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Oleksii Prasolenko, Vitalii Chumachenko
O.M.Beketov National University of Urban Economy in Kharkiv
17, Marshal Bazhanov Str., Kharkiv, 61002, Ukraine

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REGULARITIES OF THE TRAFFIC LANE CHANGE BY THE DRIVER WHEN INTERACTING WITH CAR-OBSTACLE

Summary. *The paper presents the results of experimental studies of drivers` behavior when interacting with obstacles caused by parked vehicles. Today, parking cars on two-lane streets is a significant problem for drivers while driving as it creates obstacles. Drivers need to spot a parked car in time and perform a lane change maneuver. It affects the trajectories of vehicles and the functional state of the driver. The driver needs a certain amount of time to maneuver, which consists of the reaction time, the decision to change the lane, and the execution of the action. It complicates traffic conditions for the driver and creates danger for driving. If the driver does not receive information about the parking location on the street with high-speed traffic in time, the probability of danger increases significantly. In addition, drivers try to change the traffic lane, which is further occupied by parking, in advance to reduce the impact of parking on the functional state of their bodies. There is also a deviation in the cross-section of the street when the speed of movement increases relative to the parked car, which finally indicates a change in the position in the traffic lane. It was established that drivers individually choose the trajectories of changing the traffic lane by the speed of movement. In addition, each driver subjectively decides to start changing the traffic lane at his discretion when an obstacle occurs at a certain distance. Angular velocity was used as an indicator of the probability of finding an obstacle object in a dangerous state. Angular speed is the main parameter in the orientation of the driver and signals the danger. When the angular velocity was 0.015–0.03 rad/c, drivers tried to complete the maneuver and leave a certain distance from the obstacle (safety gap). It indicates some interval of angular velocity in relation to the perception of an obstacle object in space and the sense of danger. The resulting patterns of changing lanes by drivers allow for determining the safe distance to parking and ensuring traffic safety by using appropriate markings and road signs.*

Key words: *parking, driver’s reaction time, angular velocity, braking distance, road safety, driver's field of vision, driver’s functional state.*

1. INTRODUCTION

According to statistics, about 60–70 % of road accidents occur due to wrong actions of the driver. Studies indicate that the problem of traffic safety is related to human factors [1–22]. The question of patterns of changes in the characteristics of the driver's perception and processing of information are relevant nowadays as they determine the reliability of the driver's activity. Driver's mistakes can become the causes of conflict situations. It should be noted that conflict situations are characterized not only by the occurrence of longitudinal and transverse accelerations beyond the critical limits but also by the occurrence of shifts in the driver's functional state. The danger is caused by the appearance of some object from the traffic environment in the driver's field of vision. It requires the driver to take actions aimed at ensuring traffic safety. At the same time, the object of the traffic environment can be in two states – safe and dangerous. In dense traffic, the driver spends the longest time on fixation the cars in front and thus tries to maintain the distance, which is a traffic safety parameter. Oncoming traffic flow and its characteristics also affect the distribution of fixations relative to the depth of the vision field. In intensive traffic, the driver spends more time perceiving oncoming cars and controls some “traffic corridor”, which occurs between oncoming traffic and passing traffic. The driver constantly monitors this corridor and pays maximum attention to all cars whose speeds and trajectories cause him a sense of danger. Changing lanes is also a complex and important behavior on the road. Frequent lane changes can cause serious traffic safety problems, especially on a two-lane road with parked vehicles. The indicator of danger, in this case is the angular speed of the obstacle objects relative to the driver's trajectory and the safe distance. The paper presents the regularities of the lane change when the car interacts with an obstacle located on the right lane in the direction of travel.

2. RESEARCH STATEMENT

One of the most essential problems for the largest cities is the parking of cars on the road network. On the one hand, the more cars, the more parking spaces are needed, but on the other hand, there is a greater load on the cities’ road network and the emotional state of drivers. Parking cars on the roadway create certain inconveniences for drivers, takes up space for traffic flows, obstructs the visibility of pedestrians and generally reduces the efficiency and safety of road traffic. A study of parking is carried out for various purposes – the impact on road capacity, the rational determination of the number of parking spaces, the impact on the speed of traffic flow and road safety. However, there are questions about the patterns of drivers’ behavior when interacting with parked cars, which can be considered obstacles. Parking should be arranged considering the psychophysiological features of visual perception and the driver’s reaction time.

