ABSTRACT

This paper provides a description of driver testing in a simulator. As young drivers are more susceptible to collisions, this was done to determine how young drivers behaved in simulated road situations on a motorway. One of the traffic safety concerns is the failure to keep a proper distance from the vehicle in front, which may result in a rear-end collision. The tests simulated car-following situations in which the preceding vehicle performed emergency braking. The experiments were conducted for two scenario variants using different distances from the vehicle in front. The drivers could perform the following emergency manoeuvres: braking with steering away or only braking. The driver response times were compared and analysed statistically. The results were used to determine the emergency manoeuvres performed by the drivers in the simulated road situations. The study reveals that the vehicle surroundings may have a considerable influence on the type of emergency manoeuvres and the driver response time.

KEY WORDS
simulator; young driver; response time; two-lane motorway; car-following situation;

1. INTRODUCTION

The driver behaviour is dependent on a number of factors, with some being more important than others. In a car-following situation, for instance, when vehicles need to maintain a suitable distance to ensure traffic safety, these factors are responsible for the driver response time or the choice and performance of emergency manoeuvres.

For many years researchers have been trying to determine how various factors affect the driver behaviour in various traffic situations. Investigations have been carried out in different roadway environments, i.e. on a test track, in a simulator or using special test devices, with test participants including healthy drivers as well as drivers with permanent or temporary disabilities.

Tests conducted on drivers after accidents aim to assess the progress of treatment and their physical and mental fitness to drive a vehicle and properly respond to different road situations (simulated real traffic and environment). Many investigations have been performed on drivers after complex orthopaedic surgeries, which adversely affected their physical fitness. For instance, Spalding et al. focused on drivers after a total knee replacement and their ability to perform emergency braking [1].

Other researchers have tried to determine how much time is required for patients after a total hip arthroplasty to be able to drive again [2]. Driver tests are also carried out to assess the performance of drivers with chronic diseases, e.g. Parkinson’s disease [3]. Much of the research into the effect of different factors on the driver behaviour concerned such factors as fatigue due to prolonged driving on a motorway, sleep deficit [4], sleepiness [5], alcohol impairment [5, 6] and drug impairment [7].

A number of studies also deal with the relationship between the driver response and the roadway environment [8, 9]. Recently, because of technological progress, research has been undertaken to determine the effect of gadgets, including car multimedia systems and cellular phones [10, 11, 12, 13]. Investigations into the use of mobile phone during motorway driving in a car-following situation have been carried out on younger (aged 18–25) and older (aged 65–74) drivers [14].

In the case of professional drivers, the aim of testing may be to determine their performance when affected, for instance, by sleepiness. The behaviour of lorry drivers in unexpected critical situations has also been investigated [15]. Simulator-based tests
[16] have been used to study how warning messages and variable speed limits (VSLs) influence the driving speed.

Muttart [17] analyses the driver steering behaviour with regard to the driver age, the driver fatigue, distraction, natural lighting and the buffer space available. Driver performance has been studied for many years and the tests have been conducted under real road conditions, on test tracks [18, 19, 20, 21] as well as in driving simulators [22, 23]. The investigations carried out under different circumstances and in different test environments have some advantages and disadvantages. The main strength of simulator-based investigations is that participants are tested under the same conditions.

Many studies on the subject focus on determining the driver behaviour in a car-following situation and modelling the movements of the vehicles involved. For example, the driver performance model proposed in [24] is based on the optical control of quantum flow. This dynamic and stochastic approach to the driver behaviour during a car-following situation indicates that the driver response time is largely dependent on their subjective perception of speed. Kesting and Tribier [25] use the Intelligent Driver Model (IDM) to analyse the effect of different parameters, including the driver response time, on the stability of traffic flow.

The study presented in [26] involved applying a driver model to predict dangerous car-following situations for different styles of driving.

Autonomous systems capable of fully or partially controlling the vehicle, described, for instance, in [27] have been analysed under various driving conditions to assess their reliability and, if necessary, propose further improvements.

The existing methods used to describe the driver behaviour in emergency situations have been analysed to create a cognitive model able to predict the driver response time so that future assistance systems are better equipped to assess and adjust to changes in the road situation [28].

