Study of lateral acceleration of a Ford Transit car on various road surfaces

D Kurczyński*, P Łagowski, T Stańczyk, E Szumska, A Zuska, P Grabski, M Jaśkiewicz, R Jurecki

Department of Automotive Vehicles and Transportation, Faculty of Mechatronics and Mechanical Engineering, Kielce University of Technology, Kielce, Poland

* kdarek@tu.kielce.pl

Abstract. The measurement of car acceleration in time can be used to assess driving styles and safety behaviours of drivers. The values of lateral acceleration of the car can be an indication of the driver's aggressive driving style and tendency for risky behaviour. If the lateral acceleration is too high, it may affect the car's stability and potentially cause it to roll over. The paper outlines the results of the lateral acceleration analysis of a Ford Transit car driving in a circle and in the attempt to change two driving lanes. The tests were conducted in driving practice areas. Measurements were taken for the test vehicle driving in circles with maximum attainable velocity, and changing two driving lanes with pre-specified velocity. The tests were conducted on asphalt and concrete surfaces, in dry, wet and icy conditions. The purpose of the tests was to determine the maximum lateral acceleration of the analysed vehicle. The impact of the surface condition on the lateral acceleration of the test vehicle was also determined. The obtained results can be used as threshold values to assess driving style, and to analyse causes of accidents taking into consideration the condition of the road surface.

Key words: lateral acceleration, vehicle testing, vehicle movement, vehicle dynamics

1. Introduction

Lateral acceleration of the vehicle can affect driving safety, causing the vehicle to become unstable or, in extreme cases, even to roll over. The outcome depends on a number of factors, including vehicle velocity and acceleration, its type, size and weight, but particularly its centre of gravity, the type and condition of the road surface, and the changes thereof, and sudden and unexpected lateral forces, such as strong wind gusts, as well as other possible factors. In some cases, strong wind gust can tip over a coach or a truck, especially when the vehicle is leaving the cover of a noise wall. Road tankers are particularly exposed to the risk of tipping over, because their centre of gravity is located high on the vehicle. The measured lateral acceleration values can be an indication of the driver’s driving style, for instance, whether they drive safely or take risks, make aggressive and dangerous manoeuvres, or how often do they find themselves in perilous situations. This might be of particular importance for coach
and truck drivers, especially those carrying hazardous materials. The methodology of driving style assessment is discussed in [1].

In [2], the results of the analysis of lateral acceleration of a fire truck during single lane change are presented. Fire trucks are particularly exposed to the risk of tipping over during sudden manoeuvres. The purpose of the analysis was to determine the most advantageous sites for installing accelerometers which could signal the driver that the truck is at risk of tipping over. In [3-5], the stability of armoured personnel vehicles during double lane change was analysed. It was shown that the values which affect the stability of those vehicles the most were longitudinal velocity and lateral acceleration. The vehicle movement parameters are also impacted by test conditions, such as the wheel load, tyre pressure, road conditions and weather. Also, the driver’s driving style depends on their stress level. In [6], the results of road tests of double lane change by a car are presented. The results of the road tests were compared with the simulations for various models of tyred wheels. In [7], the simulation of double lane change is discussed.

Ali G. et al. analysed the impact of factors such as vehicle velocity, driver’s age and sex, vehicle class and location on the incidence of longitudinal and lateral acceleration [8]. It was shown that velocity was the key factor for the incidence of all acceleration values. Another important factor for vehicle acceleration turned out to be the driver’s age. It was shown that both younger and older drivers caused higher longitudinal acceleration when accelerating and braking. On the other hand, the incidence of lateral acceleration decreased with the age of the drivers. The vehicle class also plays a role in the incidence of sudden accelerations. Duan K. et al. developed a model for lane changing process in a roadworks zone [9], which they based on experimental tests conducted in a driving simulator. The authors showed that in heavy traffic, drivers are more prone to aggressive behaviour, which translates into higher values of longitudinal and lateral acceleration. Mourad L. et al. discussed the issue of driving narrow urban vehicles with tilting body which have the tendency to tip over due to lateral acceleration during turns [10]. The authors proposed a method of body tilt control that would reduce the lateral acceleration felt inside the vehicle, using accelerometer and gyroscope measurements.

