INFLUENCE OF THE SCENARIO COMPLEXITY AND THE LIGHTING CONDITIONS ON THE DRIVER BEHAVIOUR IN A CAR-FOLLOWING SITUATION

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Abstract

The aim of this study was to analyse the driver behaviour in simple and complex car-following situations under day- and night-time lighting conditions (four scenarios). Nearly 70 drivers participated in the tests, each taking several trials, during which they were exposed to randomly selected situations. The tests involved driving along a two-lane motorway with a vehicle in front and responding to its sudden braking. Different distances between the vehicles were simulated. The scenarios varied in complexity ranging from none to some vehicles around the subject vehicle.

The study involved measuring different reaction times, i.e. the time to release the accelerator pedal, the time to apply the brake pedal and the time to start steering, to find out how the particular emergency manoeuvres contribute to the occurrence of collisions in the four scenarios.

The results show that both the complexity of a road situation as well as the lighting conditions determine the type of emergency manoeuvre undertaken and the time of the driver reaction.

Keywords: simulator; car-following situation; driver behaviour; reaction time

1. Introduction

In the driver–vehicle–environment system, it is still the driver behaviour that is generally the reason for a road accident. It is true that today's vehicles are capable of assisting or even replacing a human driver in many dangerous road situations, but the numerous safety features that a vehicle may be equipped with do not guarantee total protection against accidents [23, 50, 61]. Modern solutions are also being introduced to improve the "road element". These include changes to the road infrastructure aiming to simplify the driver behaviour or to make sure that driving errors do not have dangerous consequences [46]. The analysis of the driver behaviour in pre-collision situations suggests that some risky manoeuvres that may pose a threat to the traffic on the road are undertaken even by experienced drivers. With fully autonomous vehicles as yet unavailable, human factors cannot be eliminated completely. In a real pre-crash situation, the driver behaviour is difficult to predict or even unpredictable. It is usually dependent on a great variety of factors: internal,

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for instance, the driver's state of mind, health, age, or medical history, and external, such as the surroundings, changeable traffic conditions, type of road or a type of road situation.

Researchers have long been trying to establish precisely what factors influence the driver performance in dynamic situations and then characterise their contribution quantitatively and qualitatively. The type and environment of the research is specific. Tests can be performed under real traffic conditions, on test tracks [30] and using driving simulators or other special test setups. There are numerous studies on the effects of human factors such as fatigue due to prolonged driving on a motorway [5], sleep deficit [48], sleepiness [2, 7, 58], alcohol impairment [2, 45, 49], stress [25], drug impairment [26, 45] or age [1, 53, 54].

Some investigations that deal with braking responses to unexpected but common signals, such as activated brake lights on the lead vehicle [24] reveal that the braking reaction time can be about 0.25 s shorter than that registered for surprise events and that it is dependent on numerous factors, for example, the driver's age and gender, cognitive load or event urgency. Some of the latest studies focus on the relationship between collisions or near misses and inattention due to technology-related distraction (mobile phones, radio, etc.) [8, 43, 57].

For many years, tests on the track were highly recommended because of the use of a real vehicle and driving in real or close-to-real conditions; they also provided relatively reliable results [30]. On-track tests, however, were very expensive to run and there was always a possible risk of injury. With the development of computer technology, testing in a virtual environment using a driving simulator has become prevailing [15]. Some studies are concerned with the relationship between the driver response and the roadway environment [41]. In [13, 36, 39] the researchers analyse the driver behaviour on a motorway affected by variable speed limits (VSLs) and warning messages, displayed on dynamic message signs. In [27], simulator-based tests with a sample size of 48 drivers are described to show the impact of visual and cognitive distractions on driving. Many researchers indicate that driving simulators offer a safe alternative to on-road driving and are a useful tool to study, for example, the behaviour of elderly drivers [37]. There are also tests conducted on drivers involved in accidents, which aim to assess the progress of treatment and/or their physical and mental fitness. For example, Spalding et al. analyse patients with knee replacements and their ability to perform emergency braking [55]. Simulator-based tests are also crucial to assess the performance of drivers with chronic diseases, e.g. Parkinson's disease [33], Alzheimer's disease [16] or severe obstructive sleep apnea [19].

Much research has been done on the behaviour of professional lorry drivers in dynamic situations. For example, there are studies that analyse the effects of experience on the driver performance while driving a vehicle with or without an electronic stability control (ESC) system [4,40]. Some investigations focus on the influence of external factors, such as unexpected 'emotional' sounds in the cabin on their behaviour in critical situations [11].

The tests described by Muttart aimed to characterise the driver performance according to their age, fatigue, distraction, natural lighting and buffer space available [44].

Since the way drivers respond to events/stimuli on the road changes with age, driving simulators are frequently employed to study the performance of elderly drivers [38, 51]. Simulator-based tests are now the most common tests to study the driver behaviour [3]. Their major advantage, apart from safety and flexibility, is the total reproducibility of test conditions, which means that different subjects can be exposed to the same traffic, roadway, weather or lighting conditions [35].

There are numerous studies dealing with the driver behaviour in a car-following situation involving simulator-based tests. An important argument for running tests in a virtual environment is that different drivers can be exposed to exactly the same situations and conditions [15]. It is also possible to create road situations that would be problematic, risky or very costly when tested on the track or road. A driving simulator is thus an ideal tool to study the performance of drivers impaired by fatigue, alcohol, drugs, etc. Driving in such a state would be impossible to test otherwise.

Simulators have also been employed to analyse the safety of pedestrians. Petzold, for example, deals with pedestrian crossing situations, especially the so-called safe gap between passing vehicles. The experimental results reveal that crossing decisions are made after estimating the time to approach (TTA) rather than the physical distance between the vehicles. Acceptable gaps are generally shorter at higher speeds of the passing vehicles. The crossing behaviour of older participants, however, is different, as they choose larger gaps [47].

