Article citation info:
PAPIS M, JASTRZĘBSKI D, KOPYT A, MATYJEWSKI M, MIROSŁAW M. Driver reliability and behavior study based on a car simulator station tests in ACC system scenarios. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2019; 21 (3): 511–521, http://dx.doi.org/10.17531/ein.2019.3.18.

Mateusz PAPIS
Dominik JASTRZĘBSKI
Antoni KOPYT
Marek MATYJEWSKI
Marcin MIROSŁAW

DRIVER RELIABILITY AND BEHAVIOR STUDY BASED ON A CAR SIMULATOR STATION TESTS IN ACC SYSTEM SCENARIOS

ANALIZA NIEZAWODNOŚCI I ZACHOWANIA KIEROWCY Z WYKORZYSTANIEM TESTÓW NA SYMULATORZE POJAZDU OSOBOWEGOO W SCENARIUSZACH SYSTEMU ACC

Nowadays Advanced Driver Assistant Systems (ADAS) are becoming more popular in car equipment. During ADAS development process it is necessary to prepare numerical models and perform simulation tests, so the systems could be safely implemented. However, because these systems are directly connected to a human – machine interface, volunteer tests on a car simulator are conducted. They are indispensable for testing the correct operation of the system, but above all for showing differences in the operation of the system and a driver in terms of human reliability. Presented research shows results of simulator tests in two cases: extra - urban and mixed scenarios. The tests were classic, tracking tasks in which the driver was required to keep a safe, predefined distance from the leading car. Consequently, the results of experiments were compared to results of the reference car performance, i.e. the car equipped with Adaptative Cruise Control system. It made possible to assess the driver reliability. Moreover, questionnaire tests (NASA TLX) were also applied to assess subjects' workload. Finally, results of volunteers' rides were compared to results of a simulation with use a driver model based on fuzzy logic. This model, in the future, may be used in development of a car simulator equipped with ADAS.

Keywords: *ADAS, ACC, volunteer tests, driver behavior, driver reliability, car simulator, NASA TLX.*

Obecnie zaawansowane systemy wspomagania kierowcy (ADAS) stają się coraz popularniejszym elementem wyposażenia samochodów. Z procesem ich rozwoju wiąże się konieczność przygotowania modeli numerycznych i przeprowadzenie testów symulacyjnych, aby zapewnić bezpieczne wdrożenie systemów. Z faktu ich bezpośredniego powiązania z interfejsem człowiek- maszyna wynika potrzeba prowadzenia testów na symulatorze z udziałem ochotników. Są one niezbędne do sprawdzenia poprawności działania danego systemu, ale przede wszystkim do wykazania różnic w działaniu systemu i kierowcy w kontekście niezawodności człowieka. Prezentowane badania pokazują wyniki testów symulatorowych w dwóch scenariuszach: pozamiejskim i mieszanym. Testy składały się z klasycznych zadań, w których kierowca musiał utrzymywać bezpieczną, z góry określoną odległość od wiodącego samochodu. W rezultacie wyniki eksperymentów porównano z osiągami samochodu referencyjnego, wyposażonego w tempomat adaptacyjny tzw. ACC (Adaptative Cruise Control). Umożliwiło to ocenę kierowcy pod kątem jego niezawodności. Ponadto do analizy obciążenia uczestników zastosowano również testy kwestionariuszowe NASA TLX. Ostatecznie wyniki przejazdów uczestników testów porównano także z wynikami symulacji przeprowadzonej z wykorzystaniem modelu wirtualnego kierowcy (zbudowanego z użyciem logiki rozmytej). Model ten w przyszłości będzie mógł być wykorzystany do opracowania i rozwoju symulatora samochodowego wyposażonego w ADAS.

Słowa kluczowe: *ADAS, ACC, testy z ochotnikami, zachowanie kierowcy, niezawodność kierowcy, symulator pojazdu osobowego, NASA TLX.*

1. Introduction

Research on human safety is a complex, time consuming, and extremely important process. Especially in the car industry which is a huge market. Such research contains both crashworthiness of a vehicle structure, biomechanical study and research on driver behavior and his/her reactions. It may be tested either by means of computer simulations or real crash experiments. Simulations are time consuming but provide recurrent test. Unfortunately, they need a validation in a form of an experiment [33], which could be expensive. Moreover, sometimes it is impossible to make a recurrent experiment and there is a considerable risk of failure, i.e. in crash tests it may reach 13% [27]. In research on a driver behavior and reaction, both questionnaire studies and simulators can be distinguished.

Questionnaire research covers many issues and often relates to the simulator one, i.e.: user knowledge about ADAS [29], in-depth exploration of perceptions towards automated vehicles [4], evaluation of the HMI intuitiveness [8].

Simulator research is being used from 60's of XX century, when development of car simulators in UCLA [32], GM Styling Staff [3],

a) driver's screens *b) driver's seat [38]* *c) Pedals, steering wheel, gearbox [38]*

Fig. 1. Simulation station

Cornell Aero Labs and Volkswagen [19] began. In 70's and 80's more sophisticated simulators were developed (among others) in Road and Traffic Research Institute in Sweden, in VPI in Wierwille, in Institute of Perception (IZF-TNO) in Nederland, FAT in Germany and in FHWA [1, 21, 22, 31]. This led to a simulator in Daimler in Berlin which was described as next generation simulator, and further development in Sweden and a research funded by NHTSA in USA in National Advanced Driving Simulator (NADS) created current simulators [5, 9, 16, 23, 28, 30, 36]. Newest car simulators have 6 degrees of freedom, may apply acceleration of 0.8 g to a driver and they may move around 10 m in a hangar, but they are expensive and need a large space to use them.

With the development of automotive technology, the number of driver assistance systems is increasing. These systems are referred to as ADAS and the most popular are:

- Adaptive Cruise Control (ACC) systems, which adapts car's velocity to a current traffic to avoid collision. This system controls the velocity of the vehicle and, if necessary, brakes or accelerates, but the driver is still responsible for steering the vehicle [10]. ACC system should meet the relevant ISO standards [11-13].
- Advanced Emergency Braking Systems (AEBS), whose main functionality is to activate the emergency braking procedure in case of potential collision with another vehicle or obstacle.
- Lane Departure Warning (LDW) systems, whose purpose is to help the driver (via a warning signal) to keep the vehicle in the lane on highways and highway-like roads. LDW are not designed to control vehicle motions and issue warnings with respect to collisions with other vehicles [14].

The presented study was conducted as part of the *aDrive* project ("Innovative simulation technologies to evaluate vehicles driving automation systems in terms of road traffic safety") at the Warsaw University of Technology on a group of 30 volunteers with use a stationary car simulator to test AEBS operation and ACC scenarios. In the following chapters, the results from ACC experiments are presented.

2. Background

aDrive was the first Polish national project that aimed to develop an integrated simulation environment comprising realistic traffic scenarios, vehicle driving automation ADAS models, Human-Machine Interfaces (HMI) communications and control links, and Human-In-the-Loop (HIL) simulator testing capabilities for the evaluation of the PRE-CRASH phase [6].

During the project the following research and analyses were carried out:

- simulation environment - [7, 20];
- HMI analyses and virtual driver model - [7, 15, 17];
- safety analyses - [24, 26];
- simulator tests (described mainly in this paper).