The authors of this paper measured the lateral acceleration of a passenger minivan driving in circles and during double lane change. The authors showed the impact of different road surfaces on the measured lateral acceleration values.

2. Methodology

The tests were conducted in the driving practice areas of the Laboratory of the Department of Automotive Vehicles and Transportation at the Kielce University of Technology, and in Jarząb Autodrome, on asphalt and concrete roads. The test vehicle was a nine-passenger version of Ford Transit Mark VI with the curb weight of 2.070 kg. The gross vehicle weight of this model is 3.050 kg. The test vehicle was powered by a 2.198 cm³ 92 kW engine and had Continental ContiVanContact 200 205/65 R16C summer tyres with very little wear. The tyre tread depth was just 1 mm below the nominal depth. The test vehicle is shown on Figure 1. The test vehicle was equipped with traction control systems (ABS, ASR, ESP) which were turned on during the test. Before commencing the test, the vehicle’s technical condition was checked, focusing in particular on the braking system and tyres. During the test, the vehicle carried the test apparatus and two persons conducting the test activities.

During the circular test drive, the vehicle was accelerated to the maximum attainable velocity which could then be maintained for at least a dozen seconds. The driver had to maintain the specified vehicle trajectory while keeping it stable. The first test cycle was conducted on dry asphalt and dry concrete. Test drives on each road surface were performed clockwise and counterclockwise. During the tests, the lateral acceleration of the vehicle and its velocity were measured. The test drives were repeated in identical weather conditions on wet asphalt and wet concrete. Additionally, a test drive on thin ice was also performed in temperature slightly below 0°C.

For the circular test drives with maximum attainable velocity while maintaining the vehicle stability, the vectors of lateral acceleration of the vehicle at stable acceptable velocity in the given traffic conditions were determined. The following values were derived from the test: the minimum measured...
acceleration $a_{\text{omin}}$, maximum measured acceleration $a_{\text{omax}}$, difference of accelerations $a_{\text{omax}} - a_{\text{omin}}$, and the mean measured acceleration $a_{\text{om}}$.

The tests on the track also included double lane changes, which are performed in order to assess the steerability and stability of the vehicle. During the test, the vehicle response to the driver turning the steering wheel is assessed. The test of the Ford Transit passenger van was conducted in accordance with ISO 3888-1:2018 standard [11]. For safety reasons, the double lane change was performed at 50 km/h. The test was conducted on dry and wet asphalt. The manoeuvre was repeated 10 times for each road surface in identical weather conditions.

Figure 1. Ford Transit test vehicle

3. Test apparatus

For the tests, specialised measuring apparatus was used including:

- Correvit S-350 Aqua® optical sensor for measuring longitudinal velocity,
- μEEP-12 data acquisition system with ARMS™ data analysis software,
- TAA® 3-axis linear accelerometer.

The Correvit S-350 Aqua sensor makes it possible to precisely measure the distance, longitudinal and lateral velocity, and angle in dynamic tests of the vehicle, e.g. during steady circular motion in accordance with ISO 4138 standard [12]. The sensor ensures high accuracy of measurement, also in difficult conditions, on all standard measurement surfaces [13]. Also, the μEEP-12 data acquisition and analysis system dedicated for mobile vehicle testing apps was used [14]. During the tests, the μEEP-12 system was connected to a laptop. The measurement system was operated by ARMS™ software. Furthermore, the test apparatus included the TAA linear accelerometer which enabled 3-axis dynamic acceleration measurement [15]. The measurement range of the sensor was ±3 g.

4. Test results and analysis

Circular driving tests were performed with maximum attainable velocity while maintaining the stability of the test vehicle. During the tests, the vehicle accelerations were recorded, including the lateral acceleration. Figure 2 shows the measured lateral acceleration of the test vehicle while in circular counterclockwise motion. The acceleration values were determined for dry, wet and icy road surfaces. The lateral acceleration values of the test vehicle driving on the aforementioned road surfaces in clockwise motion is presented on Figure 3. The highest lateral acceleration was recorded for the vehicle driving on dry asphalt. The acceleration values for wet asphalt were slightly lower, while the lateral acceleration of the test vehicle driving on surface covered by thin layer of ice was considerably lower.

