Analysis of longitudinal acceleration during rapid minibus braking on various surfaces

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Abstract. Vehicle acceleration can be used to control vehicle traffic, evaluate driver behaviour and analyse accident causes, among others. The purpose of the testing was to designate longitudinal acceleration in limit conditions during the test vehicle’s braking on various surfaces. The paper presents selected results of testing the motion parameters of a Ford Transit during rapid braking. The testing included measurements of the vehicle’s acceleration and speed on test sections with asphalt and concrete surfaces. The test runs were conducted on a dry, wet and icy asphalt surface. The testing included determination of the impact of the road surface’s condition on the vehicle’s longitudinal acceleration. It was demonstrated that a virtually invisible and thin ice layer covering the road surface substantially affected the acceleration during braking, thereby affecting safety. A clean and wet surface caused a negligible change in the tested vehicle’s acceleration. The obtained results can be used in accident cause analysis with consideration of the road surface’s condition.

Keywords – vehicle dynamics, hard braking, vehicle

1. Introduction
Vehicle braking manoeuvres in road traffic are very important in terms of the possibility of collision or accident occurrence. They affect safety in a substantial manner. Their unexpected course can lead to the loss of life or health and property damage, including negative environmental effects. This causes the braking process to remain the subject of many studies and analyses.

The course of the braking process depends on many factors. The factors can be classified in three groups. The first group includes vehicle-related factors. These mainly include the vehicle type and braking system design. A driver should be aware of the vehicle’s capabilities deriving from its weight, size, centre of gravity, braking system design, technical condition and long-term operation capabilities, tyre type and condition, vehicle control systems, including ASR and ABS, and other assistance systems. This group also includes ergonomic factors aimed at providing the driver with the ability to adapt the workplace and optimise the working environment to ensure comfort.

The second group includes factors related to the environment in which the vehicle is driven. The group includes the surface type and technical condition, whether the surface is dry or wet, icy, covered with snow, sand or other contaminants (e.g. mud, leaves, engine oil, soil, gravel). Roads are used by various users. These include, for example, agricultural machinery or various construction machinery.
users, thereby causing the roads to be covered with various contaminants. Ambient temperature, atmospheric precipitation and wind speed are also very important parameters. In negative or near-zero degree temperatures, the driver should take into account that the road can be covered with ice.

The third group of factors affecting the vehicle’s braking process includes driver-related factors. The driver makes decisions and is responsible for the braking effects. The most important factors affecting vehicle braking deriving from the driver’s action include speed, respecting other road traffic regulations, taking into consideration the traffic conditions and the vehicle’s capabilities when making decisions. Taking into account personal capabilities, health and well-being on the given day is also important. A good driver is able to conduct self-assessment and not give in to emotions when driving. The driver must be aware that his or her mental and physical capabilities change substantially with age. All three factor groups are interrelated and affect the vehicle’s motion and braking, thereby affecting its safety.

Vehicle braking and acceleration are often subjects of scientific publications. Road conditions substantially affect vehicle motion safety. Braking parameters are being tested in various atmospheric conditions. The aim of the testing is to designate the impact of these conditions on the deceleration, braking distance and tyre grip. Braking parameters designated in various conditions provide information on the traction properties of various vehicles on various surfaces and in different conditions and are useful in accident cause analysis. Waluś K.J. tested the acceleration and braking of a passenger vehicle equipped with winter tyres on fresh snow [1]. Subsequent test series were conducted on different days at various weather conditions. It was pointed out that winter conditions feature a considerable dispersion of the obtained results even when using the same vehicle, tyres, test location, driver and measurement instruments. Braking in winter conditions was the subject of numerous studies [2, 3, 4, 5].

