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Driving Dynamics Study in Firefighting Vehicles Drivers Training on a Training Polygon

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The article deals with studying the driving dynamics of firefighting vehicles and their testing on the training polygon Automotodrom Brno. It is focused on the issue of braking and driving in a circle and on the subsequent evaluation of longitudinal and lateral acceleration. Measurements were taken on a dry asphalt with full fire extinguisher tanks. The experiments were carried out on two different firefighting vehicles construction types, TATRA with a mixed chassis and SCANIA with an urban chassis. The results of the measurements can be used for fire protection units within the driver education system to improve a safety when driving to intervene.

1. Introduction

Braking on different types of road surface in a straight line or through a dynamic turn is one of the basic driving skills a driver needs to be able to handle a critical situation on a road. The primary task of firefighting vehicles drivers is to ensure a safe and rapid transport of the fire protection unit to an emergency site. The speed of the firefighting vehicles shall be such that it can be stopped safely in crisis situations where the avoidance manoeuvre cannot be performed. The driver must make dynamic changes to the running speed before and during a turn to ensure safe driving. An analysis of accident statistics for the years 2011 to 2019 showed that excessive speed was the cause of only 54 culpable road accidents (17%) of water tender vehicles when driving to intervene. These accidents accounted for up to 71% of the total damage to vehicles (53.6 M CZK) for the period analysed (Jánošík et al., 2020). These facts have been the reason why authors have a long-term commitment to the essential dynamic driving characteristics of firefighting vehicles, such as longitudinal and lateral acceleration, measurement of braking distances and theoretical calculations of limit speeds for fire vehicles.

2. Firefighting vehicles

Firefighting vehicles dislocated at Fire Rescue Service units of the South Moravia Region (hereinafter FRS SMR) were used for testing. A management of the FRS SMR provided both firefighting vehicles, drivers, and the necessary time on the Automotodrom Brno training polygon for this research. Two firefighting vehicles were used for the measurement: SCANIA P500 4×2 (RZ: 5B8 0972) and TATRA T815-2 TerrNo1 4x4.2 (RZ: 5B4 3503).

A first tested firefighting vehicle - SCANIA P500 B4x2 (hereinafter SCANIA) has a fire specification CAS 20/3500/240-S1T and is dislocated to the Brno-Lidicka Fire Station. The length of the vehicle is 8,650 mm, width 2,550 mm, height 2,960 mm. The operating weight is 11,400 kg and the maximum permissible weight is 18,000 kg. The engine power is 368 kW, the maximum speed is 110 km.h-1 (with limiter) and the vehicle has got an Opticruise automatic transmission. The drum brakes are on both axles. The vehicle has ABS and ASR assistance systems. The vehicle was fitted with tires Continental Conti Hybrid HS3 on the front axle, Continental Conti Hybrid HD3 on the rear axle. The vehicle has been placed in service to the fire station on October 4, 2019.

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The second tested firefighting vehicle - TATRA T815-2 TerrNo1 4x4.2 (hereinafter TATRA) has a fire specification CAS 20/4000/240-S2T and has been dislocated to Fire station Pozorice. The length of the vehicle is 7,825 mm, width 2,550 mm, height 3,150 mm. The operating mass is 12,750 kg and the maximum permissible mass is 17,500 kg. Engine power is 325 kW at 1,800 rpm, maximum speed is 110 km.h-1 (no limiter) and the vehicle has got an Allison automatic transmission. The disc brakes are on both axles. The vehicle has an ABS system only. The vehicle was fitted with tires Continental Scandinavia HSW2, Winter M+S on the front axle, Continental Scandinavia HDW2, Winter M+S on the rear axle. The vehicle has been placed in service to the fire station on November 22, 2016.

3. Measuring apparatus

A Performance Box produced by Racelogic Ltd, Buckingham, England was used to measure driving characteristics. A detailed description of the apparatus is given on the manufacturer's website (Performance Box, 2019). The apparatus is designed to detect a real-time absolute position of the vehicle. The device then calculates a trajectory, speed, acceleration, and several other values. The frequency of the entries is 10 Hz. An accuracy of the device depends on determining the vehicle's position in real time by using signals from GPS and GLONASS satellite systems. An accuracy of 0.2 km/h at a resolution of 0.01 km/h is given for a speed measurement. The accuracy of 0.05 % (less than 50 cm per km) and resolution of 1 cm is given for a track measurement. The apparatus has been equipped with an SD card to which recorded data were stored. The SD card was then transferred to a computer and further processed in a VBOX Test Suite software (hereinafter VTS), version 1.7.55.2453 (Software VBOX Test Suite, 2019).