3. RELEVANCE OF THE STUDY

The study of regularities of drivers’ behavior with parked cars has not been studied much. There is no answer to the question under which parameters of visual perception and reaction time it is advisable to organize parking, and what is the safe distance required for maneuvering other road users in case of arranging parking on the carriageway of multi-lane city streets. It is also not known how parking affects the trajectories and safe distances in the longitudinal direction of traffic and the streets cross-section in the direction of the position of the parked car. Therefore, the issue of studying the patterns of driver behavior as a result of changing lanes when interacting with cars-obstacles is relevant.

4. AIM AND TASKS OF THE STUDY

The purpose of this study is to determine the impact of car parking on drivers' behavior patterns when changing lanes.

The following tasks were formulated to achieve the goal of the study:

- analyze the factors affecting the drivers’ behavior when changing lanes;
- conduct experimental studies of the drivers’ behavior when changing lanes as a result of interaction with a parked car as an obstacle;
- investigate the regularities of the characteristics of changing traffic lanes and determine the parameters of the interaction between the driver and the obstacle;
- perform modeling of the probability of finding an obstacle in a dangerous state for the driver and a safe distance for performing the maneuver, taking into account the parameters of the movement and the psychophysiological features of the driver's field of perception.

This study uses the methods of researching car movement parameters based on the GPS system, parameters of the driver's sight, and reaction time using the eye-tracking technology.

5. ANALYSIS OF RECENT RESEARCH AND PUBLICATIONS

Changing the traffic lane is one of the most common actions during driving [1–22]. The process of changing the traffic lane by the driver can be divided into three stages: perception of information, the decision to change the traffic lane, and execution of the action. Many factors influence the decision to change lanes when obstacles occur. For example, the paper [1] examines environmental factors affecting the results of drivers' actions. The greater the relative speed and distance to the obstacle, the more drivers can underestimate the distance. Therefore, drivers should be reminded that in such cases, it is necessary to pay special attention to safety when changing lanes. Today, it is essential to use GPS systems to determine movement parameters [1, 2]. Such systems can provide accurate data on the position of vehicles in space, speed, acceleration, travel path, lane change angles, etc. Thus, in the paper, the authors analyze the angles of change in the trajectories of vehicles at different speeds and the time of execution of maneuvers [3, 4]. Road conditions, the density of the traffic flow, the direction of the lane change and other vehicles that prevent the performance of the maneuver affect the duration of the lane change. The results indicate that the time needed for the lane change for passenger cars and trucks varies significantly and can last between three and 5 seconds on average. However, for both types of vehicles, the duration of the lane change is longer when the maneuver is riskier or when there are obstacles from other vehicles [5–8]. Other studies indicate the existence of a relationship between the functional state of the driver and the characteristics of the performance of maneuvers. That is, drivers choose to change the traffic lane in advance according to their condition, which indicates the relationship between the driver's reaction time and his behavior when there is a need to change the traffic lane [9–12]. Issues of traffic safety and the probability of an accident when changing lanes are considered in papers [13–15]. The main factors in road accidents are the distraction of the driver, incorrect choice of distance, incorrect estimation of the distance to the obstacle, complicated road conditions, insufficient visibility, lighting, etc. All this points to the problem of the human factor in traffic. In [16], the authors analyze the position functions of potential corner collision points from the sides, front, and rear of vehicles changing lanes and vehicles encountering obstacles.

Lane change has a significant impact on traffic flow characteristics. However, lane change models used in microscopic traffic simulation models emphasize the decision-making aspects of the problem but generally neglect the detailed simulation of the lane change action and its duration [17, 18]. Other studies have researched the number of traffic lane changes under different traffic flow parameters for capacity analysis [19]. However, these studies lacked data to identify and quantify significant traffic parameters that affect lane changing using real-world data, considering lane changing as one of the essential parameters of stable traffic and parking safety.

Microscopic simulation models are used in safety performance evaluation and accident prediction more often. These models need to be calibrated based on real-life traffic conditions before use. The main purpose of calibration is to make sure that the parameters entered into the simulation model provide the best performance indicators for traffic [20]. Due to micro modeling, it is possible to determine the parameters of the lane change, but the parameters of a human factor, which affects the subjective distance to the obstacle, can be obtained only experimentally.

Researches [21, 22] indicate that the change in movement parameters can be considered due to the influence of angular velocity on the driver and his subsequent actions regarding the choice of movement trajectories, taking into account the probability of finding an environmental object in a dangerous state. At the same time, angular speed can be considered a danger factor for the driver of some obstacles that appear in the field of vision.