Paper [6] presents broad results of testing the emergency braking of buses, tractors and commercial vehicles. The results were compared to the results obtained during passenger vehicle testing. The initial braking speed, delay rise time and mean fully developed deceleration. The parameters were designated in order to be used in road accident reconstruction. The authors of paper [7] tested the braking distance and deceleration of a passenger vehicle on various surfaces: dry, wet and contaminated. Tests were also conducted on mixed surfaces. They included driving one side of the vehicle on dry asphalt and the other on asphalt covered with dry sand, wet sand or wet asphalt covered with wet sand. It was demonstrated that braking on mixed surfaces is very dangerous. Mixed surfaces extend the braking distance and can lead to vehicle stability loss. The braking parameters of an unloaded tractor were tested in paper [8]. The designated mean fully developed deceleration (MFDD) was lower from the values achieved by passenger vehicles by approx. 20-30%. Paper [9] presents the results of braking parameters’ measurements conducted for an efficient and damaged braking system as well as efficient and inoperable ABS system. The testing was conducted on a wet skid pad. The average mean fully developed deceleration recorded for an efficient braking system and ABS amounted to 4 m/s², while the average braking distance amounted to 24.3 m. In tests conducted on the same surface and in the same conditions, the average mean fully developed deceleration recorded for an efficient braking system and inoperable ABS amounted to 2.33 m/s², while the average braking distance amounted to 41.6 m. The lack of an efficient ABS resulted in a substantial extension of the braking distance.

Kordani et al. conducted simulation tests of the impact of weather-dependent friction on the braking process. The testing was conducted for three car models: sedan passenger car, commercial vehicle and bus. The tests were carried out with the use of the Adams/car software [10]. The authors demonstrated that the friction of 0.9, 0.8, 0.7 and 0.6 achieved in the simulation show no substantial differences in braking distance. They can be assigned to weather conditions featuring no atmospheric precipitation. The authors determined that the friction of 0.5, 0.4, 0.28 and 0.18 can be assigned to wet, rainy, snowy and icy weather conditions, respectively.

Pokorski J et al proposed the method of measuring the tyre grip by using the SRT-4 skid resistance tester consisting of a special dynamometric trailer, tractor and measurement instrumentation [11]. The
speed characteristics of the tyre grip and grip characteristics in the wheel skid function were designated for various tyre types and in different road conditions. The authors demonstrated differences in the designated characteristics depending on atmospheric conditions and tyre type.

Road traffic conditions change and are often unpredictable for the driver. Road safety can be improved by notifying the driver about the road’s slipperiness. This would enable the driver to adapt his or her behaviour (speed, distance between cars) to the road conditions. Jang J. proposed the possibility of road slipperiness detection based on wheel skid and wheel acceleration [12]. He pointed out that digital tachograph sensor data can be used for this purpose.

The paper’s authors tested the braking process on different surfaces and with different technical conditions of these surfaces. The testing was conducted, among others, on asphalt covered with a virtually invisible, thin layer of black ice. The tests were carried out on a minibus. It was demonstrated that the surface’s technical condition affected the braking parameters.

2. Testing methodology

The testing of motion parameters during intense braking were conducted on test sections (test tracks) at the Kielce University of Technology’s Car and Tractor Laboratory and the Jastrząb Autodrome near Radom. The tests were carried out on test sections with asphalt and concrete surfaces. The testing was conducted on dry and wet asphalt and concrete surfaces. Furthermore, the asphalt surface testing was conducted when the surface was covered with a thin, invisible layer of ice (so-called black ice).

The test subject was a sixth-generation Ford Transit intended to transport 9 passengers, with a curb weight of 2,070 kg. The car was equipped with a compression ignition engine, cubic capacity of 2,198 cm³ and rated power of 92 kW. The vehicle featured traction improvement systems (ABS, ASR, ESP) which were enabled during testing. Such vehicles are often referred to as minibuses and can be used as delivery trucks after adequate interior adaptation. Figure 1 presents the tested vehicle.