Simulator-based driving has proved suitable to study the driver behaviour in a variety of road situations, including car-following situations [5, 18, 29], particularly when distractions are involved. The relationship between the mobile phone use and the driving performance in a car-following situation on a motorway is analysed, for instance, in [22], where the subjects were younger adults (aged 18–25) and older adults (aged 65–74). Tests involving high speeds and distractions would be too hazardous to run under real-world conditions.

It is commonly recommended that, when in a car-following situation, the driver should keep an appropriate distance from the vehicle in front [9, 10]. A safe distance between vehicles moving on a motorway was investigated, for example, by Brakstone et al. [6]. Enhancing safety in critical situations requires maintaining driving stability [32]. Current studies on safe following distances between vehicles moving at motorway speeds include improving control algorithms for driving assistance systems, especially adaptive cruise control (ACC) [34, 42, 56].

Simulator-based tests conducted by the author in 2016 [30], similar to these described here, confirm that the driver reaction times in dynamic driving situations, including rapid braking to avoid a collision with a vehicle in front, are dependent on the distance between the vehicles. The tests described in this article were run at modified scenario parameters, in the presence or absence of additional vehicles around the subject vehicle under daytime and night-time conditions. The aim of the study was to determine the emergency manoeuvres and driver reaction times in different car-following situations.

2. Test methodology

2.1. Description of the driving simulator

The testing was carried out at the Laboratory of Automotive Engineering of the Kielce University of Technology using an Oktal® Premium dynamic. The driving simulator (Fig. 1) replicates the driving compartment and instruments of a real vehicle. It features a CKAS™ W4s motion platform able to move horizontally in two directions (linear motion) and rotate about three axes (angular motion), this giving six degrees of freedom (DOF).

Fig. 1. Driver compartment on the motion platform and the monitors

The linear displacement of the platform along the three coordinate axes is +/- 50 mm and the linear acceleration does not exceed 3 m/s^2. The rotations about the axes, i.e. the pitch, roll and yaw angles, are +/- 10°, while the angular velocity is approximately +/-15°/s.

The driving compartment mounted on the motion platform has the features of the 2006 Hyundai Getz interior with the same geometrical and functional characteristics. There is no ignition key 'to start the engine', but the driver uses a real-size steering wheel with control levers (indicator, main beam headlights, windscreen wipers) and a horn button, a dashboard with a revolution counter, a speedometer, controls, a hazard light switch, etc. [30].

Depending on the emergency situation, the driver can control the vehicle motion in the longitudinal direction (by applying the brake pedal or steering around the leading vehicle) and in the lateral direction (by turning left or right); they can also sound the warning horn or apply the parking brake. The simulator is equipped with a passive force feedback system for the clutch and brake pedals and an active electric force feedback system for the wheel so that vibrations of the wheels in contact with a rough road surface can be felt in the steering wheel.

Road situations to be tested in the driving simulator – scenarios – are designed using special software. The program is responsible for developing, modifying and displaying the view of the road and its surroundings. The visualization system consists of three full HD monitors mimicking the windshield. The driver is able to observe the situation at the rear in three other monitors, which serve as the rear and wing mirrors.

The driver can hear driving-related sounds generated by a surround sound system 5.1; these include the sound of a working engine or noise produced by the wheels in contact with the road surface [29]. The lab room in which the tests were performed was adjusted to simulate night time.

2.2. Description of the test scenarios

The simulations were run in 2018 on 70 subjects, 59 male and 11 female, aged 21-28, 22.79 on average (with a standard deviation of 1.84 years). The experience of the drivers was determined on the basis of the number of kilometres covered, which, on average, was about 85 thousand, and the license holding period, on average, being about 6 years. Before the tests, all the subjects were trained on how to use the driving simulator. Each person performed several randomly selected tests so that the element of surprise would not be lost. The tests took approximately 20 minutes per person.

The simulations consisted in driving on a motorway with two traffic lanes (each approx. 4 m in width) and an emergency stopping lane. The subject vehicle was moving with a speed of about 100 km/h in the right lane. At a certain distance in front of it, there was another vehicle moving with the same initial speed. Suddenly, i.e. at a randomly selected moment, the lead vehicle began braking with a deceleration of about 9 m/s2, which is a maximum braking deceleration on a flat dry asphalt surface [14, 29, 32]. The initial distance from the preceding vehicle ranged from 10 to 50 m.

The drivers were not given any instructions on how to respond to the simulated road situations. They were free to make subjective decisions about which collision avoidance manoeuvre to select: braking, steering away or combined braking and steering away.

There were four scenarios the drivers were subjected to:

- scenario 1: daytime driving in the right lane with one car in front and no other vehicles behind or in the left lane (Fig. 2),
- scenario 2: daytime driving in the right lane with a car in front and a lorry behind as well as a small lorry, a tourist coach and a few other cars in the left lane (Fig. 3),

Fig. 2. View from the driver seat in scenario 1 (Oktal™ simulator)

Fig. 3. View from the driver seat in scenario 2 (Oktal™ simulator)

- scenario 3: night-time driving in the right lane with a car in front and no other vehicles behind or in the left lane (Fig. 4),
- scenario 4: night-time driving in the right lane with a car in front and a lorry behind as well as a small lorry, a tourist coach and a few other cars in the left lane (Fig. 5).