When perceiving objects in the road environment, their angular velocities are transformed into visible ones. With the help of apparent speeds, the driver perceives the absolute distance of moving objects, and with the help of differences or changes in apparent velocity– differences or changes in absolute distances. The conditional-reflex relationship between apparent speed and absolute distance is formed throughout life because of learning orientation in space. Moving away or approaching the object of the environment to the line of the driver's direction of movement intensifies the effect of angular velocity.

A considerable convergence of the object to the driver can lead to a collision. Therefore, the small distance of the object is perceived as a danger for further movement. The connection between the remoteness of an object and its danger is formed throughout a person's life. Therefore, the angular speed of the object and its position relative to the direction of the driver's movement can be considered conditional stimuli that inform the driver about the distance of the object and its danger for further movement.

6. PRESENTATION OF BASIC MATERIAL

Experimental studies on the example of the streets of Kharkiv were carried out in the summer of 2021. A laboratory car with a “racelogic” Videovbox traffic parameters registration system and an obstacle car, parked on the roadway in the extreme right lane parallel, were used for this purpose. The experiment was considered completed without other obstacles from road users. It is necessary so that there is no influence on the set speed and trajectory of the driver during interaction with the obstacle. At the same time, a set of parameters was recorded: the speed distribution, longitudinal acceleration, transverse acceleration and the distance of the car's deviation from the obstacle in the cross-section of the street. All these data were obtained during the movement of the laboratory car. Analysis of the results was performed using the VBOX Test Suite software (Fig. 1).

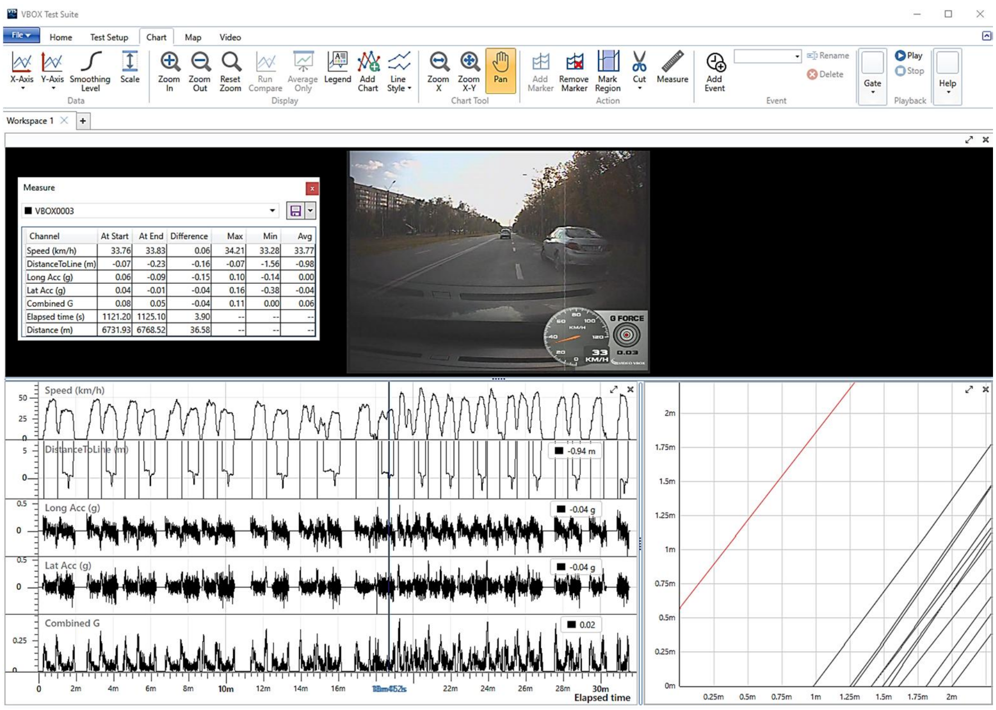

Fig. 1. Analysis window of vehicle movement parameters during interaction with an obstacle

The experiment was performed as follows. The driver was asked to move at a speed of 20, 30, 40, 50, 60 km/h. When the driver subjectively believed that he needed to start changing the traffic lane before the obstacle car from the right to the left, he made his own decision. The number of runs for each speed range was 10 units. Traffic parameters when interacting with an obstacle car are as follows. One – the zone of the beginning of the traffic lane change from the right to the left; 2 – the subjective safe distance to the obstacle vehicle, which the driver leaves after performing a lane change maneuver; 3 – fixation of the position of the car relative to the obstacle in the cross-section of the street; 4 – return of the driver to the original right lane.