Many studies involve using computer simulations or simulator-based tests.

A vital argument for conducting investigations in a virtual environment is to perform identical, pre-programmed situations and tests with the same parameters [29]. Some virtually created road situations can be impossible or dangerous to perform under real conditions on test tracks as they may involve risk to the participants and damage to the measurement devices [23]. Another important argument for simulator testing is also that we can check the driver performance under specific driving conditions: strong fatigue, alcohol impairment, etc.

Driving simulators can also be used to improve the safety of pedestrians. For example, Petzold studied pedestrian crossing situations, focusing on the safe gap between passing cars based on the time to arrival (TTA) judgements [30].

Driving simulators can be used to simulate different road situations, for instance, a car-following situation [31, 32]. Under real-world conditions, tests involving vehicles following one another at high speeds on motorways could be difficult and hazardous to perform. Many publications recommend that in a car-following situation an appropriate distance should be maintained to ensure an appropriate level of safety. Brakstone et al. [33] studied the distance between vehicles moving on motorways using a specially equipped vehicle. Different factors were taken into consideration to analyse traffic safety in such situations [34]. Problems related to car-following situations have been dealt with by numerous researchers [35, 36].

This paper discusses the behaviour of young adult drivers in a car-following situation on a two-lane motorway. The tests involved measuring and analysing the times of response to rapid braking by the lead vehicle in order to determine the safe distance between vehicles in two different situations. The paper focuses on emergency manoeuvres undertaken by drivers in a car-following situation. Section 2 will discuss briefly the methodology of the simulator-based tests, while Section 3 will present and analyse the test results for both scenarios of road situations.

2. METHODOLOGY

2.1 Characteristics of the driving simulator

The testing was conducted at the Automotive Engineering Laboratory using an Oktal® dynamic driving simulator. The simulator consists of a fragment of a car compartment and three 1920x1080 42 inch monitors, placed on a mobile hybrid platform. The 6 DOF platform enables the following motions of the compartment: an angular rotation of ±10° about the X, Y and Z axes with an angular acceleration of ±150°/s2 and a linear displacement platform of ±50 mm with an acceleration of up to 3m/s2. In the simulator cabin, there is an adjustable driver seat equipped with an inertia-reel seat belt.

Drivers sitting in the simulator have a real vehicle dashboard in front of them and all the typical driving elements used in vehicles. There is also a 10-inch LCD digital instrument panel with configurable display elements specific for the make and model selected. While driving on rough surface, the driver feels vibration on the steering wheel. Similarly, while turning the steering wheel during an emergency steering manoeuvre, the driver feels some resistance on the steering wheel. The driver’s compartment also comprises 5.1 speakers that can reproduce sounds related to the vehicle movement through traffic, i.e. noise of the engine, noise produced by wheels in contact with the road.
surface, and any other noise from the surroundings. The system uses two computers for visualising the created traffic situation and controlling the platform motion. The simulator comprises Scanner Studio® software which allows drivers to create their own type of vehicle (e.g. by modifying the parameters of the existing models), generate a new road profile and the road environment and design a test scenario.

Road modification may involve changes to the road surface properties, e.g. a change in the pavement type, coefficient of grip and road roughness, which are used by the model of the vehicle dynamics. The simulator software contains an advanced simulation model of a vehicle (Callas® model), which, depending on the options used, can have from 15 to 43 DOF [8, 37].

2.2 Description of the test procedure

In the simulation-based tests performed in 2016, sixty young adult drivers were included. They were male students with little driving experience, aged 21–25, with the age average being 22.54 (standard deviation 0.91 years). Young drivers were selected to take part in the simulations because in Poland drivers aged 20–24 are reported to be at the highest risk of being killed in a car crash (per 1 million people) [38]. The subjects were driving in the right lane of the road, as shown in Figure 1. The measurements began at a speed of about 100 km/h and a pre-determined constant distance of 10–50 m from the preceding vehicle. The road situation can be simulated on a motorway, a dual carriageway or other types of roads divided into lanes. The road along which the subject vehicle was moving was flat and had two traffic lanes and an emergency lane. Each lane was about 4 m in width. In version 1 of the scenario, there were no other vehicles moving next to the subject vehicle. At a randomly selected moment, the lead vehicle decelerated by 9 m/s². This value of the maximum braking is a typical physical limit on dry surface roads [34].