Fig. 4. View from the driver seat in scenario 3 (Oktal™ simulator)

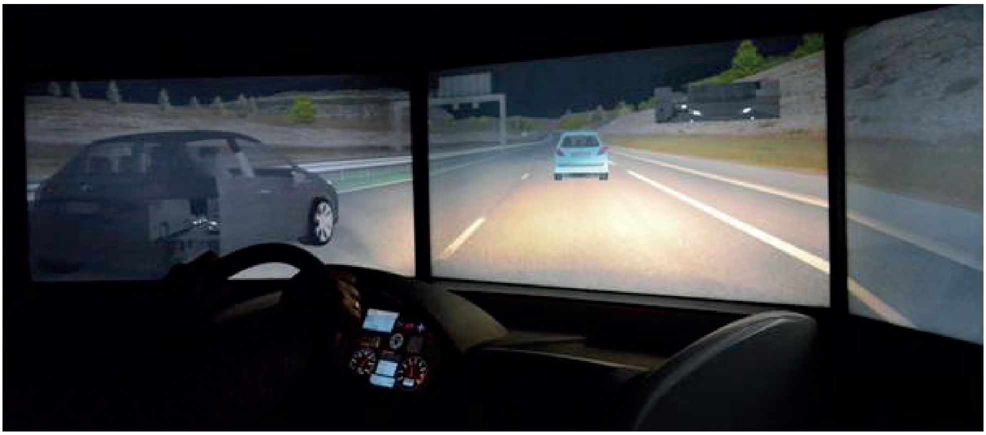


Fig. 5. View from the driver seat in scenario 4 (Oktal™ simulator)

The data registered during the tests were used to determine the driver behaviour and the reaction time.

The parameters measured were:

- the steering angle to determine the steering reaction time,
- the displacements of the braking and accelerator pedals to determine the braking reaction time and the accelerator release reaction time, respectively,
- the speed of and the path covered by the subject vehicle,
- the deceleration of the subject vehicle.

In scenarios 2 and 4, the main collision avoidance manoeuvre was rapid braking; the manoeuvre of steering to the left to overtake the leading vehicle was extremely difficult if not impossible to perform because of the presence of other road users in the left lane and behind the subject vehicle. Overtaking to the right, which was frequently observed, meant driving in the hard stopping shoulder, which is banned.

The primary objective of the study was to analyse how the road situation and the time of day could affect the driver behaviour. Different distances from the vehicle in front were considered as the distance is a crucial parameter affecting the driver reaction time [29]. The study involved comparing daytime driving with night-time driving to see how the reaction times changed.

As indicated in some publications (especially those dealing with accident reconstruction), the comparison of the driver reaction times requires measuring them under the same or very similar conditions for the same or very similar scenarios [30, 31].

Although the results obtained by means of a simulator may differ quantitatively from those registered under real conditions, they provide some general information on how drivers behave in dangerous situations. Tests with real vehicles in real traffic would involve too much risk. As emphasized in the author's earlier paper, the driver reaction times registered on the track and in a simulator for identical emergency situations may differ but there is some correlation between them [30].

Numerous studies concerning the driver reaction time show that there are various factors affecting the driver performance such as fatigue and sleepiness, which may be responsible for an increase in the reaction time [12].

The aim of this article is to show how the time of day and scenario complexity affect the driver behaviour in a car following situation.

3. Test results

The data registered during the simulator-based tests were:

- the accelerator release reaction time, measured as the time between the onset of the brake lights on the leading vehicle and the release of the accelerator pedal in the subject vehicle,
- the braking reaction time, measured as the time between the onset of the brake lights on the leading vehicle and the application of the brake pedal in the subject vehicle,
- the steering reaction time, measured as the time between the onset of the brake lights on the leading vehicle and the initial application of steering to overtake the vehicle.

The emergency manoeuvres performed by the subjects were registered and analysed. Collisions were also taken into consideration.

3.1 Driver reaction time

The time to release the accelerator pedal is a parameter not frequently considered by researchers. This reaction, however, is very important because it usually initiates the reaction to apply the brake pedal. The later the driver releases the accelerator pedal, the later they apply the brake pedal.

Figure 6 shows the distance-dependent accelerator release reaction times registered for the four scenarios. The longest accelerator release times were reported for scenario 1, where, except for the leading vehicle, there was no other traffic on the road and the driving took place during the day.

The finding was true for all the analysed distances from the lead vehicle. Figure 6 presents the mean accelerator release times RTa. As can be seen, there is a large discrepancy in the reaction times between the scenarios.

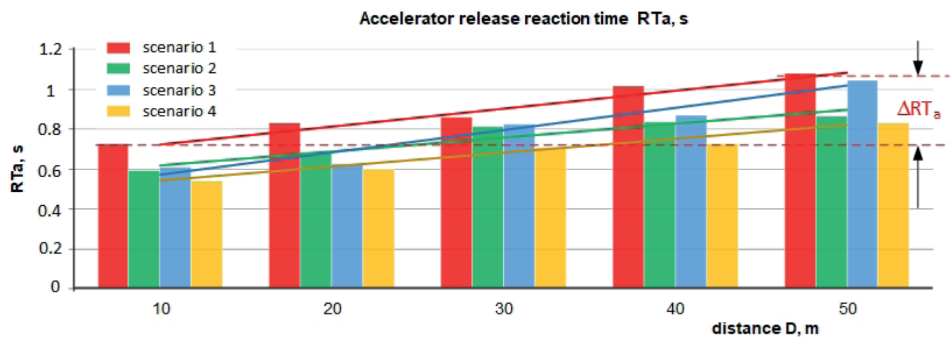


Fig. 6. Accelerator release times for the four scenarios

Table 1 shows the mean reaction times to the accelerator pedal release RT_a with the standard deviations (SD) for different distances between the vehicles S. Table 1 also provides the coefficients for the linear regression equations for the mean accelerator release times obtained in the particular scenarios.

As can be seen from Table 1, the SD values increase with increasing distance from the leading vehicle D. The SD values are much higher in scenarios 1 and 3 than in scenarios 2 and 4.

From Figure 6 it is clear that the values of the accelerator release times increase with increasing distance from the preceding vehicle D.