The possible braking distance of the car was analyzed at the first stage of the study to assess the actions of the driver during maneuvering. The braking distance was determined by the formula:

$$S_{br} = \frac{V^2}{2 \cdot \phi_{ad} \cdot j}, \tag{1}$$

where S_{br} – braking distance, m; V – speed of movement, m/s; ϕ_{ad} – adhesion coefficient; j – average relative deceleration during braking, m/s^2.

The results of the calculations of the braking distance and the analysis of the distance left by the driver to the obstacle after changing the lane (subjective safety gap of the driver in the longitudinal direction of movement) are presented in Fig. 2. It can be seen from the graphs that when the speed of movement increases, the difference between the possible braking distance and the distance left by the driver subjectively when sensing danger increases rapidly. That is, the question arises, how does the driver feel this distance? What factors influence such a choice? At the same time, the distance required to change the traffic lane (S_1) also naturally increases with increasing speed (Fig. 3).

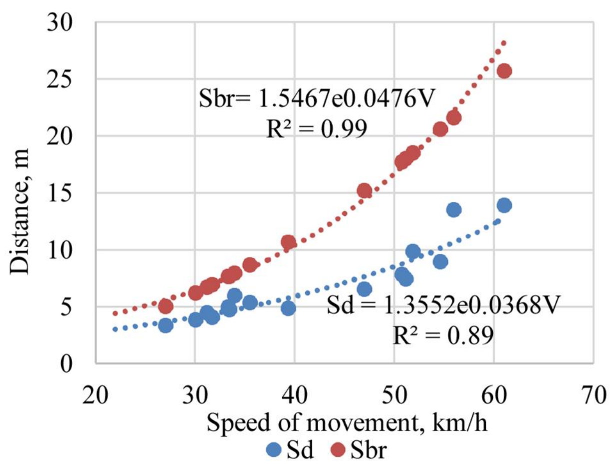

Fig. 2. Parameters of the driver's subjective safety gap in the longitudinal direction of movement (S_d) and braking distance (S_{br})

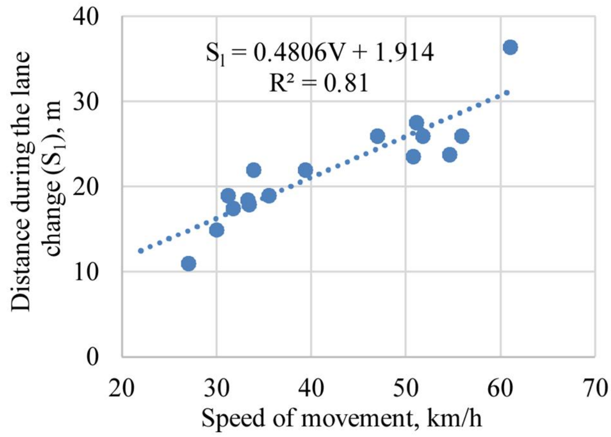

Fig. 3. Dependence of the distance during the lane change (S_1) from the primary speed

The driver's subjective feeling of danger during the maneuver can be defined as the difference between the distance to the obstacle, which the driver subjectively feels while trying to perform the maneuver and eliminate the impact of the obstacle on his functional state, and the actual braking distance (1):

$$\Delta S = S_d - S_{br}, \tag{2}$$

where S_{br} – braking distance, m; S_d – the distance left by the driver to the obstacle after changing lanes, m. (the driver's subjective safety gap in the longitudinal direction of movement).

The results of the difference between the actual braking distance and the distance to the obstacle (ΔS), subjectively felt by the driver, are presented in Fig. 4. The parameter (ΔS) has a linear dependence on the speed of movement, and therefore the parameters of the braking distance and the distance to the obstacle left by the driver have a dependent relationship. However, a rapid increase in the difference (ΔS) with an increase in the speed of movement indicates an error in the driver's sense of danger, i.e. the results of the activity go beyond certain limits, which are limited by the psychophysiological properties of the driver's field of perception.

It is known that angular velocity signals the presence of objects in space and their possible danger to the driver. Therefore, let us analyze the ratio of the initial speed when changing the traffic lane and the subjective safety gap in the cross-section of the street, to which the driver will deviate when performing the maneuver. To do this, we will use the scheme of the location of vehicles during interaction and mark the main parameters of the movement to determine the angular velocity relative to the object of the obstacle (Fig. 5).