The analysis of the lateral acceleration values shown on Figure 2 and Figure 3 shows that the amplitude of acceleration values measured for the vehicle driving clockwise on dry and icy asphalt is higher than for the test vehicle driving counterclockwise. Driving the vehicle in circles clockwise on dry and icy surface, it was more difficult for the driver to maintain constant velocity than when driving in circles counterclockwise.
Figure 2. Lateral acceleration of Ford Transit during circular counterclockwise motion (left) with the maximum attainable velocity, on dry, wet and icy asphalt surface.

Figure 3. Lateral acceleration of Ford Transit during circular clockwise motion (right) with the maximum attainable velocity, on dry, wet and icy asphalt surface.

For each circular test drive, the acceleration of the vehicle was measured at least a dozen seconds after the vehicle had stabilised its maximum attainable velocity. The table lists the mean measured acceleration \( a_{\text{om}} \), the minimum measured acceleration \( a_{\text{omin}} \), and the maximum measured acceleration \( a_{\text{omax}} \). The difference of the maximum and minimum measured acceleration \( a_{\text{omax}} - a_{\text{omin}} \) is also specified. The acceleration values \( a_{\text{om}}, a_{\text{omin}} \) and \( a_{\text{omax}} \) were highest for dry asphalt, followed closely by wet asphalt, and considerably lower for icy asphalt. The calculated \( a_{\text{omax}} - a_{\text{omin}} \) for clockwise circular motion of the vehicle on dry and icy surface was significantly lower than for counterclockwise circular motion. For the clockwise circular motion, the measured accelerations \( a_{\text{om}}, a_{\text{omin}} \) and \( a_{\text{omax}} \) were lower than for counterclockwise circular motion.

The accelerations of the Ford Transit test vehicle were also measured during circular motion on concrete surface. Figure 4 and Figure 5 show the measured lateral accelerations of the test vehicle on dry and wet concrete surface, driving counterclockwise (Figure 4) and clockwise (Figure 5).
Table 1. Lateral acceleration of Ford Transit during circular motion with the maximum attainable velocity, on dry, wet and icy asphalt surface.

| Parameter                          | Asphalt   |               |               |               |               |
|------------------------------------|-----------|---------------|---------------|---------------|---------------|
|                                    | dry       | wet           | icy           |               |               |
| Mean measured acceleration $a_{om}$, m/s² | 4.57      | 4.16          | 4.08          | 3.60          | 2.65          | 2.30          |
| Minimum measured acceleration $a_{omin}$, m/s² | 4.31      | 4.00          | 3.88          | 3.20          | 2.40          | 1.92          |
| Maximum measured acceleration $a_{omax}$, m/s² | 4.80      | 4.30          | 4.35          | 4.05          | 2.88          | 2.67          |
| $a_{omax} - a_{omin}$, m/s²         | 0.49      | 0.30          | 0.47          | 0.85          | 0.48          | 0.75          |

Figure 4. Lateral acceleration of Ford Transit during circular counterclockwise motion (left) with the maximum attainable velocity, on dry and wet concrete surface.

Figure 5. Lateral acceleration of Ford Transit during circular clockwise motion (right) with the maximum attainable velocity, on dry and wet concrete surface.

Table 2 presents the measured lateral acceleration values of the vehicle driving in circles on concrete. When driving in circles counterclockwise, the lateral acceleration was lower on wet concrete as compared to dry concrete. When driving in circles clockwise, the $a_{om}$, $a_{omin}$ and $a_{omax}$ values were
slightly higher on wet concrete than on dry concrete. On dry concrete, the measured lateral acceleration values fluctuated significantly when driving clockwise. This might have been caused by the presence of concrete surface wear residues which might have affected the test results. This possibility is further highlighted by the values of $a_{\text{omax}} - a_{\text{omin}}$ which were higher for circular motion on dry concrete as compared to circular motion on dry asphalt, and also higher than on dry and icy asphalt.