4. Theoretical basis for an acceleration evaluation

Besides of measuring braking distances, this analysis was aimed at evaluating vehicle accelerations. The telemetry and the VST software make it possible to calculate instantaneous values of longitudinal acceleration - a_x and lateral acceleration - a_y from the recorded data. The values of acceleration are presented as multiples of a gravitational acceleration (g). Longitudinal acceleration is applying at a start (a positive value) and at braking (a negative value) of the vehicle in a straight ride. An arc ride is characterized by lateral acceleration. These two parameters determine, as a results, the basic force actions between a tire of the vehicle and a road surface by directions of the *x* and *y* axes, according to a general equation:

$$F_{x,y} = m \cdot a_{x,y} \tag{1}$$

The lateral acceleration a_y can be calculated by:

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

Both, longitudinal acceleration a_x, and lateral acceleration a_y can be calculated by:

$$|a_{x,y}| = g \cdot \mu_{x,y} \tag{3}$$

An indication of the axes *x* and *y* directions for vehicle movement is based on definitions, see (Vlk, 2003). Using units of gravitational acceleration *g*, values of the acceleration numerically represent a coefficient of adhesion $\mu_{x,y}$. Both coefficients of adhesion characterize the tire's adhesion force in a contact with a road, which is used for starting and braking in the longitudinal direction (*x*-axis) and for the lateral line in the perpendicular direction (*y*-axis). According to (Bradáč et al., 1999), a separation of the two components of adhesion is shown by a so-called adhesion ellipse. The ellipse determines a maximum sum adhesion that can be used when driving in a desired direction. It depends on an instantaneous speed and on a given radius of the vehicle's center of gravity when riding in an arc. The vector sum of longitudinal and lateral adhesion indicates the amount of usable adhesion for the vehicle wheel to contact the road. If we use maximum of adhesion during the emergency braking, then there will be almost nothing left to guide the wheel in a lateral direction, for an avoidance maneuver. Similarly, if the vehicle goes in a bend at a speed that is close to the limit speed, the adhesion will be used to overcome a centrifugal force by exerting a reactive centrifugal force, leaving almost no adhesion to brake. If a driver will start braking then, the vehicle will roll uncontrollably around a curve of a larger radius and pull out of its direction of ride into the opposite direction - on a right-hand bend, or out of the road - on a left-hand bend (Bradáč et al., 1999).

5. Methods

Experimental measurements of braking tracks and driving in a circle were carried out on the training polygon of Automotodrom Brno on June 10, 2021. A surface of the experimental track was dry asphalt bituminous. First measurement started at 8.30 a.m. and the total measurement time did not exceed 30 minutes. The air temperature was 16 °C at the beginning of the measurement. An example of recording the position of a SCANIA vehicle on a map basis during an evaluation in the VTS software is shown in Figure 1. A vehicle's instantaneous speed was checked using a Performance Box meter which was fixed in a longitudinal axis of the vehicle in the vehicle’s cab on a windscreen.