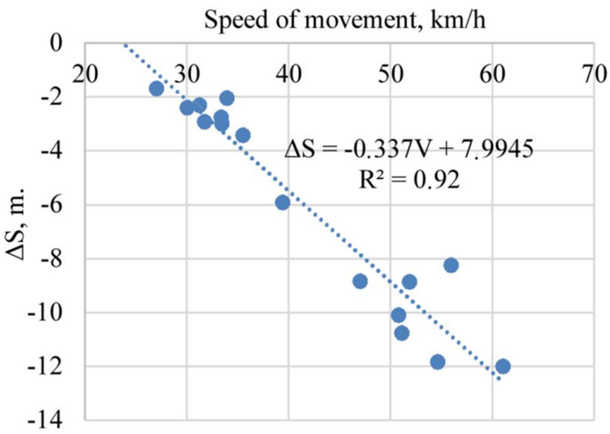

Fig. 4. The difference in the driver's subjective safety gap in the longitudinal direction of movement (S_d) and braking distance (S_{br})

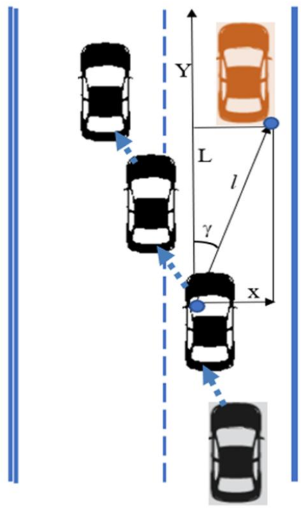

Fig. 5. Scheme of location of vehicles for determining the angular speed

The angular speed of movement was calculated according to the formula [22]:

$$\omega = \frac{V_a \cdot sin\gamma}{l}, \tag{3}$$

where ω – the angular velocity of the object-obstacle relative to the driver, rad/s; V_a – linear speed of movement of the mobile laboratory, m/s; l – distance from the driver to the center of gravity of the contour of object-obstacle, m; γ – the angle between the direction of movement of the mobile laboratory and the line that connects the driver with the center of gravity of the contour of the object-obstacle, degrees.

The distance from the driver to the center of gravity of the contour of the object-obstacle is determined by the formula:

$$l = \sqrt{L^2 + X^2}, \tag{4}$$

where L – distance from the driver to the obstacle in the direction of the car, m; X – lateral distance perpendicularly from the driver to the obstacle, m (safety gap in the cross-section of the street).

The safety gap in the cross-section of the street was calculated according to the formula:

$$X = x - (x_a + x_p), \tag{5}$$

where X – safety gap in the cross-section of the street, m; x – distance from the driver to the center of gravity of the visible contour of the obstacle in the cross-section of the street, m; x_a – the distance from the driver to the side of the running laboratory in the cross-section of the street in the direction of the obstacle's position; x_p – half the size of the obstacle in the cross–section of the street.

The change in the angular speed of movement relative to the object of the obstacle when changing the traffic lane is presented in Fig. 6.

According to (Fig. 6), we can see that the driver keeps the angular speed in the range of 0.015 to 0.03 rad/s and performs the maneuver only under such conditions. That is, the driver's sense of danger prompts him to take actions to maneuver only under such conditions. At the same time, it is known that the largest value of the probability of finding an obstacle in a dangerous state is at an angular speed of more than 0.06 rad/s. [22].

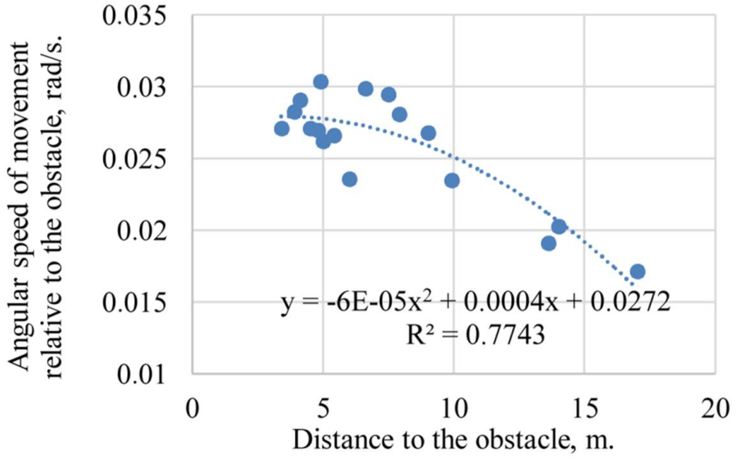

Fig. 6. Dependence of the change in angular velocity on the distance to the obstacle

