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Article

Mathematical models for analyzing and predicting the dynamics of the main characteristics of the road transport system with the correction procedure

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Abstract. This article discusses a set of mathematical models that utilize the system-dynamic approach. We have created a set of interconnected system dynamics models, enabling us to forecast key road safety indicators in Russia. These indicators were carefully chosen by referring to the regulatory documents of the State Traffic Inspectorate under the Ministry of Internal Affairs in Russia. The findings will be used to enhance the traffic control systems' software.

Keywords: road transport network, system dynamics models, safety, cause-and-effect relationship, analysis, forecasting

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Математические модели анализа и прогнозирования динамики основных характеристик дорожно-транспортной системы с процедурой коррекции

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Аннотация. Разработан комплекс взаимосвязанных моделей системной динамики, предназначенный для прогнозирования ключевых индикаторов безопасности дорожного движения в Российской Федерации. Выбор указанных индикаторов был осуществлен на основании анализа нормативно-правовых актов, регламентирующих деятельность Государственной автомобильной инспекции МВД России. Полученные результаты исследования послужат основой для дальнейшего совершенствования математического обеспечения систем управления дорожно-транспортным движением, что, в свою очередь, может способствовать повышению уровня безопасности на автомобильных дорогах.

Ключевые слова: дорожно-транспортная сеть, модели системнои динамики, безопасность, причинно-следственная взаимосвязь, анализ, прогнозирование

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Introduction

Road transport remains the dominant mode of transportation in Russia, playing a critical role in the country's economy by facilitating the movement of goods and passengers. The number of vehicles on Russian roads continues to grow annually. However, road transportation is also among the least safe modes of travel, as evidenced by concerning trends in safety statistics.

One of the most pressing issues facing Russia's road transport system is the high incidence of traffic accidents. According to official data from the State Traffic Inspectorate of the Ministry of Internal Affairs, nearly 33,000 road accidents occurred in the first half of 2023 alone. These incidents resulted in the tragic loss of approximately 3.500 lives and left more than 42.000 individuals injured[1] [1]. This alarming situation highlights the urgent need for improved safety measures and a comprehensive approach to mitigating risks within the road transport sector.

In this context, several articles published between 2018 and 2023 offer valuable ideas and methods for analyzing and predicting road safety indicators.

One significant study by I. E. Ilina examines the modeling of accident rates involving trucks in Russia [2]. The author analyzes existing data and proposes methods to enhance road safety, particularly relevant given the increasing number of freight transportations.

In a review conducted by Jameel and Evdorides, existing indicators of the road safety system are explored, and modifications are suggested to improve their effectiveness [3]. The authors emphasize the importance of adapting indicators to modern conditions and the transport system's challenges.

M. Polyakov, V. Ivashchenko, and I. Shuvalov presented a model predicting the main indicators of road transport system safety [4]. Their work utilizes a system dynamics approach for analysis and forecasting, which can assist in developing more effective traffic management strategies.

Finally, the article by O. Mayboroda and B. Sarymsakov discusses ways to improve the system of road safety indicators in the context of analyzing the quality of motor vehicle transportation [5]. The authors propose new approaches to assessing and monitoring safety, which can help reduce the number of road traffic accidents.

However, the results of these studies do not contain results on management using the proposed mathematical models, as well as information on procedures for correcting models of system dynamics, the need for which is very urgent.

The article is structured as follows. Section 1 contains a statement of the problem and approach to its solution. Section 2 describes the complex of mathematical models proposed for solving the problem. The third section presents the results of the numerical solution of a system of differential equations. Section 4 contains information about the correction of the mathematical model. The fifth section contains information related to the use of the proposed results by decision makers. Section 6 contains brief conclusions on the article.

1. Statement of the problem and approach to its solution

To effectively analyze and predict the primary safety characteristics of the road transport system, it is essential to develop a complex of mathematical models. These models should leverage a system-dynamic approach, regression models, and products to formalize the cause-and-effect relationships of a complex structure between model variables.

Considering the aforementioned information, employing system dynamics is the appropriate method for addressing this issue. System dynamics has proven effective in modeling diverse complex processes and systems multiple times [2, 3, 6].

The construction of the proposed mathematical model complex involves several structured steps, as illustrated in Fig. 1.

[1]Assessment of the road traffic safety situation. Available at: http://stat.gibdd.ru/ (accessed June 22, 2024); About the road traffic safety. Federal law FZ-16 ot 09.02.2007. Available at: http://base.garant.ru/12151931/ (accessed June 23, 2024).

