ISSN 0005-1179 (print), ISSN 1608-3032 (online), Automation and Remote Control, 2024, Vol. 85, No. 10, pp. 981–994.

TOPICAL ISSUE

System Dynamics Models for Control the Road Transport System of a Mega City

A. D. Tsvirkun[*,a], **A. S. Bogomolov**[**,b], **O. I. Dranko**[*,c], **V. A. Kushnikov**[**,d], **M. S. Polyakov**[**,e], **A. F. Rezchikov**[*,f], **and I. A. Stepanovskaya**[*,g]

[*] *Trapeznikov Institute of Control Sciences, Russian Academy of Sciences, Moscow, Russia*
[**] *Saratov Scientific Center, Russian Academy of Sciences, Saratov, Russia*
e-mail: [a]*tsvirkun@ipu.ru,* [b]*bogomolov@iptmuran.ru,* [c]*olegdranko@gmail.com,* [d]*kushnikoff@yandex.ru,* [e]*maxg6000@mail.ru,* [f]*rw4cy@mail.ru,* [g]*irstepan@ipu.ru*

Received May 27, 2024
Revised July 6, 2024
Accepted July 25, 2024

Abstract—We have developed a set of system-dynamic models for managing the road transport system of a metropolis, taking into account traffic safety indicators. We determined the main indicators of the road transport system in accordance with the Road Safety Strategy in the Russian Federation for 2018–2024, as well as on the basis of regulatory documents of the State Traffic Inspectorate of the Ministry of Internal Affairs of Russia for the city of Moscow. The results of the work are intended to improve the mathematical support of traffic control systems in large cities.

Keywords: system dynamics model, road transport network, management, traffic safety

DOI: 10.31857/S0005117924100067

1. INTRODUCTION

In accordance with the Road Traffic Safety Strategy in the Russian Federation [1], a promising direction for the development of road transport systems in megacities is the use of intelligent traffic control systems. The main purpose of the operation of such large-scale systems is to ensure the required level of basic road safety indicators (hereinafter referred to as indicators) (Fig. 1).

The values and dynamics of these indicators are taken into account when developing the transport infrastructure of megacities, planning the activities of federal and municipal authorities, developing measures to reduce road traffic accidents and injuries, analyzing the causes of road accidents, developing and justifying urban planning decisions, planning the activities of companies involved in auto insurance, etc.

An important problem that complicates the development of the road transport system in Russia and hinders the application of the concept of intelligent traffic control systems in its megacities is the fairly high level of accidents on the country's roads and the associated significant number of deaths in road accidents (Fig. 2).

One of the ways to improve road safety is related to the development and improvement of models and algorithms for decision support systems for traffic management.

The theoretical substantiation of the principles of functioning of large-scale decision support systems of an interdisciplinary nature, widely used in intelligent traffic management, was carried out in

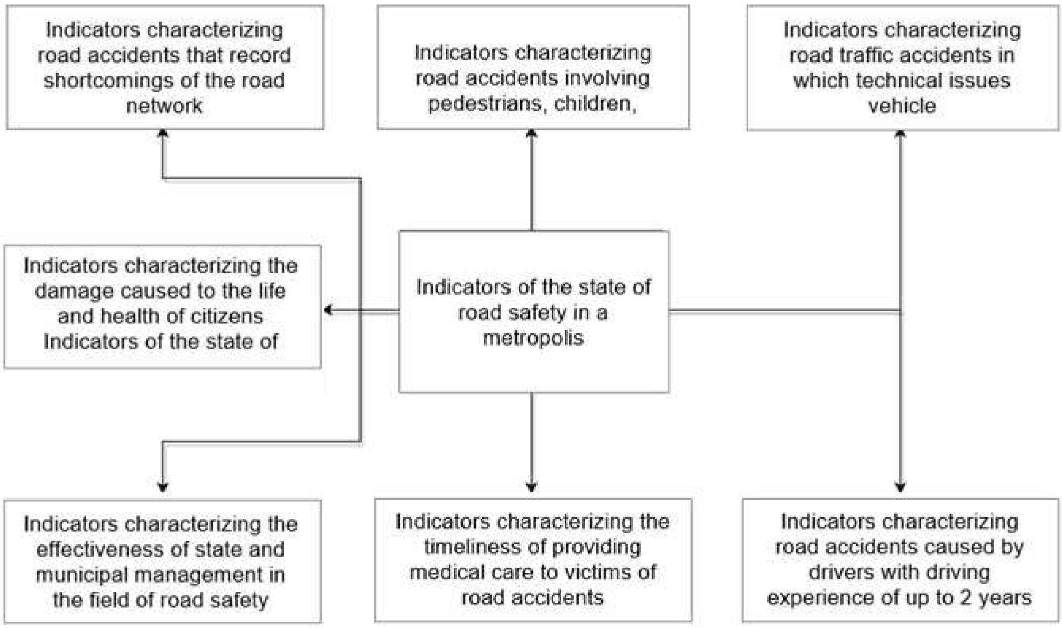


Fig. 1. Road safety indicators [1].

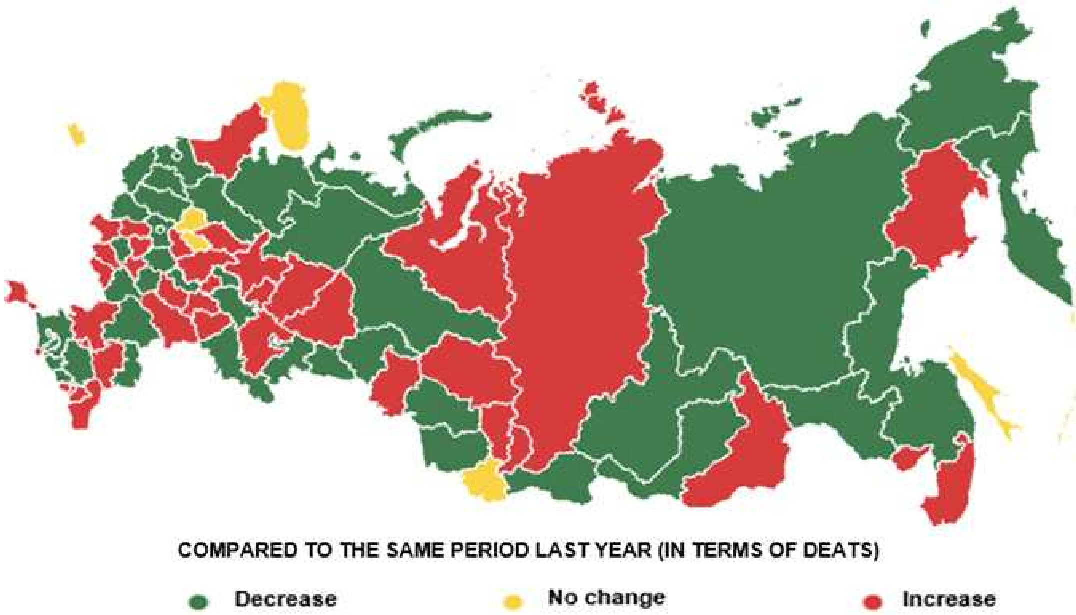


Fig. 2. Dynamics of the number of deaths in road accidents in Russia during the year [2].