Tab. 1. Times to the accelerator pedal release, RT_a

Distance to the lead vehicle D, m	10	20	30	40	50	Coefficients for the linear regression equations $RT_a = a*D+b$	
Scenario	Accelerator Release Times RT_a (SD), s					a	B
1	0.72 (0.30)	0.83 (0.41)	0.86 (0.34)	1.02 (0.49)	1.08 (0.71)	0.090	0.631
2	0.59 (0.25)	0.69 (0.21)	0.81 (0.24)	0.84 (0.35)	0.87 (0.38)	0.070	0.548
3	0.61 (0.11)	0.63 (0.23)	0.82 (0.27)	0.87 (0.56)	1.04 (0.61)	0.111	0.463
4	0.54 (0.09)	0.60 (0.19)	0.71 (0.20)	0.73 (0.28)	0.83 (0.36)	0.070	0.471

The accelerator release times ΔRT_a were analysed by determining the differences between the mean accelerator release times obtained for different distances between the vehicles (Fig. 6).The results indicate that the time to release the accelerator pedal was dependent on the distance from the vehicle in front D; in some cases, the difference between the longest and shortest times exceeded 0.4 s (Fig. 7). The greatest differences between ΔRT_a were observed for scenarios 1 and 3, when there were no other vehicles around the subject vehicle, while the smallest differences were reported for scenarios 2 and 4.

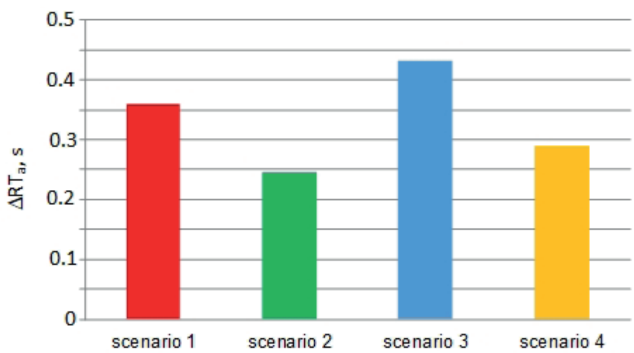


Fig. 7. Differences between the mean accelerator release times ΔRT_a in the four scenarios

The time to apply the brake RT_b is a very important parameter, commonly used by forensic scientists [52, 60] to reconstruct accidents [17]. Figure 8 shows the braking reaction time for all the scenarios. From Fig. 8 it is evident that, in such a dynamic situation, the braking reaction time depends on the initial distance between the vehicles. The braking reaction time increases with increasing distance from the preceding vehicle D. The highest mean values of RT_b were reported for scenarios 1 and 3, as was the case with the accelerator release times. It is interesting to note that, in night-time driving (scenarios 2 and 4), the mean reaction times were slightly shorter than those reported for daytime driving (scenarios 1 and 3).

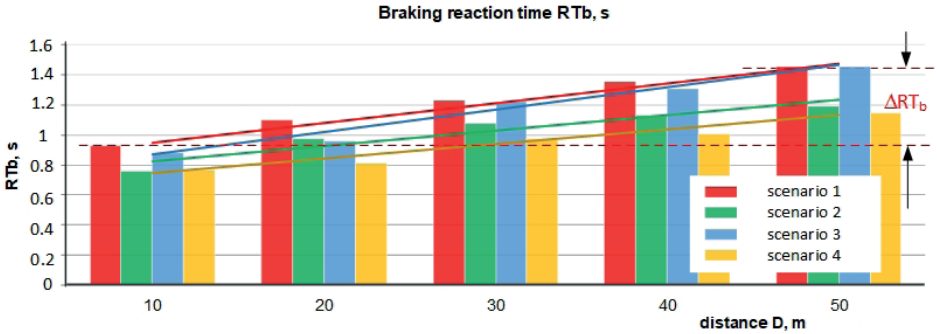


Fig. 8. Braking reaction times for the four scenarios

Table 2 gives the reaction times to the application of the brake pedal RT_b with the standard deviations SD for different distances from the preceding vehicle D. The table also includes the coefficients for the linear regression equation for the mean braking reaction times. The standard deviations SD increase with increasing distance from the vehicle in front, as was the case with the accelerator release time. It can be seen that the differences between the braking reaction times (SD values) are much bigger in scenarios 1 and 3 than in scenarios 2 and 4.

Tab. 2. Braking reaction times, RT_b

Distance to the lead vehicle D, m	10	20	30	40	50	Coefficients for the linear regression equations $RT_b = a*D+b$	
Scenario	**Accelerator Release Times RT_b (SD), s**					**a**	**B**
1	0.93 (0.30)	1.09 (0.47)	1.23 (0.38)	1.36 (0.58)	1.46 (0.83)	0.132	0.815
2	0.76 (0.17)	0.97 (0.30)	1.08 (0.28)	1.13 (0.41)	1.19 (0.46)	0.102	0.721
3	0.88 (0.21)	0.96 (0.31)	1.22 (0.35)	1.31 (0.52)	1.45 (0.56)	0.149	0.718
4	0.76 (0.14)	0.80 (0.22)	0.98 (0.26)	1.00 (0.35)	1.14 (0.41)	0.096	0.651

The data concerning the time to the application of the brake pedal were studied for different distances from the preceding vehicle. The differences between the mean braking reaction times ΔRT_b are illustrated in Fig. 9. The results are qualitatively similar to those concerning the accelerator release time with the differences being even bigger. The biggest differences between the mean braking reaction times (more than 0.55 s) were reported for scenarios 1 and 3, i.e. when there were no other vehicles around the subject vehicle. The smallest values reaching 0.4 s were registered for scenario 4.

