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DEVELOPMENT OF MODELS FOR ASSESSING A DRIVER'S FAILURE-FREE OPERATION IN A TRANSPORTATION SYSTEM UNDER CONDITIONS OF TRAFFIC CONGESTION

N. Gyulyev
Doctor of Technical Sciences, Associate Professor*
E-mail: ngulev2@gmail.com
V. Voronko
Doctor of Technical Sciences, Professor*
S. Ostashevskyi
Doctor of Technical Sciences, Associate Professor**
D. Ponkratov
PhD, Associate Professor*
S. Psol
PhD, Associate Professor**
I. Bugayov
Assistant*
*Department of Transport Systems and Logistics
O. M. Beketov National University of Urban Economy in Kharkiv
Marshala Bazhanova str., 17, Kharkiv, Ukraine, 61002
**Department of Vehicles and Special Cars
National Academy of the State Border Guard Service of Ukraine named after Bohdan Khmelnytskyi
Shevchenka str., 46, Khmelnytskyi, Ukraine, 28001

Розглядається задача визначення безвідмовності водія в транспортній системі міста з урахуванням заторів. Перебування водія в заторах призводить до зростання його психоемоційної напруженості, підвищенню рівня втоми і, як наслідок, до зниження безвідмовності. Рівень безвідмовності водія безпосередньо впливає на безпеку дорожнього руху. Безвідмовність водія на елементах транспортної системи визначена ймовірністю скоєння дорожньо-транспортної пригоди, яка залежить не тільки від параметрів мережі і транспортних потоків, а насамперед й від часу реакції водія.

Розроблено моделі оцінки безвідмовності водія на ділянках транспортної мережі і в транспортних вузлах з урахуванням заторів руху, які дозволяють оцінити ймовірність скоєння дорожньо-транспортної пригоди для середньостатистичного водія. У цих моделях вплив затору враховується зміною часу реакції водія, яка є функцією зміни рівня його стомлення.

Для визначення у скільки разів ймовірність скоєння дорожньо-транспортної пригоди середньостатистичного водія на ділянках транспортної мережі і в транспортних вузлах з затором вище, ніж ця ж ймовірність на тих же елементах транспортної системи без затору, було розглянуто співвідношення цих ймовірностей.

Визначено адекватність моделей шляхом співставлення відношення ймовірностей скоєння дорожньо-транспортної пригоди з затором на ділянках транспортної мережі і без нього до відповідного відношення кількості дорожньо-транспортних пригод на цих же ділянках транспортної мережі та на перехрестях.

Розроблені моделі оцінки безвідмовності водія на елементах транспортної мережі з урахуванням транспортних заторів дозволяють порівняти і оцінити різні варіанти проектних рішень з підвищення безпеки дорожнього руху

Ключові слова: безвідмовність водія, дорожньо-транспортна пригода, транспортна система, дорожній затор, час реакції

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1. Introduction

The efficiency and failure-free operation of a driver in a transport system depend greatly on specific working conditions under which a driver operates. The parameters of a transportation process, which exist in specific situations, determine these conditions. One such situation is a traffic jam, which arises due to the excess of traffic intensity over the capacity of streets and roads. A traffic jam has a negative impact on the psychophysiology of a driver. It leads to an increase in the level of the driver's fatigue, an increase in response time and an increase in the probability of a traffic accident after leaving a traffic jam [1, 2].

Road safety depends greatly on a driver's failure-free operation as the main link of the system in the transport system in such circumstances.

The driver's reliability is an ability to keep parameters of functioning within the limits ensuring the safety of movement and corresponding modes of movement and conditions of the use of a car [3]. The driver's failure-free operation is a complex capability. One can define it with simpler ones, such as reliability, recoverability, safety, and durability. The driver's failure-free operation is an ability to keep working capacity within the established working hours calculated in hours. The driver's failure-free operation varies throughout a working day in different ways [3].

Safety and reliability of operation of "a driver – a car – a road – an environment" depends on the uninterrupted and high-quality operation of all its components and elements. Failures and accidents occur in this system usually because of the fault of a driver in most cases.

The above allows us to argue that the study of the impact of parameters of a traffic jam on changes in the driver's state is an expedient problem. Its solution affects largely the failure-free operation of a transport system. It follows that it is necessary to investigate how traffic jams affect a functional state and reliability of a driver.

2. Literature review and problem statement

Traffic jams restrict driver's freedom of action significantly and lead to an increase in his emotional state and an increase in fatigue. Authors of paper [4] showed that traffic jams, which affect the mood and actions of a driver directly, became a serious problem at peak hours in most cities in China. The study of a mood and actions of a driver in traffic jams is insufficient currently, so it is necessary to study the relationship between the mood and actions of a driver and traffic jams. We know that drivers perform dangerous maneuvers to change lanes, creating emergencies in traffic jams. The authors did not find any relationship between a change in the stress level and probability of road accidents occurring after a traffic jam in the important studies on the assessment of a driver's state in traffic jams.

Study [5] examines the properties of the emotional state of drivers and their relationship with aggressive driving. The authors carried out studies in five Chinese cities. They interviewed drivers and assessed their state by a custom scale. There was a connection between a high emotional state of a driver with aggressive driving. An analysis of the importance of the factors, which affected emotions, showed that slow driving close to traffic jams is the most negative factor. However, there was no correlation between emotions and driver's reliability.

Authors of work [6] investigated the impact of emotions on the behavior of drivers also. Two groups of drivers experienced conditions, which increased their emotional mood or not in simulated driving situations. Driven by different situations, drivers reported higher increases in angry moods compared to the control group after initial driving, and the increase remained stable during subsequent neutral driving. The authors found that drivers with higher levels of tension needed more time to take corrective action to avoid potential collisions. However, the study did not investigate traffic jams, which are potential sources of worsening of a driver's mood and an increased level of stress.

Paper [7] analyzed a model of traffic jams in the city center at peak hours based on the ideas put forward by William Vickrey. It showed the relationship between speed and traffic density. However, it did not investigate the impact of traffic jams on the driver's state.

Authors of work [8] investigated and showed a mechanism of the formation of traffic jams on China's highways. However, there were no studies related to changes in a driver's state.

Authors of paper [9] carried out a study and found a relationship between the duration of floods due to rainfall in some parts of China and the behavior of drivers, which led to traffic jams. They revealed in a simulation process that the behavior of a driver had a different impact on the formation of traffic jams of different durations. However, there were no studies on the assessment of the impact of traffic jams on the driver's failure-free operation.

Authors of work [10] presented the results of studies aimed at the determination of the dependence of the appearance of traffic jams due to traffic accidents. However, they did not investigate a driver's behavior and reliability and a relationship between traffic jams and the probability of an accident after leaving a traffic jam.

Paper [11] states that traffic jams have a negative effect on the psychophysiological state of a driver and cause deterioration of his functional state and mental disorders. However, the paper does not propose models for changes in the driver's state in traffic jams to evaluate the driver's failure-free operation after a traffic jam.

Work [12] notes that traffic jams are the biggest problems in road traffic. The work considers a driver's model, which predicts traffic jams based on changes in a driver's behavior. A driver does not rely on monitoring of traffic flows in this case. However, the work does not consider how traffic jams affect the driver's state and the probability of an accident after a traffic jam.