Figure 1 – View from the driver seat of an Oktal™ simulator and a diagram of version 1 of the scenario

The drivers of the following vehicle, i.e. the drivers tested, were free to choose between the emergency manoeuvres: braking, steering around the lead vehicle or combined braking and steering. The data registered during the tests were used to assess the driver behaviour and the driver response time. The parameters measured included:
- the steering angle characteristics (to determine the steering response time),
- the displacements of the braking and accelerator pedals (to determine the braking pedal response time and the accelerator pedal response time, respectively),
- the speed and driving paths of the vehicles,
- the vehicle deceleration.

In version 2 of the scenario, two other vehicles, i.e. a bus and a lorry present in the left lane, were added to the simulated road situation (see Figure 2). As the subject vehicle was moving at a speed of about 100 km/h, the driver could perform only one emergency manoeuvre - rapid braking. The aim of the simulator-based investigations was to determine the behaviour of drivers faced with sudden braking by the preceding vehicle. The main parameter determined during the tests was the driver response time.

Figure 2 – View from the driver seat of an Oktal™ simulator and a diagram of version 2 of the scenario

Before the tests, the participants were trained to use the driving simulator and drove a similar route several times. Each subject took ten tests but the version of the scenario and the test parameters were selected at random to ensure as much realism as possible. The total experiment time was about 45 minutes per person. Our future projects will involve testing older drivers with more driving experience to compare their behaviour depending on the experience. We also intend to perform tests based on identical scenarios but under night driving conditions when the low-beam visibility of the vehicle in front is limited.

The main purpose of the study was to analyse how a road situation could affect the driver response time. It was important to question whether the driver response times obtained in the simulations of the car-following situations would differ for different distances between vehicles. Another objective was to determine whether a change in the stimulus that the drivers were exposed to (from a warning message displayed on the screen to an emergency situation with a preceding vehicle braking suddenly viewed on the screen) would affect the response times.

The scenario considered in the earlier research project [8] was simpler; the average braking response time was about 0.9. However, there was a large scatter
Numerous investigations concerning the driver response time show that there are other factors affecting the driver performance, e.g. fatigue and sleepiness, which may increase the response time [4].

3. RESULTS

The tests involved registering the following data:
- the accelerator pedal response time, i.e. the time measured from the moment the brake lights come on the preceding vehicle to the moment when the driver of the subject vehicle responds by easing the pressure on the accelerator pedal;
- the braking response time, i.e. the time from the moment the brake lights come on the preceding vehicle to the moment when the driver of the subject vehicle begins to press the braking pedal;
- the steering response time, i.e. the time from the moment the brake lights come on the preceding vehicle to the moment when the driver of the subject vehicle begins to turn the steering wheel (analysed only for version 1 of the scenario).

The emergency manoeuvres were determined for each driving test. If a collision occurred, the fact was registered [37].

### 3.1 Version 1 of the scenario

In version 1 of the scenario, there were no limitations to the driver performance, because there were no other vehicles in the left adjacent lane. While analysing the data, we can see that there is a large discrepancy in the measured values of the response time. Although the data concerning the accelerator pedal response time are not taken into consideration, e.g. by experts in forensic investigations to reconstruct an accident, it is important to note that the accelerator pedal response is likely to initiate the braking pedal response.

As shown in Figure 4, the values of the accelerator pedal response time $t_a$ increase with increasing distance to the lead vehicle $S$.
distance S from the preceding vehicle. Figure 4 shows the regression lines for the median and the 0.1 and 0.9 quantiles of the accelerator pedal response time according to the distance to the lead vehicle.