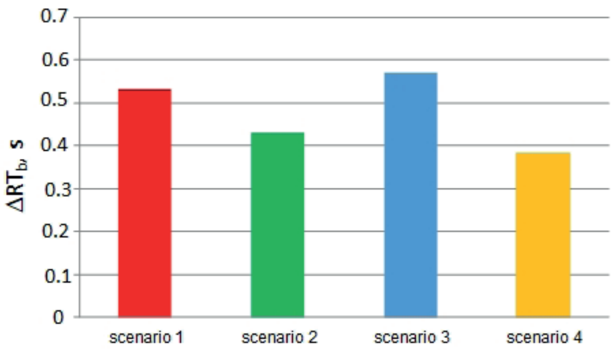


Fig. 9 Differences between the mean braking reaction times ΔRT_b in the four scenarios

Another important parameter used to analyse the driver behaviour is the steering reaction time RT_S. If the manoeuvre is undertaken early enough, the driver is able to overtake the slowing vehicle in front. In the tests, the steering reaction time was measured as the time between the onset of the brake lights on the lead vehicle to the initial application of steering by the driver. The values of the steering reaction time are shown in Fig. 10. It can be seen that the times increase with increasing distance between the vehicles D. The lowest values were reported for night-time driving with other vehicles around the subject vehicle.

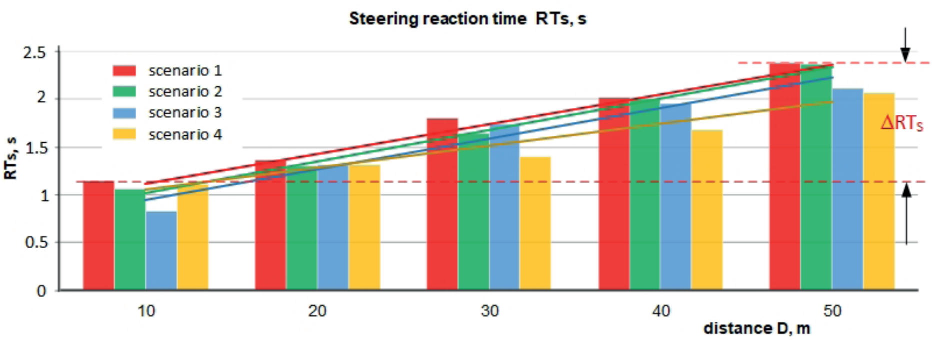


Fig. 10. Steering reaction times for the four scenarios

Table 3 provides the steering reaction times RTs with the standard deviations SD obtained at different distances from the lead vehicle. It also includes the corresponding values of the coefficient for the linear regression equations.

Tab. 3. Steering reaction times, RT_s

Distance to the lead vehicle D, m	10	20	30	40	50	Coefficients for the linear regression equations $RT_s = a*D+b$	
Scenario	Accelerator Release Times RT_s (SD), s					a	B
1	1.15 (0.45)	1.36 (0.62)	1.80 (0.77)	2.01 (0.66)	2.38 (0.74)	0.311	0.805
2	1.06 (0.18)	1.30 (0.18)	1.63 (0.27)	2.00 (0.25)	2.36 (0.40)	0.321	0.628
3	0.83 (0.27)	1.32 (0.56)	1.74 (0.59)	1.95 (0.53)	2.16 (0.79)	0.329	0.685
4	1.11 (0.21)	1.32 (0.32)	1.40 (0.46)	1.68 (0.31)	2.07 (0.42)	0.229	0.828

From the linear regression lines it is evident that they are similar for scenarios 1, 2 and 3 (similar values of the coefficient for the linear regression equations). For scenario 4, the line is different. Like in the previous cases, the standard deviations (SD) determined for the steering reaction times increase with increasing distance from the vehicle in front. It can be seen that the SD values are the highest for scenario 1 and the lowest for scenarios 2 and 4. For scenarios 1, 2 and 3, the differences between the minimum and maximum mean values of the steering reaction time ΔRT_S (calculated as a function of the distance from the preceding vehicle) (Fig. 11) are very small, not exceeding 1.2 s.

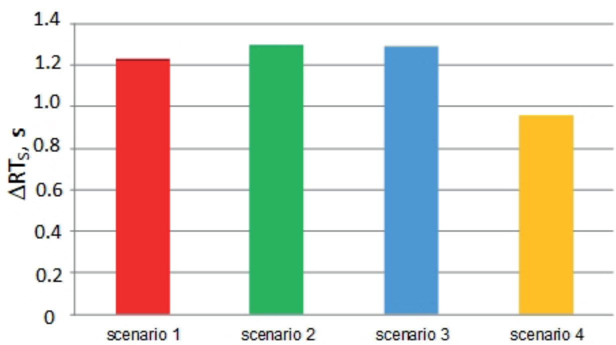


Fig. 11. Differences between the mean steering reaction times in the four scenarios

The steering reaction times were most varied during driving in night-time lighting conditions with no other vehicles around (scenario 3). The most difficult scenario, i.e. scenario 4, had the least variation (about 1 s).

3.2 Analysis of the emergency manoeuvres

One of the major aims of the simulator-based tests was to determine what collision avoidance manoeuvres were undertaken in each emergency situation and by how many drivers. As mentioned above, the driver could apply the brake only, steer away to overtake the vehicle in front or use the two manoeuvres simultaneously.

The percentage of the braking manoeuvre is shown in Fig. 12. It is clear that it is the most frequent manoeuvre in all the scenarios where there are other vehicles around. It was undertaken by as many as 60% of the drivers tested. This manoeuvre was also observed in several cases (15-28%) in scenario 1.