the works of a number of major domestic and foreign scientists, such as N.P. Buslenko, S.N. Vasiliev, A.J. Wilson, Yu.B. Germeyer, K.F. Daganzo, H. Inose, D.A. Novikov, A.F. Rezchikov, T. Hamada, A.D. Tsvirkun et al. As a result of the practical application of the results obtained, effective means of monitoring and controlling traffic have been created and are successfully operating, including in modern megacities. The development of such systems is supported by research on many different aspects of the problem of road safety in Russia and abroad [3–9]. However, there are no publications on Russian systems for monitoring and managing the dynamics of safety indicators of city road transport systems in their complex interconnected complex. Insufficient elaboration of the theoretical aspects of creating mathematical support for such intelligent control systems reduces the accuracy of the forecast of the main indicators of road traffic, reduces the efficiency and quality of decisions made. This circumstance determines the practical significance of the topic of the work.

2. THE PROBLEM OF CONTROL THE ROAD TRANSPORT SYSTEM OF A METROPOLIS

When forming a criterion for the effectiveness of the problem being solved, characterizing the amount of losses from violations of road safety in a metropolis, a number of problems arise. The main ones are related to the influence of the human factor that is difficult to formalize, the high dimensionality of the problems being solved, and the impossibility or irreproducibility of full-scale experiments. There are also certain difficulties in a complete formal description of lists and individual loss factors associated with violations of the safety of a large and complex system (road traffic in this case), identifying a satisfactory set of control variables and disturbances, etc. In this regard, when developing the formulation of the problem, assumptions were made, which, according to the authors, are quite often met in the process of functioning of the road transport system of a metropolis.

1) Regular or fairly frequently recurring situations that affect road safety are considered (for example, changes in road conditions in the autumn-winter period, emergency situations arising due to the inattention of pedestrians or drivers).

2) With time and other resource limitations, loss reduction can be achieved through more efficient and high-quality management decisions, which are formulated in the form of sets of measures (plans).

3) Decision-makers in the field of metropolitan road safety have an informed opinion about the desired indicative values of the indicators. These values may vary within certain limits depending on the situational context, dynamics in neighboring and similar regions. The basic average values of indicators are selected on the basis of expert experience and existing standards. In what follows we will call them recommended indicator values.

4) The damage from a security breach depends on the weighted sum of indicator deviations X_i^*, $i=\overline{1,n}$, from recommended values $X_i^*(t)$, $i=\overline{1,n}$. We assume that with increasing deviations $X_i^* - X_i(t,p(t))$ damage to people, vehicles, infrastructure, etc., or the costs of operating the metropolitan road transport system increases.

5) Decision-makers have several alternative solutions to improve the safety of the road transport system, for each of which an action plan $p(t) \in P$ has been built. Each of these plans involves certain costs that must fit within the existing resource constraints.

Taking into account these assumptions, we can imagine the problem of choosing a plan that achieves a minimum of the target function, equal to the weighted sum of squared deviations of indicators from the recommended values. This requirement is reflected in condition (1).

Conditions (2) and (3) reflect restrictions on the rates and boundaries of changes in variables. These restrictions are established based on the analysis of cause-and-effect relationships in the area under consideration and taking into account the meaning of the problem.

Given the above, the problem may have the following formulation.

To develop mathematical models and methods for managing the road transport system of a metropolis, allowing for a period of time $t \in [t_0; t_N]$ determine an action plan $p(t) \in P$, which minimizes the objective function under consideration:

$$Z(p(t)) = \int_{t_0}^{t_N} \sum_{i=1}^{n} (X_i^* - X_i(t,p(t))^2 \gamma_i dt \to \min . \tag{1}$$

With restrictions:

$$\frac{dX_i(t)}{dt} = f_i(t, X_1(t), \ldots, X_n(t), p(t)), \quad i = \overline{(1, n)},$$
$$X_i(t_0) = X_{i0}, \quad i = \overline{1, n}, \tag{2}$$

$$\forall t \in [t_0; t_N]\, X_i^{\min} \leqslant X_i(t, p(t)) \leqslant X_i^{\max}, \quad i = \overline{1, n}, \tag{3}$$

and boundary conditions:

$$F_i^{t_0}(X, X', p) = 0, \quad F_j^{t_N}(X, X', p) = 0, \quad i = \overline{1, k_1}, \quad j = \overline{1, k_2},$$

$X_i(t),\ i = \overline{1, n}$, and X_i^* – indicators and their recommended values;
γ_i – weight coefficients;
$X_i^{\min}, X_i^{\max}$ – minimum and maximum value of the indicator.

Approach to solving the problem. When solving problem (1)–(3), we use system dynamics equations as a control model. During their formation, the well-known dynamic model

$$\frac{dI_j(t)}{dt} = F_j(I_1, \ldots, I_n), \quad j = \overline{1, n}, \tag{4}$$

interpreted as:

$$\frac{dI_j(t)}{dt} = \alpha_{j,0} + \sum_{k=1}^{n} \alpha_{j,k} \prod_{l}^{n} \omega_{j,k,l}(I_l) I_k, \quad j = \overline{1, n}. \tag{5}$$

The validity of the transition from (4) to (5) is explained as follows. If a comparison of the collected statistical information with the calculated values shows that system (5) describes the control object with the required accuracy, then it can be used to solve the problem. Extensive experience in applying the system-dynamic approach [10–14] has shown that systems of the form (5) describe a fairly wide class of various phenomena.

3. MATHEMATICAL MODEL

Mathematical models are built for all action plans. The main stages of constructing the model are shown in Fig. 3.

The lists of indicators of a large-scale system (Fig. 1) contain many hundreds of items; their detailed analysis is hardly advisable to carry out within the framework of one article. Therefore, without loss of generality, let us consider those presented in Table 1 as such indicators.

Indicators were selected based on expert analysis of the Strategy [1] taking into account the availability of open and reliable data on these indicators for several years [2]. External factors affecting road safety are taken into account in the work as disturbances (Table 2). These factors were selected based on an analysis of the results of a survey of road users in large cities of the Russian Federation.