![Figure 1. Ford Transit during testing.](image)

The vehicle’s technical condition, especially the tyres and braking system elements were checked prior to testing. During the tests, the vehicle was loaded with the testing instrumentation and two people: the driver and the person operating the instrumentation (approx. 180 kg). The tested vehicle was equipped with summer Continental ContiVanContact 200, 205/65 R16C tyres with very little wear. The tread depth demonstrated wear of approx. 1 mm when compared to the nominal value.

Rapid (emergency) braking cycles were conducted on the test sections in each test series. The driver was accelerating the vehicle to approx. 50 km/h and then pressed the brake pedal sharply as in the case of an impending collision.

The measurements were used to develop plots for vehicle acceleration and speed during braking. An analysis of the plots allowed for the designation of the initial braking speed \( V_o \) and mean fully developed deceleration (MFDD). The mean fully developed deceleration (MFDD) was calculated as the average measured acceleration for the tested vehicle’s speed range from 0.8 of the initial braking speed \( V_o \) to 0.1 of the initial braking speed \( V_o \).

3. Testing instrumentation

The rapid braking parameters were measured by using specialist measurement instrumentation including the following elements:
- Correvit S-350 Aqua optoelectronic longitudinal speed sensor [13],
- uEEP-12 Datron® data acquisition station with the ARMS® data analysis software [14],
- TAA three-axis linear acceleration sensor [15].

4. Test results and their analysis
The tests conducted during rapid braking allowed for obtaining acceleration over time for the Ford Transit on various surface types and surface conditions. Figure 2 presents acceleration over time during emergency braking tests conducted for three asphalt surfaces: dry, wet and covered with a thin ice layer.

Figure 2.a presents acceleration over time during emergency braking on a dry asphalt surface, while Figure 2.b presents acceleration over time during emergency braking on wet asphalt. No substantial differences in the obtained maximum accelerations can be seen when comparing the acceleration values from both plots. The acceleration presented in Figure 2.b demonstrated greater amplitude of changes in the acceleration recorded during fully developed braking. Two instances of acceleration over time feature greater rapid acceleration changes in the second part of the fully developed braking. The difference in the acceleration over time instances when comparing the wet and dry surfaces is most probably an effect of the operation of the ABS system which provides protection against wheel locking and affects the measured acceleration values. Figure 2.c presents the acceleration over time measured on asphalt covered with a thin ice layer. The acceleration values obtained during fully developed braking are considerably smaller in this instance. These acceleration over times instances demonstrate substantial changes in the recorded acceleration values at the start and, in the case of some plots, end of braking. At the start of braking, the changes are caused by the ABS system that prevents the wheels from locking and uncontrolled vehicle skidding. The amplitudes of changes in the measured acceleration are substantially smaller in the latter part of braking. Some plots feature acceleration increases at the end of braking. In one instance, the recorded acceleration at the end of braking is substantially higher than the value recorded during fully developed braking.

Figure 2. Ford Transit’s longitudinal acceleration over time during rapid braking on asphalt surfaces: a) dry, b) wet, c) covered with a thin ice layer.
The initial braking speed \( V_o \) and mean fully developed deceleration for particular rapid braking attempts on dry, wet and icy asphalt are presented in Table 1. The table also features mean initial braking speeds \( V_{om} \) and average mean fully developed deceleration MFDD\(_m\) during rapid braking attempts on asphalt with various surface conditions. The calculations also included the standard deviation for the designated \( V_o \) and the MFDD on their average value. The MFDD\(_m\) for wet asphalt is slightly lower than the MFDD\(_m\) for dry asphalt. On the other hand, the MFDD\(_m\) for asphalt covered with a thin ice layer amounted to 2.27 m/s\(^2\) and is substantially lower than the MFDD\(_m\) for dry asphalt, which amounted to 9.51 m/s\(^2\). Paper [4] specifies the MFDD on a surface covered with a thick black ice layer of 1.18 to 2.55 m/s\(^2\). On the other hand, paper [16] presents the MFDD on an ice-covered surface for various tyres as well as with the ABS system enabled and disabled. In the case of summer tyres, the MFDD with the ABS system enabled amounted to 1.96–1.28 m/s\(^2\), whereas with the ABS system disabled, the MFDD amounted to 1.57–1.47 m/s\(^2\).