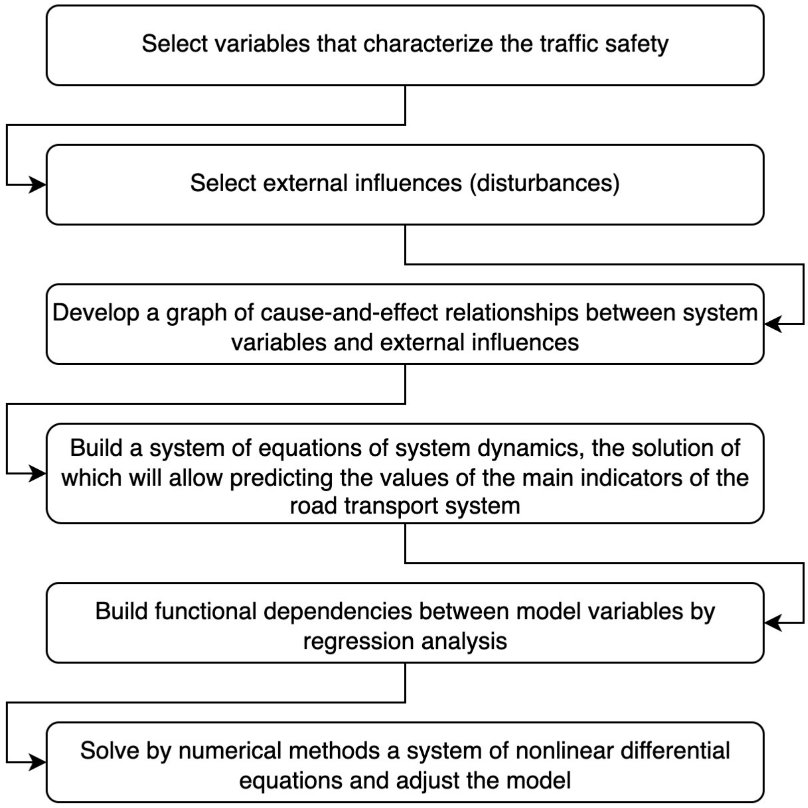


Fig. 1. Stages of developing a system dynamics model to predict the main characteristics of the road transport system

Considering the preceding, the following variables, indicated in Table 1, are taken as indicators characterizing the safety of the country's road transport system. In Table 1, all values are shown for the annual period.

Table 1

Key safety indicators of the road transport system

Variable notation	Description
$X_1(t)$	Total number of traffic accidents
$X_2(t)$	Number of fatalities in traffic accidents
$X_3(t)$	Number of injured in traffic accidents
$X_4(t)$	Number of traffic accidents with particularly severe consequences
$X_5(t)$	Number of traffic accidents during dark hours
$X_6(t)$	Number of traffic accidents involving drivers who refused medical examination
$X_7(t)$	Number of traffic accidents caused by traffic rule violations by drivers with less than two years of driving experience
$X_8(t)$	Number of traffic accidents caused by traffic rule violations by drivers with 10 to 15 years of driving experience
$X_9(t)$	Number of traffic accidents involving children under 16 due to their carelessness
$X_{10}(t)$	Number of traffic accidents on regional or intermunicipal roads
$X_{11}(t)$	Number of traffic accidents on federal highways
$X_{12}(t)$	Number of traffic accidents in the capitals of the constituent entities of the Russian Federation

In practice, quantitative scales with a clear physical meaning are used despite some of the variables being qualitative. The study assumes that for numerical modeling of the process of changing safety variables, we use the apparatus of the theory of fuzzy sets to transition to such representations. We calculate the normalized values of the variables by measuring them on a quantitative scale and using their normalized values in the calculations, determined from the following expression:

$$X_i(t) = \frac{X_i^*(t)}{X_i^{norm}}, \quad i = 1, ..., 17,$$

where $X_i(t)$ — the normalized value of the indicator used in the model; $X_i^*(t)$ — the present value of the indicator, determined by the numerical scale; X_i^{norm} — normalization coefficient. Additionally, the model considers external factors that affect road safety, and these factors are presented in Table 2.

