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Methodology for Reducing the Duration of the Free Development of Fire

Методология уменьшения продолжительности свободного развития пожара

Metodologia skrócenia czasu swobodnego rozwoju pożaru

ABSTRACT

Objective: The task is to develop a methodology for reducing the duration of the free development of fire, based on the principles of optimising the route of fire and rescue vehicles from the fire department to the place of call. To do this, it is necessary to analyse and distinguish factors that affect the duration of fire truck's travel to the place of call to reduce the duration of the free development of fire. To solve this problem, the behaviour of the fire vehicle in the «driver – car – road – environment» system was investigated.

Methods: Theoretical research was carried out on the basis of methods of mathematical analysis, mathematical statistics, probability theory, and graph theory. The accuracy of the results of theoretical studies is suitable for engineering calculations. The processing of the results was carried out using the STATISTICA and Microsoft Excel software. Simulation methods were used to develop an algorithm for reducing the duration of the free development of fire, as well as the Monte Carlo method.

Results: The study shows that the fire truck travel time to the place of call has the greatest influence on the duration of the free development of fire. The necessity of investigating the behaviour of fire vehicles in the system of "road conditions – traffic flows" was substantiated in order to reduce the duration of its travel to the place of call. A graph model of optimising the route of fire vehicles from the depot to the place of call has been developed. The simulation model for predicting the duration of the fire and rescue unit's travel to the place of call is developed, which will make it possible to determine the optimal travel route and reduce the duration of the free development of fire.

Conclusions: The methodology of reducing the duration of the free development of fire on the basis of optimisation of the fire and rescue vehicle route from the fire department to the place of emergency is developed in this study. The theoretical calculations show that the developed methodology makes it possible to reduce the length of travel of special vehicles and, consequently, reduce the duration of free fire development on average by 7%. It is established that in order to determine all possible variants of the fire-propulsion traffic route, it is expedient to use the theory of graphs; such a model is presented in the study. In the future, it will be beneficial to develop and improve the existing mathematical models of fire vehicle movement, taking into account the parameters of traffic flows and road safety.

Keywords: fire, fire vehicle, duration of travel, free development of fire, street and road network, travel route, graph model, simulation model

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АННОТАЦИЯ

Цель: Ставится задача разработать методологию уменьшение продолжительности свободного развития пожара на основе оптимизации маршрута движения пожарно-спасательной техники от пожарного депо до места вызова. Для этого необходимо провести анализ и выделение факторов, влияющих на продолжительность следования пожарного автомобиля к месту вызова для уменьшения продолжительности свободного развития пожара. Для решения обозначенной задачи исследовалась поведение пожарного автомобиля в системе «водитель – автомобиль – дорога – среда».

Методы: Проведение теоретических исследований осуществлялось на основе методов математического анализа, математической статистики, теории вероятностей и теории графов. Точность результатов теоретических исследований является допустимой для проведения инженерных расчетов. Обработка полученных результатов осуществлялась с использованием пакетов прикладных программ STATISTICA и Microsoft Excel. Для разработки алгоритма уменьшения продолжительности свободного развития пожара использовались методы имитационного моделирования, а также метод Монте-Карло.

Результаты: В работе показано, что наибольшее влияние на продолжительность свободного развития пожара имеет время следования пожарного автомобиля к месту вызова. Обоснована необходимость исследований поведения пожарного автомобиля в системе «дорожные условия – транспортные потоки» с целью уменьшения продолжительности его следования к месту вызова. Разработана графовая модель

оптимизации пути следования пожарного автомобиля от депо до места вызова. Разработана имитационная модель прогнозирования продолжительности следования пожарно-спасательного подразделения к месту вызова, что позволяет определить оптимальный маршрут следования и уменьшить продолжительность свободного развития пожара.
Выводы: В работе разработана методология уменьшение продолжительности свободного развития пожара на основе оптимизации маршрута движения пожарно-спасательной техники от пожарного депо до места возникновения чрезвычайной ситуации. Теоретические расчеты показывают, что разработанная методология позволяет уменьшить продолжительность следования специальных транспортных средств и, как следствие, уменьшить продолжительность свободного развития пожара в среднем на 7%. Установлено, что для определения всех возможных вариантов маршрута движения противопожарной техники целесообразно использовать теорию графов, в частности, такая модель приведена в работе. В дальнейшем целесообразно разрабатывать и совершенствовать существующие математические модели движения пожарного автомобиля путем учета параметров транспортных потоков и безопасности дорожного движения.
Ключевые слова: пожар, пожарная техника, продолжительность следования, свободное развитие пожара, улично-дорожная сеть, маршрут следования, графовая модель, имитационная модель
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ABSTRAKT