**Table 1.** Ford Transit’s motion parameters during rapid braking on dry, wet and icy asphalt.

| asphalt | Test run no. | \( V_o \) km/h | \( V_{om} \) km/h | SD  | MFDD m/s\(^2\) | MFDD\(_m\) m/s\(^2\) | SD  |
|---------|--------------|-----------------|-------------------|-----|----------------|-----------------------|-----|
| dry     | 1            | 49.1            |                   |     | 9.66           |                       |     |
|         | 2            | 52.2            |                   |     | 9.94           |                       |     |
|         | 3            | 48.56           |                   |     | 9.63           |                       |     |
|         | 4            | 49.69           |                   |     | 9.59           |                       |     |
|         | 5            | 52.81           | 52.10             | 2.52| 9.31           | 9.51                  | 0.31|
|         | 6            | 54.03           |                   |     | 9.72           |                       |     |
|         | 7            | 52.88           |                   |     | 9.54           |                       |     |
|         | 8            | 56.25           |                   |     | 8.87           |                       |     |
|         | 9            | 53.35           |                   |     | 9.32           |                       |     |
| wet     | 1            | 52.37           |                   |     | 9.05           |                       |     |
|         | 2            | 52.05           |                   |     | 9.38           |                       |     |
|         | 3            | 51.59           |                   |     | 9.32           |                       |     |
|         | 4            | 51.52           |                   |     | 8.03           |                       |     |
|         | 5            | 53.15           | 50.50             | 2.21| 9.47           | 9.16                  | 0.45|
|         | 6            | 49.66           |                   |     | 9.27           |                       |     |
|         | 7            | 49.22           |                   |     | 9.33           |                       |     |
|         | 8            | 46.22           |                   |     | 9.54           |                       |     |
|         | 9            | 48.73           |                   |     | 9.07           |                       |     |
| icy     | 1            | 52.18           |                   |     | 2.20           |                       |     |
|         | 2            | 52.67           |                   |     | 2.17           |                       |     |
|         | 3            | 51.11           |                   |     | 2.32           |                       |     |
|         | 4            | 53.79           |                   |     | 2.07           |                       |     |
|         | 5            | 52.57           |                   |     | 2.18           |                       |     |
|         | 6            | 54.62           | 52.68             | 1.239| 2.23           | 2.27                  | 0.138|
|         | 7            | 51.84           |                   |     | 2.23           |                       |     |
|         | 8            | 54.21           |                   |     | 2.54           |                       |     |
|         | 9            | 50.94           |                   |     | 2.42           |                       |     |
|         | 10           | 52.82           |                   |     | 2.36           |                       |     |

Figure 3 presents acceleration over time during rapid braking on a dry and wet concrete surface. The acceleration measured during braking features substantial change amplitudes for both dry and wet concrete surfaces. Acceleration over time during fully developed braking on wet asphalt has an upward trend during this process.
Figure 3. Ford Transit’s longitudinal acceleration over time during rapid braking on concrete surfaces: a) dry, b) wet.

Table 2 presents the initial braking speed $V_o$ and mean fully developed deceleration MFDD for particular rapid braking attempts on dry and wet concrete. Other presented values include the mean initial speed $V_{om}$, MFDD$_m$ as well as standard deviations of the determined values from their average values. The MFDD$_m$ designated for emergency braking amounted to 9.05 m/s$^2$ on dry concrete and 8.46 m/s$^2$ on wet concrete.