Authors of paper [13] showed the negative role of traffic jams in their study. They considered periodic and persistent traffic jams and how they affected changes in speed and loss of time for movement. They transformed the losses into a monetary form as a payment to society for the creation of traffic jams. They did not consider aspects of a negative impact of traffic jams on road safety in the paper.

Authors of paper [14] considered such qualities of a driver as a response time of a driver, work experience, and temperament in their studies. They noted that being in a traffic jam had a negative effect on the psychophysiological qualities of a driver increasing the response time. However, the paper did not assess the driver's failure-free operation after a traffic jam.

Study [15] presented data on the level of stress of a driver depending on traffic conditions and a type of a road. The authors noted that traffic conditions defined as traffic jams also affected the driver's stress level significantly when using a vehicle speed criterion of 40 km/h and a standard speed deviation of 20 km/h. There were no further studies to investigate the impact of a driver's level of tension on the probability of an accident in the study.

Study [16] determined the dynamics of changes in the level of fatigue, which affects road safety, for the average driver in a traffic jam. The authors of the study developed linear and nonlinear models of the impact of traffic jams on the level of fatigue for a driver. The models gave the possibility to assess a driver's state depending on the age and duration of traffic jams. They noted that the level of fatigue of a driver determined by the change in his functional state increased during his time in the traffic jam. However, there were no assessments of the driver's failure-free operation after a traffic jam in the study.

Authors of paper [17] conducted studies related to the formation of traffic jams due to redistribution of passenger traffic from passenger cars to buses and vice versa. On the one hand, they carried out an initial survey to determine the transition from a bus to a car when buses were unavailable. They used it to assess the positive impact of buses on a decrease in the number of traffic jams. On the other hand, they investigated the negative impact of buses, taking into account the impact of bus stops on vehicle traffic. However, there were no further studies to determine the impact of traffic jams on the states of drivers.

Authors of work [18] investigated problems of traffic flow management in traffic jams. They constructed an accident model for traffic flow at random load. They analyzed a critical state of a transport network at a random traffic jam using this model. They proposed a scheme for traffic flow management to maximize throughput. However, they did not consider issues related to a driver's state and his failure-free operation in the work.

Paper [19] considered an impact of road conditions on truck drivers. The authors used a galvanic skin reaction method and an electrocardiogram method based on the assessment of heart rate variability to assess a driver's state. The obtained results showed that it was possible to assess a degree of danger in a real driving situation by changing the functional state of a driver as a response to a change in the limiting characteristics of a driver's state. The authors did not consider changing the state of a driver under conditions of traffic jams.

Authors of work [20] identified a connection between the driver's distraction and response time. The analysis showed that the duration of a driver's distraction was the main direct cause of an increase in response time, and other factors had indirect impacts. The response time of a driver is an important characteristic. Road safety depends on it. However, the study did not investigate a change in the response time, which affects the failure-free operation of a driver, in traffic jams.

Paper [21] considered a question of an impact of the response time of a driver on the probability of an accident and the probability of an accident on elements of a transport network. However, the authors did not provide a model for changing the driver's failure-free operation due to traffic jams.

Authors of work [22] considered the issues related to the impact of traffic speed on the occurrence of an accident. They showed that drivers, who exceeded the speed limit, had a longer response time. They proposed recommendations for changing the estimated response time of drivers when carrying out road accident examinations. However, they did not define causes, which led to an increase in the driver's response time. They did not investigate changes in the response time in traffic jams, which may cause these changes.

Authors of work [23] proposed a dynamic model and a stochastic model of driver's perception based on the quantum theory of optical flow to investigate a relationship between the uncertainty of perceived relative speed and response time during the passage of a car. In particular, the proposed model assumed that the speed perceived by a driver and the response time varied over time. They are uncertain. However, the study did not investigate the corresponding relationships under conditions of traffic jams.

Authors of study [24] established a relationship between the response time of a driver and driving conditions. They found that the response time of a driver is closely connected over time, especially in the delay phase. It was possible to forecast a time interval if they knew the response time and the initial time shift. However, the study did not define a relationship between the driver's response time and the probability of an accident due to traffic jams.

An analysis of literature data [4–24] shows that there is no full study of traffic jams at present. All studies are fragmented. The studies concerned either a driver alone or a change in characteristics of the traffic flow without taking into account a human factor and its impact on road safety.

Therefore, we need a systematic approach in the study of traffic jams and their consequences, taking into account changes in the functional state of a driver. It is necessary to develop models for assessment of the driver's failure-free operation in a transport system, taking into consideration traffic jams, in order to predict the development of a traffic situation after them and to improve traffic safety.

3. The aim and objectives of the study

The objective of the study is to develop models for the assessment of the driver's failure-free operation in the city transportation system taking into account traffic jams.

We set the following tasks to achieve the objective:

– assessment of the probability of an accident with an individual traffic participant taking into account a traffic jam;

– selection of a structure of models, which describe the impact of traffic jams on the driver's failure-free operation on elements of a transport system;

– identification of patterns of changes in the probability of a traffic accident, taking into consideration traffic jams;

– determination of the adequacy of the developed models.

4. Assessment of the driver's failure-free operation in a transport system taking into account traffic jams

4. 1. Assessment of the probability of an accident with an individual traffic participant

One can interpret reliability [3] as the reliable operation of a system, and as fail-safety or probability of an accident within the framework of this study. The lower the probability, the greater the reliability.

An analysis of methods for determination of the level of accident rate on sections of a transport network showed that their application does not make it possible to assess the possible probability of an accident with an individual traffic participant quantitatively. The available methods for assessment of the level of the accident rate at intersections of streets and roads can help to determine the probability of an accident for an individual traffic participant in case of their refinement.

We developed a mathematical model for determination of the probability of an accident on sections of a transport network with an individual traffic participant based on [25]:

$$P_1 = \frac{\left(\vec{F}^{0.75} + \vec{F}^{0.35}\right) \cdot \vec{F}^{1.25} \cdot l \cdot k_a \cdot 2 \cdot 10^{-10}}{H}, \tag{1}$$

where k_a is the final accident rate; l is the length of a road section, km; $\vec{F}$, $\overleftarrow{F}$ is the intensity of traffic of passing and oncoming flows of vehicles, respectively, cars/h; H is the width of a roadway, m.

We improved the mathematical model for determining the probability of an accident in transport nodal points with an individual traffic participant [25]:

$$P_2 = \frac{50 \cdot k_i \cdot M_i \cdot N_i}{k_p \cdot 10^{14}} \cdot \frac{N_{\tau i} + M_{\tau i}}{N_i + M_i}, \tag{2}$$

where k_i is the coefficient of complexity of a conflict point; k_p is the coefficient of annual unevenness of traffic intensity; M_i, N_i is the total traffic intensities on intersecting roads, vehicles/day; $M_{\tau i}$, $N_{\tau i}$ are the intensities of flows crossing at a conflict point during the passage of a vehicle through the intersection, vehicles/day.

It is necessary to continue refinement of the models (1) and (2) to determine the probability of an accident for an individual traffic participant in the presence of traffic jams. Previous studies showed that a traffic jam affects a level of fatigue and response time of drivers of all temperaments, except phlegmatic, negatively [26]. Therefore, it seems possible to include the coefficients, which reflect the changes, in the models (1) and (2). Then the models take the following form:

$$P_1 = \frac{\left(\vec{F}^{0.75} + \vec{F}^{0.35}\right) \cdot \vec{F}^{1.25} \cdot l \cdot k_a \cdot 2 \cdot 10^{-10}}{H} \cdot k_c, \tag{3}$$

$$P_2 = \frac{50 \cdot k_i \cdot M_i \cdot N_i}{k_p \cdot 10^{14}} \cdot \frac{N_{\tau i} + M_{\tau i}}{N_i + M_i} \cdot k_c, \tag{4}$$

where k_c is the coefficient, which takes into account the impact of a traffic jam.

