had an outer drum diameter of approximately 460 mm and its drum cylinder height was approximately 300 mm. The Rosenbauer Panther had an outer drum diameter of approximately 280 mm and a drum cylinder height of 360 mm. That was probably one of several reasons for the decrease in braking efficiency at higher speeds and a repeated braking.

Unfortunately, it was not possible to find out what kind of brake pads the tested vehicles had. Both vehicles still have had the original brake pads from their acquisition and commissioning at the airport in 2010.

According to the description of the example exit of this vehicle when driving to the intervention on the runway of the airport, there should be at least four braking manoeuvres before entering the turns. These manoeuvres were as follows:

1. Exit from the fire station towards the taxiway (F), braking and turning into the direction of travel to the place of an intervention.
2. Arriving at the appropriate connecting runway (A to E) nearest to the scene of an intervention, braking and then making a 90° turn. In the case of driving to outermost lanes A or E, the vehicle may approach at a speed up to 105 km.h^{-1}.
3. Arriving to the end of the connecting runway, braking, and taxiing to the runway.
4. Driving to the scene of the emergency on the runway and braking the vehicle to a standstill at the scene.

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The overheating of the brakes would probably occur after the 3rd braking manoeuvre; therefore, the driver should have a space long enough for a possible longer braking distance during the 4th manoeuvre.

Conclusion

During measurements, better braking distances were achieved with the M-B Buffalo. When evaluating the longitudinal adhesion coefficient μ_x at braking, results consistent with the literature were obtained (Vlk, 2003). Unsatisfactory results were obtained for the Rosenbauer Panther vehicle due to the brake overheating. Based on the results of the testing, a theoretical training can be recommended, followed by a practical training focused on a vehicle handling during repeated braking with the possibility of a risk of the brake overheating. However, in an acceleration from a standstill on the 100 m-track the Rosenbauer Panther vehicle was faster (see Table 4). The velocity is a very essential characteristics of an ARFF vehicle for airport interventions.

Acknowledgments

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