Cel: Zadaniem autorów jest opracowanie metodologii skrócenia czasu swobodnego rozwoju pożaru dzięki optymalizacji tras jednostek ratowniczo-gaśniczych między remizą a miejscem wezwania. Aby zrealizować ten cel należy przeprowadzić analizę oraz określić czynniki, które wpływają na czas dojazdu samochodu pożarniczego na miejsce wezwania. Na potrzeby realizacji określonego celu zbadano zachowanie się samochodu w systemie „kierowca – samochód – droga – otoczenie".
Metody: Przeprowadzone badania teoretyczne bazowały na metodach analizy matematycznej, statystyki matematycznej, rachunku prawdopodobieństwa i teorii grafów. Dokładność wyników badań teoretycznych została określona jako akceptowalna dla przeprowadzenia obliczeń inżynierskich. Otrzymane wyniki były przetwarzane z użyciem pakietów programów STATISTICA i Microsoft Excel. Do opracowania algorytmu skrócenia czasu swobodnego rozwoju pożaru wykorzystano modelowania symulacyjne oraz metodę Monte Carlo.
Wyniki: W artykule wykazano, że największy wpływ na okres swobodnego rozwoju pożaru ma czas dotarcia samochodu pożarniczego na miejsce wezwania. Udowodniono konieczność prowadzenia badań nad zachowaniem się samochodu pożarniczego w systemie „warunki drogowe – przepływ ruchu" w celu skrócenia czasu jego dotarcia na miejsce wezwania. Opracowano model grafowy optymalizacji trasy samochodu pożarniczego od remizy do miejsca zdarzenia oraz model symulacyjny do prognozowania czasu dojazdu samochodu pożarniczego na miejsce zdarzenia, umożliwiający wyznaczenie optymalnej trasy dojazdu i skrócenie czasu swobodnego rozwoju pożaru.
Wnioski: W artykule opracowano metodologię skrócenia czasu swobodnego rozwoju pożaru dzięki optymalizacji tras jednostek ratowniczo-gaśniczych między remizą a miejscem zdarzenia. Obliczenia teoretyczne potwierdzają, że opracowana metodologia pozwala skrócić czas dojazdu jednostek, i tym samym czas swobodnego rozwoju pożaru średnio o około 7%. Wykazano, że w celu określenia wszystkich możliwych wariantów trasy pojazdów pożarniczych należy wykorzystać teorię grafów. Przykład modelu grafowego został przedstawiony w artykule. W kolejnym kroku należy wykorzystywać i doskonalić istniejące modele matematyczne ruchu pojazdu pożarniczego wraz z uwzględnieniem w nich parametrów przepływu ruchu i bezpieczeństwa drogowego.
Słowa kluczowe: pożar, technika pożarnicza, czas dojazdu, swobodny rozwój pożaru, sieć drogowa, trasa dojazdu, model grafowy, model symulacyjny
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Formulation of the problem

Reducing the duration of the free development of fire is one of the key issues in the field of fire safety. This, in turn, will limit the damage caused by the fire. An analysis of the components of the duration of the free development of fire indicates that in most cases its substantial share is followed by fire and rescue units to the place of call. Therefore, today the problem of finding measures to reduce the duration of firefighters' travel to the place of call is extremely topical. A prerequisite for this is an analysis of the factors affecting the duration of the fire engine's travel to the place the call.

As stated above, in order to solve the priority task of reducing the duration of the free development of fire, it is necessary to search for directions for the optimisation of the time needed for the fire truck to reach the place of call. Scientific studies presented to date rarely focus on the analysis of the behaviour of a fire vehicle in the driver – car – road – environment system, which allows to distinguish factors that affect the length of travel of the fire truck to the place of call. Therefore, this study is aimed at solving an actual scientific and technical problem, which involves an analysis of the factors influencing the duration of the fire truck's travel to the place of call.