One can determine the coefficient, which takes into account the impact of a traffic jam, based on changes in (ΔT_r) response time of a driver according to the model developed in [27], and (T_r) reaction time of a driver equal to 0.8 s.

In addition, we take the value of k_c coefficient to be equal to $\frac{T_r + \Delta T_r}{T_r}$.

Then the models take the following form:

$$P_1 = \frac{\left(\vec{F}^{075} + \vec{F}^{0.35}\right) \cdot \vec{F}^{1.25} \cdot l \cdot k_a \cdot 2 \cdot 10^{-10}}{H} \cdot \frac{T_r + \Delta T_r}{T_r}, \tag{5}$$

$$P_2 = \frac{50 \cdot k_i \cdot M_i \cdot N_i}{k_p \cdot 10^{14}} \cdot \frac{N_{\tau i} + M_{\tau i}}{N_i + M_i} \cdot \frac{T_r + \Delta T_r}{T_r}. \tag{6}$$

The model of changes in (ΔT_r) response time of a driver developed in [14, 27] takes the following form**:**

$$\Delta T_r = 0.029 + 0.022 \cdot \left(F_2 - F_1\right)^2, \tag{7}$$

where F_2 is the average indicator of the level of fatigue of the entire set of drivers during leaving a traffic jam, stand. units; F_1 is the average indicator of the level of fatigue of the entire set of drivers at the arrival to a traffic jam, stand. units.

The base of the approach for collecting statistical data is the approach by Academician A. K. Mitropolsky in the development of model (7). The approach implies determining the sample size from a table of sufficiently large numbers for its correspondence to the general aggregate [28]. The table shows how a large number of observations (the sample size) depend on a "degree of certainty", a magnitude of the admissible error, and an unknown fraction itself. We eliminate the dependency on the unknown fraction choosing the worst value for it. Therefore, a large number turns out to be overestimated.

A sufficiently large number of observations is 384 if the probability of the correspondent conclusion is equal to 0.95 and the admissible error is 0.05.

The sample includes drivers aged from 19 to 67 with four main types of temperament. If we investigate the same driver in several traffic jams, for example, in four of them, then we include these studies as four independent observations in the sample.

The developed model (7) applies to the average driver because the sample includes drivers of different ages and temperaments.

We used a device, which consisted of a telescopic antenna, a timer, a pointer, and a light switch to determine the response time of a driver. We determined the response time of a driver by the moment a driver pressed a special indication of the corresponding section of the telescopic antenna after signaling. At the time of signaling, a timer was activated. It stopped after touching the antenna with the pointer. A driver chose a convenient time to determine the response time by himself to ensure road safety.

There were corresponding studies presented in [14] to construct a mathematical model (7) of an impact of traffic jams on the functional state of a driver and his response time. We measured the functional state and the response time of drivers before a traffic jam, during their stay in a traffic jam and after it [27].

Formulas (5), (6) take the following form considering model (7):

$$P_1 = \frac{\left(\vec{F}^{0.75} + \vec{F}^{0.35}\right) \cdot \vec{F}^{1.25} \cdot l \cdot k_a \cdot 2 \cdot 10^{-10}}{H} \times \\ \times \frac{T_r + 0{,}029 + 0{,}022 \cdot \left(F_2 - F_1\right)^2}{T_r}, \tag{8}$$

$$P_2 = \frac{50 \cdot k_i \cdot M_i \cdot N_i}{k_p \cdot 10^{14}} \cdot \frac{N_{\tau i} + M_{\tau i}}{N_i + M_i} \times \\ \times \frac{T_r + 0{,}029 + 0{,}022 \cdot \left(F_2 - F_1\right)^2}{T_r}. \tag{9}$$

We determined the level of fatigue using the method by Professor R. Baevsky through the measurement of an electrocardiogram and analyzing a sequence of cardio intervals of the electrocardiogram, which encoded information about the processes occurring in the driver's body [28].

The level of fatigue made it possible to differentiate between different levels of stress of regulatory systems and to assess the adaptive capacity of a body [28]. One can calculate it according to the algorithm, which takes into account five criteria. They are a total impact of regulation (by indicators of mathematical expectation), a function of automatism (by the average quadratic deviation, by a variational span and by a coefficient of variation), vegetative homeostasis (by a set of indicators such as a variance span, a mode amplitude, an index of tension of regulatory systems), stability of regulation (by a coefficient of variation), activity of subcortical nerve centers (based on relative capacities of respiratory waves and waves of the first and second-order with selection of states of pronounced and moderate enhancement of activity of subcortical nerve centers).

F_2, the average indicator of the level of fatigue of the entire set of drivers during leaving a traffic jam developed in [16] takes the following form:

$$F_2 = 0.018 \cdot A_d + 1.278 \cdot D_t^{0.41} + 0.291 \cdot F_1, \quad (10)$$

where A_d is the driver's age, years; D_t is the traffic jam duration, min.

Studies examined drivers with all types of the nervous system to develop a regression model (10) for the average driver. Drivers of all age groups and categories participated in the studies. The experimental studies consisted of registering the electrocardiogram of drivers at their arrival to a traffic jam, in a traffic jam and when leaving it.

Formulas (8) and (9) for the assessment of the probability of an accident at sections of a transport network and at transport nodal points with an individual traffic participant considering model (10) take the following form:

$$P_1 = \frac{\left(\vec{F}^{0.75} + \vec{F}^{0.35}\right) \cdot \vec{F}^{1.25} \cdot l \cdot k_a \cdot 2 \cdot 10^{-10}}{H} \times$$
$$\times \frac{T_r + 0.029 + 0.022 \cdot \left(0.018 \cdot A_d + 1.278 \cdot D_t^{0.41} - 0.709 \cdot F_1\right)^2}{T_r}, \quad (11)$$

$$P_2 = \frac{50 \cdot k_i \cdot M_i \cdot N_i}{k_p \cdot 10^{14}} \cdot \frac{N_{\tau i} + M_{\tau i}}{N_i + M_i} \times$$
$$\times \frac{T_r + 0.029 + 0.022 \cdot (0.018 \cdot A_d + 1.278 \cdot D_t^{0.4} - 0.709 \cdot F_1)^2}{T_r}. \quad (12)$$

It follows from formulas (11) and (12) that the probability of getting into an accident on elements of a transport system depends on the intensity of traffic flows, response time of a driver in a traffic jam, an age of a driver, a level of fatigue at arrival to a traffic jam, and duration of a traffic jam.