Table 2. Lateral acceleration of Ford Transit during circular motion with the maximum attainable velocity, on dry and wet concrete surface.

| Parameter                      | dry | wet |
|-------------------------------|-----|-----|
|                               |     |     |
|                               | left | right | left | right | left | right |
| Mean measured acceleration $a_{\text{om}}$, m/s$^2$ | 4.58 | 3.73 | 4.36 | 4.05 |
| Minimum measured acceleration $a_{\text{omin}}$, m/s$^2$ | 4.22 | 3.15 | 3.97 | 3.68 |
| Maximum measured acceleration $a_{\text{omax}}$, m/s$^2$ | 5.04 | 4.18 | 4.82 | 4.36 |
| $a_{\text{omax}} - a_{\text{omin}}$, m/s$^2$ | 0.82 | 1.03 | 0.85 | 0.68 |

Figure 6 presents a comparison of the mean measured lateral accelerations of Ford Transit during circular motion, with the maximum attainable velocity, on different road surfaces. The lowest acceleration was measured for test drives on icy asphalt. The mean lateral acceleration measured on wet concrete surface were slightly higher than on wet asphalt surface. The mean lateral acceleration measured on dry asphalt and dry concrete are virtually identical. The mean lateral acceleration measured for driving in circles clockwise was lower than for driving in circles counterclockwise.

![Figure 6](image_url)

Figure 6. Comparison of the mean measured lateral accelerations of Ford Transit during circular motion, with the maximum attainable velocity, on different road surfaces.

The second phase of the tests involved measuring lateral acceleration of the test vehicle during double lane change. The measurements were conducted in Jarząb Autodrome, on dry and wet asphalt. On each road surface type, 10 double lane change manoeuvres were performed at 50 km/h. Figure 7 shows the lateral acceleration measured during double lane change by the test vehicle on dry asphalt, while Figure 8 shows the acceleration on wet asphalt. For wet asphalt, fluctuations of the lateral acceleration values are clearly visible. In each test on wet asphalt, lateral acceleration fluctuations were observed in exactly the same phase. For tests on dry asphalt, no such fluctuations of the measured acceleration were found. This might have been caused by the onboard systems preventing the test vehicle from losing stability which would be more likely on wet asphalt.
Figure 7. Examples of lateral acceleration values during double lane change by the test vehicle on dry asphalt at 50 km/h.

Figure 8. Examples of lateral acceleration values during double lane change by the test vehicle on wet asphalt at 50 km/h.

For each lateral acceleration during double lane change, the following values were determined: the maximum lateral acceleration $a_{max}$, the minimum lateral acceleration $a_{min}$ and the sum of absolute maximum and absolute minimum accelerations $|a_{max}| + |a_{min}|$. The mean values of lateral accelerations from 10 test attempts were calculated, along with the standard deviations. The values of those parameters are listed in table 3 and table 4. The lateral accelerations of the test vehicle were higher for all double lane changes on wet asphalt, as compared to the accelerations measured for the vehicle driving on dry asphalt. This was likely caused by the ESP system which prevented the vehicle from losing traction. The ESP system operates by applying the brakes to the appropriate wheels and reducing the engine torque, which may result in higher vehicle acceleration values.

Table 3. Lateral acceleration values during double lane change by the test vehicle on dry asphalt at 50 km/h.