The aim of this study was to compare the operation of the ACC system developed as part of the aDrive project with volunteers driver behavior. The analyses of chosen ride performance parameters in prepared tasks according to pre-defined criteria (e.g. velocity, distance from the preceding vehicle) in relation to parameters of the reference ride (car with ACC system) were made. At the same time, the driver's workload level was examined for two tasks, using the NASA Task Load indeX questionnaires [37].

3. Simulator environment and station

Scenarios were prepared in *PreScan* environment. Simulations were performed in *MATLAB*® and *Simulink*®. This combination allows to use 2D dynamics model and stay with real time performance. One station was used for both types of tests (Software-in-the-Loop and Human-in-the-Loop). The station was composed of three PCs and 5 LCD screens to display the test environment to the driver (Fig.1a), a seat (Fig. 1b), steering wheel, pedals and automatic gearbox (Fig. 1c)

In reference ride simulation the trajectory of the leading car was operated by the outer controller, while velocity was controlled by an ACC system. One of the developed algorithms has passed ISO norms [11-13], where smooth velocity and acceleration changes are required. Moreover, an additional module that allowed to fully stop the vehicle was added. The ACC system based on second algorithm had much more aggressive characteristic. For further research the first one was used.

4. Description of the experiment

4.1. The aim of the simulator experiment

The main goals of the research were:

- comparison between volunteers' and a reference ride's (a car equipped with ACC system) parameters. The study showed to what extent a person can "imitate" the operation of ACC system. The following driving parameters were analyzed:
  - car velocity,
  - distance from the leading vehicle,
  - time gap (time to a potential collision if the tracked car was stationary),
  - smoothness of driving based on the number of brake activations,
- verification of the model of virtual driver using modules of fuzzy logic ("fuzzy driver") [14, 16].

4.2. Experiment procedure

Simulator tests lasted about 30 minutes and proceeded according to the following scheme:

- familiarization of a volunteer with the course of the experiment and filling out the documents and surveys,
- a test ride to familiarize the volunteer with the dynamics and characteristics of the vehicle,
- performance of two tasks consisting in “tracking” a car,
- filling the NASA TLX (Task Load Index) questionnaires [37] after each task.

According to the experiment procedure, two various scenarios: mixed and extra-urban were tested. Each scenario had a different accomplishment criterion. In the extra urban scenario, the subject was asked to follow the car moving with the constant speed of 90 km/h. In the second one the assignment of the volunteer was to follow the car in more complex and demanding environment, where turns, stops, traffic etc. were included. The driver had a speedometer in the car simulator, but to increase subjects’ performance an additional pop-up window was generated (Fig. 2, Fig. 3). The purpose of this system was to enforce the proper drivers’ reaction.

4.3. Simulator screen and driver’s panel

In the Fig. 2 and Fig. 3 the simulator screen and indicators available for the driver are presented. During the simulator test, the driver had at his disposal a speedometer, tachometer and indicators (“lights”) determining the distance - the time gap parameter from a leading car:

– red light (on the right) will occur if the driven vehicle is too close to the tracked vehicle (time gap less than 1.5 s) – Fig. 3a,
– green (middle) light means that volunteer driver position relative to the tracked car is adequate (time gap from 1.5 to 2.5 s) – Fig. 3b,
– yellow light on the left means that volunteer car is too far from the tracked vehicle (time gap above 2.5 s) – Fig. 3c.

Fig. 2. Driver ’s panel

4.4. Tasks Description

The tasks to be carried out by the volunteer were as follows:

– **Test ride** to familiarize with the dynamics and characteristics of the vehicle,
– **Task 1:** Tracking a leading car that moved with a constant speed (extra-urban scenario),
  - The driver’s task was to drive a car with a constant speed (90 km/h = 56mph);
  - During the ride different events (e.g. an accident at the side of the road) appeared;
  - The trajectory of the vehicle was simple (Fig. 4a);
  - The track is determined by the leading car;
  - If the leading car disappeared from the view, the instructor helped the driver to follow the proper route;
  - The volunteer had at his disposal information about the velocity on the dashboard (speedometer). Additionally, the indicators (Fig. 3) informed the driver whether the current distance was appropriate.

– **Task 2:** Tracking a vehicle moving with a variable speed (mixed scenario):
  - The driver had a task to follow the leading car;
  - In this case, the leading car had a variable speed profile over time. In this task indicators (Fig. 3) had a significant role;
  - The trajectory of the vehicle movement in a mixed scenario (Fig. 4b) was more diverse than in the first task;
  - Similarly, to the first task, the driving route is determined by the car in front. In case of disappearing of the leading car from the view, the instructor helped with the navigation.

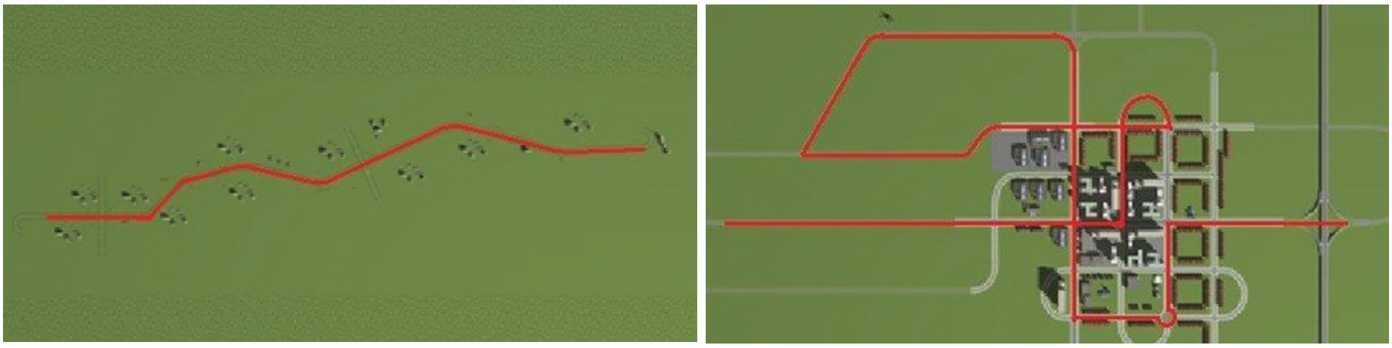
5. Selection of the sample for simulation tests

Many studies indicate that with the age a man changes his/her anatomical, physiological and biochemical nature, which can negatively influence a human efficiency as a driver. On the other hand, the driving experience is growing, and habits (correct and incorrect) are becoming more and more established [2]. To make the simulation experiment as accurate as possible, the chosen sample of volunteers should represent the structure of drivers in Poland. The selection of volunteer structure (age and sex) for simulation tests was prepared based on:

– structure of the population in Poland (considering age groups and sex) [34];
– percentage of people with a driving license (considering age groups and sex) [35];

a) red light *b) green light* *c) yellow light*

Fig. 3. Indicators available to the driver



a) extra-urban scenerio b) mixed scenerio

Fig. 4. Scenarios routes

– the frequency of driving a car by women and men age groups [35].

Many other factors, such as the volunteer's place of residence and the level of experience as a driver were omitted. Although, the second factor was considered indirectly by consideration of age. However, in a relatively small sample, considering every factor in the selection of volunteers group is impossible. Consideration of age and sex of the driver significantly increased the reliability of the conducted research.

5.1. Population data

The data used to estimate the sample structure are presented in Table 1.