The probability of finding an obstacle in a dangerous state for the driver was determined by formulas (6)–(9) [21]:

$$P_r = 1 - e^{-\lambda(\omega - \omega_o)}, \tag{6}$$

where P_r – the probability of finding an obstacle in a dangerous condition for the driver; ω_0 – lower absolute threshold of angular velocity; λ – degree indicator.

The degree indicator is determined by the formula:

$$\lambda = (0.29586 + 0.0047249 \cdot L - 0.00010148 \cdot L^2) \cdot \omega_O^{-0.861}, \tag{7}$$

The lower absolute threshold of angular velocity is determined by the formula:

$$\begin{aligned} \omega_0 &= (0.019 - 0.00575757 \cdot D_c) + y0.00829616 \cdot D_c^{-0,4056459} && \text{at } D_c < 3.4 \\ \omega_0 &= y0.00829616 \cdot D_c^{-0.4056459} && \text{at } D_c \geq 3.4 \end{aligned} \tag{8}$$

A subjective impact factor can be used to quantitatively characterize the type of obstacle object:

$$D_c = \frac{G_P \cdot F_a}{G_a \cdot F_P}, \tag{9}$$

where G_P, G_a – the weight of the obstacle and the mobile laboratory, respectively; F_P, F_a – estimated areas of the cross-section of the obstacle and the mobile laboratory, respectively.

As result of modeling the influence of the obstacle on the parameters of the lane change, the following two-factor model of the dependence of the probability of a parked vehicle being in a dangerous state (obstacle object) on the location of the obstacle in the cross-section of the street and the speed of movement was obtained:

$$P = 0.3382 \cdot ln(V) - 0.2466 \cdot X^2 + 0.27864 \cdot X \text{ -0.51}, \tag{10}$$

where P – the probability of finding an obstacle in a dangerous state for a driver performing a lane change maneuver; X – lateral distance to the obstacle (safety gap in the transverse direction). The model has a correlation coefficient of 0.99 and an approximation error of 2.26 %.

The graphic representation of the model in the form of a surface is shown in Fig. 7. Model (10) can be used in the organization of a safe parking location by providing the appropriate sizes of parking spaces, both on the roadway with the use of road markings and in pockets at different angles or parallel to the sidewalk. It should be noted that the obtained data on the probability of finding an obstacle in a dangerous state are conditional and signal the driver's sense of danger. Therefore, in the calculations, it is advisable to consider the entropy of the driver's perception field, taking into account the obtained probabilities. Only in this case these indicators will allow taking into account all objects and traffic parameters relative to the driver's field of perception.