For the variables and disturbances under consideration, differential equations of the form are constructed

$$\frac{dX(t)}{dt} = X^+(t) - X^-(t). \tag{6}$$

($X^-(t), X^+(t)$ – negative and positive rates of change of a variable).

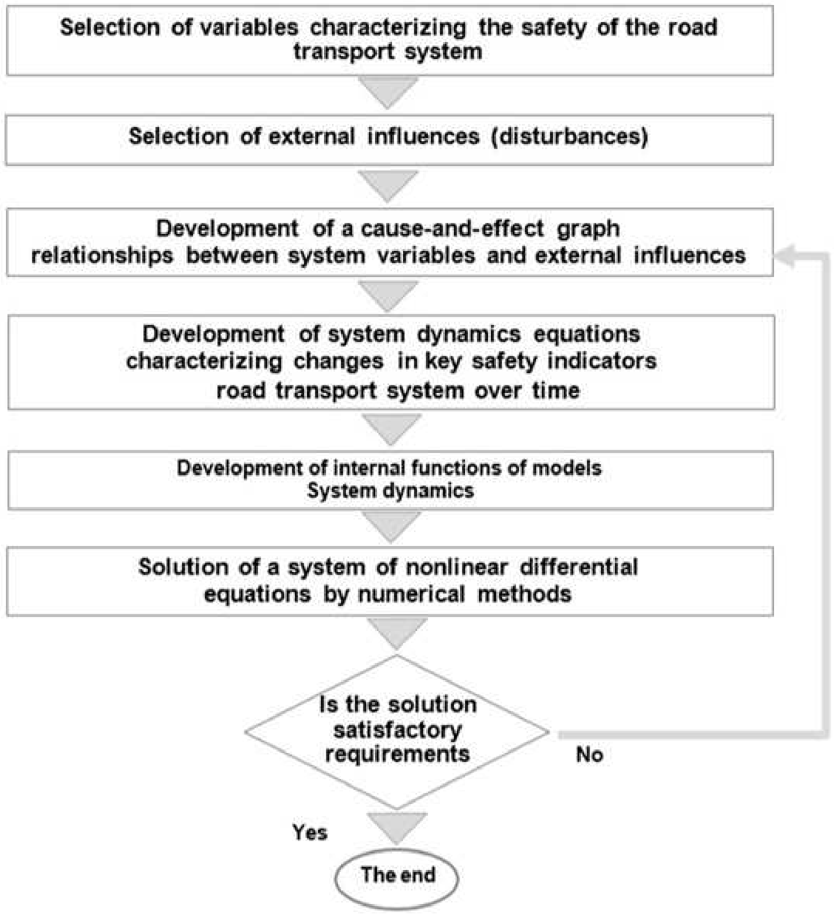


Fig. 3. Stages of model development.

Table 1. Main safety indicators of the road transport system, number per year

Variable	Designation
Accidents on public roads	$X_1(t)$
Accidents at railway crossings	$X_2(t)$
Road accident, vehicle fled from the scene	$X_3(t)$
Road accident, the driver fled the scene, the vehicle is still there	$X_4(t)$
Accident with unidentified vehicles	$X_5(t)$
Accidents with injured drivers	$X_6(t)$
Road accident with injured passengers	$X_7(t)$
Accidents with injured pedestrians	$X_8(t)$
Road accidents involving children under 18 years of age	$X_9(t)$
Road accidents in populated areas	$X_{10}(t)$
Accidents involving drunken pedestrians	$X_{11}(t)$
Road accidents due to violations by car drivers	$X_{12}(t)$
Road accidents due to violations by drivers 16-18 years old	$X_{13}(t)$
Road accidents due to violations by male drivers	$X_{14}(t)$
Road accidents due to violations by female drivers	$X_{15}(t)$

Table 2. Disturbances affecting key safety indicators

External factor	Designation
Number of vehicles older than 10 years	$G_1(t)$
Degree of vehicle wear	$G_2(t)$
Number of complexes of photo-video recording of violations	$G_3(t)$
Number of issued driver's licenses	$G_4(t)$
Length of road sections	$G_5(t)$
Average fine for traffic violation	$G_6(t)$

Table 3. Causal relationships between model variables

	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}	X_{13}	G_1	G_2	G_3	G_4	G_5	G_6
X_1	0	0	0	0	0	0	+	+	+	+	+	+	0	+	+	–	P_1	–	–
X_2	0	0	0	+	+	0	0	+	+	0	+	0	0	0	+	–	–	–	–
X_3	0	0	0	0	0	+	+	+	+	+	+	+	+	+	+	0	–	0	–
X_4	0	+	0	0	+	0	+	+	+	0	+	0	0	0	+	–	–	–	–
X_5	0	+	0	+	0	0	+	+	0	0	+	0	0	+	+	–	–	–	–
X_6	0	0	+	0	0	0	+	+	+	+	+	0	+	0	0	–	–	0	–
X_7	+	–	0	0	–	0	0	+	0	–	0	0	+	+	0	–	–	–	P_2
X_8	+	0	0	0	0	0	+	0	+	0	+	+	0	+	+	0	–	0	–
X_9	+	–	–	0	0	0	0	0	0	+	+	+	0	+	0	0	0	0	0
X_{10}	+	–	–	0	0	0	+	+	+	0	0	0	+	+	0	–	–	–	–
X_{11}	+	0	0	0	0	0	0	+	0	0	0	+	0	0	P_3	0	–	0	–
X_{12}	+	0	0	0	0	0	+	+	0	0	+	0	0	0	+	0	–	0	0
X_{13}	+	+	+	+	+	+	+	+	0	0	0	0	0	0	+	–	–	–	–

A multiplicative representation of the influence of factors is allowed:

$$X^{\pm}(t) = f(F_1(t), F_2(t), \ldots, F_k(t)) = f_1(F_1(t))f_2(F_2(t)) \ldots f_k(F_k(t) \tag{7}$$

$F_1 \ldots F_k$ – factors (variables or external influences).

In our work we assume that the system variables are quantitative in nature. Then their normalized values can be used in calculations:

$$X_i^*(t) = \frac{X_i(t)}{X_i^{norm}}, \quad i = \overline{1, \ldots, 17}, \tag{8}$$

(X_i^{norm} – normalization coefficient). Normalization allows you to avoid inconsistencies in the dimensions of various system indicators and improve the comparability of their values. If variables and disturbances are measured qualitatively, then the apparatus of the theory of fuzzy sets can be used to move to quantity.