The percentage of people who declare their ability to drive a car (having a driving license) was based on CBOS (Public Opinion Research Center) surveys [35]. In addition, there was an information that „Men more often than women drive a car (65% vs. 58%), and women with a driving license more often than men do not drive at all (16% vs. 10%). This relationship is weaker among younger respondents up to the age of 35, among whom men and women equally frequent have the ability to drive". Unfortunately, the short (public) version of the survey results does not contain detailed data on the age groups. Therefore, for men, a coefficient 0.65 was adopted, while for women from 0.48 to 0.64 (weighted average: 0.58) depending on the age group. These coefficients were used to better estimate the sample by considering the disproportion in the frequency of car driving by men and women (especially in older age groups).

5.2. Calculations

Based on the data from Table 1, the number of subjects in the age groups were estimated. It is assumed that 18 men and 11 women were expected to participate in the simulation tests. Table 2 shows the detailed results of the estimates for 29 volunteers.

More information about description of the experiment and selection of the sample for simulation tests you can find in [25].

Table 1. Drivers in Poland [34, 35]

Age	Men	% men with a driving license	Men with a driving license	Men who often drive	Women	% women with a driving license	Women with a driving license	Women who often drive
18 and more	**15054615**	**80%**	**11888302**	**7727396**	**16482499**	**51%**	**8305106**	**4816742**
18-24	1581897	67%	1059871	688916	1517356	56%	849719	542121
25-34	3035983	70%	2125188	1381372	2941716	69%	2029784	1295002
35-44	3005196	82%	2464261	1601769	2939786	66%	1940259	1125350
45-54	2353299	87%	2047370	1330791	2368783	56%	1326518	769381
55-64	2607916	84%	2190649	1423922	2881777	39%	1123893	586672
65 and more	2470324	81%	2000962	1300626	3833081	27%	1034932	498216

Table 2. The sample structure for 29 volunteers

Number of volunteers				29
Age	Men	Number of men	Women	Number of women
18 and more	**61.6%**	**18**	**38.4%**	**11**
18-24	5.5%	2	4.3%	1
25-34	11.0%	3	10.3%	3
35-44	12.8%	4	9.0%	3
45-54	10.6%	3	6.1%	2
55-64	11.4%	3	4.7%	1
65 and more	10.4%	3	4.0%	1

6. The results of the experiment

6. 1. Analyzed parameters

As mentioned, the analyzes concerned, first, the comparison between volunteer ride parameters and the "reference" ride (with an active ACC system). It was decided that the following indicators were used:

– *vel* – car speed
– *dist* – distance from the tracked car
– *TG* – time gap defined as (eq.1):

$$TG = \frac{dist}{vel} \tag{1}$$

– *NB* – number of brakes (based on *brake* - pressure in the braking system - input signal for the dynamics (0-150 bar), that is proportional to the braking torque)

6.2. Quality factors

In order to be able to assess individual performance of participants' rides, and then to develop summary results, appropriate quality factors were defined, in which the reference was the ride with active ACC system. The basic coefficient used in the subsequent quality measures was the difference between the parameter from the volunteer's and reference ride (with ACC) defined as follows (eq. 2):

$$e_q = \left| q - q_{ACC} \right| \tag{2}$$

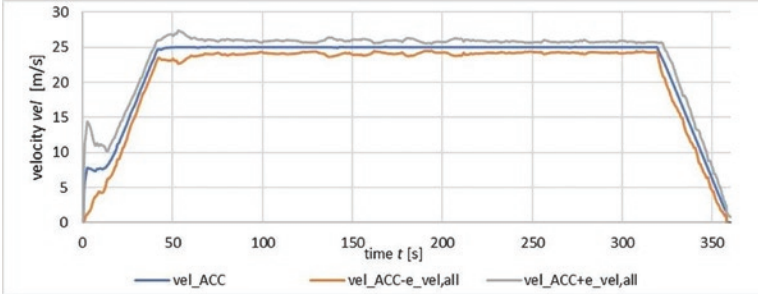


Fig. 5. Velocity for a car with ACC taking into account $e_{vel,\,all}$ parameter in task 1

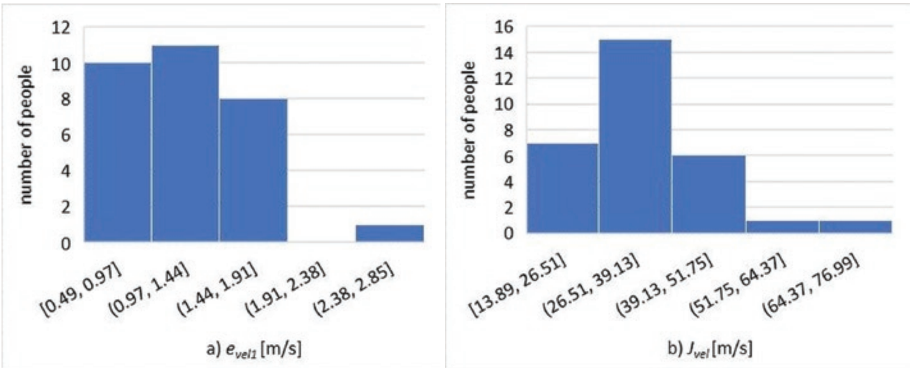


Fig. 6. Histograms for evel1 and J_{vel} parameters in task 1

where q is the parameter (except for *brake*) for the volunteer's ride (e.g. *vel*), while q_{ACC} is the same parameter for reference ride with the active ACC.

In the carried out analysis the following factors were used:

- $e_{q,\,all}$, which is the average of the e_q coefficients for all volunteers for a given moment,
- e_{q1}, which is the average of the e_q coefficient for a single volunteer for the whole ride,
- $J_q{}^2$ and J_q, which are the integral parameters defined as follows (eq. 3, eq. 4):

$$J_q{}^2 = \int_{t_1}^{t_2} e_q^2 \mathrm{d}t \tag{3}$$

$$J_q = \sqrt{J_q{}^2} \tag{4}$$

where t_1 and t_2 are respectively the start and end of the simulation.

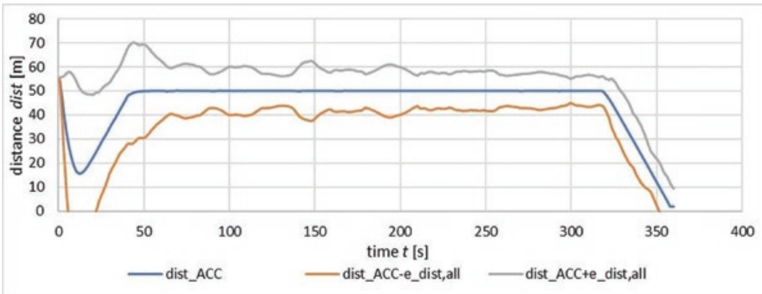


Fig. 7. Distance for a car with ACC taking into account $e_{dist,\,all}$ parameter in task 1

In addition, the distributions (histograms) of the described coefficients were made for the entire volunteers' group. Moreover, the number of brakes during a ride was calculated to assess the smoothness of the volunteer's ride and the reference ride (with the ACC system).

6.3. Results of task 1

The experiment was carried out on a group of 30 people with a very similar structure to that described in this paper in the part: *The selection of sample for simulation tests*. The results are presented in graphs (Fig. 5 - Fig. 11).

In Fig. 5 it is presented how and to what extent, on average, the volunteer's velocity changed in time. For this purpose, the average difference of velocity between volunteers and the reference ride - $e_{vel,\,all}$ was added to and subtracted from the velocity of the car equipped with ACC for each moment of time.