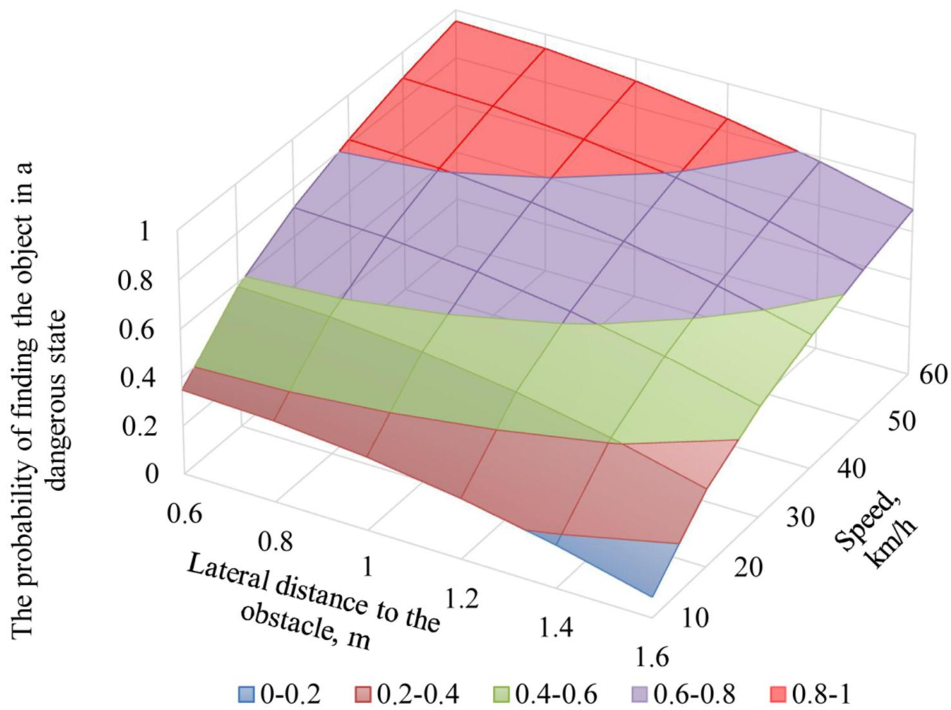

Fig. 7. Probability of finding an object-obstacle in a dangerous state

It is also advisable to consider how the driver's reaction time affects the overall safe distance to the obstacle before the maneuver taking into account the actual parameters of the vehicle movement during the maneuver. It is also necessary to consider all the time components spent on assessing the road situation. The time required to estimate the road situation includes time to recognize the obstacle, transfer the gaze from the object to the rear-view mirrors to ensure a safe change of the traffic lane from right to the left and return to the obstacle by visually searching for it in the field driver's vision.

Studies of the driver's sight were carried out using the eye-tracking technology with the headset of the company “pupil labs”. The table 1 presents the statistically reliable results of the analysis of the parameters of the driver's sight.

Table 1.

Driver sight parameters

Parameter	The time of moving the sight to the left side mirror of the rear view + returning to the dangerous object, s	The time of moving the sight to the interior mirror + returning to the dangerous object, s	The average time of sight fixation in the mirror, s	Number of fixations, units
Intensive attention	0.252+0,302	0.186+0,257	0.198	2
Moderate attention	0.378+0,446	0.219+0,311	0.227	4

It should be noted that the total time for evaluating the road situation when the driver interacts with the obstacle is 1.732 s with moderate attention under the condition that the driver changes his sight in the direction of movement from the central part of the field of vision to the side rearview mirror, taking into account the data of studies of the time spent on the search for visual information by the driver. It is the longest time, so in the future, we will take it into account in the research. In addition, it is necessary to record the driver's vision of the obstacle for 0.3 s to recognize its position. Therefore, the driver's reaction time should be at a value of two s.

The following model was obtained taking into account the driver's reaction time using the obtained relationships of the dependence of the distance during the change of the traffic lane from the initial speed and the subjective safety gap of the driver in the longitudinal direction of movement (Fig. 2–3) (11):

$$S_S = \frac{\mathrm{V}}{3.6} \cdot T + 0.4806 \cdot \mathrm{V} + 1.3552 \cdot \exp\left[0.0368 \cdot \mathrm{V}\right] + 1.914, \tag{11}$$

where S_S – safe distance of the location of the obstacle, m (parked car); T – the time required to assess the road situation, taking into account the parameters of the driver's sight and reaction time, s.

Model (11) has a correlation coefficient of 0.97 and an approximation error of 2.72 %. Next, we will simulate the safe distance of the location of the obstacle. At the same time, we take into account the driver's reaction time in the calculations several times more to ensure traffic safety (Fig. 8).

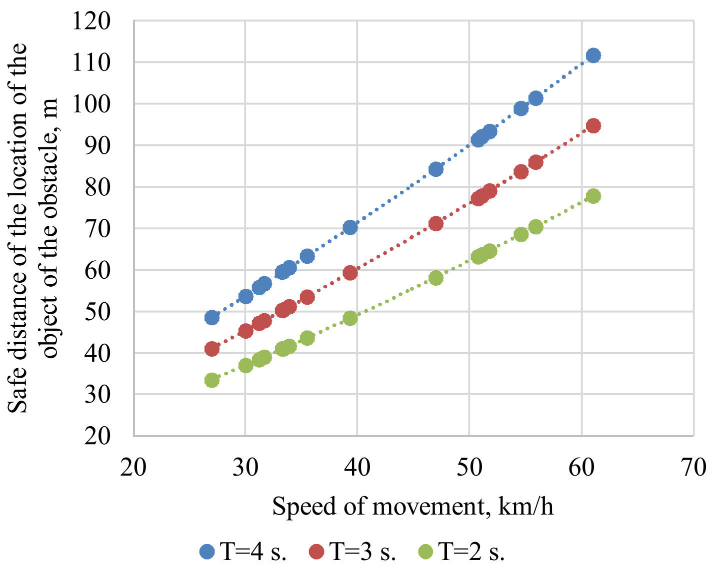

Fig. 8. Dependence of the safe distance of the location of the obstacle on the speed of movement for different values of the driver's reaction time