4. 2. Description of the structure of models, which affect the failure-free operation of a driver in the elements of a transportation system

To determine by how many times the probability of an accident for the average driver on sections of a transport network with a traffic jam (P_c) is higher than the same probability without a traffic jam (P_{wc}), we considered the relation of the mentioned probabilities using formula (11):

$$\frac{P_c}{P_{wc}} = \frac{\dfrac{\left(\vec{F}_c^{0.75} + \vec{F}_c^{0.35}\right) \cdot \vec{F}_c^{1.25} \cdot l \cdot k_a \cdot 2 \cdot 10^{-10}}{H}}{\dfrac{\left(\vec{F}_{wc}^{0.75} + \vec{F}_{wc}^{0.35}\right) \cdot \vec{F}_{wc}^{1.25} \cdot l \cdot k_a \cdot 2 \cdot 10^{-10}}{H}} \times$$
$$\times \frac{T_r + 0.029 + 0.022 \cdot \left(0.018 \cdot A_d + 1.278 \cdot D_t^{0.41} - 0.709 \cdot F_1\right)^2}{T_r}, \quad (13)$$

where $\vec{F}_c, \vec{F}_c$ is the intensity of traffic of passing and oncoming traffic flows at traffic jams, vehicles/h; $\vec{F}_{wc}, \vec{F}_{wc}$ is the traffic intensity of passing and oncoming traffic flows of vehicles without traffic jams, respectively, vehicles/h.

We determined the ratio of the probability of getting into an accident with and without traffic jams for a driver in transport nodal points taking into account formula (12) as:

$$\frac{P_c}{P_{wc}} = \frac{\dfrac{50 \cdot k_c \cdot M_c \cdot N_c}{k_p \cdot 10^{14}} \cdot \dfrac{N_{\tau c} + M_{\tau c}}{N_c + M_c}}{\dfrac{50 \cdot k_{wc} \cdot M_{wc} \cdot N_{wc}}{k_p \cdot 10^{14}}} \times$$
$$\times \frac{T_r + 0.029 + 0.022 \cdot \left(0.018 \cdot A_d + 1.278 \cdot D_t^{0.41} - 0.709 \cdot F_1\right)^2}{\dfrac{N_{\tau wc} + M_{\tau wc}}{N_{wc} + M_{wc}} \cdot T_r}, \quad (14)$$

where M_c, N_c are the total traffic intensities on roads intersected by traffic jams vehicles/day; $M_{\tau c}$, $N_{\tau c}$ are the intensities of flows intersecting at a conflict point when a vehicle passes through a traffic intersection at a traffic jam, vehicles/day; M_{wc}, N_{wc} are the total traffic intensities on intersecting roads without traffic jams, vehicles/day; $M_{\tau wc}$, $N_{\tau wc}$ are the intensities of flows intersecting at a point of conflict when a vehicle passes through an intersection without traffic jams, vehicles/day.

Formulas (13) and (14) will take the following final form after the corresponding transformations:

$$\frac{P_c}{P_{wc}} = \frac{\left(\vec{F}_c^{0.75} + \vec{F}_c^{0.35}\right) \cdot \vec{F}_c^{1.25} \cdot \left(T_r + 0.029 + 0.022 \cdot \left(0.018 \cdot A_d + 1.278 \cdot D_t^{0.41} - 0.709 \cdot F_1\right)^2\right)}{\left(\vec{F}_{wc}^{0.75} + \vec{F}_{wc}^{0.35}\right) \cdot \vec{F}_{wc}^{1.25} \cdot T_r}, \quad (15)$$

$$\frac{P_c}{P_{wc}} = \frac{M_c \cdot N_c \cdot \dfrac{N_{\tau c} + M_{\tau c}}{N_c + M_c} \cdot \left(T_r + 0.029 + 0.022 \cdot \left(0.018 \cdot A_d + 1.278 \cdot D_t^{0.41} - 0.709 \cdot F_1\right)^2\right)}{M_{wc} \cdot N_{wc} \cdot \dfrac{N_{\tau wc} + M_{\tau wc}}{N_{wc} + M_{wc}} \cdot T_r}. \quad (16)$$

Thus, the ratio of the probability of getting into an accident with and without traffic jams for the average driver comes down to determining the ratio of flow intensities and changes in the response time.

Since the intensities of traffic flows were accepted per hour in formula (15), and per day in formula (16), we can assume that they would be aligned during these periods and would be the same. Then the intensities of traffic flows with and without traffic jams will decrease or their ratio will be equal to a constant close to unity. It is then possible to assess the driver's failure-free operation after the impact of traffic jam conditions only by changing his functional state and response time:

$$\frac{P_c}{P_{wc}} = C \cdot \frac{T_r + 0.029 + 0.022 \cdot \left(0.018 \cdot A_d + 1.278 \cdot D_t^{0.41} - 0.709 \cdot F_1\right)^2}{T_r}, \quad (17)$$

where C is the constant (we assumed C was equal to one in our study).

4. 3. Patterns in changing the probability of a traffic accident taking into account traffic jams

It is necessary to estimate the ratio of the probabilities of an accident on sections of a traffic system with and without traffic jams to assess the probability of an accident for the average driver. The final values of the ratios in a traffic jam will be values of the levels of the driver's failure-free operation on a section of a network immediately after a traffic jam. We calculated the corresponding ratios of probabilities for drivers of twenty and sixty years at different durations of traffic jams for six options of traffic jams (3 to 18 minutes at 3-minute intervals) and different initial values of fatigue before traffic jams for the assessment using model (17).

Fig. 1–8 show changes in the ratio of the probabilities of road accidents taking into account a traffic jam and without it depending on the duration of a traffic jam combined in one chart.

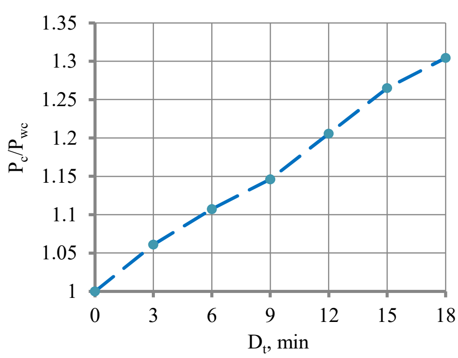

Fig. 1. Changes in the ratio of the probabilities of an accident with and without a traffic jam for the average 20 years driver depending on the duration of a traffic jam at F_1=2 stand. units

One can see in Fig. 1 that the ratio of the possibilities of accidents with and without traffic jams increases with an increase in the duration of a traffic jam for the average driver when leaving a traffic jam and at the duration of 18 minutes and reaches 1.3 at F_1=2 stand. units in a traffic jam.

Therefore, a traffic jam with a duration of 18 minutes increases the possibility of an accident in a section of a network after a traffic jam by 30 % compared to the same section without a traffic jam. A traffic jam with a duration of 9 minutes increases the probability by 15 %. Similarly, one can define the possibility of an accident on a section of a network after traffic jams of any duration in Fig. 1.

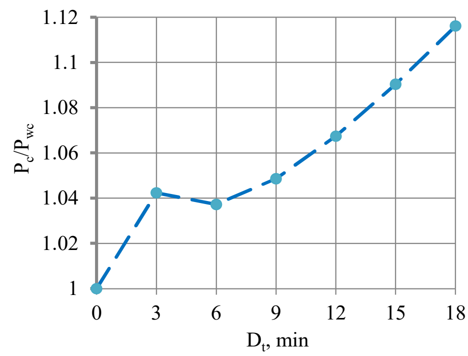

Fig. 2. Changes in the ratio of the probabilities of an accident with and without a traffic jam for the average driver at the age of 20 depending on the duration of a traffic jam at F_1=4 stand. units

Fig. 2 shows changes in the ratio of the probabilities of an accident with and without a traffic jam for the average driver at the age of 20 at F_1=4 stand. units. The ratio of the probabilities of an accident with and without a traffic jam for the average driver increases slightly before minute 3 of a traffic jam. By the sixth minute, the ratio almost does not change until minute 6, and then it increases to 1.12.