Fig. 6 shows histograms for the parameters: e_{vel1} and J_{vel}. The calculations show that the average difference between velocity of the volunteer's ride and the car with the ACC system was 1.23 m/s (about 4.5 km/h)

The next figures (Fig. 7-10) show analogous graphs for parameters such as: distance from the "tracked" car *dist* and time gap *TG*. Time gap parameter, when the "tracked" car accelerated or decelerated was not analyzed (for this reason, from the recorded data the first 50 seconds and the last minute were "cut out").

Fig. 10 c shows a histogram for the average value of the time gap parameter. It can be concluded that people usually kept a longer distance from the car with the ACC system - the average of *TG* was 2.13

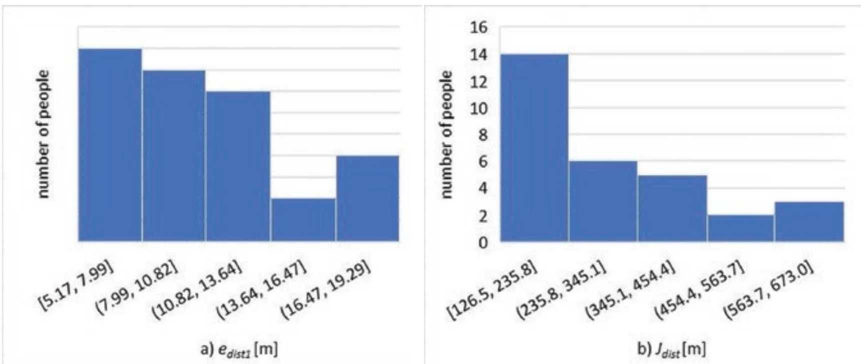


Fig. 8. Histograms for edist1 and J_{dist} parameters in task 1

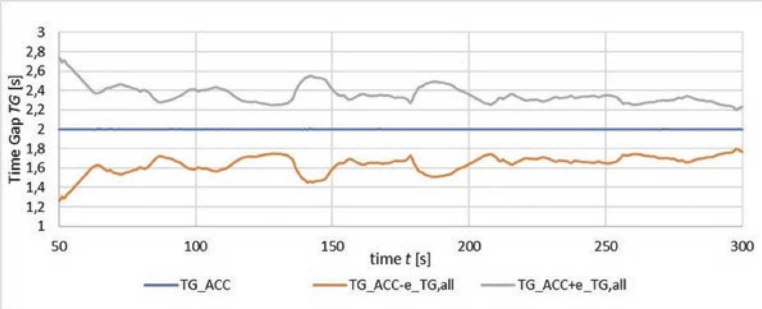


Fig. 9. Time Gap for a car with ACC taking into account $e_{TG,\,all}$ parameter (in case of constant vel of the tracked car) in task 1

s, 0.13 s more than this parameter for reference ride (where TG_{ACC} was 2.00s).

To assess the smoothness of driving of the participants in the experiment, the number of braking processes of each volunteer was calculated. It was considered that the braking process was defined as the situation when the average braking pressure for at least 5 consecutive recorded time samples (parameters in the task were registered every 0.05 sec) was at least 20 bars – Fig. 11.

During the experiment, the car equipped with the ACC system braked once. The participants activated the brake more times (from 4 to 23 – Fig. 11a), however, it was mainly related to the necessity of braking at the end of the task. For this reason, Fig. 11b shows the number of braking processes when the "tracked" car drove at a constant velocity. In this case, the car with the ACC system also drove at a constant speed (without braking). During this time also, the majority of volunteers managed to drive at the constant velocity without braking process – 19 people braked 2 times or less and 14 volunteers not at all.

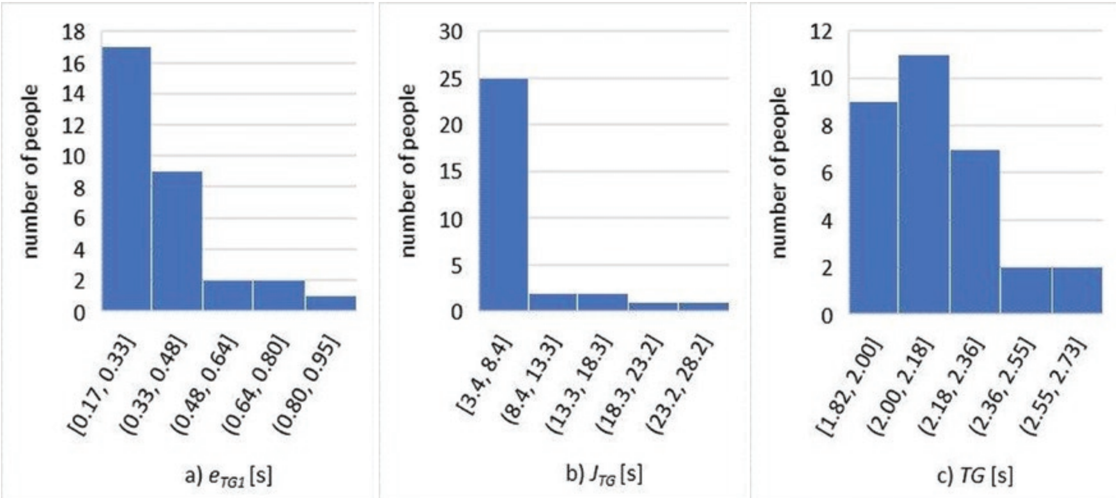


Fig. 10. Histograms for eTG1, J_{TG} and TG parameters in task 1

6. 4. Results of task 2

The second task was completed by 28 volunteers. Two subjects have not finished it because they had symptoms of simulator disease. In this task the same parameters and in the same way as in task 1 were analyzed. The results are presented in graphs (Fig. 12 - Fig. 18).

Fig. 13 shows histograms for the parameters: e_{vel1} and J_{vel}. The calculations show that the average difference between velocity of the volunteer's ride and the car with the ACC system was 1.98 m/s (about 7 km/h). The difference is much bigger (about 2.5 km/h) than in task 1 (where the tracked car drove with a constant speed). It can be concluded that the more complicated task caused difficulties in maintaining the stability and smoothness of the volunteer's rides.

Fig. 17c shows a histogram for the average value of the time gap parameter. It can be concluded that people usually kept a longer distance from the car with the ACC system - the average of TG was 2.37 s, 0.34 s more than this parameter for reference ride (where TG_{ACC} was 2.03s). In addition, the average value of time gap in this experiment was more than 0.2 s higher than in task 1. It can be concluded that in a more difficult experiment (where the tracked car changes speed more often) human tries to maintain a greater distance. In this experiment, the average time gap only for one volunteer was lower than 2s.