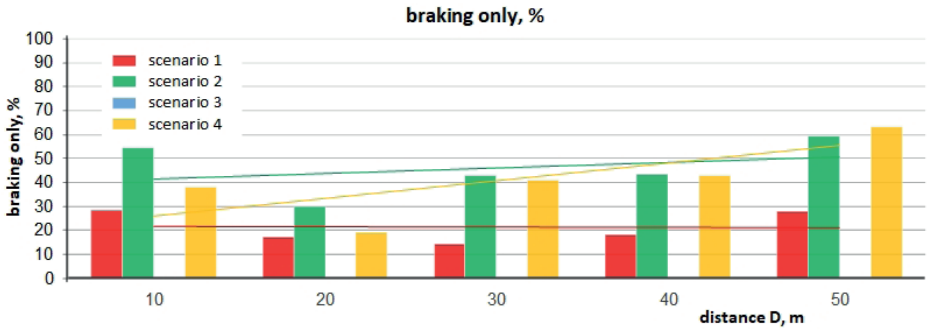
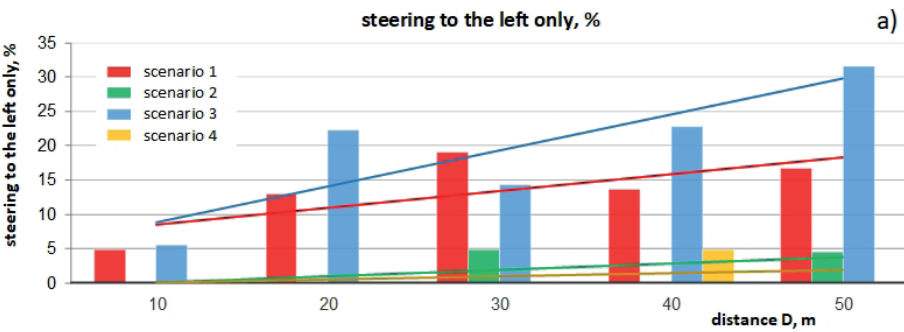


Fig. 12. Percentage of the braking manoeuvre

Figure 13 analyses the steering (overtaking) manoeuvre. Steering to the left (Fig. 13a) was performed more frequently when the distance from the preceding vehicle was large. It was a predominant manoeuvre observed in more than 30% of the drivers in scenarios 1 and 3, where there were no other vehicles travelling alongside the subject vehicle. The manoeuvre was also reported to be performed by single drivers in scenarios 2 and 4, despite the fact there was a high likelihood of collision with the vehicles moving in the left lane.



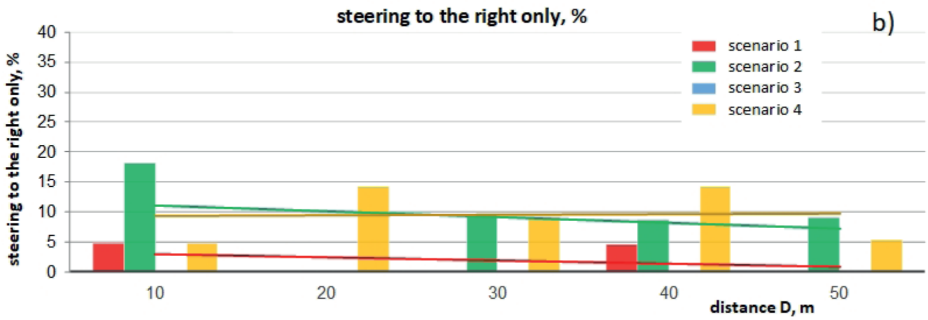
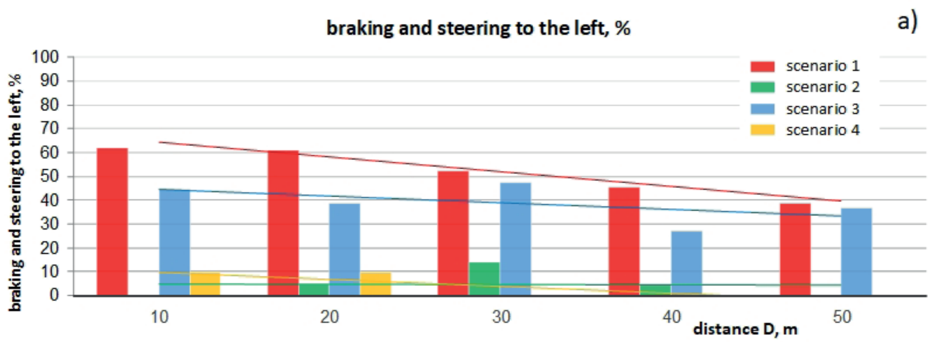


Fig. 13. Percentage of the steering manoeuvre; a) to the left only, b) to the right only

The percentage of the steering to the right manoeuvre is illustrated in Fig. 13b. Although right overtaking using the hard shoulder is banned, this manoeuvre was undertaken in certain situations, particularly in scenarios 2 and 4, to avoid a collision. Figure 14 shows how many drivers used the combined braking and steering manoeuvres. It can be seen that the manoeuvre of left overtaking performed simultaneously with braking (Fig. 14a) was undertaken less frequently when the distance from the vehicle in front was smaller. The highest percentage of the combined manoeuvres was observed in scenarios 1 and 3, which involved no other vehicles to the left or behind the subject vehicle. In scenario 4, this manoeuvre was undertaken by about 10% of the drivers when the distance from the vehicle in front was 10 or 20 m.