| concrete | Test run no. | $V_o$ km/h | $V_{om}$ km/h | SD | MFDD m/s$^2$ | MFDD$_m$ m/s$^2$ | SD |
|----------|--------------|------------|---------------|----|--------------|------------------|----|
| dry      | 1            | 49.94      | 51.06         | 1.75 | 9.20         | 9.05             | 0.19 |
|          | 2            | 50.96      |               |     | 8.96         |                  |     |
|          | 3            | 50.62      |               |     | 9.31         |                  |     |
|          | 4            | 52.52      |               |     | 9.19         |                  |     |
|          | 5            | 54.21      |               |     | 9.16         |                  |     |
|          | 6            | 49.74      |               |     | 9.10         |                  |     |
|          | 7            | 48.54      |               |     | 8.77         |                  |     |
|          | 8            | 49.45      |               |     | 9.17         |                  |     |
|          | 9            | 52.04      |               |     | 8.81         |                  |     |
|          | 10           | 52.60      |               |     | 8.83         |                  |     |
| wet      | 1            | 52.43      | 50.33         | 1.28 | 8.20         | 8.46             | 0.20 |
|          | 2            | 50.62      |               |     | 8.47         |                  |     |
|          | 3            | 52.01      |               |     | 8.66         |                  |     |
|          | 4            | 48.84      |               |     | 8.18         |                  |     |
|          | 5            | 50.72      |               |     | 8.46         |                  |     |
|          | 6            | 50.28      |               |     | 8.48         |                  |     |
|          | 7            | 49.74      |               |     | 8.57         |                  |     |
|          | 8            | 50.33      |               |     | 8.85         |                  |     |
|          | 9            | 48.15      |               |     | 8.43         |                  |     |
|          | 10           | 50.16      |               |     | 8.32         |                  |     |

Figure 4 presents a comparison of Ford Transit’s average mean fully developed deceleration MFDD$_m$ designated during emergency braking on dry, wet and icy asphalt surfaces as well as dry and wet concrete surfaces. It is clear that the MFDD$_m$ recorded for the ice-covered surface is substantially smaller than in the case of other surfaces.
5. Conclusions

Longitudinal acceleration during braking is very important in terms of road traffic safety. It depends on many factors. It is difficult to ensure repeatable braking conditions. The driver’s actions are therefore most important for safety. Modern cars are equipped with systems intended to protect the driver and other road users against their own errors.

The parameters of the braking process were tested for various road surfaces and an initial speed of the test car of about 50 km/h. The designated average mean fully developed deceleration MFDD$_m$ for the dry and wet asphalt and concrete surfaces do not differ substantially during emergency braking. The MFDD$_m$ for dry and wet asphalt is slightly higher than the values obtained on concrete. The MFDD$_m$ amounted to 9.51 m/s$^2$ on dry asphalt and 9.05 m/s$^2$ for dry concrete. The MFDD$_m$ amounted to 9.16 m/s$^2$ on wet asphalt and 8.46 m/s$^2$ on wet concrete. The least favourable MFDD$_m$ value was obtained on asphalt covered with a thin ice layer. It amounted to 2.27 m/s$^2$. The braking distance is substantially longer for such a MFDD$_m$.

The MFDD$_m$ value determined on the wet asphalt was only 3.7% lower compared to the dry asphalt. The value of MFDD$_m$ on icy asphalt decreased by 76.1% compared to dry asphalt. In contrast, the value of MFDD$_m$ on icy asphalt decreased by 75.2% compared to wet asphalt. An invisible thin layer of ice on the road surface poses a serious threat to road safety.

The acceleration designated as part of the conducted testing can be used to assess the driver’s behaviour and in accident cause analysis [17,18]. The acceleration values presented are limit values for the tested vehicle type. A driver who frequently obtains similar acceleration values in normal road traffic may be considered to be driving dangerously.

Acknowledgements

The research was carried out as part of the Innovative system research project supporting the motor vehicle insurance risk assessment dedicated to UBI (Usage Based Insurance) No. POIR.04.01.04 00 0004/19 00 financed by the National Centre for Research and Development.

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