If a constant value of the initial speed is assumed, the response time increases with the time to collision (TTC), which is a parameter used in numerous analyses [19, 20]. The difference in the median value is almost 0.5 s for the response time determined at distances of 10 m and 50 m. It should be borne in mind, however, that a vehicle moving at a speed of 100 km/h covers a distance of 27.8 m in 1 second so, in many cases, responses are initiated either at the moment the vehicle collides into or begins to steer away from the preceding vehicle. Analysing the response times from the range between 0.1 and 0.9 quantiles constituting 80% of all the response times obtained by the drivers, we can conclude that the differences in the driver response time increase with the increasing distance between the vehicles.

The values of the braking response time were assessed in the same manner. The statistical parameters of the braking response time are provided in Table 1.

The analysis of Figure 5 indicates that there is a relationship between the braking response time and the initial test distance between the vehicles in an emergency situation. For the initial car-following distances, the braking response time increases but less rapidly than the accelerator pedal response time. For distances of 20–40 m, the median value of the braking response time is in the range of 1.1–1.15 s. From the results it is evident that an increase in the distance between the vehicles leads to an increase in the difference in response time, which is particularly visible for the 0.1 and 0.9 quantiles. Figure 5 shows the regression lines for the median and the 0.1 and 0.9 quantiles of the braking response time according to the distance from the lead vehicle.

The driver response times obtained for this scenario were compared with the braking response times from the author’s earlier tests conducted with a driving simulator [8].

The analysis reveals that the braking response time is similar to that from the previous test only when the distance between the vehicles is very short, e.g. 10 m. For other distances, the driver response times for braking are 0.2–0.5 s longer. Previous investigations by the author show that the test participants ‘driving on a motorway’ did not respond to a real road situation, but to the braking instruction ‘brake’ displayed on the screen. The response was similar in nature to a simple response because the driver responded to a simple light incentive. It is important to note that the

![Figure 5](image.png)

Figure 5 – Values of the braking pedal response time $t_B$

Table 1 – Statistical parameters of the braking response time $t_B$

<table>
<thead>
<tr>
<th>Distance between vehicles</th>
<th>0.1 Quantile</th>
<th>0.25 Quantile</th>
<th>Median</th>
<th>0.75 Quantile</th>
<th>0.9 Quantile</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 m</td>
<td>0.65</td>
<td>0.71</td>
<td>0.85</td>
<td>0.93</td>
<td>1.15</td>
</tr>
<tr>
<td>20 m</td>
<td>0.76</td>
<td>0.85</td>
<td>1.15</td>
<td>1.30</td>
<td>1.47</td>
</tr>
<tr>
<td>30 m</td>
<td>0.85</td>
<td>0.91</td>
<td>1.10</td>
<td>1.30</td>
<td>1.62</td>
</tr>
<tr>
<td>40 m</td>
<td>0.80</td>
<td>0.85</td>
<td>1.10</td>
<td>1.50</td>
<td>1.76</td>
</tr>
<tr>
<td>50 m</td>
<td>1.00</td>
<td>1.22</td>
<td>1.45</td>
<td>1.90</td>
<td>2.10</td>
</tr>
</tbody>
</table>

Table 2 – Statistical parameters of the steering response time, $t_S$

<table>
<thead>
<tr>
<th>Distance between vehicles</th>
<th>0.1 Quantile</th>
<th>0.25 Quantile</th>
<th>Median</th>
<th>0.75 Quantile</th>
<th>0.9 Quantile</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 m</td>
<td>0.55</td>
<td>0.63</td>
<td>0.70</td>
<td>0.85</td>
<td>0.90</td>
</tr>
<tr>
<td>20 m</td>
<td>0.62</td>
<td>0.78</td>
<td>1.03</td>
<td>1.20</td>
<td>1.60</td>
</tr>
<tr>
<td>30 m</td>
<td>0.85</td>
<td>0.91</td>
<td>1.20</td>
<td>1.43</td>
<td>1.80</td>
</tr>
<tr>
<td>40 m</td>
<td>0.85</td>
<td>1.00</td>
<td>1.40</td>
<td>2.10</td>
<td>2.45</td>
</tr>
<tr>
<td>50 m</td>
<td>1.23</td>
<td>1.83</td>
<td>2.52</td>
<td>3.00</td>
<td>3.40</td>
</tr>
</tbody>
</table>
driver could perform only one predetermined emergency manoeuvre - braking. The fact that the response times in comparable situations were different indicates that the type of the analysed situation has a significant effect on the findings concerning the response time. Table 2 presents the statistical data of the steering response time.