| Attempt no. | $a_{max}$ m/s$^2$ | $a_{maxm}$ m/s$^2$ | SD | $a_{min}$ m/s$^2$ | $a_{minm}$ m/s$^2$ | SD | $|a_{max}| + |a_{min}|$ m/s$^2$ | $(|a_{max}| + |a_{min}|)_m$ m/s$^2$ | SD |
|-------------|-------------------|-------------------|----|-------------------|-------------------|----|-------------------------------|------------------------------|----|
| 1           | 2.91              | 3.07              | 0.23 | -3.10             | -3.31             | 0.31 | 6.01                           | 6.38                          | 0.47 |
| 2           | 2.75              | -2.86             |      | -3.09             | -3.19             |      | 6.09                           | 6.21                          |      |
| 3           | 2.99              | -3.09             |      | -3.19             | -3.27             |      | 6.47                           | 6.60                          |      |
| 4           | 3.02              | -3.19             |      | -3.27             | -3.33             |      | 6.60                           | 6.60                          |      |
| 5           | 3.20              | -3.28             |      | -3.33             | -3.46             |      | 6.60                           | 6.96                          |      |
| 6           | 3.27              | -3.46             |      | -3.54             | -3.54             |      | 6.62                           | 6.62                          |      |
| 7           | 2.79              | -3.54             |      | 7.15              | 7.15              |      | 6.62                           | 6.62                          |      |
| 8           | 3.50              | -3.46             |      | -3.54             | -3.54             |      | 6.62                           | 6.62                          |      |
| 9           | 3.09              | -3.54             |      |                  |                  |      | 6.62                           | 6.62                          |      |
| 10          | 3.14              | -4.00             |      |                  |                  |      | 7.15                           | 7.15                          |      |
Table 4. Lateral acceleration values during double lane change by the test vehicle on wet asphalt at 50 km/h.

| Attempt no. | $a_{\text{max}}$ m/s$^2$ | $a_{\text{max}}$ m/s$^2$ | SD     | $a_{\text{min}}$ m/s$^2$ | $a_{\text{max}}$ m/s$^2$ | SD     | $|a_{\text{max}}|+|a_{\text{min}}|$ m/s$^2$ | $|a_{\text{max}}|+|a_{\text{min}}|$ m/s$^2$ | SD     |
|-------------|-----------------|-----------------|-------|-----------------|-----------------|-------|-----------------|-----------------|-------|
| 1           | 3.91            | 4.06            | 0.39  | -3.47           | -3.72           | 0.33  | 7.38            | 7.78            | 0.62  |
| 2           | 4.01            | -3.56           | 7.57  |                 |                 |       |                 |                 |       |
| 3           | 4.25            | -3.70           | 7.96  |                 |                 |       |                 |                 |       |
| 4           | 3.33            | -3.52           | 6.84  |                 |                 |       |                 |                 |       |
| 5           | 4.22            | -3.35           | 7.57  |                 |                 |       |                 |                 |       |
| 6           | 3.97            | -3.42           | 7.39  |                 |                 |       |                 |                 |       |
| 7           | 4.15            | -3.73           | 7.88  |                 |                 |       |                 |                 |       |
| 8           | 3.65            | -4.00           | 7.65  |                 |                 |       |                 |                 |       |
| 9           | 4.41            | -4.22           | 8.64  |                 |                 |       |                 |                 |       |
| 10          | 4.70            | -4.25           | 8.94  |                 |                 |       |                 |                 |       |

5. Conclusions
The study analysed the lateral acceleration of a Ford Transit passenger van. The study tests were conducted on the test vehicle driving in circles with the maximum attainable velocity on dry and wet asphalt, and dry and wet concrete surfaces. Furthermore, tests were also conducted for the asphalt surface covered by a thin layer of ice. In addition, the lateral acceleration of the vehicle during double lane change was tested on dry and wet asphalt.

The measured lateral acceleration values of the test vehicle during circular motion were slightly higher on dry asphalt as compared to wet asphalt. For circular motion on asphalt covered by a thin layer of ice, the acceleration values were considerably lower. Similar correlation was found for counterclockwise and clockwise circular motion. On dry concrete, the lateral acceleration for counterclockwise circular motion was also slightly higher than on wet concrete. For clockwise circular motion, the results were different. On wet surface, the mean measured lateral acceleration was slightly higher than the acceleration measured on dry surface. This might have been caused by the presence of the concrete surface wear residues. For all counterclockwise circular test drives, higher lateral acceleration values were measured than for clockwise test drives.

For double lane change tests on wet asphalt, higher lateral acceleration of the test vehicle was measured as compared to the acceleration measured on dry asphalt. This was most likely caused by the ESP system which applies traction control to stabilise the vehicle on the trajectory chosen by the driver.

The obtained results may be useful for the assessment of driving styles. Drivers, who in normal traffic conditions record lateral acceleration values similar to those presented herein, might be considered aggressive and potentially dangerous. The results presented in this study may also be used in the analysis of road accidents in which Ford Transit vans are involved.

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