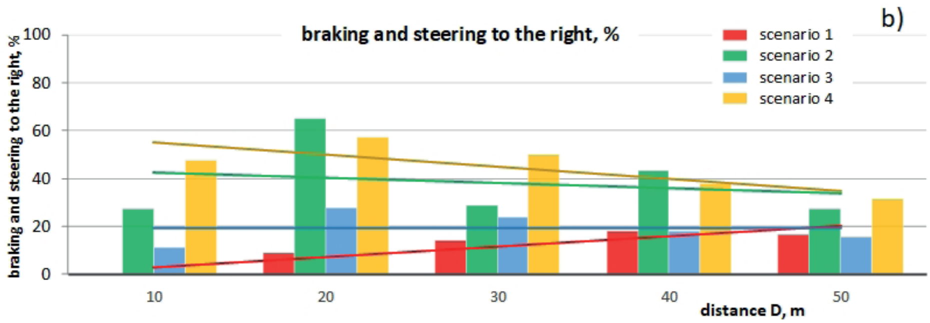


Fig. 14. Percentage of the combined braking and steering manoeuvres

Figure 14b shows the percentage of combined braking and steering to the right. Steering to the right to avoid a collision (using the shoulder) was a manoeuvre undertaken relatively frequently, i.e. by as many as 65% of the drivers, especially in scenarios 2 and 4.

3.3 Occurrence of accidents

Many accidents involving collisions with the vehicle in front or vehicles in the left lane were reported during the tests. They occurred in all the four scenarios mainly at the smallest distances between the vehicles and they were more frequent for night-time driving (Fig. 15a).

Rear-end collisions, in which the subject vehicle runs centrally into the rear of the preceding vehicle (Fig. 15b), most often took place at a distance of 10 m. An increase in the distance between the vehicles to 20 or 30 m caused a decrease in the number of such accidents to 20%. When the distance was 50 m, no such accidents were reported.

The findings are important as they confirm the necessity to have and follow the rules of the highway code concerning a safe distance between vehicles driving on a motorway. Such rules exist in many countries. In France, for example, 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). Not maintaining the right distance between vehicles may result in high fines. On Slovakia's roads, a safe following distance (given in meters) is dependent on the type of road.

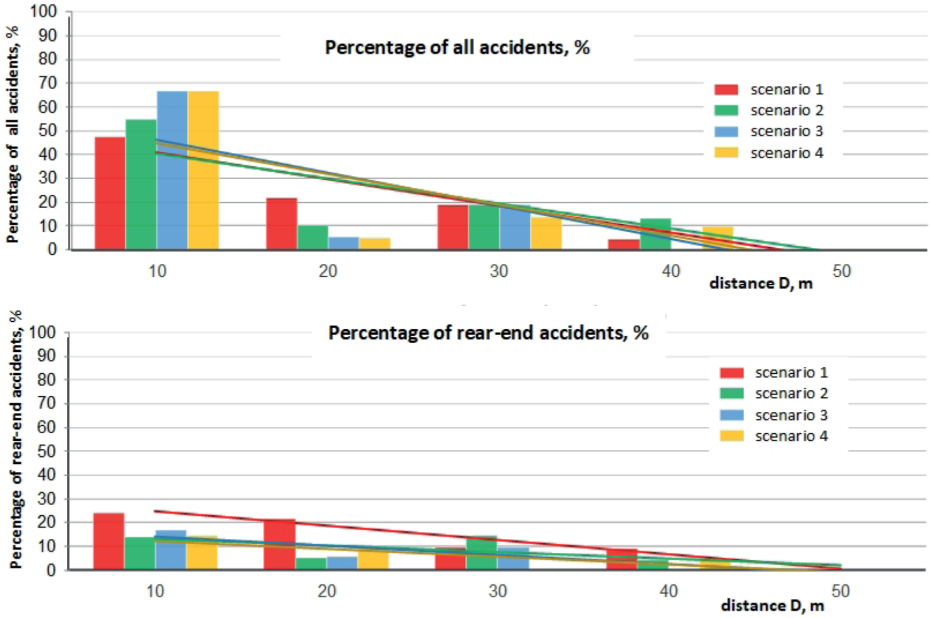


Fig. 15. Accidents registered during the driving simulations

In Poland, the term 'safe distance' has not been defined precisely. This implies that drivers are, to some extent, free to interpret it. The only case when a minimum distance to be maintained from the vehicle in front is specified is for driving in a tunnel.

4. Discussion

The aim of this study was to determine how drivers responded to rapid braking of the vehicle in front while driving on a motorway. Different pre-crash situations were considered.

The experimental data show that, although emergency manoeuvres are affected by a number of factors, they are strongly dependent on the presence of other road users. Four road situations (four scenarios) were simulated to register the type of crash avoidance manoeuvre and the time of the driver reaction. Longer reaction times were reported for longer distances from the vehicle in front. The reaction times were shorter when the driving was done at night or in the presence of other vehicles.

The simulation data from scenarios 1 and 3, where there were no other vehicles in the vicinity except for the one in front, reveal that the mean reaction times were shorter at night than during the day. They were about 0.15 s shorter when the accelerator pedal was released, 0.05 s shorter when the brake pedal was applied, and 0.1 s shorter when the steering manoeuvre was chosen.

The analysis of the results registered for the more complex scenarios (scenarios 2 and 4), where the left lane was occupied, suggests that the mean reaction times were approximately 0.1 s shorter for all the manoeuvres during night-time driving than for those during daytime driving.

When the complexity of the scenarios was considered, the differences between the mean reaction times for scenarios 1 and 2 were approximately 0.2 s for the accelerator release manoeuvre as well as the brake application manoeuvres and 0.1 s for the steering manoeuvre; the differences reported for scenarios 3 and 4 were 0.1 s, 0.25 s and 0.1 s, respectively.

These differences constitute qualitative confirmation of the findings described in [29]. Obviously, in real traffic conditions, the driver reaction time is likely to be longer, as shown in some studies [30,59]. By analogy, the emergency manoeuvres may also be different [20, 21, 28].

An important question is how the driver responded to the emergency situation: by braking, by steering away or by combining the two manoeuvres. The percentage of manoeuvres undertaken in each scenario varies considerably. As suggested in the author's earlier publication [28], even a slight modification of the situation may have a significant impact on the driver behaviour. Figure 16 analyses the emergency manoeuvres undertaken in the four scenarios.