To display the cause-and-effect relationships of the dynamics of indicators, similarly to [15], a matrix and graph are constructed:

$$U_{i,j} = \begin{cases} -, & \text{increase in variable } X_j \text{ or external factor } G_j \text{ leads to a decrease } X_i, \\ 0, & \text{variable } X_j \text{ or external factor } G_j \text{ or external factor } X_i, \\ +, & \text{increase in variable } X_j \text{ or external factor } G_j \text{ leads to a increase } X_i, \\ P_i, & \text{influence } X_j \text{ to increase or decrease } X_i \text{ is determined by a system of conditions.} \end{cases}$$

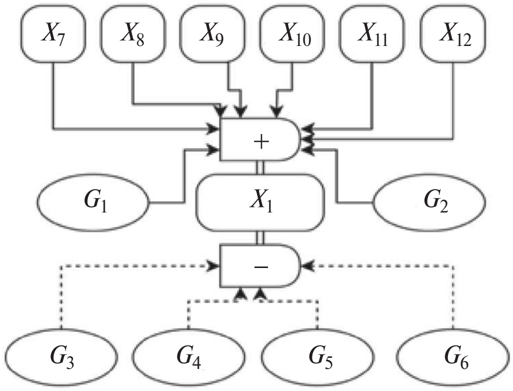


Fig. 4. Subgraph for variable X_1.

Based on the analysis of current data of the subject area in the example under consideration, we took $Pr_1 = 1$; $Pr_2 = 1$; $Pr_3 = -1$.

The arcs of the graph define the cause-and-effect relationships between variables. In Fig. 4 shows the vertex of the graph for X_1.

Based on the matrix and graph of cause-and-effect relationships, system dynamics equations are constructed:

$$\frac{dX_i}{dt} = \frac{1}{X_i^{norm}} \left(\prod_{i,j} f_{i,j}(X_j^+) \times \sum_m G_m^+ - \prod_{i,k} f_{i,k}(X_k^-) \times \sum_n G_n^- \right). \tag{9}$$

Expressions of the form $f_{A,B}(X_B)$ denote the dependence of X_A on X_B, which are established using regression analysis.

The functional dependencies determined by the above method are substituted into (9), the initial conditions are set, and the resulting system of differential equations is solved by one of the numerical methods, for example, Runge–Kutta of the fourth order of accuracy. The results obtained are approximated by polynomials of small degrees. Then these polynomials are substituted into the integrand (1) and the value of a certain integral is calculated corresponding to the action plan for which the mathematical model (9) is built. The solution to the problem is the plan with the smallest value of the objective function.

4. MODEL EXAMPLE

For the model example, the statistical data given in [2] was used. To illustrate the technique, consider the procedure for generating functions $f_{1,B}(X_B)$ expressing the dependence of the total number of accidents on the number of accidents due to various reasons:

$$\begin{aligned} f_{1,7}(X_7(t)) &= 6.7X_7^2 - 11.3X_7 + 5.66, \\ f_{1,8}(X_8(t)) &= -1.51X_8^2 + 2.45X_8 - 0.04, \\ f_{1,9}(X_9(t)) &= -0.95X_9^2 + 1.64X_9 + 0.24, \\ f_{1,10}(X_{10}(t)) &= -2.65X_{10}^2 + 5.24X_{10} - 1.64, \\ f_{1,11}(X_{11}(t)) &= -0.58X_{11}^2 + 0.83X_{11} + 0.65, \\ f_{1,12}(X_{12}(t)) &= -1.55X_{12}^2 + 2.74X_{12} - 0.28. \end{aligned} \tag{10}$$

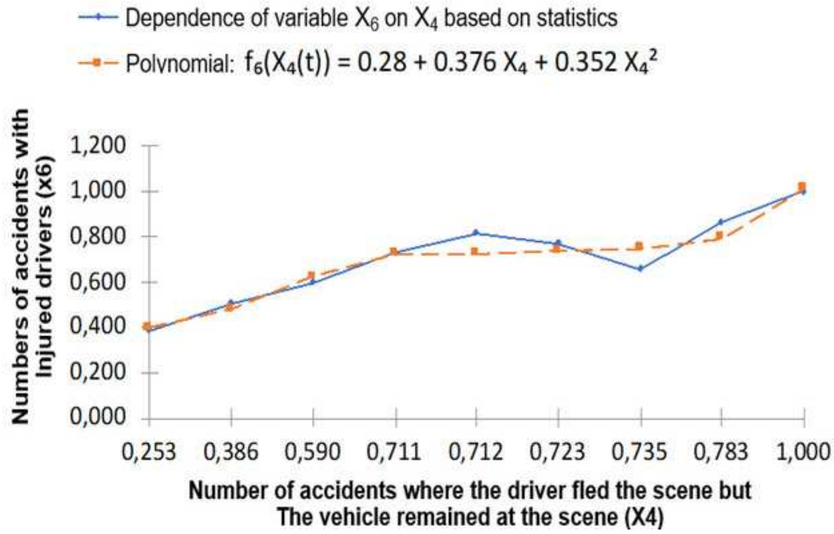


Fig. 5. Graph of the dependence of the number of accidents with injured drivers (indicator X_6 on the number of accidents from the scene of which the driver fled, but the vehicle remained in place indicator X_4).

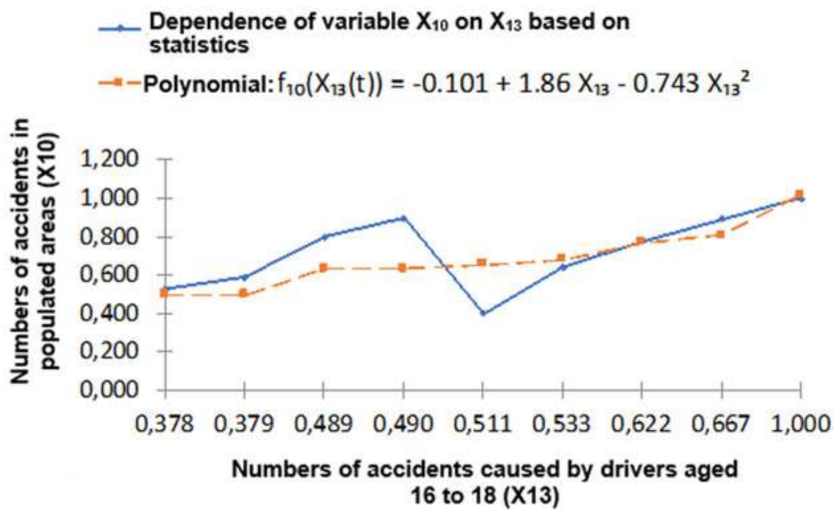


Fig. 6. Graph of the dependence of the number of accidents (indicator X_{10}) on the number of accidents due to violation of traffic rules by drivers whose age is from 16 to 18 years (indicator X_9).

In Figs. 5 and 6 show graphs of the indicated dependencies as an example.