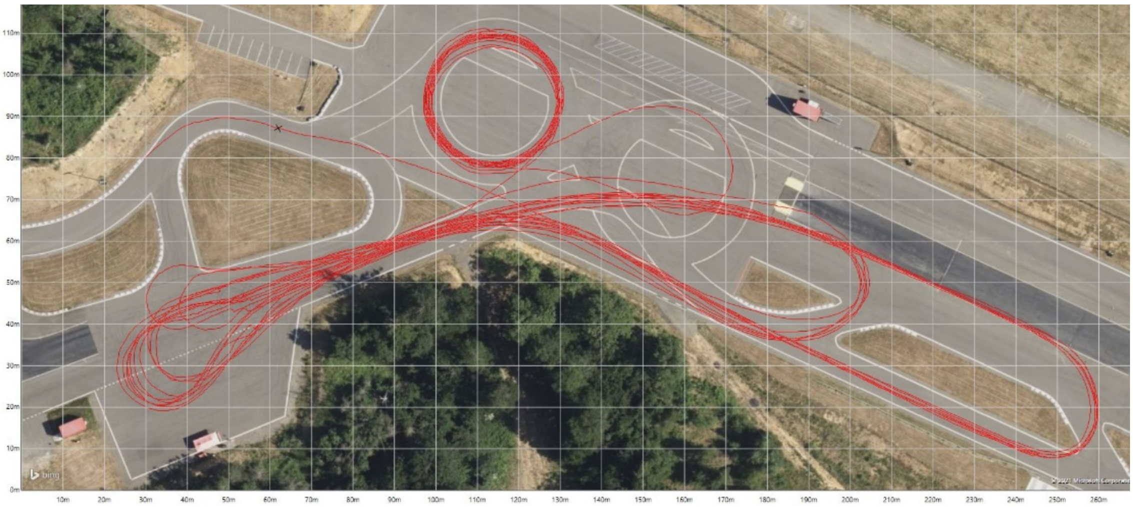

Figure 1: Vehicle SCANIA position recording during testing

The experimental measure of driving performance took place on a training polygon and involved two different tests.

Test No. 1: Braking on a dry surface with full fire extinguishing tanks at initial speeds v_0 = 50 km.h^{-1} and 60 km.h^{-1}. Default conditions were determined by performing at least 5 experimental runs for each initial speed to exclude any invalid trial where the prescribed initial speed would not be reached.

Test No. 2. Driving in a circle in a right-hand and then a left-hand direction of ride on a dry circular path with a marked internal radius of 13 m (an external radius was not defined) with full fire extinguishing tanks and with maintaining an achieved speed of 30 km.h^{-1} that is less than a theoretical rollover speed.

6. Results

A presentation of recorded values and results of each experiment is summarized below. On Figure 2, there is a graphic recording of speed depending on the TATRA vehicle's relative driving time when measuring the braking distances. The recording shows a continuous progress of all 6 measurements from the initial speed v_0 = 60 km.h^{-1} until the vehicle stopped.

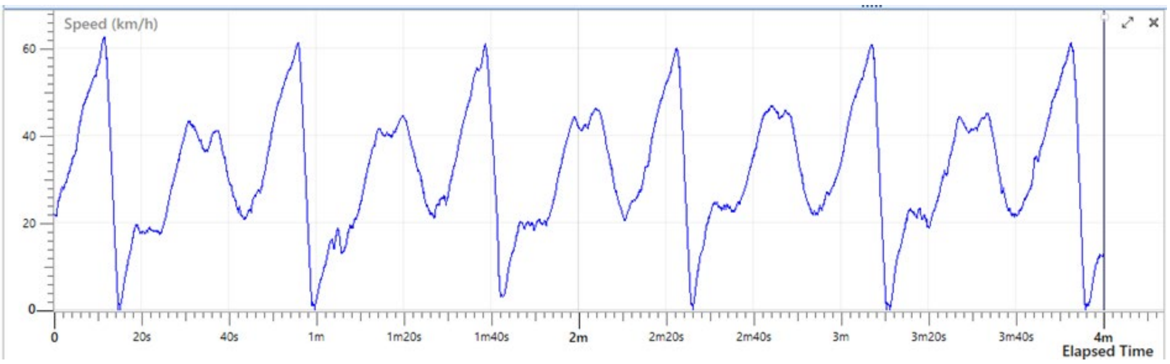

Figure 2: Record speed versus time when testing TATRA vehicle braking from 60 km.h^{-1}

An evaluation of measured data was done in the VTS software. Calculated values from measurements of the braking distances of the two vehicles tested are given in Table 1. A standard evaluation of longitudinal acceleration in measuring braking distances using the VTS software produced some unexpected results. Measured values are given in Table 2. An ECE, 1958, Regulation No. 13 procedure was used to correct them. According to this Regulation, a braking distance shall be evaluated from an interval of 80 % to 10 % of the initial speed v_0. For example, for a speed of 50 km.h^{-1}, the evaluated speed interval is from v_0 = 40 km.h^{-1} to v_0 = 5 km.h^{-1}. In this way, non-linear data are trimmed, both at the start of braking before the braking system is fully applied, and at the end of braking when the vehicle is swinging.

Table 1: Vehicle braking distance measurement results

Vehicle	SCANIA				TATRA			
v_0 (km.h^{-1})	50		60		50		60	
Run	braking time (s)	braking distance (m)	braking time (s)	braking distance (m)	braking time (s)	braking distance (m)	braking time (s)	braking distance (m)
1	2.22	15.74	2.98	23.78	2.27	15.69	3.16	23.37
2	2.29	15.86	3.19	26.76	2.84	16.49	2.78	22.82
3	2.23	16.57	3.06	24.36	2.65	16.77	3.07	23.82
4	2.73	17.76	3.36	25.46	2.33	15.83	2.82	24.09
5	2.86	21.06	3.02	23.13	2.17	13.94	2.77	23.57
6	2.74	18.22	3.05	24.55			2.83	23.93
7	2.54	16.65						
8	2.45	15.18						
9	2.46	15.43						
Avg	2.50	16.94	3.11	24.67	2.45	15.74	2.91	23.60
Min	2.86	21.06	3.36	26.76	2.84	16.77	3.16	24.09
Max	2.22	15.18	2.98	23.13	2.17	13.94	2.77	22.82
Std Dev	0.23	1.85	0.14	1.29	0.28	1.10	0.17	0.46