During this experiment, the car equipped with the ACC system braked 19 times. Volunteers braked more times (from 24 to 74 times- Fig. 18). However, if the derivate of the brake pressure was analyzed, the number of local braking pressure

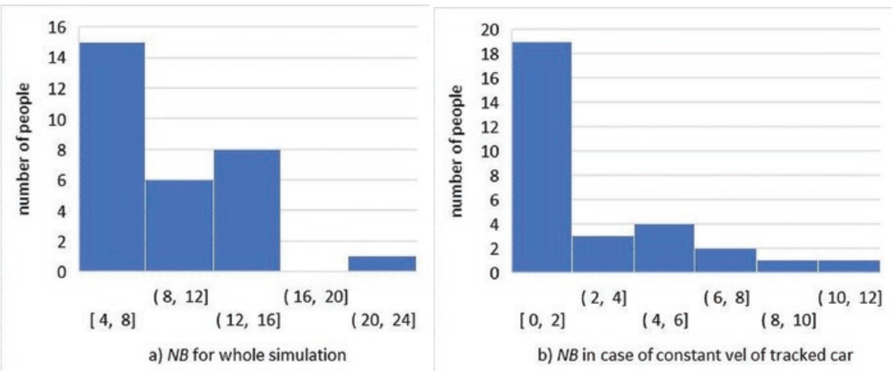


Fig. 11. Histograms for number of braking processes in task 1

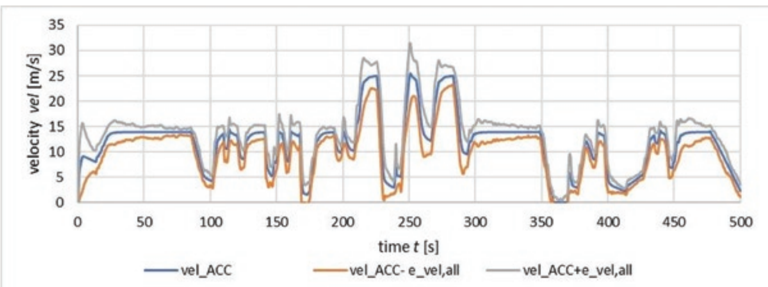


Fig. 12. Velocity for a car with ACC taking into account $e_{vel,\,all}$ parameter in task 2

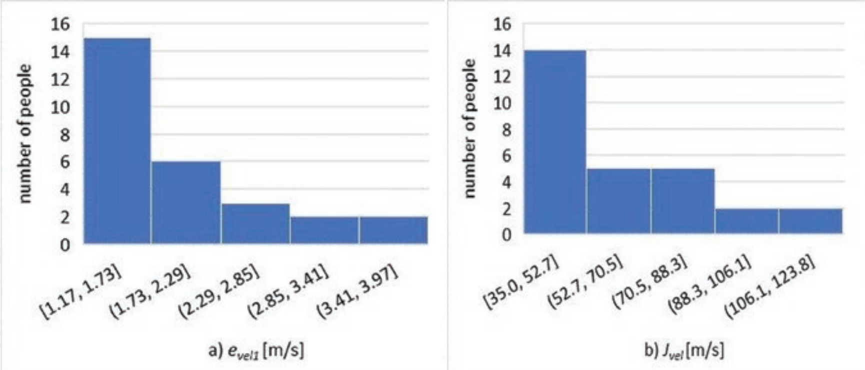


Fig. 13. Histograms for evel1 and J_{vel} parameters in task 2

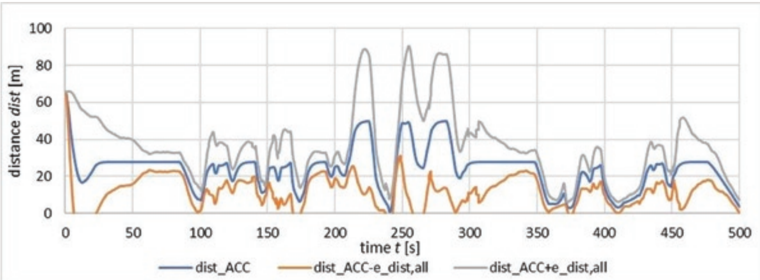


Fig. 14. Distance for a car with ACC taking into account $e_{dist,\,all}$ parameter in task 2

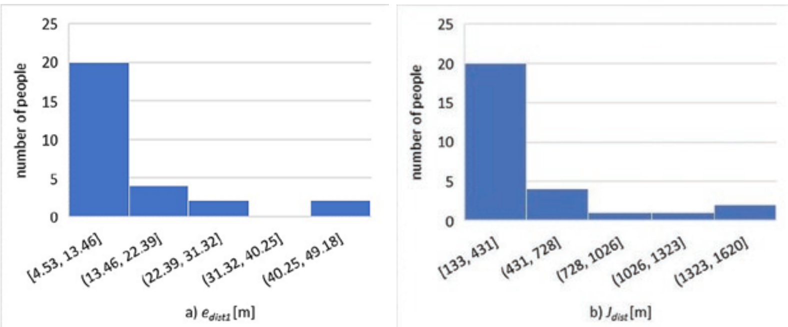


Fig. 15. Histograms for edist1 and J_{dist} parameters in task 2

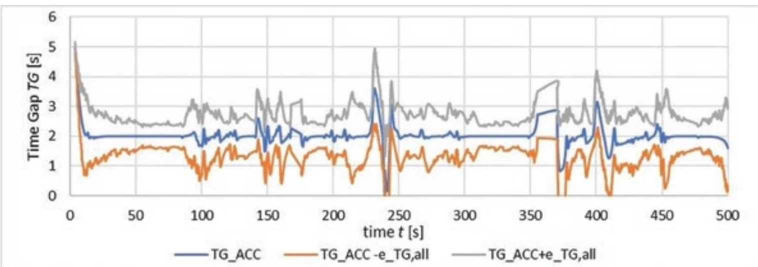


Fig. 16. Time Gap for a car with ACC taking into account $e_{TG,\,all}$ parameter (in case of constant vel of tracked car) in task 2

maxima for the ACC were as much as 219, for volunteers it was on average more than 2 times less. This means that in the case of the ACC system more often braking cycles occurred, where the braking pressure have not changed in a sudden manner, the braking of volunteer was more intense. The recorded braking pressure for the car equipped with ACC compared to one of the volunteers is presented in Fig. 19.

Comparing all data from experiments and figures concerning task 1 (Fig. 5 - 11) and task 2 (Fig. 12 - 19) it can be concluded that the ACC system operates more smoothly than humans. The ride with the ACC system was basically the ride of the tracked car with some small differences (greater for larger velocity changes) with a delay of 2.0 s. Humans, of course, could not drive so perfectly. The differences for individual parameters and the number of brakes relative to the reference ride were greater for a more complex task (task 2).

6.5. The results of surveys and NASA questionnaires

Before the experiment all volunteers completed the questionnaire in order to get personal information needed for the experiment. One of the questions referred to their driving style (careful, optimal, aggressive) and their actual psychophysiological state

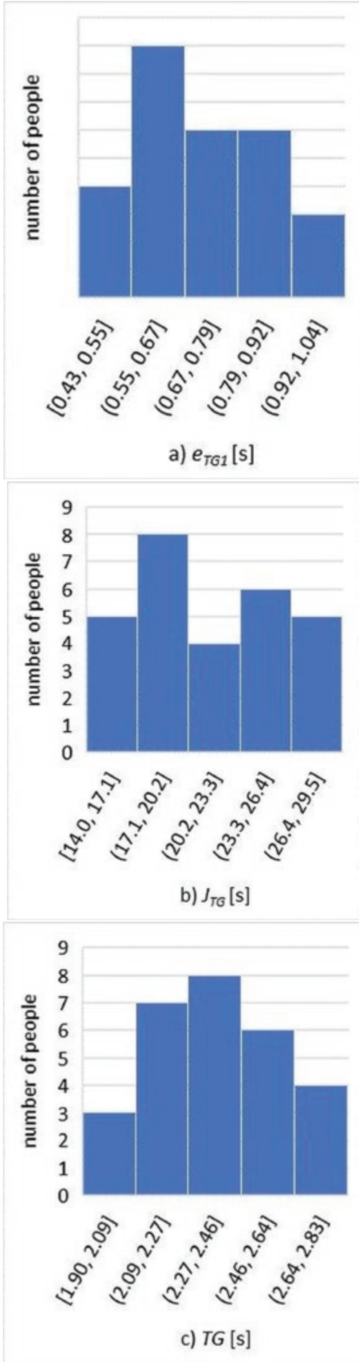


Fig. 17. Histograms for e_{TG1}, J_{TG} and TG parameters in task 2

(bored, optimal and overloaded). The subjects' answers are presented in Fig. 20.