Figure 6 shows steering response times $t_S$.

As can be seen, they vary more than the accelerator pedal response times and the braking response times. It is worth mentioning that in this case, the largest scatter of results is observed for a distance of 50 m, where the values of 0.9 and 0.1 quantiles differ by up to 2.1 s.

3.2 Version 2 of the scenario

Version 2 of the scenario differed from version 1 in that during the rapid braking of the lead vehicle there were other vehicles present in the left adjacent lane. As a result, it was very difficult to steer around the lead vehicle. The steering manoeuvre usually ended with a collision. Figure 7 shows values of the accelerator pedal response time.

As can be seen, the times obtained in this version of the scenario are much shorter. The values of the response time increase with the distance from the lead vehicle, but it is important to note that the increase is not so large as in version 1 of the scenario. The values of the quantiles suggest that the response times are more comparable.

The values of the braking response time were assessed in the same manner. The statistical parameters of the braking response time are provided in Table 3. The driver response times obtained for this scenario were shorter than the braking response times from version 1 of the scenario.

Table 3 – Statistical parameters of the braking response time $t_B$ in version 2 of the scenario

<table>
<thead>
<tr>
<th>Distance between vehicles</th>
<th>Braking response time $t_B$ [s]</th>
<th>0.1 Quantile</th>
<th>0.25 Quantile</th>
<th>Median</th>
<th>0.75 Quantile</th>
<th>0.9 Quantile</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 m</td>
<td>0.65</td>
<td>0.75</td>
<td>0.81</td>
<td>0.85</td>
<td>1.03</td>
<td>1.125</td>
</tr>
<tr>
<td>20 m</td>
<td>0.71</td>
<td>0.79</td>
<td>0.85</td>
<td>0.975</td>
<td>1.225</td>
<td>1.345</td>
</tr>
<tr>
<td>30 m</td>
<td>0.75</td>
<td>0.8175</td>
<td>1.22</td>
<td>1.41</td>
<td>1.65</td>
<td></td>
</tr>
<tr>
<td>40 m</td>
<td>0.71</td>
<td>0.83</td>
<td>1.15</td>
<td>1.25</td>
<td>1.70</td>
<td></td>
</tr>
<tr>
<td>50 m</td>
<td>0.78</td>
<td>0.92</td>
<td>1.15</td>
<td>1.25</td>
<td>1.70</td>
<td></td>
</tr>
</tbody>
</table>
indicates, for instance, that the driver’s awareness of the possible risk of an emergency may have a substantial influence on their behaviour, and accordingly, their response time.

Figure 8 shows the values of the braking response time. The median values of the braking response time in version 2 of the scenario ranged 0.8 – 1.2 s; they were about 0.05 – 0.30 s shorter than those recorded in version 1 of the scenario (when the driver could perform both braking and steering away).

Figure 9 – Values of the steering response time in version 2 of the scenario

The driver response in version 2 of the scenario was, in most cases, limited to the braking manoeuvre, because the vehicles in the left lane made the steering away manoeuvre difficult to perform. As braking was the major emergency manoeuvre, the braking response time was shorter.

Table 4 presents statistical parameters of the steering response time. The median values of the steering response time for different distances between the vehicles increase with increasing distance from the lead vehicle.

Figure 9 presents values of the steering response time for the median, the mean and the 0.1 - 0.9 and 0.25 - 0.75 quantile ranges.

The steering response differs from other responses in this version of the scenario; the differences in the steering response time are the greatest. It should be noted that the scatter of results increases with increasing distance from the lead vehicle. The greatest scatter of results was reported for the distance of 50 m and it was approximately 2.2 s.