Table 2: Longitudinal acceleration measurements results in brake testing

Vehicle	SCANIA		TATRA		SCANIA		TATRA	
v_0 (km.h^{-1})	50	60	50	60	50	60	50	60
Run	Longitudinal Acceleration (g) – standard evaluation				Longitudinal Acceleration (g) – according to ECE, 1958, Regulation No. 13			
1	-0.51	-0.17	-0.47	-0.22	-0.62	-0.67	-0.59	-0.66
2	-0.49	-0.55	-0.13	-0.08	-0.61	-0.57	-0.57	-0.65
3	-0.59	-0.07	-0.03	-0.28	-0.70	-0.60	-0.48	-0.62
4	-0.12	-0.02	-0.42	-0.61	-0.67	-0.49	-0.69	-0.67
5	-0.56	-0.23	-0.14	-0.60	-0.61	-0.36	-0.60	-0.63
6	-0.05	-0.14		-0.44	-0.60	-0.61	-0.65	-0.61
7	-0.10				-0.63			
8	-0.05				-0.68			
9	-0.14				-0.64			
Avg	-0.29	-0.20	-0.24	-0.37	-0.64	-0.55	-0.60	-0.64
Min	-0.05	-0.02	-0.03	-0.08	-0.60	-0.36	-0.48	-0.61
Max	-0.59	-0.55	-0.47	-0.61	-0.70	-0.67	-0.69	-0.67
Std Dev	0.24	0.19	0.19	0.21	0.04	0.11	0.07	0.02

To detect lateral acceleration from circle driving testing, average values were evaluated using the VTS software. Figure 3 shows a graphic record of speed and lateral acceleration, depending on the TATRA vehicle's relative driving time in a right-hand circle.

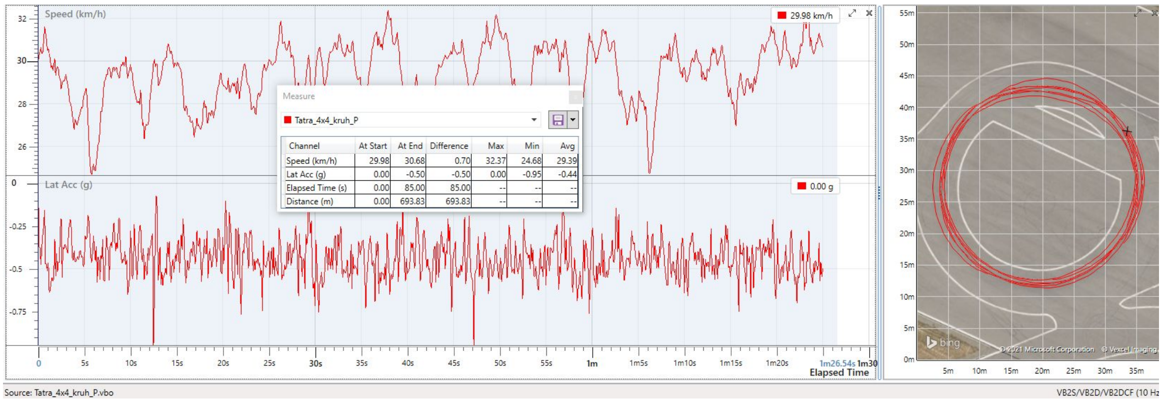

Figure 3: Record speed versus time of the TATRA vehicle when driving in a right-hand circle

Recorded data sets from the circle driving test were converted to a .csv format and then evaluated in MS Excel to determine a frequency of lateral acceleration measured. An example of the frequency distribution of lateral acceleration values is graphically shown in Figure 4.