Fig. 2 implies, for example, that a traffic jam with a duration of 6 minutes leads to a 4 % increase in the probability of an accident on a section of a network after it and by 7 % at the duration of 12 minutes.

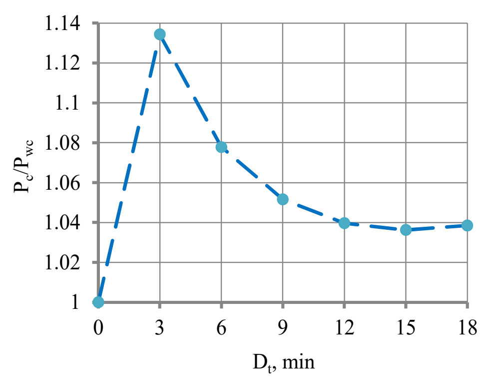

Fig. 3. Changes in the ratio of the probabilities of an accident with and without a traffic jam for the average driver at the age of 20 depending on the duration of a traffic jam at F_1=6 stand. units

Fig. 3 shows the dynamics of changes in the ratio of the probabilities of an accident with and without traffic jams for the average driver in the traffic jam at F_1=6 stand. units.

The ratio of the probabilities of an accident with and without traffic jams increases for him significantly to 1.135 until the third minute of a traffic jam due to inertial processes in the body of a driver, as he enters a traffic jam in the condition of a high level of fatigue. Further, the ratio decreases for the average driver. It reaches 1.04 at the end of a traffic jam. The effects of traffic jams on a driver's state are negligible in this case. A driver "rests" in a traffic jam (comes to a normal state) after entering it with a high level of fatigue.

Fig. 4 shows changes in the ratio of the probabilities of an accident with and without traffic jams for the average driver in a traffic jam in three dimensions derived using formula (17).

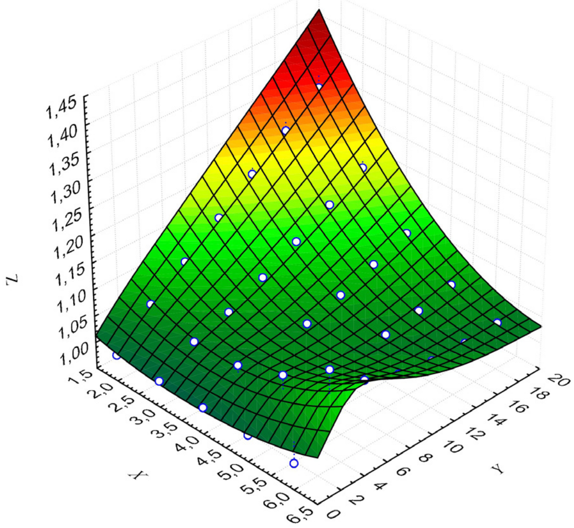

Fig. 4. Dependence ratio of road accidents with and without traffic jams (*Z*) for the average driver at the age of 20, depending on the initial level of fatigue (*X*) and duration of traffic jams (*Y*)

The ratio of the probabilities of an accident with and without a traffic jam increases slightly for the average driver at F_1=6 stand. units until the third minute of a traffic jam. Further, the ratio decreases const antly for the average driver. It reaches 1.04 at the end of a traffic jam (Fig. 4).

Fig. 5 shows the tendency of changes in the ratio of the probabilities of a traffic accident with and without traffic jams similarly to the changes shown in Fig. 1 if the initial level of fatigue is 2 stand. units for drivers at 60. The ratio of the probabilities of accidents with and without traffic jams increases for drivers. It reaches 1.44 at the end of a traffic jam for the average driver. Therefore, a traffic jam with a duration of 18 minutes leads to a 40 % increase in the probability of road accidents on a section of a network.

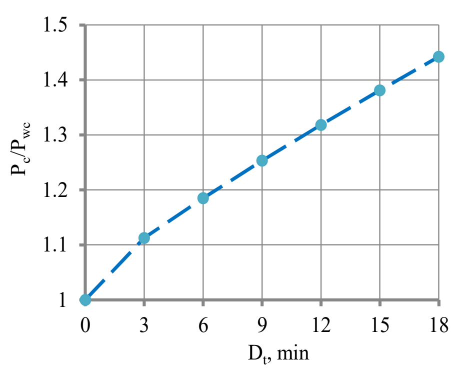

Fig. 5. Changes in the ratio of the probabilities of an accident with and without traffic jams for the average driver at the age of 60 depending on the duration of a traffic jam at F_1=2 stand. units

The tendency of changes in the ratio of the probabilities of an accident with and without traffic jams occurs similarly to the changes shown in Fig. 2 at F_1=4 stand. units (Fig. 6). The change reaches 1.2 at the end of a traffic jam for the average driver. That is, a traffic jam leads to an increase in road accidents by 20 %. For example, an increase is 12 % if the duration of a traffic jam is 12 minutes.

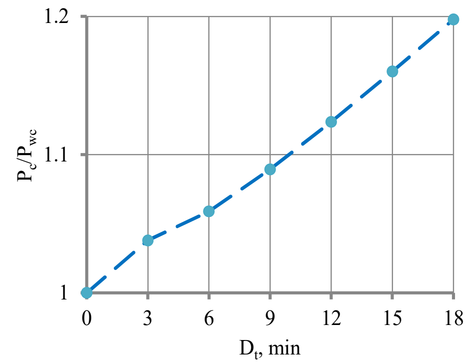

Fig. 6. Changes in the ratio of the probabilities of an accident with and without traffic jams for the average driver at the age of 60 depending on the duration of a traffic jam at F_1=4 stand. units

Fig. 7 shows that the ratio of the probabilities of a traffic accident with and without traffic jams increases until the third minute of a traffic jam for the average driver due to inertial processes in the body of a driver. Then, it decreases to the sixth minute, then increases again, reaching 1.07 at the end of a traffic jam. The same state as a state of the twenty-year-old drivers provides a less relative increase in the probability of an accident than it occurs in a normal state (F_1=2 units), when the percentage increase in the probability of an accident due to traffic jams can reach 15 % on sections of a transport system.

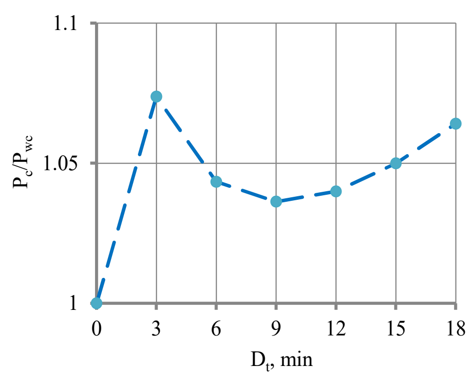

Fig. 7. Changes in the ratio of the probabilities of an accident with and without traffic jams for the average driver at the age of 60 depending on the duration of a traffic jam at F_1=6 stand. units

Fig. 8 shows changes in the ratio of the probabilities of an accident with and without traffic jams on sections of a transport system for the average driver at the age of 60 in a traffic jam in three dimensions derived by using formula (17).