As it is presented in the figure 21, most of the subjects specified themselves in both categories: state 77% and driving style 66%. The tasks performed by the volunteers were various, and the biggest difficulty in the second one was that car velocity changed along the path. At the end of the both tasks the subjects had to answer the NASA Task Load Index questionnaire [37]. The NASA TLX form was to confirm the tasks difficulty and to assess what engagement parameters were the most active during the tasks. The NASA TLX form consist of 6 various parameters to assess:

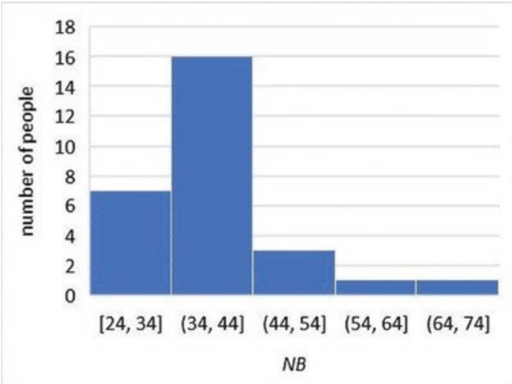


Fig. 18. Histogram for number of brakes processes in task 2

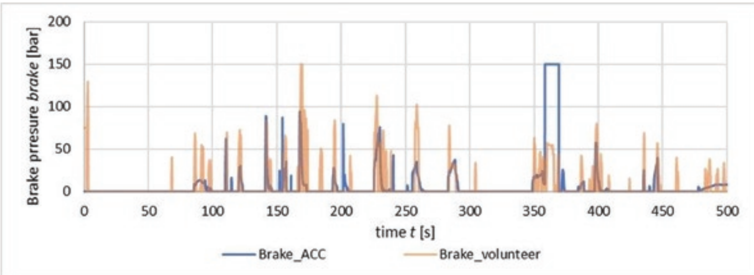


Fig. 19. Function of braking pressure in time for ACC and a volunteer rides in task 2

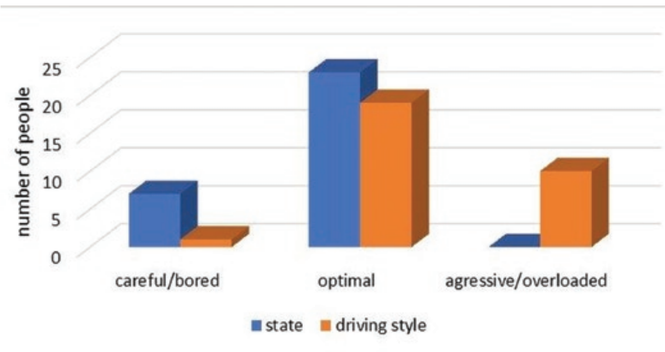


Fig. 20. Subjects' state and driving style

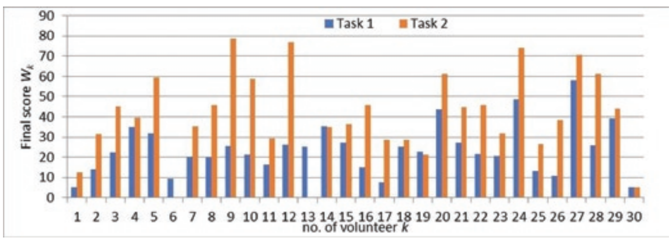


Fig. 21. NASA TLX results

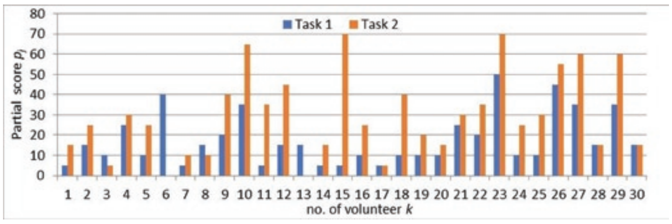


Fig. 22. NASA TLX physical demand partial results

- mental demand,
- physical demand,
- temporal demand,
- performance,
- effort,
- frustration.

Each of the elements was in a scale from 0 - 100. The second part of the form was to select from all parameters pairs which one was more impacting during the task. The detailed questionnaire procedure can be found in [18]. The final, overall result was calculated using the formula (eq. 5):

$$W_k = \sum_{j=1}^{6} \left(F_j \cdot \frac{p_j}{15} \right) \tag{5}$$

where:
- W_k presents a result,
- k – number of volunteers,
- j – parameter,
- F_j – number of parameters chosen for pairs matching,
- p_j – partial score (value for each parameter j).

The overall result that indicates the subject's workload is presented in the Fig. 21.

From the gathered data it was clearly seen that second – city scenario was much more impacting on subjects' physiological state. The overall result shows that 87% subjects indicated that the second scenario was much more demanding. Such a result was in line with the expectation since the second task was more difficult. The detailed result showed that the partial results, the physical demand (Fig. 22) was also one of the most impact factors. Finally, the result of 83% higher scores in second task comparing to the first one, shows that in the second scenario the physical demand was a key factor. That could be explained by a fact that the number of foot movements and actions needed to be more frequent than in the first scenario.

Similar result was in the mental demand were 80% of the subjects indicated the second task more demanding (Fig. 23). Those two parameters impacted the most on the final NASA TLX questionnaire results.

The NASA TLX questionnaire results proved that the second task was much more demanding comparing to the first one. Those results confirmed the results from a simulation analysis where time gap parameter was analyzed. The questionnaire results show how important

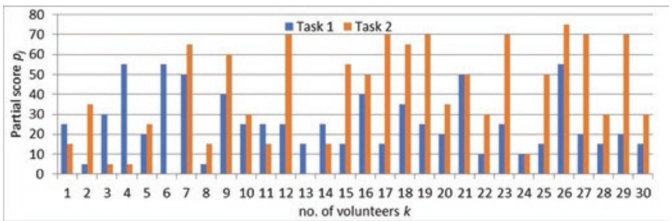


Fig. 23. NASA TLX mental demand partial results

factor is not only the physical but also mental subject's state. Those two parameters impact significantly to the subject's performance.

7. Fuzzy logic driver model

7.1. Description of the model

Car simulator is a useful tool for a research on drivers' behavior. It provides research on many levels – from a road behavior to physical reactions. However, the more accurate environment of the simulator, the more precise research may be performed on it. Because "actor-drivers" used in simulators as other cars are programmed accordingly to one behavior pattern, each of them behaves in the same way. While observing real driving environment wide range of different behaviors may be observed. A driver model was developed during the project to break the monotony of the experiment and make the environment closer to the real one. The model was based on fuzzy logic, and there is a possibility to use it as a "block" which may be added to a working autonomous car driving model.