Analysis of recent research and publications

It is worth noting that a number of scientists are engaged in the outlined problem. In particular, there are well-known studies aimed at optimising the areas of departure of fire and rescue units. In [1], new distances for outlying areas for fire departments were obtained, in which there was a more even distribution of the number of calls for fire units and a 9% reduction in the time of arrival to the place of call. Due to the optimisation of the boundaries of service areas by fire and rescue units in [2], the time of travel to the place of call was reduced by 3%. In [3], an analysis of areas of service of fire and rescue districts of the city was considered, on the basis of which it was found that it is expedient to create a module for the division of the city into service areas, the algorithm of which is based on Voronoi diagrams.

The issues of the optimisation of travel routes are considered in the studies by Ukrainian scientists [4-6]. In [7], a model for selecting the route for special vehicles is proposed on the basis of track record data and special vehicle traffic routes collected for four years in North Virginia (USA). In [8], predicting the length of travel of special vehicles takes into account such factors as the intensity of traffic flow, the number of lanes on the highway network and the average speed of traffic flow. Paper [9] considers a model for the dynamic design of the routes covered by special vehicles, taking into account the time of the day, and, accordingly, the intensity of traffic flow. In [10], modeling of the process of motion of special vehicles takes into account their ability to deviate from some traffic rules, for example, to drive past prohibitory traffic signs. However, in these studies insufficient attention is paid to the impact of factors (for example, the arrangement of the street-road network, its characteristics, parameters of transport streams, and the technical means of the organisation of traffic) on the duration of travel to the place of call. Certain cases of the outlined problem were considered by the authors of this article in papers [4, 11–17].

Statement of the problem and its solution

The task is to develop a methodology for reducing the duration of the free development of fire on the basis of the choice of the optimal route for transporting fire equipment from the fire department to the place of calling the fire and rescue services. To do this, it is necessary to analyse and distinguish factors that affect the duration of the fire truck travel to the place of call, to reduce the duration of the free development of the fire.

According to the current legislation, in Ukraine, the radius serviced by one fire-rescue unit, i.e. one fire depot, is 3 km, which, depending on the area, translates into 28-30 km^2. Proceeding from this standard, it is possible to indicate areas of service in cities in the form of circles, the areas of which may partly overlap adjacent districts [4].

Of course, in reality, there is no such division of cities into areas of service of fire and rescue units. In practice, the distribution of districts is carried out based on certain streets, which are used as boundaries, allocating areas up to 30 km^2 for each unit of the service. In most cases such areas take the shape of polygons in which fire depots are usually displaced with respect to their centres.

The speed and safety of the fire truck movement is significantly influenced by traffic flow intensity, which varies not only depending on the parameters of the street-road network, but also on time of the day. The irregularity of traffic flow time directly affects the speed and, consequently, the length of travel of the fire truck to the place of call. The hourly irregularity of traffic flow intensity reflects the daily oddity factor k_d, which is determined by the average daily to hourly traffic intensity in a surveyed hour. Daily non-uniformity of traffic flow intensity can be traced from Fig. 1, which shows the dependence of the coefficient of daily inequality [17] on the intensity of traffic flows at a time of day.

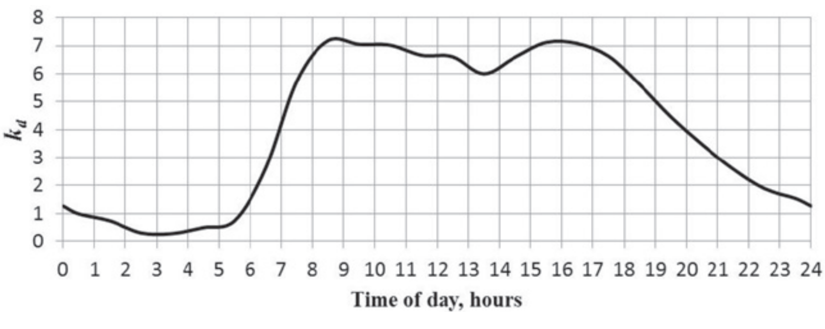


Figure 1. Dependence of the coefficient of daily irregularity of the intensity of traffic flow on time of day
Source: Own elaboration.

In order to achieve the goal, namely to reduce the duration of the free development of fire through the optimisation of the travel of fire engines to its place of destination, one should consider the proposed algorithm for solving this problem.