Based on similarly identified dependencies, a system of nonlinear differential equations was constructed, for solving which the Runge–Kutta method of 4th order of accuracy was used (part of one of the Python libraries). The solution to the system was obtained under the initial conditions given in Table 4; the solution results in the form of graphs are shown in Fig. 7 and approximated

Table 4. Initial conditions

X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}	X_{13}
0.89	1	0.86	1	0.95	0.87	0.84	1	1	0.95	1	0.95	0.62

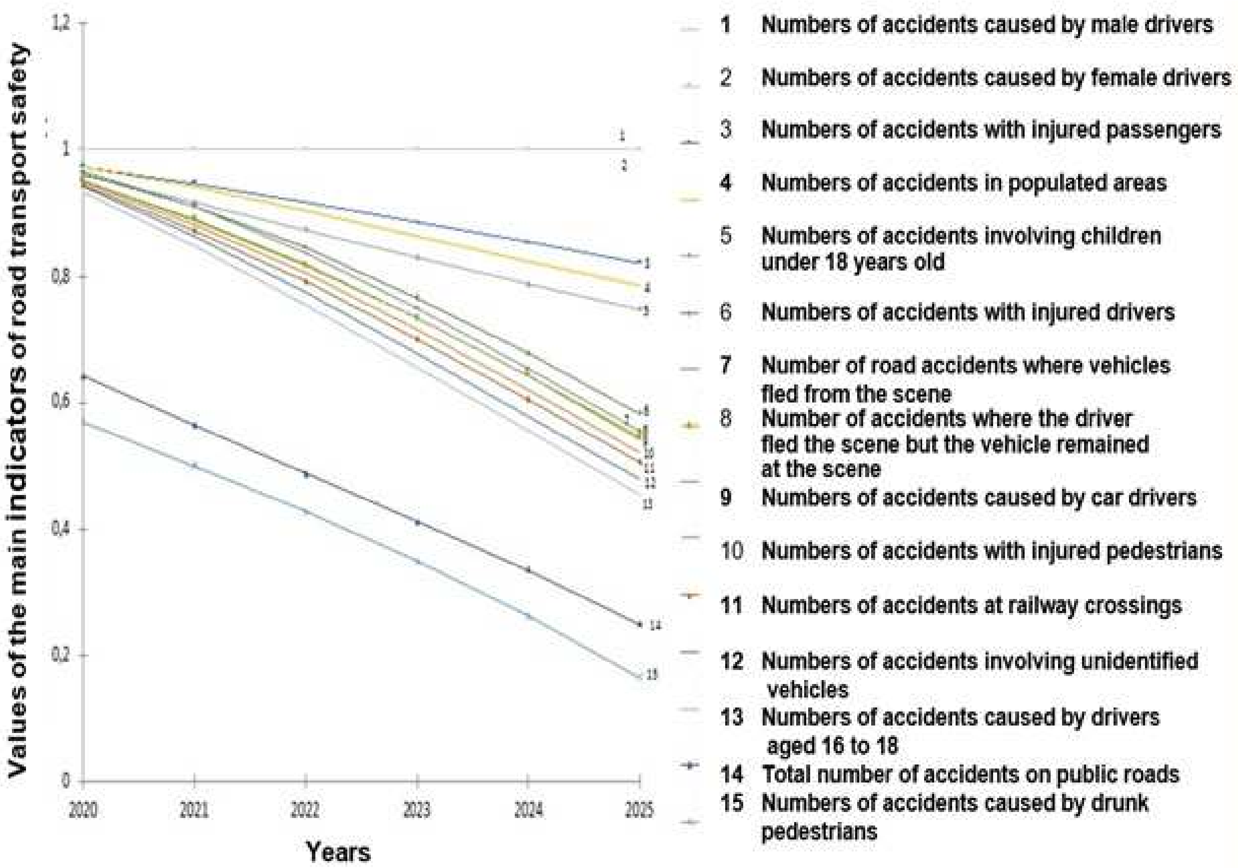
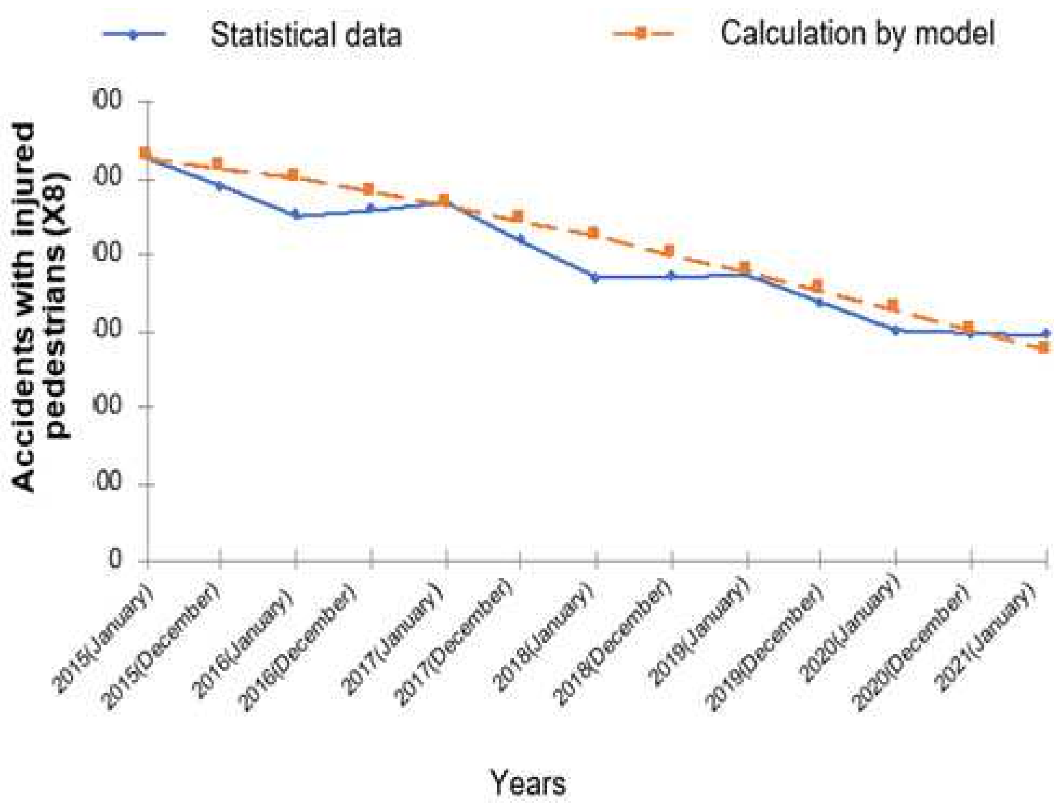


Fig. 7. Solution results.

by polynomials (12).