7. CONCLUSIONS AND FUTURE RESEARCH PERSPECTIVES

Parking cars on the roadway is a modern problem in cities. Vehicles parked on the roadway occupy free space in the traffic lane. This problem has the following consequences: accidents and reducing traffic flow efficiency. The problem of accidents is primarily related to the situation when drivers move in a group mode, the first driver can notice an obstacle in time and change the lane, and the driver behind may not have time to react and collide with a stationary vehicle. Research results show that a safe distance is required to maneuver at a certain speed. This distance consists of the required distance for performing the maneuver when changing the lane before the car, which is an obstacle, and the subjective safe distance to the parked car, which the driver leaves after subconsciously performing the lane change maneuver. Therefore, when organizing parking on the roadway, it is advisable to apply either speed limits or ensure that drivers are informed about the possible traffic lane. As a rule, the driver changes the traffic lane at his own request to avoid a conflict with a parked vehicle in the right lane. The driver needs choosing some time interval for the maneuver if he is in the right lane. Changing the traffic lane requires the driver to concentrate and assess the distance when maneuvering. The total distance for the maneuver depends on the driving speed and the subjective distance that the driver subconsciously leaves to the vehicle when the lane change has occurred. The models obtained can be used to plan information support for drivers, namely in the justification of warning signs and the organization of safe parking. It should be noted that the patterns of drivers' behavior when interacting with an obstacle are subjective in nature. Each driver has own psychophysiological characteristics. The study considered the activities of drivers with 3–5 years of driving experience. According to statistics, these drivers most often get into road accidents. Therefore, in the study, we relied on the results of their activities as the worst.

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ЗАКОНОМІРНОСТІ ЗМІНИ СМУГИ РУХУ ВОДІЄМ ПРИ ВЗАЄМОДІЇ З АВТОМОБІЛЕМ ПЕРЕШКОДОЮ

Анотація. *Представлено результати експериментальних досліджень поводження водіїв під час взаємодії з об'єктами-перешкодами, які зумовлені припаркованими транспортними засобами. На сьогодні паркування автомобілів на двосмугових вулицях є значною проблемою для водіїв під час руху та створює перешкоди. Водіям потрібно вчасно помітити припаркований автомобіль та виконати маневр зміни смуги руху. Все це впливає на траєкторії руху транспортних засобів та функціональний стан водія. Водієві потрібен певний проміжок часу для виконання маневру, який складається з часу реакції, прийняття рішення про зміну смуги руху та виконання дії. Все це ускладнюється умовами руху для водія та створює небезпеку для керування. Якщо водій вчасно не отримає інформацію про розташування паркування на вулиці зі швидкісним рухом, імовірність небезпеки значно підвищується. Крім того, водії для зменшення впливу паркування на функціональний стан організму заздалегідь намагаються змінити смугу руху, яка зайнята попереду паркуванням. Також спостерігається відхилення у поперечному перерізі вулиці за збільшення швидкості руху відносно припаркованого автомобіля, що остаточно вказує на зміну положення на смузі руху. Було встановлено, що водії індивідуально обирають траєкторії зміни смуги руху відповідно до швидкості руху. Крім того, кожен водій на власний розсуд суб'єктивно приймає рішення про початок зміни смуги руху під час виникнення перешкоди на певній відстані. В якості індикатора імовірності знаходження об'єкта перешкоди у небезпечному стані було використано кутову швидкість. Кутова швидкість є основним параметром в орієнтовній діяльності водія та сигналізує про небезпеку. За значень кутової швидкості від 0,015–0,03 рад/с водії намагались завершити маневр та залишити певну відстань до перешкоди (зазор безпеки). Це вказує на певний інтервал кутової швидкості щодо сприйняття об'єкта перешкоди у просторі та відчуття небезпеки. Отримані закономірності зміни смуги руху водіями дозволяють визначити безпечну відстань до паркування та забезпечити безпеку руху шляхом використання відповідної розмітки та дорожніх знаків.*

Ключові слова: *паркування, час реакції водія, кутова швидкість, гальмівний шлях, безпека руху, поле зору водія, функціональний стан водія.*