In the first stage, it is necessary to divide the service area into several sectors according to the directions of fire vehicle operated in the operational and dispatching service (for 5-6 sectors with the boundaries on the streets) so that each sector has within its limits 3-5 roads for possible travel in the radial direction from the fire depot to the extreme boundary of the service area sector using transverse roads for moving to radial roads that are characterised by smaller traffic congestion.

In the second stage, for each sector adopted, it is necessary to develop cascading graphs of road variants for the passage from the fire depot in a radial direction to the extreme boundary of the sector, taking into account all the possible intersections.

Recommendations [4, 5] should be taken into account. An example of a cascade graph is depicted in Fig. 2.

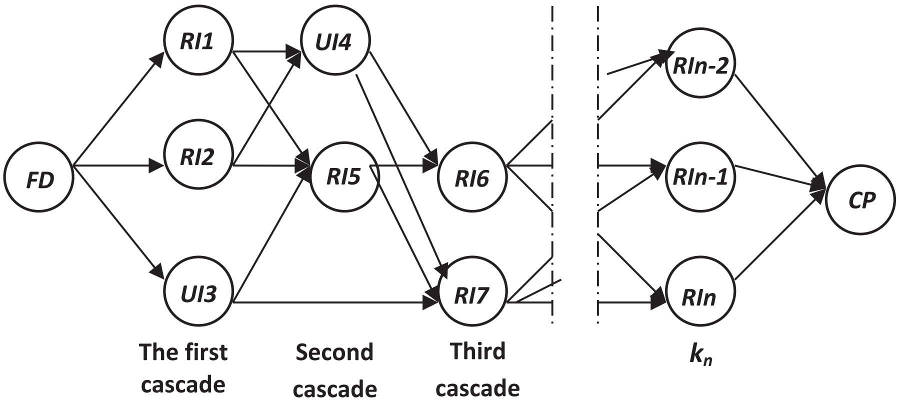


Figure 2. Cascade graph of options for the passage of a fire vehicle from a fire depot (FD) to the place of call (CP) along the roads with a length of l_i (edges of the graph) taking into account regulated (RI) and unregulated (UI) intersections [4]

The cascade graph of the variants of the routes of a fire vehicle from its fire depot (FD) to the place of call (CP) (Fig. 2) is constructed taking into account all the possible radial and transverse roads, whose length l_i corresponds to each individual edge of the graph. Each vertex of the graph corresponds to a crossroads that can be regulated using traffic lights (RI_i) or unregulated (UI_i).

In the third stage, it is necessary to determine, based on the results of observations, the average value of traffic intensity N of vehicles for the street-road network of the studied area. After that, taking into account Fig. 1, the influence of the operational time of day τ_{op} on the traffic load and accordingly on the intensity of traffic is established, based on the results of observations. Its influence on the coefficient k_1 is also taken into account. The value of coefficient k_1 can be determined by the results of observations performed, based on the formula

$$k_1 = \frac{N_d}{N} \quad (1)$$

where N_d – the actual value of traffic intensity, unit/s.

The results of observations can be presented as shown in Fig. 3.

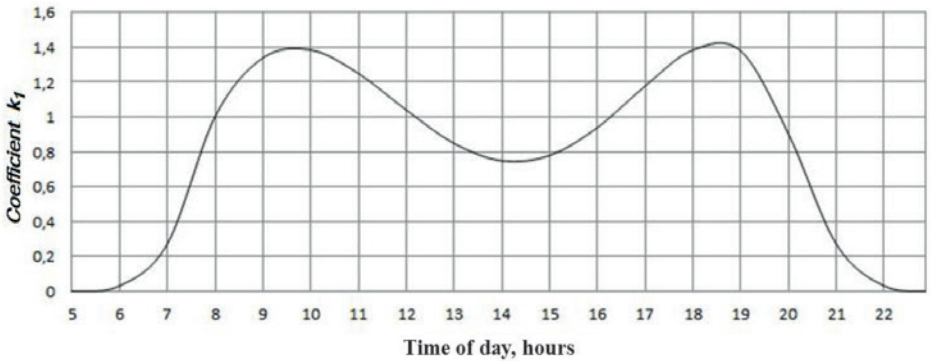


Figure 3. Influence of the operating time of day τ_{op} on the value of the coefficient k_1
Source: Own elaboration.