Table 2

External factors that affect the road transport system

Variable notation	Description
$F_1(t)$	Administrative offense cases initiated
$F_2(t)$	Warnings issued to police officers by court decisions
$F_3(t)$	Fines imposed on police officers by court decisions
$F_4(t)$	Decisions forwarded to bailiffs for enforcement
$F_5(t)$	Decisions received from courts regarding administrative arrest
$F_6(t)$	Decisions received from courts regarding driving license revocation, including those with an additional administrative fine

The construction of system dynamics models is carried out based on selected variables and external factors, called, in terms of system dynamics, levels that characterize the system's functioning. Based on these scales, we constructed differential equations of the form:

$$\frac{dX(t)}{dt} = X^+(t) - X^-(t),$$

where $X^+(t)$, $X^-(t)$ represent the positive and negative values of the rate of change of the variable $X(t)$, respectively. These values encompass all factors contributing to the growth and decrease of said variable.

It is assumed that rates are functions that depend on factors. The rates look like:

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

where $F_1, ..., F_k$ are factors that can function as as both variables and external functions.

2. Mathematical model

2.1. Development of a graph of cause-and-effect relationships of system variables and external factors

Experts in the field of road safety establish connections between road safety characteristics that have both positive and negative impacts on the behavior of these characteristics over time, relying on their judgments [7]. The presence of these relationships allows the building of an incidence matrix for security characteristics, shown in Table 3.

Table 3

Incident matrix for safety performance of the road transport system

	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}	F_1	F_2	F_3	F_4	F_5	F_6
X_1	0	0	0	0	0	0	+1	+1	+1	+1	0	+1	+1	+1	−1	P_1	−1	−1
X_2	0	0	0	+1	+1	0	0	+1	0	0	0	+1	0	+1	−1	−1	−1	−1
X_3	0	0	0	0	0	+1	+1	+1	+1	+1	+1	+1	+1	+1	0	−1	0	−1
X_4	0	+1	0	0	+1	0	+1	+1	0	0	0	+1	0	+1		−1	−1	−1
X_5	0	+1	0	+1	0	0	+1	+1	0	0	0	+1	+1	+1	−1	−1	−1	−1
X_6	0	0	+1	0	0	0	+1	+1	+1	0	+1	+1	0	0	−1	−1	0	−1
X_7	+1	−1	0	0	−1	0	0	+1	−1	0	+1	+1	+1	0	−1	−1	−1	P_2
X_8	+1	0	0	0	0	0	+1	0	0	+1	0	+1	+1	+1	0	−1	0	−1
X_9	+1	−1	−1	0	0	0	+1	+1	0	0	+1	+1	+1	0	−1	−1	−1	−1
X_{10}	+1	0	0	0	0	0	+1	+1	0	0	0	+1	0	+1	0	−1	0	0
X_{11}	+1	+1	+1	+1	+1	+1	+1	+1	0	0	0	+1	0	+1	−1	−1	−1	−1
X_{12}	+1	+1	+1	+1	+1	+1	+1	+1	+1	0	0	0	0	0	0	0	0	0

The variable $U_{i,j}$ located at the intersection of the corresponding lines, characterizes the mutual influence of model variables, taking into account external environmental factors:

$$U_{i,j} = \begin{cases} -1, & \text{variable of external factor } X_j \text{ negatively affects } X_i, \\ 0, & \text{variable of external factor } X_j \text{ does not affect } X_i, \\ +1, & \text{variable of external factor } X_j \text{ has a positive effect on } X_i, \\ P_i, & \text{productions or element of production rule system.} \end{cases}$$

Let us determine the production values P_i, $i = 1, ..., N$, characterizing the influence of the environment on the model parameters, which are determined at the stage of adaptation of the developed model to the selected control object. Productions consist of two parts: a sensory precondition (or "IF" statement) and an action ("THEN"):

$$P_i = \begin{cases} -1, & \text{if condition 1 is met,} \\ 0, & \text{if condition 2 is met,} \\ 1, & \text{if condition 3 is met.} \end{cases}$$

After the condition is met and the action is activated, the model products look like: $P_1 = +1$; $P_2 = +1$; $P_3 = -1$.

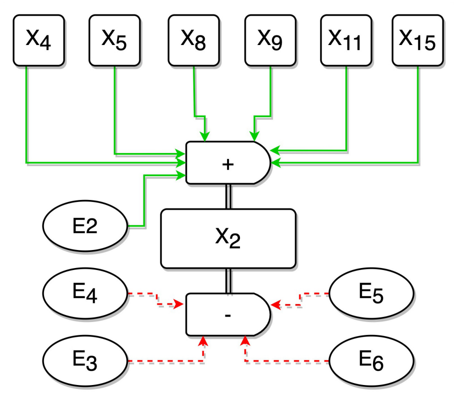


Fig. 2. A subgraph of cause-and-effect relationships for safety indicators of the functioning of the road transport system for the variable X_2

We construct the model by constructing a cause-and-effect relationship graph based on the incidence matrix. Figure 2 shows a subgraph for the variable X_2. The generated graph can describe the complex system of causal relationships between the analyzed variables and external factors. The graph's vertices represent the variables $X_1 - X_{13}$ and external factors $F_1 - F_6$, while the arcs determine the cause-and-effect relationships between them, including the direction and type of connection [4].