One can see in Fig. 8 that the relative increase in the probability of an accident on sections of a transport system with a traffic jam to the probability of an accident without a traffic jam increases to 1.6 for the average driver. Therefore, the age of a driver slightly affects the relative increase in the probability of an accident with a traffic jam to the probability of an accident without a traffic jam.

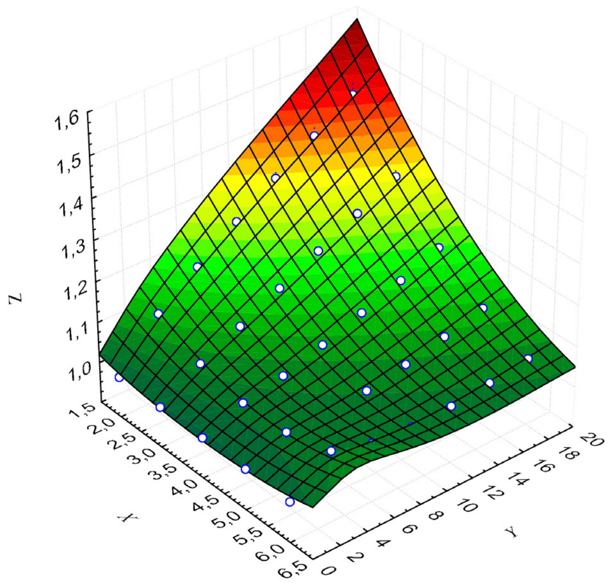

Fig. 8. Dependence of ratio of the probabilities of accidents with and without traffic jams (*Z*) for the average driver at the age of 60 depending on the initial level of fatigue (*X*) and the duration of traffic jams (*Y*)

5. Assessment of the adequacy of the developed models

We calculated the level of fatigue at leaving a traffic jam by using model (10) and changing the response time of a driver by using model (7) to assess the ratio of the probability of an accident on sections of a transport system with and without traffic jams for the average driver. We determined the ratio for drivers of different age groups at different initial functional states and different durations of traffic jams (Table 1).

We developed the following approach to verify the adequacy of the obtained value of the ratio of the probabilities of an accident with and without traffic jams for the average driver. It is a comparison of this value and the corresponding ratio of the number of traffic accidents on sections of a transport network and at intersections.

Data from the State traffic inspectorate's journals about road accidents in the city of Kharkiv were processed for this purpose. We compared the number of accidents, which occurred in sections of a transport network and at intersections during the year, with the number of accidents per hour. Three options were considered when traffic jams lasted for 3.5; 4.0 and 4.5 hours. The total driving time was 16 hours: from 6 am to 10 pm.

Table 1

Assessment of the ratio of the probabilities of road accidents on sections of a transport system with and without traffic jams for the average driver

No.	Age of a driver, years	Duration of a traffic jam, min	Initial level of fatigue, stand. units	Changes in the response time of a driver, s	Ratio of the probabilities of accidents with and without traffic jams
1	2	3	4	5	6
1	20	3	2	0.049	1.061
2	20	6	2	0.086	1.107
3	20	9	2	0.125	1.156
4	20	12	2	0.165	1.206
5	20	15	2	0.204	1.255
6	20	18	2	0.243	1.304
7	20	3	3	0.03	1.038
8	20	6	3	0.047	1.058
9	20	9	3	0.071	1.089
10	20	12	3	0.098	1.123
11	20	15	3	0.127	1.159
12	20	18	3	0.157	1.196
13	20	3	4	0.034	1.042
14	20	6	4	0.03	1.037
15	20	9	4	0.039	1.049
16	20	12	4	0.054	1.067
17	20	15	4	0.072	1.09
18	20	18	4	0.093	1.116
19	20	3	5	0.06	1.075
20	20	6	5	0.035	1.044
21	20	9	5	0.029	1.036
22	20	12	5	0.032	1.04
23	20	15	5	0.04	1.05
24	20	18	5	0.051	1.064
25	20	3	6	0.108	1.134
26	20	6	6	0.062	1.078
27	20	9	6	0.041	1.052
28	20	12	6	0.032	1.04
29	20	15	6	0.029	1.036
30	20	18	6	0.031	1.039
31	40	3	2	0.067	1.083
32	40	6	2	0.114	1.143

Continuation of Table 1

1	2	3	4	5	6
33	40	9	2	0.161	1.201
34	40	12	2	0.207	1.258
35	40	15	2	0.252	1.315
36	40	18	2	0.296	1.37
37	40	3	3	0.037	1.046
38	40	6	3	0.064	1.08
39	40	9	3	0.096	1.119
40	40	12	3	0.129	1.161
41	40	15	3	0.163	1.204
42	40	18	3	0.198	1.248
43	40	3	4	0.029	1.037
44	40	6	4	0.036	1.045
45	40	9	4	0.052	1.065
46	40	12	4	0.074	1.092
47	40	15	4	0.097	1.122
48	40	18	4	0.123	1.153
49	40	3	5	0.044	1.055
50	40	6	5	0.03	1.037
51	40	9	5	0.031	1.039
52	40	12	5	0.04	1.05
53	40	15	5	0.053	1.067
54	40	18	5	0.069	1.087
55	40	3	6	0.08	1.101
56	40	6	6	0.046	1.057
57	40	9	6	0.032	1.04
58	40	12	6	0.029	1.036
59	40	15	6	0.032	1.04
60	40	18	6	0.038	1.048
61	60	3	2	0.09	1.113
62	60	6	2	0.148	1.185
63	60	9	2	0.203	1.253
64	60	12	2	0.255	1.318
65	60	15	2	0.305	1.381
66	60	18	2	0.354	1.442
67	60	3	3	0.049	1.062
68	60	6	3	0.087	1.108
69	60	9	3	0.126	1.157
70	60	12	3	0.166	1.207
71	60	15	3	0.206	1.257
72	60	18	3	0.245	1.306
73	60	3	4	0.03	1.038
74	60	6	4	0.047	1.059
75	60	9	4	0.072	1.089
76	60	12	4	0.099	1.124
77	60	15	4	0.128	1.16
78	60	18	4	0.158	1.198
79	60	3	5	0.034	1.042
80	60	6	5	0.03	1.037
81	60	9	5	0.039	1.049
82	60	12	5	0.054	1.068
83	60	15	5	0.073	1.091
84	60	18	5	0.094	1.117
85	60	3	6	0.059	1.074
86	60	6	6	0.035	1.043
87	60	9	6	0.029	1.036
88	60	12	6	0.032	1.04
89	60	15	6	0.04	1.05
90	60	18	6	0.051	1.064
The average value of the ratio of the probabilities of an accident with and without traffic jams for the average driver					1.116

Table 2 shows the results of the processed data from the State traffic inspectorate's journals on road accidents for a 4-hour variant.

The average value of the ratio of the number of accidents with and without traffic jams at a traffic jam with a duration of 3.5 hours is 1.055, and it is 1.219 at a traffic jam with a duration of 4.5.

The results from data collected by the State traffic inspectorate's journals on the number of accidents over a year in network nodal points confirm the following values.

The average value of the ratio of the number of accidents with and without traffic jams at a traffic jam with the duration of 3.5 hours is 1.131, at traffic jam with the duration of 4.0 hours is 1.184, and at a traffic jam of 4.5 hours is 1.24.