After processing the statistical data by employing the method of mathematical statistics, we can obtain a polynomial dependence for determining coefficient k_1 from the operational time of day τ_{op}.

$$k_1 = b_0 + b_1\tau_{op} + b_2\tau_{op}^2 + \ldots + b_5\tau_{op}^5 \quad (2)$$

where τ_{op} – operational time of day during which the departure of the fire vehicle from the fire department to the place of call can be performed (hour).

For example, for Lviv, coefficient k_1 was obtained by a polynomial model

$$k_1 = -19.04 + 3.93 \cdot \tau_{op} + 0.05312 \cdot \tau_{op}^2 - 0.05402501 \cdot \tau_{op}^3 +$$
$$+ 0.0037642 \cdot \tau_{op}^4 - 0.000078125 \cdot \tau_{op}^5$$

In addition, it is necessary to take into account the influence of the seasons by using coefficient k_2 regarding the intensity of traffic. Having adopted the symbol for the seasons $S = 1$ – summer; $S = 2$ – autumn; $S = 3$ – winter; $S = 4$

– spring, we can determine the value of k_2 using the following dependence

$$k_2 = 1.935 - 0.644S + 0.09S^2 \tag{3}$$

Undoubtedly, the intensity of traffic is also influenced by the days of the week. This effect is taken into account by introducing a coefficient k_3 whose value can be obtained by using the dependence in which days of the week correspond to the following: $D = 1$ – Monday; $D = 2$ – Tuesday; … $D = 7$ – Sunday. Then we get

$$k_3 = 0.8314 + 0.1807D - 0.0061D^2 - 0.0039D^3 \tag{4}$$

On the basis of the data obtained, it is possible to determine the actual value of the intensity of traffic N_d

$$N_d = Nk_1k_2k_3 \tag{5}$$

In the fourth stage, it is necessary to determine the time of vehicle delay τ_d at regulated and unregulated intersections. This issue is investigated by the authors in [4, 18]. Taking this into account, we can determine the total delay time τ_d:

$$\tau_d = \sum_{i=1}^{n} \tau_{ULi} + \sum_{i=1}^{k} \tau_{RLi} + \sum_{i=1}^{z} \tau_{TLi} \tag{6}$$

where n – number of unregulated intersections on the route taken; τ_{ULi} – time spent passing an unregulated intersection, which is determined by method [4, 17]; k – number of regulated intersections on the route taken; τ_{RLi} – time spent passing a regulated intersection, which is determined by method [4, 17]; z – the number of transport interchanges at different levels on the route taken; τ_{TLi} – time spent passing a transport interchange at various levels, which is determined by method [4, 17].

The fifth stage determines the total number of options for driving to the place of call using the following dependence

$$B = \left(\sum_{i=1}^{n} B_{1i}\right) \cdot \left(\sum_{i=1}^{n} B_{2i}\right) \cdot \ldots \cdot \left(\sum_{i=1}^{n} B_{ki}\right) \tag{7}$$

where B_{1V}, B_{2V}, …, B_{kV} – variants of crossroads according to all stages of the graph (Fig. 2) (from 1st to *kth*); n – the number of variants of the intersection on the corresponding cascade graph.

The sixth stage was carried out using a suite of PC applications developed at the Lviv State University of Life Safety, calculations of travel route L_j and delay times T_j for all variants of routes B from the fire department to the place of call using dependencies

$$L_j = \sum_{i=1}^{k} l_i\,; \quad T_j = \frac{1}{60} \sum_{i=1}^{k} \tau_{d.i} \tag{8}$$

where l_i – the length of the roads between the intersections along the route j, km; $\tau_{d.i}$ – time delays at road crossings along the route j, min (calculated values $\tau_{d.i}$ according to dependence (6) in seconds).

In the seventh stage, we determine the travel time $\tau_{f.j}$ for all variants of routes B from the fire department to the place of call. In [2], the results of experimental studies on the speed of the fire and rescue vehicle in the city during its travel to the place of the fire in different parts of the city at any time of day are given. In carrying out these studies, we took into account the distance from the fire and rescue unit to the place of call L_i and the time of day τ_i. Empirical dependencies were obtained for determining the time of travel from the fire department to the place of call and, accordingly, the average speed of the fire and rescue vehicle [2]:

$$V_i = \frac{60L_i}{4.18 + 1.97L_i - 0.2\tau_i} \tag{9}$$

where L_i – distance from the fire depot to the object, km; τ_V – time of day 0–24 (from 0 to 8 hours in dependence (9); using 24-hour clock) (hour).