To increase reality of the driver model there was a necessity of systemization actions of a real driver. For this purpose, driver actions were divided into 3 groups – "reaction", "vision" and "data interpretation". Each of the groups represents different driver actions – "reaction" is connected to a time consumed by taking an action (for example: time of moving feet from the accelerator to the brake pedal). "Vision" is connected to accuracy of interpretation of data collected by the sense of sight, like estimation of the distance to the next car. The last group is responsible for the influence of data interpretation time, such as road signs recognition, or car to driver indicators. Moreover, drivers were divided by type (careful, optimal and aggressive) and by workload level (bored, optimal and overloaded).

The model input was:

- driver type,
- level of workload,
- value read from the sensor.

Additionally, as an input there was also a random number, which meaning will be explained in a further part of the article. Based on a previously selected membership functions and conditional statements, the model chose whether the driver operation will be weakened, and if so – to what extent. For each of the action groups and for each of the driver types and workload levels, the parameters were chosen. These parameters characterized efficiency of the corresponding action group (Tab. 3). There were three levels - low, middle or high. Low mean, that value read from the sensor will be modified in the range of +-30%, middle – the modification will be in the range 10% and high-level mean, that there will be no modification. The modified (or not-modified) value was an output value from the model. In this way, the perfect readings from the sensor were blurred, similar to the real driver estimations. Furthermore, when analyzing charts from the car tracking experiments, there may be noticed seemingly a random inaccuracy which characterizes real drivers. Therefore, it was decided to add the random parameter to the fuzzy driver model, which will be responsible for the level of blurring of the modified value (in a previously selected range). Moreover, there was a distinguish between an aggressive and careful driver in a different probability of choosing modified parameters value. Values of actions based on vision for the aggressive driver were more likely to be read as lower than the precise value read from the sensor, and the same values for a careful driver were more likely to be read as higher. More precise description of the model can be found in [17].

Table 3. Fuzzy parameters input / output relation

Input signals level			Output signals level		
Behavior	Workload		Vision	Data Int.	Reaction Time
Careful	Low		Medium	Low	Middle
	Optimal		Medium	Medium	Middle
	High		Medium	Low	Long
Normal	Low		Medium	Medium	Short
	Optimal		Perfect	Perfect	Short
	High		Medium	Medium	Middle
Aggressive	Low		Medium	Low	Short
	Optimal		Perfect	Medium	Short
	High		Low	Low	Short

To make explanations clearer, an example is presented. Consider careful, bored (with low workload level) driver. Fuzzy logic model based on relations (rules base) from Tab. 3. used a conditional statement: "If the driver is careful and bored, the values of vision, data interpretation and reaction time are respectively: medium, low, medium". Exemplary input parameter – own speed value. According to model assumptions, own speed value reading is associated with "vision". The "vision" level is "medium" so range of blurring is equal to the precise value +-10%. Then the random number is drawn, and based on it, the modified value of own speed is collected (with higher probability of choosing a value higher than the input one).

7.2. Experiment with a fuzzy driver model

Experiment with a fuzzy driver was conducted for extra-urban scenario. Detailed description of the analyses for distance parameter is presented below.

To simulate group of fuzzy drivers' rides SAE10 filter was used. Two extreme driver fuzzy models are presented – overloaded aggressive driver (*fuzzy 100_100*), and bored careful one (*fuzzy 1_1*). Filtered results of the fuzzy-driver rides, compared to the corridors based on volunteer rides in Task 1 (Fig. 7) for distance parameter are presented in Fig. 24.

It is clearly visible, that the model of aggressive driver is close to the lower corridor, which refers to the group of people keeping closer distance to the next car. The model of a careful driver is close to the upper corridor – a corridor corresponding to volunteers who prefer to keep a greater distance. In both cases (aggressive as well as careful) their behavior is too strict for the assumed character – aggressive drives too close to the next car and careful one keeps too large distance.

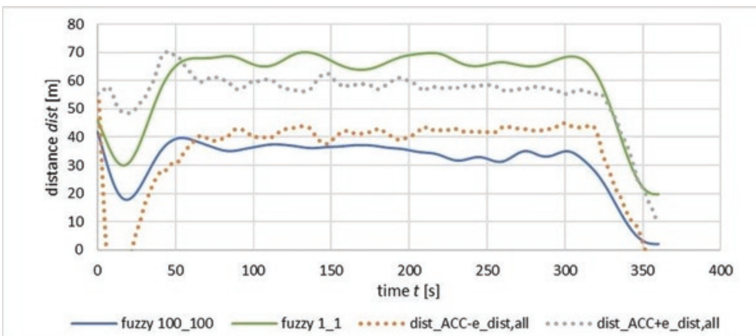


Fig. 24. Fuzzy logic driver model of overloaded aggressive, and bored careful driver, compared to volunteers' corridor

8. Conclusion

Each simulator has its limitations and does not fully reproduce the reality. This simulator, due to the simplifications used, did not perfectly imitate the actual driving, however, it allowed to analyze important issues related to ACC systems and driver behavior.

The experiment and conducted analyses showed that the ACC system worked more smoothly than a human. A human, of course, could not drive as perfectly as ACC system, his reliability was significantly lower. The differences for individual parameters relative to the reference ride were greater for a more complex task. Significant difference in tasks' difficulties were also observed in NASA TLX questionnaires. It can be concluded that the development of ACC systems will improve not only road safety, but also comfort and smoothness of driving as well as reduce travel costs (optimizing fuel consumption).

Research associated with ADAS can also be carried out using model of virtual driver, e.g. using fuzzy logic. However, it seems necessary to validate the results with a real experiment. It was proved that the created fuzzy driver model is correct although it requires some improvements.

Acknowledgement

Presented work has been financed and supported by the project aDrive - PBS3/B6/28/2015 project within Applied Research Program of the National Centre for Research and Development. This project is the first in Poland, which covers issues related to autonomous cars.