Table 2

The number of road accidents over a year on sections of a transport network with a traffic jam with a duration of 4.0 hours

Section No.	Number of accidents on sections of a network per hour, units/h		The ratio of the number of accidents on sections of a network with and without traffic jams
	with a traffic jam	without a traffic jam	
1	2	3	4
1	0.00137	0.001142	1.200
2	0.002055	0.002283	0.900
3	0.00137	0.000913	1.500
4	0.00274	0.001826	1.500
5	0.00274	0.002968	0.923
6	0.002055	0.001598	1.286
7	0.00274	0.002055	1.333
8	0.000685	0.000685	1.000
9	0.00274	0.00137	2.000
10	0.00274	0.002511	1.091
11	0.00137	0.00137	1.000
12	0.002055	0.002283	0.900
13	0.002055	0.001142	1.800
14	0.00137	0.002055	0.667
15	0.00137	0.001142	1.200
16	0.00137	0.000913	1.500
17	0.000685	0.002055	0.333
18	0.000685	0.000685	1.000
19	0.002055	0.002511	0.818
20	0.000685	0.001826	0.375
21	0.00274	0.001598	1.714
22	0.003425	0.00274	1.250
23	0.00137	0.001598	0.857
24	0.000685	0.00137	0.500
25	0.00137	0.002511	0.545
26	0.00137	0.00137	1.000
27	0.00274	0.002055	1.333
28	0.00137	0.002283	0.600
29	0.000685	0.000913	0.750
30	0.000685	0.000685	1.000
31	0.00137	0.001826	0.750
32	0.002055	0.001142	1.800
33	0.00137	0.001598	0.857
34	0.000685	0.001142	0.600
35	0.00137	0.000913	1.500
36	0.000685	0.000913	0.750
37	0.002055	0.001826	1.125
38	0.00274	0.001598	1.714
39	0.002055	0.002511	0.818
40	0.000685	0.000913	0.750
41	0.000685	0.000685	1.000
42	0.000685	0.002055	0.333
43	0.003425	0.002511	1.364
44	0.00137	0.001142	1.200
45	0.002055	0.00274	0.750

Continuation of Table 2

1	2	3	4
46	0.000685	0.000685	1.000
47	0.000685	0.001826	0.375
48	0.00274	0.002511	1.091
49	0.002055	0.001598	1.286
50	0.00137	0.001826	0.750
51	0.00137	0.001598	0.857
52	0.002055	0.002055	1.000
53	0.000685	0.000913	0.750
54	0.000685	0.000685	1.000
55	0.000685	0.001598	0.429
56	0.002055	0.001142	1.800
57	0.00137	0.00274	0.500
58	0.000685	0.001142	0.600
59	0.000685	0.000913	0.750
60	0.000685	0.000685	1.000
61	0.002055	0.001826	1.125
62	0.00274	0.001598	1.714
63	0.002055	0.002511	0.818
64	0.000685	0.001826	0.375
65	0.00274	0.001598	1.714
66	0.002055	0.002511	0.818
67	0.00137	0.000913	1.500
68	0.00137	0.000685	2.000
69	0.002055	0.00274	0.750
70	0.00137	0.002055	0.667
71	0.000685	0.001826	0.375
72	0.00274	0.001598	1.714
73	0.000685	0.000685	1.000
74	0.00274	0.001826	1.500
75	0.002055	0.002055	1.000
76	0.000685	0.000685	1.000
77	0.00274	0.001826	1.500
78	0.003425	0.002511	1.364
79	0.00274	0.001598	1.714
80	0.000685	0.000913	0.750
81	0.00274	0.002968	0.923
82	0.00274	0.001826	1.500
83	0.00274	0.001598	1.714
84	0.000685	0.000685	1.000
85	0.003425	0.001826	1.875
86	0.002055	0.002055	1.000
87	0.000685	0.000685	1.000
88	0.000685	0.001826	0.375
89	0.00274	0.001598	1.714
90	0.000685	0.000913	0.750
91	0.003425	0.002055	1.667
92	0.00274	0.001826	1.500
93	0.00274	0.001598	1.714
94	0.00411	0.00274	1.500
95	0.00137	0.001142	1.200
96	0.000685	0.00137	0.500
97	0.000685	0.001826	0.375
98	0.002055	0.001598	1.286
99	0.00411	0.00274	1.500
100	0.00274	0.002055	1.333
The average value of the ratio of the number of accidents with and without traffic jams			1.082

Table 3 shows the comparison of assessments of the ratio of the probabilities of accidents with and without traffic jams for the average driver and average values of the ratio of the number of traffic accidents with and without traffic jams on some sections of a transport network.

Table 3 implies that the average approximation error of deviation of assessments of the ratio of the probabilities an accident with and without traffic jams for a driver calculated by the model (17) and average values of the ratio of the number of accidents with and without traffic jams on sections of a network calculated according to the State traffic inspectorate journals about accidents happened in Kharkiv is admissible.

Fig. 9–11 show changes in the number of road accidents over a year in sections of a transport system with and without traffic jams for the average driver in three dimensions with the application of STATISTICA 6.0 statistical software package for three and a half, four, and four and a half hours.

Fig. 9–11 show that the number of accidents increases with an increase in the duration of a traffic jam.

Table 3

The ratio of assessments of the probabilities of accidents on sections of a transport system with and without traffic jams and average values of the ratio of the number of accidents

Observation No.	Duration of a traffic jam, min	The ratio of the number of accidents with and without traffic jams	The ratio of the probabilities of accidents with and without traffic jams	Mean observation error, %
1	3	1.191	1.08	9.32
2	6	1.299	1.15	11.5
3	10	1.34	1.22	8.96
4	12	1.299	1.25	3.77
5	15	1.34	1.22	8.96
6	19	1.531	1.25	18.4
7	4	1.021	1.04	1.86
8	6	1.021	1.07	4.8
9	10	1.191	1.13	5.12
10	13	1.021	1.08	5.78
11	15	1.299	1.12	13.8
12	18	1.34	1.15	14.2
13	3	0.975	1.02	4.62
14	5	1.021	1.05	2.84
15	8	0.975	1.11	13.8
16	11	1.429	1.12	21.6
17	15	1.34	1.14	14.9
18	16	1.299	1.21	6.85
19	4	1.021	1.05	2.84
20	7	1.021	1.09	6.76
Average approximation error, %				9.03

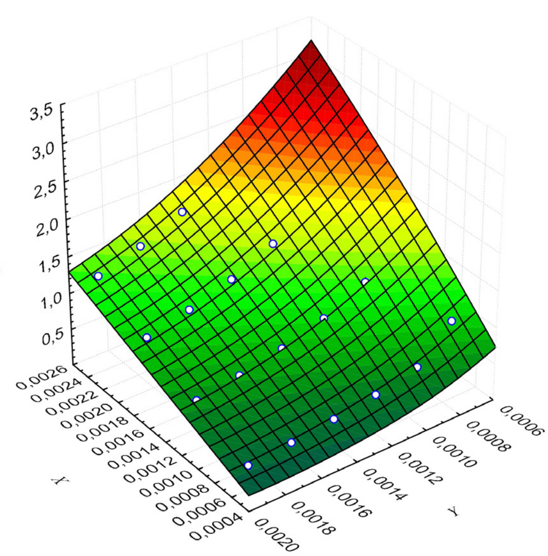

Fig. 9. Dependence of the ratio of the number of accidents over a year with and without traffic jams (*Z*) for the average driver for three and a half hours depending on the number of road accidents on sections of a transport system with a traffic jam (*X*) and without it (*Y*)