$$
\begin{aligned}
X_1(t) &= -0.00072t^2 - 0.0728t + 0.7135,\\
X_2(t) &= -0.0035t^2 - 0.0638t + 1.0128,\\
X_3(t) &= -0.0054t^2 - 0.0456t + 1.0198,\\
X_4(t) &= -0.0044t^2 - 0.0503t + 1.0058,\\
X_5(t) &= -0.0027t^2 - 0.0743t + 1.0198,\\
X_6(t) &= -0.0054t^2 - 0.0385t + 1.0081,\\
X_7(t) &= -0.0006t^2 - 0.0267t + 1.0017,\\
X_8(t) &= -0.0043t^2 - 0.056t + 1.0097,\\
X_9(t) &= 0.0004t^2 - 0.045t + 1.0041,\\
X_{10}(t) &= -0.0006t^2 - 0.0338t + 1.0092,\\
X_{11}(t) &= -0.0036t^2 - 0.0555t + 0.6269,\\
X_{12}(t) &= -0.0052t^2 - 0.0469t + 1.0035,\\
X_{13}(t) &= -0.0017t^2 - 0.0846t + 1.0217.
\end{aligned}
\tag{11}
$$

The results obtained correlate quite well with the statistical data presented on the website of the State Traffic Inspectorate of the Ministry of Internal Affairs of Russia [2]. The smooth nature of the graphs can be explained by the fact that Strategy [1] provided for a uniform decrease in the values of these indicators.



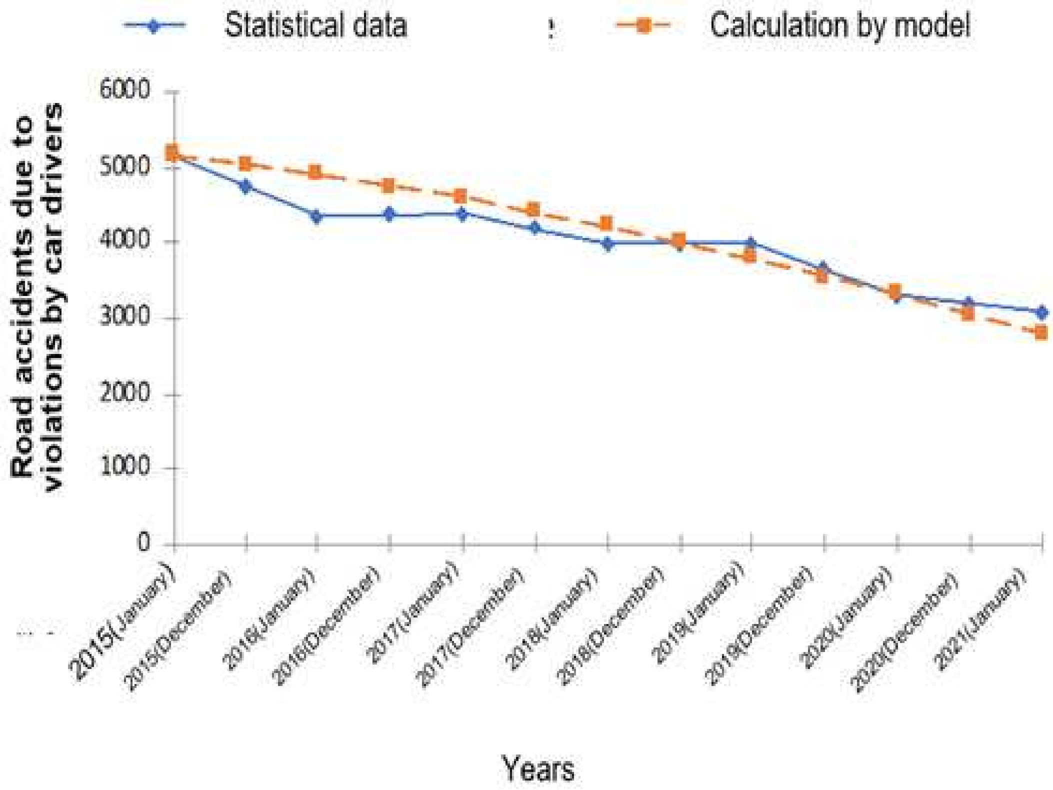


Fig. 8. Comparison of statistical and calculated data for safety indicators $X_8(t)$ and $X_{12}(t)$.

4.1. Model correction

When developing a mathematical model of a large-scale system, a number of conflicting requirements must be met. Firstly, one should take into account the high dimension of the modeling object, the presence of a complex system of relationships between its parameters, as well as their possible significant time drift. Secondly, it is necessary to ensure the required accuracy of the model, especially over long time intervals, and also to maintain the duration of its development acceptable for the decision maker. Fulfillment of these requirements forces us to simplify the mathematical description of a large-scale system, which leads to a reduction in the complexity, time and accuracy of the created model and makes it necessary to carry out its periodic correction. Correction of the mathematical model is carried out by changing the list of cause-and-effect relationships of indicators and factors, adding new indicators in order to increase the accuracy of the modeling. When solving problem (1)–(3), the model is corrected if the error in determining at least one of the main indicators $X_i(t),\ i = \overline{1.15}$ exceeds 10%. This value was chosen as a result of generalizing the opinion of specialists responsible for ensuring the transport safety of the city and the developers of the system dynamics model; if necessary, the amount of permissible error can be changed. Let us consider, as an example, the procedure for correcting the calculated value of the variable X_4. To do this, we will use statistical data characterizing the change in this variable in 2004–2020 [2].