The analysis of dependence (9) allowed us to specify the response surface of the length of travel of the fire truck to the place of call τ_f from distance L and at time of day T (Fig. 4).

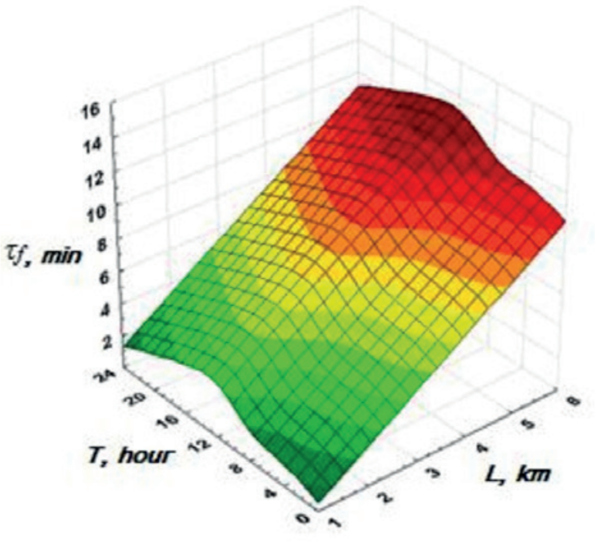
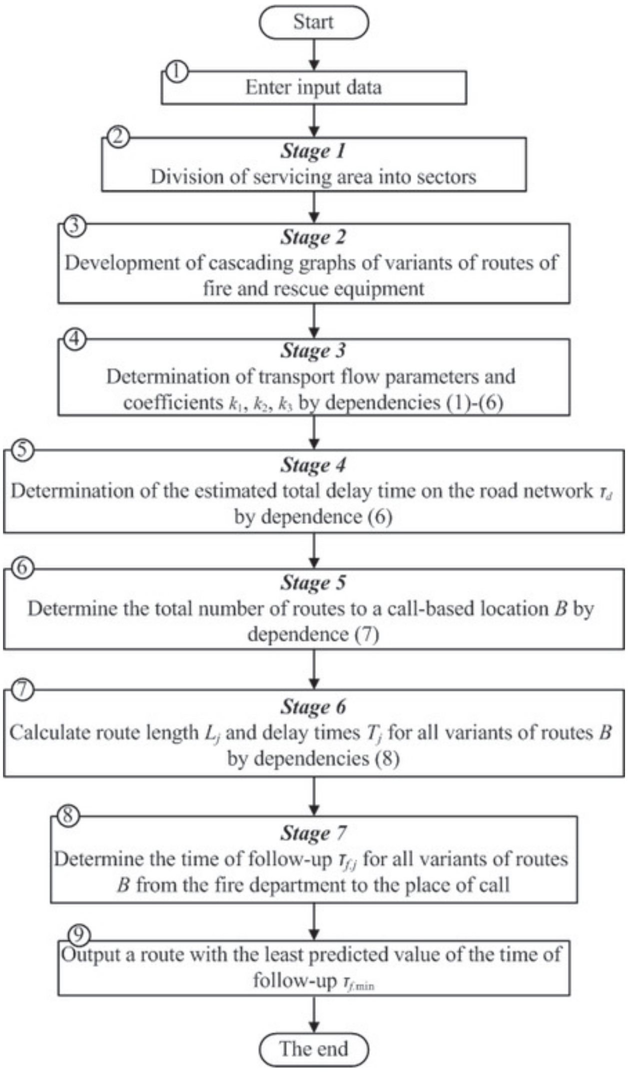


Figure 4. Surface response depending on the length of travel of fire vehicle to place of call *τf* from distance *L* and time of day *T*
Source: Own elaboration.

After defining the travel time $\tau_{f.j}$ for all routes B, we select the least time $\tau_{f.min}$ from the obtained values and accept the appropriate travel route at that time.

To implement the methodology described above, an algorithm was developed in the form of an imitation model (Fig. 5).