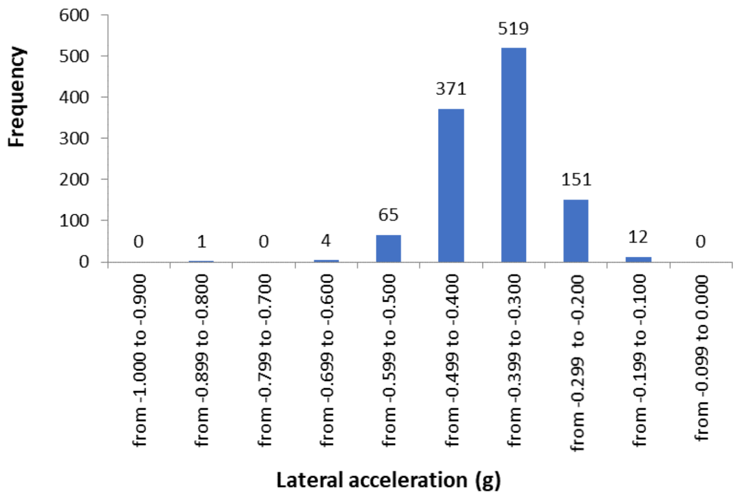

Figure 4: Frequency of lateral acceleration values of the SCANIA vehicle when driving in a right-hand circle

During the test, average lateral acceleration values were measured and then calculated, as shown in Table 3. These values were measured at an average speed 29 km.h^{-1} when driving in a circle, with a radius of the vehicle's center of gravity trajectory R = 16 m.

Table 3: Calculated values of lateral acceleration (g)

Vehicle	SCANIA		TATRA	
Driving in a circle	Left-hand	Right-hand	Left-hand	Right-hand
Avg	0.404	-0.380	0.458	-0.434
Min	0.116	-0.805	0.093	-0.947
Max	0.915	-0.139	0.925	-0.072

7. Conclusions

Chapter 2 Resulting braking distance of a vehicle is primarily affected by tyres. In performed measurements, a slightly unexpected improvement of a braking distance was achieved by the TATRA vehicle, which had winter tyres. At the start of testing, it was sunny, and the air temperature was 16 °C. The above-mentioned results might be caused by disc brakes fitted to the TATRA vehicle, which generally have had better braking performance, while the SCANIA vehicle had drum brakes. The difference in a length of the average braking distance between the vehicles tested was 1.20 m for the initial braking speed v_0 = 50 km.h^{-1}, and 1.07 m for v_0 = 60 km.h^{-1}.
Chapter 3 In results of measurements, a theoretical basis was confirmed that the coefficient of adhesion decreased with increasing speed. When evaluating the coefficient of longitudinal adhesion μ_x for braking, more accurate results were obtained corresponding to (Vlk, 2003) using correction (ECE, 1958, Regulation No. 13), when observed μ_x values ranged from -0.55 to -0.64.
Chapter 4 When evaluating the coefficient of lateral adhesion μ_y when driving in a circle, a frequency of occurrences of lateral acceleration (g) absolute values at intervals $|a_y| \geq 0.400$ g was detected. For the TATRA vehicle, when driven in a left-hand circle, 70 % of measured values μ_y were ≥ 0.401. When driven in a right-hand circle 62 % of measured values $|\mu_y| \geq -0.400$. For the SCANIA vehicle, when driven in a left-hand circle, 48 % of measured values μ_y were ≥ 0.401. When driven in a right-hand circle up to 39 % of measured values $|\mu_y| \geq -0.400$. The difference in achieving higher values for the TATRA vehicle is caused by a unique design of a chassis. The main principle is the use of a central load-carrying tube and axles with independently suspended swinging half-axles bolted together into a single unit. This concept used on the TATRA vehicle better copes with changes in dynamic driving than the SCANIA vehicle does. A second difference in the measured values of μ_y was found in a driving direction. A left-handed driving was more dynamic than a right-handed one for both vehicles. This is due to both a driver's seat position on a left-hand side of a cab, and a subjective driver’s feeling of better handling a left-hand ride than driving in a right-hand direction.

Nomenclature

Avg – arithmetic mean, -
F_x – inertial force in x-axis direction, N
F_y – inertial force in y-axis direction, N
g – gravitational acceleration, 9.81 m.s^{-2}
m – vehicle weight, kg
Min – minimum value, -
Max – maximum value, -
R – radius of the vehicle's centre of gravity trajectory when riding the curve, m
Std Dev – standard deviation, -
a_x – longitudinal acceleration, m.s^{-2}
a_y – lateral acceleration, m.s^{-2}
v – speed, m.s^{-1}
v_0 – initial speed, km.h^{-1}
x, y – cartesian coordinates, -
μ_x – longitudinal adhesion coefficient, -
μ_y – lateral coefficient of adhesion, -

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