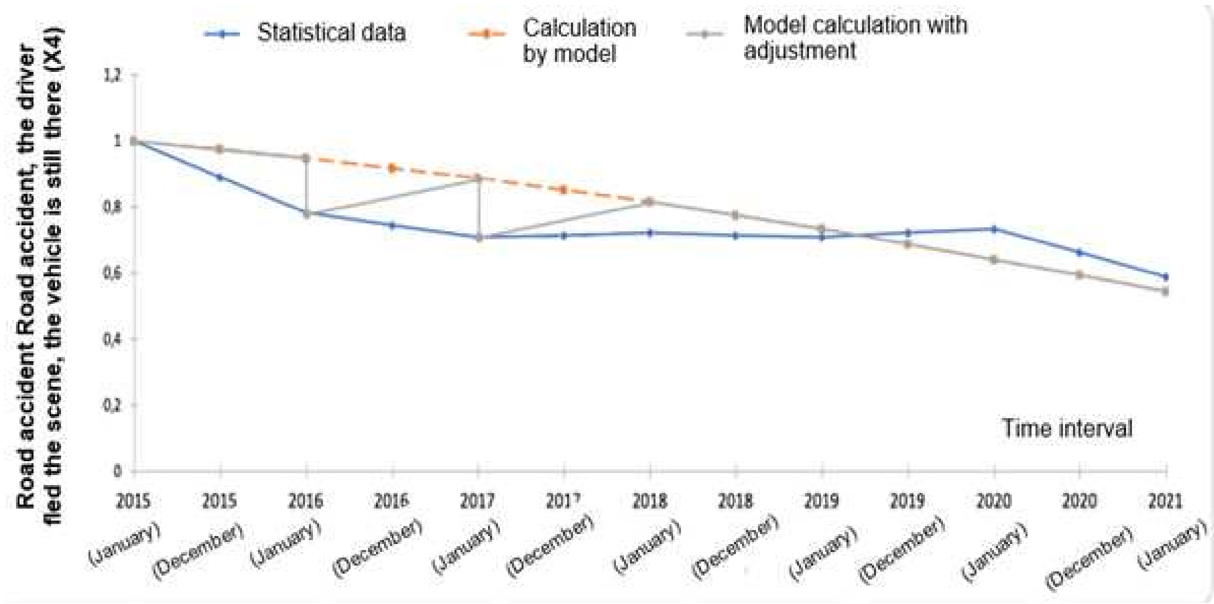


Fig. 9. Correction for variable $X_4(t)$.

In Fig. 9 it can be seen that from January 2004 to June 2005, no correction was made, and then it was carried out (broken line).

4.2. Procedure for solving the problem for a model example

Without reducing the generality of the reasoning, let us assume that the set of alternative plans P, which the decision maker developed to solve problem (1)–(3), consists of three elements p_1, p_2, p_3. In accordance with the formulation of problem (1)–(3), to solve it it is necessary to determine such an action plan $p_i,\ i = \overline{1,3}$, which corresponds to the minimum value of the objective function $Z(p(t))$. In addition, this plan must satisfy condition (3), according to which the main indicators must not go beyond the boundaries specified for them. The limits are determined for each

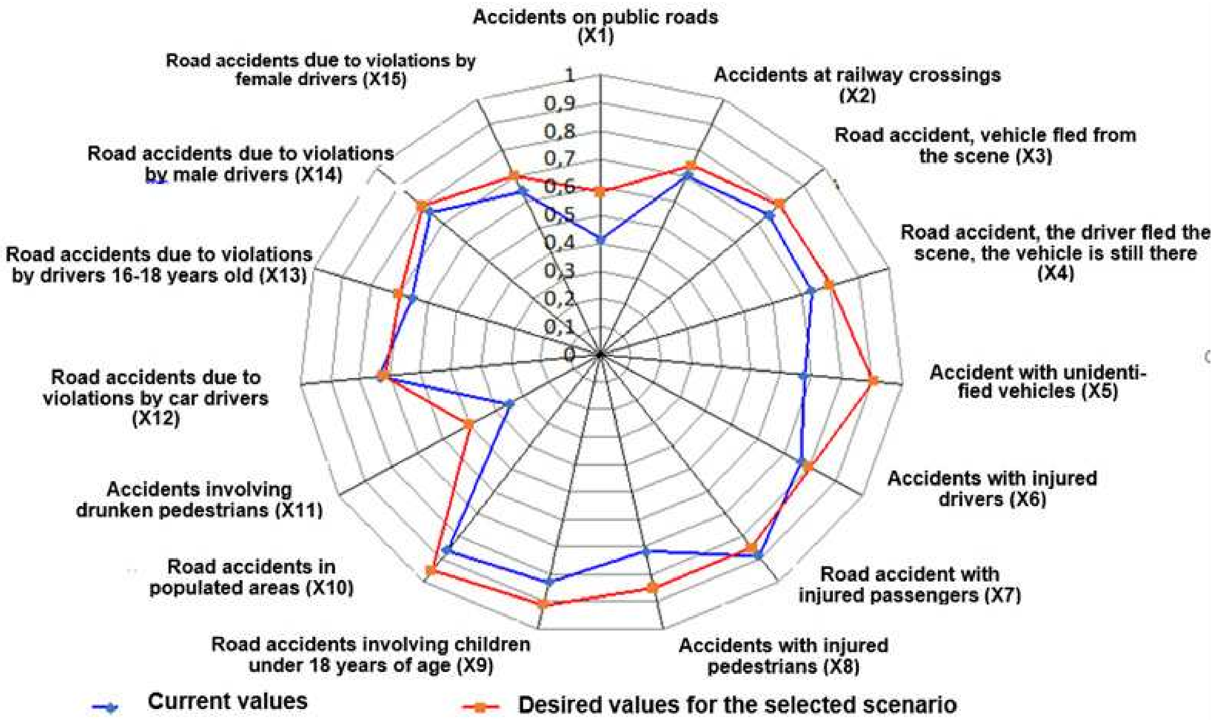


Fig. 10. Changes in the main indicators of road safety in Moscow in 2023.