4. DISCUSSION

The aim of the study was to determine the way young drivers responded to rapid braking of the vehicle in front when on a motorway. Young drivers with little driving experience do not know or do not strictly follow the motorway driving rules. Driving at high speeds on motorways differs considerably from driving on ‘regular’ roads. Many countries have a special rule concerning the safe distance between two vehicles. For example, in France the minimum distance from the vehicle in front corresponds to the distance covered in 2 s. In Germany, drivers are required to leave a gap (in meters) of 50% of the actual speed (in km/h). In Slovakia, a proper following distance (given in metres) is dependent on the limit speed. Failure to follow the rules pertaining to keeping a safe distance between vehicles may result in high fines.

In Poland there are no precise rules. The decision on the safe distance is taken by the driver subjectively. In periods of higher traffic flow, especially during holidays, the distance between vehicles may decrease and may result in a rear-end collision. Despite the fact that simulator-based tests are not able to fully indicate, for instance, that the driver’s awareness of the possible risk of an emergency may have a substantial influence on their behaviour, and accordingly, their response time.
was quite high and it ranged 14–47% depending on the distance to the preceding vehicle. When the distance between the vehicles was 10 m, almost 100% of collisions were reported in both versions of the scenario. It is interesting to note that for a distance of 20–50 m, fewer collisions were observed in version 2 of the scenario. We might ask why. How can we explain that the number of collisions in a more difficult road situation was lower? A thesis can be formulated that the presence of other vehicles made the drivers become more concentrated, respond faster and perform more effective emergency manoeuvres. When the distance between the vehicles was about 20 m, 15–23% collisions occurred. For larger distances, the number of collisions was approximately 10%. At large distances (50 m), young drivers (with no particular experience) responded too late, which made the number of collisions higher.

5. CONCLUSION

The values of the braking response time are of great significance when emergency situations are analysed. It is these values that can be used in simulation programmes aiming to reconstruct a road accident. The values of the response time used in simulation programmes generally come from manuals, where average values are provided. Because of large discrepancies in the response time, the distance that guarantees safety can be assessed differently. Obviously, in real road conditions, the response time is likely to be longer, as shown in some studies [23, 39]. The fact that drivers perceive the safe following distance subjectively may in practice lead to a serious traffic hazard.

Interesting conclusions can be drawn from the results obtained for version 2 of the scenario, when it was almost impossible to steer around the vehicle in front. When the adjacent lanes are occupied, driving concentration levels are higher and response times are shorter. High concentration will result in a slightly shorter response time. When faced with an emergency, most drivers will apply the brake only. They must,
however, be aware of the dynamically changing situation on the road. As mentioned above, in version 1 of the scenario, the drivers were free to decide on the emergency manoeuvre. Apart from braking, they could also steer around the vehicle in front. These manoeuvres are frequently combined in emergency situations. Since today’s vehicles are equipped with modern electronic systems such as ABS and ESP, it is possible to combine rapid braking and steering away with no threat that the vehicle’s stability will be lost (both systems being active during the tests in the simulator). Comparing the steering response times with the braking response times, we can see that the combined responses are initiated almost simultaneously. Different studies show that the safe distance is a relative term and it changes dynamically depending on circumstances. In version 1 of the scenario, when there are no other vehicles around, a distance of an order of 30 m seems fairly safe (with the number of collisions being nearly 10%). It is interesting to note that the risk of collision occurrence is slightly smaller when the subject vehicle is ‘accompanied’ by other vehicles - version 2 of the scenario.

Our future investigations will focus on comparing the behaviour of older drivers according to their driving experience. Another problem to be analysed is night driving with limited low-beam visibility of the vehicle in front, which will be tested using identical scenarios.

ACKNOWLEDGEMENT

This work was supported by the Slovak Research and Development Agency under the Contract No. SKPL-2015-0019 and VEGA No. 1/0143/17.

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ZACHOWANIE MŁODYCH KIEROWCÓW W NIEbezPIECZNEJ SYTUACJI DROGOWEj PODCZAS JAZDy W KOLUMNIE

STRESZCZENIE


SŁOWA KLUCZOWE

symulator; młodzi kierowcy; czas reakcji; autostrada o 2 pasach ruchu; jazda w kolumnie;

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