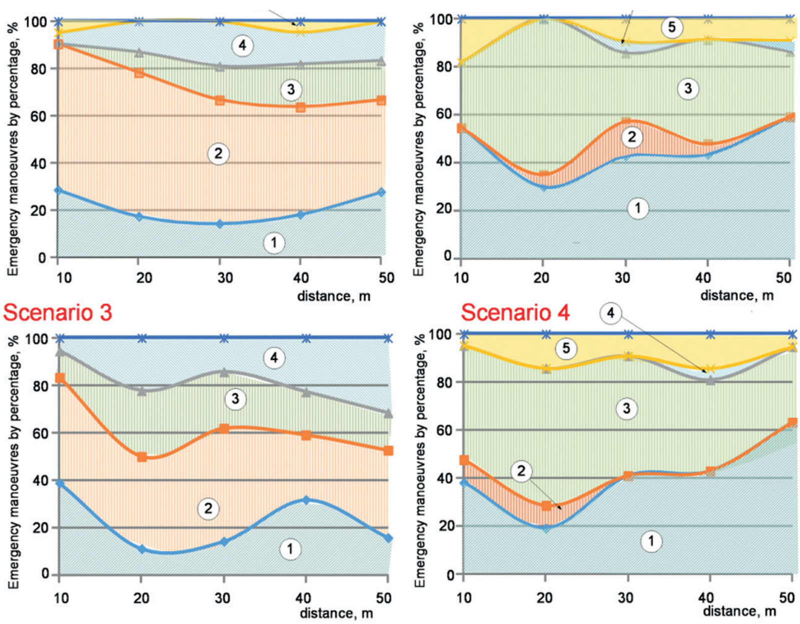


Fig. 16. Percentage of the emergency manoeuvres performed in the four scenarios; Manoeuvres: 1- braking only; 2- combined braking and steering to the left, 3- combined braking and steering to the right, 4- steering to the left only, 5- steering to the right only

The plots in Fig. 16 suggest that:

- there was a high qualitative similarity in the emergency manoeuvres between scenarios 1 and 3 and between scenarios 2 and 4;
- the *braking alone* manoeuvre was used less seldom in scenarios 1 and 3 than in scenarios 2 and 4;
- the combined *braking and steering* to the left manoeuvres were the most frequent behaviour reported in scenarios 1 and 3 (40-60% of the drivers tested); in scenarios 2 and 4, on the other hand, these manoeuvres were used only by 10-15% of the drivers and they were selected only for a certain range of distances from the leading vehicle;
- the combined *braking and steering to the right* manoeuvres were most frequently observed in scenarios 2 and 4; at a distance of 20 m, they were undertaken by about 60% of the drivers; in scenarios 1 and 3, these manoeuvres were applied by 10-25% of the drivers;
- the *steering to the left* manoeuvre was undertaken by 20-25% of the drivers in scenarios 1 and 3; the use of this manoeuvre in scenarios 2 and 4 can be regarded as negligible;
- the *steering to the right* manoeuvre was applied by as many as 15-20% of the drivers in scenarios 2 and 4; the use of this manoeuvre in scenario 1 was rare and it did not occur in scenario 3;
- the qualitative and quantitative impact of the time of day on the choice of emergency manoeuvres was more visible in simple road situations (scenarios 1 and 3);

5. Conclusion

Since the driver behaviour is one of the major elements contributing to road accidents, it is essential, from the utilitarian point of view, that all factors affecting it be thoroughly investigated.

The study described in this paper analysed the driver behaviour in emergency situations caused by sudden braking of the vehicle in front. The tests were carried out in daytime and night-time lighting conditions for scenarios differing in complexity. The distance between vehicles had significant influence on the driver reaction times. The longer the distance, the longer the driver reaction time was determined in the test. The simulator-based tests confirmed qualitatively the findings reported by other researchers [29].

An interesting observation was that in night-time lighting conditions, the driver reaction times were slightly shorter, irrespective of whether or not there were other vehicles around the subject vehicle. The tests result does not suggest, however, that darkness or worse lighting conditions contribute to a reduction in the driver reaction time. The data obtained by means of a simulator may not correspond to real-traffic results. It should be noted that, since the tests per person did not take long, factors such as fatigue and sleepiness that are likely to occur in night-time driving were not taken into account.

In the more complex scenarios, when it was almost impossible to steer around the vehicle in front because the left lane was occupied, driving concentration levels were higher and the reaction times were shorter. An interesting finding is that the reaction time and the type of driver manoeuvre are dependent on the road situation (scenario) and the distance from the lead vehicle.

The analysis of the driver behaviour in all the scenarios shows that the predominant manoeuvre is steering, combined or not with braking. The data are in agreement with the results obtained by other researches from on-track testing [28]. Despite the fact that in two scenarios steering away was very difficult to perform, this manoeuvre was undertaken by as many as 70-80% of the drivers tested.

The test results confirm that keeping a safe distance from the vehicle in front is crucial as it is one of the main ways to prevent rear-end collisions. The analysis of the number of accidents taking place in simulated road situations shows that at an initial speed of 100 km/h, the longer the distance to the leading car, the lower the number of accidents. When the distance was 10 m, the percentage of drivers involved in a crash was as high as 75-85% with most crashes being rear-end collisions. Rear-end collisions on motorways are very dangerous as they are likely to result in multi-vehicle crashes. At longer distances of 20-30 m, the risk of an accident declines to 30-40%. The 50 m distance can be regarded as safe as no accidents were reported for it.

The experimental data confirm the need for legal regulations that would specify minimum safe distances between vehicles in car following situations. They could also provide guidelines on preventive and educational measures in this area. Candidates for driving jobs could find them useful when learning proper car-following behaviour, depending on the road situation and/or weather conditions.

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