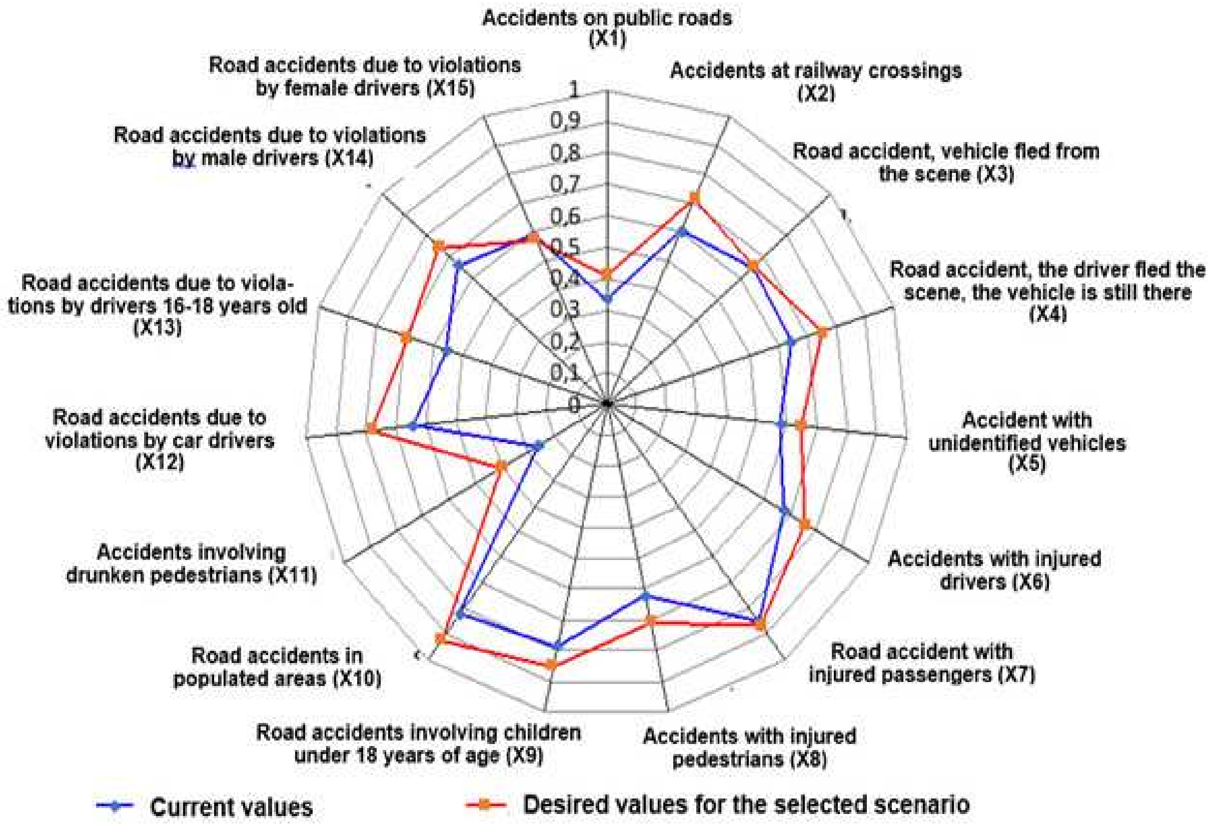


Fig. 11. Changes in the main indicators of road safety in Moscow in 2024.

indicator separately; their values are based on experience and modern traffic safety requirements. These boundaries in Figs. 10 and 11 such boundaries are marked in red. In Fig. 10 shows that in 2023 for the plan p_2 the values of all indicators are in the acceptable region. However, in 2024, as follows from Fig. 11, the indicator X_7 when implementing p_2 will go beyond the permissible limits. Therefore, such a plan is excluded from further consideration.

Let us solve problem (1)–(3) on the set of control actions, consisting of the two remaining plans p_1 and p_3. We get the value $Z(p_1(t)) = 1.6031$. Similarly, we define $Z(p_3(t)) = 1.8573$. Since $Z(p_1(t)) < Z(p_3(t))$, then the solution to the problem is plan p_1.

5. CONCLUSION

In the article, we formulated the formulation of the problem of managing the road transport system of a metropolis according to the safety criterion. We have proposed a mathematical model of the dynamics of the main indicators of traffic safety in a metropolis and a procedure for solving the problem, illustrated by a model example. The example illustrates the construction of a system of nonlinear differential equations. The solution of this system makes it possible to simulate the dynamics of the indicators under consideration at the required time intervals. We propose a procedure for correcting the mathematical model with a certain increase in the prediction error. We checked the results of the solution using statistics on traffic safety indicators in Moscow [2].

REFERENCES

1. Order of the Government of the Russian Federation dated January 8, 2018 N 1-r "On approval of the Road Safety Strategy in the Russian Federation for 2018–2024."
[Electronic resource]: http://static.government.ru HYPERLINK http://static.government.ru

2. Website of the State Traffic Inspectorate of the Ministry of Internal Affairs of Russia, information on road safety indicators. [Electronic resource]: http://stat.gibdd.ru/ (24.03.2023).

3. Yannis, G., Weijermars, W., Gitelman, V., Vis, M., Chaziris, A., Papadimitriou, E., and Azevedo, C.L., Road safety performance indicators for the interurban road network, *Accident; analysis and prevention*, 2013, vol. 60, pp. 384–395.

4. Salmon, P.M., Read, G.J.M., Thompson, J., McLean, S., and McClure, R., Computational modelling and systems ergonomics: a system dynamics model of drink driving-related trauma prevention, *Ergonomics*, 2020, vol. 63(8), pp. 965–980.

5. Brun, E.A., Burtsev, A.A., and Bakanov, K.S., Analysis of indicators of driving while intoxicated in the Russian Federation in 2007–2019, *Narcology*, 2020, vol. 19, no. 6, pp. 32–43.

6. Guo, Q. at al., The effect of road network patterns on pedestrian safety: A zone-based Bayesian spatial modeling approach, *Accident; analysis and prevention*, 2017, vol. 99(Pt A), pp. 114–124.

7. Dell'Acqua, G., Luca, M.D., and Mauro, R., Road Safety Knowledge-Based Decision Support System, *Procedia Social and Behavioral Sciences*, 2011, vol. 20, pp. 973–983.

8. Gettman, D.M. and Head, L., Surrogate Safety Measures from Traffic Simulation Models, *Transportation Research Record*, 2003, vol. 1840, pp. 104–115.

9. Bakanov, K.S. et al., *Dorozhno-transportnaya avariinost' v Rossiiskoi Federatsii za 6 mecyatsev 2022 goda* (Road traffic accidents in the Russian Federation for 6 months of 2022), Moscow: Scientific Center for Road Safety of the Ministry of Internal Affairs of the Russian Federation, 2022.

10. Forrester, J., *Principles of systems*, Cambridge: Wright Allen Press, 1960.

11. Burkov, V.N., Loginovskiy, O.V., Dranko, O.I., and Hollay, A.V., The mechanisms of smart management for industrial enterprises, *Applied Mathematics and Control Sciences*, 2020, no. 1, pp. 59–73.

12. Khamutova, M.V., Kushnikov, V.A., and Dranko, O.I., A mathematical model for choosing an action plan for the prevention and elimination of flood effects, *IFAC-PapersOnLine*, 2022, vol. 55, no. 3, pp. 113–118.

13. Tsvirkun, A.D., Rezchikov, A.F., Kushnikov, V.A., et al. Models and methods for verifying the accessibility and feasibility of goals and plans in large-scale systems by example for the elimination of consequences floods *Avtomat. i Telemekh.*, 2023, no. 12, pp. 49–63.

14. Rezchikov, A.F., Kushnikov, V.A., Ivaschenko, V.A., Fominykh, D.S., Bogomolov, A.S., and Filimonyuk, L.Yu., Controlling the welding process in robotic technological complexes by the criterion of product quality, *Mechatronics, Automation, Control*, 2019, vol. 20, no. 1, pp. 29–33.

15. Polyakov, M.S., Kushnikov, V.A., Bogomolov, A.S., and Rezchikov, A.F., System dynamics models for analyzing the characteristics of the road transport system in Russia, *Management of the development of large-scale systems (MLSD'2023): Proceedings of the Sixteenth international conference*, Moscow, Russia, 2023, pp. 1002–1012. DOI 10.25728/mlsd.2023.1002.

This paper was recommended for publication by A.A. Galyaev, a member of the Editorial Board