* time of follow-up -> travel time

Figure 5. Structural scheme of the algorithm-simulation model for reducing the duration of the free development of fire on the basis of choosing the optimal route for the fire vehicle
Source: Own elaboration.

On the basis of the results of theoretical and experimental research, using the STATISTICA application package, it was possible to obtain the response surface of the dependence of the duration of the fire truck travel to the call point at the distance and time of day in conditions of the Lviv street and road network (Fig. 6).

Also, the dependencies describing the surface (Fig. 6) were obtained and the length of travel of the fire truck to the place of call according to the optimal route based on the proposed methodology (Fig. 6, a) was determined:

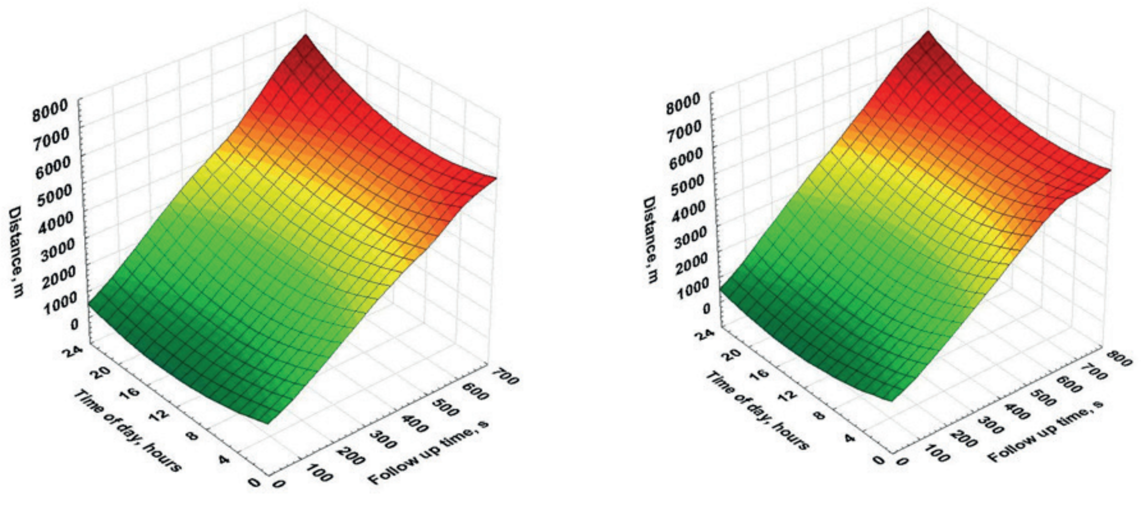
$$\tau_{f.est.} = -42.5725 + 16.553T + 0.0983L - \\ -0.6755T^2 - 0.0003TL + 0.0000028471L^2 \qquad (10)$$

where T – time of day 0-24 (instead of 0 in dep. (10) substitute 24), hour, L – distance to the call location, m.

and the set route in accordance with the operational fire extinguishing plan (Fig. 6, b):

$$\tau_{f.sh.} = -65.4236 + 19.4235T + 0.1149L - \\ -0.7976T^2 - 0.000096041TL + 0.0000011559L^2 \qquad (11)$$

The analysis of the obtained surfaces (Fig. 6) and dependencies (10), (11) shows that the use of the developed methodology in the conditions of the street-road network in Lviv will make it possible to reduce the duration of the travel of fire and rescue vehicles by optimising the route by approximately 7% and, respectively, limit the duration of the free development of fire.



a) b)

Figure 6. Surveys of response depending on the length of travel of the fire truck to the place of call τ_f conditional on distance L and time of day T in conditions of the street-road network in Lviv: a – according to the optimal route based on the proposed methodology; b – according to the established route based on the operational fire extinguishing plan

Source: Own elaboration.

Conclusions

This work develops the methodology of reducing the duration of the free development of fire on the basis of optimising fire and rescue vehicles movement routes from the fire department to the place of emergency. Theoretical calculations show that the developed methodology makes it possible to reduce the length of travel of special vehicles and, consequently, reduce the duration of free fire development on average by 7%. It is established that in order to determine all the possible variants of the fire-propulsion traffic route it is expedient to use the theory of graphs, in particular the model presented in the study. In the future, it will be beneficial to develop and improve the existing mathematical models of fire vehicle movement, taking into account the parameters of traffic flow and road safety.

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