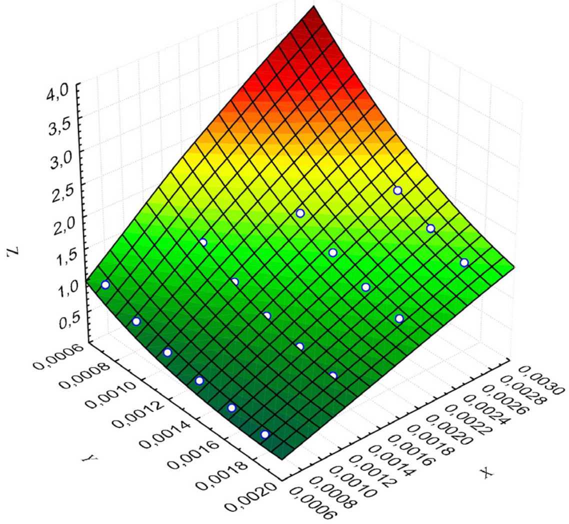

Fig. 10. Dependence of the ratio of the number of accidents over a year with and without traffic jams (*Z*) for the average driver for four hours depending on the number of road accidents on sections of a transport system with a traffic jam (*X*) and without it (*Y*)

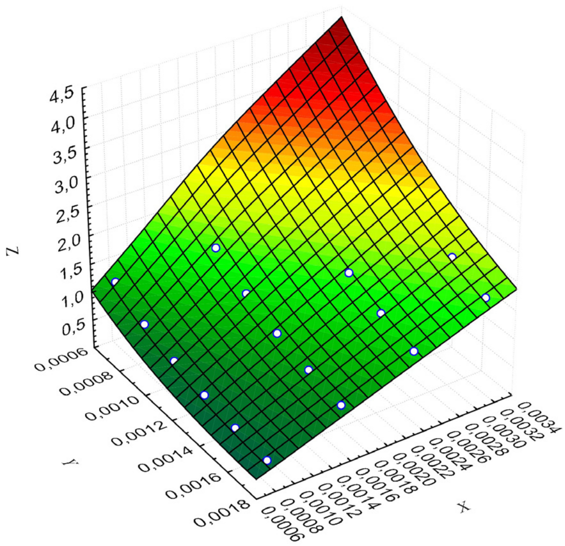

Fig. 11. Dependence of the ratio of the number of accidents over a year with and without traffic jams (*Z*) for the average driver for four and a half hours depending on the number of road accidents on sections of a transport system with a traffic jam (*X*) and without it (*Y*)

6. Discussion of results of studying the model for assessing driver failure-free operation in a transport system taking into account traffic jams

The main results of this study are the developed mathematical models for the assessment of the reliability of the average driver on sections of a transport network (15) and at transport nodal points (16). The resulting model (17), which reflects changes in the driver's state due to being in a traffic jam, makes it possible to assess the probability of an accident on elements of a transport system after a traffic jam. We assessed it by determining the ratio of the probabilities of road accidents on sections of a transport system, depending on the presence of traffic jams and without them for an individual traffic participant.

We should note that, in contrast to existing approaches, the probability of an accident for a particular vehicle on a section of a transport network depends not only on parameters of a network and traffic flows as in models (3) and (4). The probability also depends on the variable driver's response time, which increases, in turn, with the level of his fatigue – models (5) to (7).

The basis for determining the level of fatigue is the analysis of the functioning of the cardiovascular system of a person. The analysis checks irregularity of the heart rate, that is, the sequence of cardio intervals of the electrocardiogram, which is encoded information about processes occurring in a driver's body – used in the development of model (10).

Such an approach is fundamentally new in terms of human factors for the assessment of the probability of road accidents on sections of a transport network and at transport nodal points for an individual traffic participant.

Charts in Fig. 1–8 make it possible to identify patterns of changes in the level of driver failure-free operation at different durations of traffic jams. We found that the probability of road accidents on a section of a network after a traffic jam can increase from 5 to 40 % depending on the value of the initial level of fatigue of a driver at the start of a traffic jam and its duration.

We assessed the adequacy of the developed models by comparing the value of the ratio of the probabilities of road accidents on sections of a transport system with a traffic jam and without it and the corresponding ratio of the number of traffic accidents (Tables 1–3).

We showed changes in the ratio of the number of traffic accidents for the average driver on sections of a transport system with traffic jams of different duration. It follows from the data that an increase in the duration of a traffic jam leads to an increase in the number of accidents on sections of a system (Fig. 9–11).

It is possible to refine the results of application of the developed mathematical models for an individual driver when developing appropriate models of changing the level of fatigue and response time for each type of temperament.

Application of the approach for the assessment the probability of road traffic accidents on elements of a transport network taking into account traffic jams makes it possible to compare and assess different options for project decisions to improve road safety.

City authorities could apply the results from this study for the development and adjustment of public passenger transport routes to improve road safety. Also, city authorities and transport companies can use the results in the design and organization of a route system to minimize the duration of traffic jams for drivers and, thus, to prevent excess fatigue and response time. Passenger business executives can use the study results to adjust driving and rest modes for drivers for work on routes by regulation of idle time at their final destinations. Also, relevant organizations can apply the study results in the professional selection and training of drivers to develop recommendations so that a future driver can take into account the obtained patterns in their activities. The state and response time change in different traffic jams of different duration that affect the probability of an accident.

It is possible to use the results of the study and the developed models to assess the driver's failure-free operation in cases of continuous traffic jams, which last from 3 to 60 minutes.

A possible direction for further development of the obtained results could be the determination of patterns of changing the level of fatigue of drivers on sections of a city transport network after leaving a traffic jam. The studies on the assessment of the probability of a traffic accident by drivers on sections of a transportation network taking into account the driver's temperament may also be very important.

7. Conclusions

1. We improved the existing model and determined the probability of a traffic accident for an individual traffic participant on sections of a transport network taking into account a traffic jam. The probability depends not only on parameters of a network and traffic flows but, most of all, on the driver's varying response time, which, in turn, increases directly proportionally depending on the level of his fatigue.

2. We developed the models for the assessment of the driver's failure-free operation on sections of a transport network and in transport nodal points depending on the presence of traffic jams on them. Underlying it is an approach, which consists of the assessment of the ratio of the probabilities of road accidents on sections of a transport network with and without traffic jams for the average driver. It is necessary to determine the ratio of changes in his response time due to a traffic jam to the same parameters without a traffic jam for this purpose.

3. The patterns of changes in the ratios of the probabilities of road accidents for different conditions of being in a traffic jam for younger and older drivers have been defined. The final values of the ratios in a traffic jam are initial values for the assessment of the driver's failure-free operation on a section of a network immediately after a traffic jam. It was found that the percentage of an increase in the probability of an accident on sections of a transport system due to traffic jams can reach from 10 to 50 % depending on the conditions of the time in a traffic jam and its duration.

4. We verified the adequacy of the developed models by comparing the value of the ratio of the probabilities of an accident due to traffic jams calculated by the model and without a traffic jam and the corresponding ratio of the actual number of traffic accidents. The average errors of approximation of deviation of assessments of the ratio of the probabilities of an accident with and without traffic jams are 9 % for the average driver.

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