References

1. Alicandri E. HYSIM: The next best thing to being on the road. Public Roads 1994; 57(3): 19-23.
2. Bąk J, Bąk-Gajda D. Psychological factors in road safety. Eksploatacja i Niezawodnosc - Maintenance and Reliability 2008; 3(39): 22-29.
3. Beinke R E, Williams J K. Driving simulator. The General Motors Corporation Automotive Safety Seminar 1968. Milford, Michigan. USA.
4 Buckley L, Kaye S-A, Pradhan A K. A qualitative examination of drivers' responses to partially automated vehicles. Transportation Research Part F: Traffic Psychology and Behaviour 2018; 56: 167-175, https://doi.org/10.1016/j.trf.2018.04.012.
5. Drosdol J, Panik F. The Daimler-Benz driving simulator a tool for vehicle development. SAE International Congress and Exposition 1985. SAE Technical Paper 850334, https://doi.org/10.4271/850334.
6. Dziewoński T, Golon K, Jastrzębski D, Kopyt A., Mirosław M, Matyjewski M, Papis M. From aDRIVE Project to INTEGRATED Safety. IRCOBI Conference Proceedings 2017: 34-35. Antwerp, Belgium.
7. Dziewoński T, Jastrzębski D, Mirosław M, Golon K. Simplified car simulator usage in HMI research in chosen active safety systems conditions, for semi-autonomous vehicles. Autobusy - Technika, Eksploatacja, Systemy Transportowe 2016. 12: 1003-1009.
8. Guo C, Sentouh C, Popieul, J-C, Haué J-B, Langlois S, Loeillet J-J, Soualmi B, Nguyen That T. Cooperation between driver and automated driving system: Implementation and evaluation. Transportation Research Part F: Traffic Psychology and Behaviour 2019; 61: 314-325, https://doi.org/10.1016/j.trf.2017.04.006.
9. Hahn W, Käding W. The Daimler-Benz driving simulator - presentation of selected experiments, SAE International Congress and Exposition 1988, SAE Technical Paper 880058, https://doi.org/10.4271/850334.
10. Higashimata A, Adachi K, Hashizume T, Tange S. Design of a headway distance control system for ACC. JSAE Review 2001. 22 (1): 15 -22, https://doi.org/10.1016/S0389-4304(00)00091-6.
11. ISO 15622:2010. Intelligent transport systems - Adaptive Cruise Control systems - Performance requirements and test procedures.
12. ISO 22178:2009. Intelligent transport systems - Low speed following (LSF) systems Performance requirements and test procedures.
13. ISO 22179:2009. Intelligent transport systems - Full speed range adaptive cruise control (FSRA) systems - Performance requirements and test procedures.
14. ISO 17361:2017. Intelligent transport systems - Lane departure warning systems - Performance requirements and test procedures.
15. Jastrzębski D, Kopyt A, Golon K, Mirosław M, Dziewoński T. Fuzzy logic as a model of an actor-driver in simulator scenarios. IRCOBI Conference Proceedings 2017: 595-596. Antwerp, Belgium.
16. Käding W. The advanced Daimler-Benz driving simulator. International Congress & Exposition 1995. SAE Technical Paper 950175, https://doi.org/10.4271/950175.
17. Kopyt A, Dziewoński T, Jastrzębski D, Golon K, Mirosław M. Modeling of a Human Driver for a Car Driving Simulator. Conference Proceedings of the 50th Annual Simulation Symposium SpringSim 2017. Virginia, USA, https://doi.org/10.22360/ springsim.2017.anss.005.
18. Kopyt A, Biernacki M, Piotrowski M. The Study on the Mental Stress Impact on Pilots on the PZL SW-4 Flight Simulator, Transactions of the Institute of Aviation 2014; 32 (3): 26-34, https://doi.org/10.5604/05096669.1130243.
19. Lincke W, Richter B, Schmidt R. Simulation and Measurement of Driver Vehicle Handling Performance. National Automobile Engineering Meeting 1973. SAE Technical Paper 730489, https://doi.org/10.4271/730489.
20. Mirosław M, Golon K, Dziewoński T, Jastrzębski D. ADAS functionalities based on DARPA Urban Challenge championship. Autobusy - Technika, Eksploatacja, Systemy Transportowe 2016; 12: 333-338.
21. Nordmark S, Lidström M, Palmkvist G. A moving base driving simulator with wide angle vision system, 64th Annual Meeting, Transportation Research Board 1985, Washington, https://doi.org/10.4271/845100.
22. Nordmark S. VTI driving simulator. Mathematical model of a four-wheeled vehicle for simulation in real time, Swedish Road and Traffic Institute 1984. VTI Rapport 267A.
23. Nordmark S. The new Trygg Hansa truckdriving simulator: an advanced tool for research and training, Swedish Road and Transport Research Institute, VTI Reprint 187. Proceedings of the International Symposium on Advanced Vehicle Control 1992 (AVEC '92), Japan, Yokohama.
24. Papis M, Dziewoński T, Matyjewski M. Preliminary assessment of the advanced driver assistance systems efficiency from the safety point of view. Autobusy - Technika, Eksploatacja, Systemy Transportowe 2017; 6: 371-375.
25. Papis M, Jastrzębski D, Mirosław M, Kopyt A, Dziewoński T, Matyjewski M. Opracowanie testów symulatorowych w scenariuszach systemu ACC na stanowisku symulatora pojazdu osobowego. Autobusy - Technika, Eksploatacja, Systemy Transportowe 2018; 4: 75-81, https://doi.org/10.24136/atest.2018.024.

26. Papis M, Matyjewski M. Assessment of the influence of the advanced emergency braking systems on pedestrian safety. The Archives of Automotive Engineering - Archiwum Motoryzacji 2017; 77(3): 97-109, http://dx.doi.org/10.14669/ AM.VOL.77.ART7.
27. Perz R, Matyjewski M. Risk of experimental failure - analysis of crash test reliability, Journal of KONBiN 2014; 29 (1): 41-48, https://doi.org/10.2478/jok-2014-0005.
28. Stall D A, Bourne S. The national advanced driving simulator: potential applications to ITS and AHS research. Proceedings of the 1996 Annual Meeting of ITS America 1996. Houston, TX, https://doi.org/10.1037/e533362008-001.
29. Viktorová L, Šucha M. Learning about advanced driver assistance systems - The case of ACC and FCW in a sample of Czech drivers. Transportation Research Part F: Traffic Psychology and Behaviour 2018, https://doi.org/10.1016/j.trf.2018.05.032.
30. Weir D H, Bourne S M. An overview of the DRI driving simulator. International Congress & Exposition 1995. SAE Technical Paper 950173, https://doi.org/10.4271/950173.
31. Wierwille W W. Driving simulator design for realistic handling. Proceedings of the Third International Conference on Vehicle System Dynamics 1975, Swets and Zeitlinger, Amsterdam.
32. Wojcik CK, Hulbert S F. The driving simulator - a research tool. American Society of Mechanical Engineers 1965, Paper 65-WA/HUF-13.
33. Zöller I, Abendroth B, Bruder R. Driver behaviour validity in driving simulators - Analysis of the moment of initiation of braking at urban intersections. Transportation Research Part F: Traffic Psychology and Behaviour 2019; 61: 120-130, https://doi.org/10.1016/j.trf.2017.09.008.
34. [dataset] Główny Urząd Statystyczny (Central Statistical Office). Ludność. Stan i struktura oraz ruch naturalny w przekroju terytorialnym (31.12.2016 r.) - tablice. 2017, (http://stat.gov.pl/download/gfx/portalinformacyjny/pl/defaultaktualnosci/5468/6/21/1/stan_i_struktura_ludno_oraz_ruch_naturalny_w_przekroju_teryt_stan-na-31-12-2016_-_tablice.zip/ Accessed 3 March 2019).
35. [dataset] Omyła - Rudzka M. CBOS (Public Opinion Research Center). Komunikat z badań nr 86/2017. Styl jazdy polskich kierowców. 2017. (https://cbos.pl/SPISKOM.POL/2017/K_086_17.PDF Accessed 3 March 2019).
36. http://www.nads-sc.uiowa.edu/ Accessed 3 March 2019.
37. https://humansystems.arc.nasa.gov/groups/tlx/ Accessed 3 March 2019.
38. https://playseat.com.pl/ Accessed 4 July 2017

Mateusz PAPIS
Dominik JASTRZĘBSKI
Antoni KOPYT
Marek MATYJEWSKI
Marcin MIROSŁAW
Institute of Aeronautics and Applied Mechanics
Faculty of Power and Aeronautical Engineering
Warsaw University of Technology
ul. 24 Nowowiejska, 00-665 Warsaw, Poland

E-mails: mpapis@meil.pw.edu.pl, djastrzebski@meil.pw.edu.pl, akopyt@meil.pw.edu.pl, mmatyjew@meil.pw.edu.pl, mmiroslaw@meil.pw.edu.pl