2.2. Equations of system dynamics

System dynamics models are constructed by utilizing the cause-and-effect relationship graph. To develop a model, a subset of levels $X = X_i$, $i = 1, ..., 13$, is chosen to establish the functional dependencies between them [8]. These dependencies are determined by analyzing the available statistics provided by the State Traffic Inspectorate of the Ministry of Internal Affairs of Russia.

The variables X_i, $i = 1, ..., 13$, are defined within the admissible range: $0 < X_i(t) \leqslant 1$. Based on the cause-and-effect graph that represents the safety indicators of road transport systems, we created equations in the following format:

$$\frac{dX_i}{dt} = \prod_{i,j} f_{i,j}(X_j^+) \sum_m F_{i,m}^+ - \prod_{i,k} f_{i,k}(X_k^-) \sum_n F_{1,n}^-. \tag{1}$$

In general, the system of equations will look like this:

$$\frac{dX_1}{dt} = f_{1,7}(X_7)f_{1,8}(X_8)f_{1,9}(X_9)f_{1,10}(X_{10})f_{1,11}(X_{11})f_{1,12}(X_{12})f_{1,14}(X_{14})f_{1,15}(X_{15})\times$$
$$\times(F_1+F_2+F_4)-(F_3+F_5+F_6) \tag{2}$$

$$\frac{dX_2}{dt} = f_{2,4}(X_4)f_{2,5}(X_5)f_{2,8}(X_8)f_{2,9}(X_9)f_{2,11}(X_{11})f_{2,14}(X_{14})f_{2,15}(X_{15})F_2-$$
$$-(F_3+F_4+F_5+F_6), \tag{3}$$

$$\frac{dX_3}{dt} = f_{3,6}(X_6)f_{3,7}(X_7)f_{3,8}(X_8)f_{3,9}(X_9)f_{3,10}(X_{10})f_{3,11}(X_{11})f_{3,12}(X_{12})f_{3,13}(X_{13})\times$$
$$\times f_{3,14}(X_{14})f_{3,15}(X_{15})(F_1+F_2)-(F_4+F_6), \tag{4}$$

$$\frac{dX_4}{dt} = f_{4,2}(X_2)f_{4,5}(X_5)f_{4,7}(X_7)f_{4,8}(X_8)f_{4,9}(X_9)f_{4,11}(X_{11})f_{4,14}(X_{14})f_{4,15}(X_{15})F_2-$$
$$-(F_3+F_4+F_5+F_6), \tag{5}$$

$$\frac{dX_5}{dt} = f_{5,2}(X_2)f_{5,4}(X_4)f_{5,7}(X_7)f_{5,8}(X_8)f_{5,11}(X_{11})f_{5,14}(X_{14})f_{5,15}(X_{15})(F_1+F_2)-$$
$$-(F_3+F_4+F_5+F_6), \tag{6}$$

$$\frac{dX_6}{dt} = f_{6,3}(X_3)f_{6,7}(X_7)f_{6,8}(X_8)f_{6,9}(X_9)f_{6,10}(X_{10})f_{6,11}(X_{11})f_{6,13}(X_{13})f_{6,14}(X_{14})f_{6,15}(X_{15})-$$
$$-(F_3+F_4+F_6), \tag{7}$$

$$\frac{dX_7}{dt} = f_{7,1}(X_1)f_{7,8}(X_8)f_{7,13}(X_{13})f_{7,14}(X_{14})f_{7,15}(X_{15})(F_1+F_6)-f_{7,2}(X_2)f_{7,5}(X_5)\times$$
$$\times f_{7,10}(X_{10})(F_3+F_4+F_5), \tag{8}$$

$$\frac{dX_8}{dt} = f_{8,1}(X_1)f_{8,7}(X_7)f_{8,9}(X_9)f_{8,11}(X_{11})f_{8,12}(X_{12})f_{8,14}(X_{14})f_{8,15}(X_{15})(F_1+F_2)-$$
$$-(F_4+F_6), \tag{9}$$

$$\frac{dX_9}{dt} = f_{9,1}(X_1)f_{9,7}(X_7)f_{9,8}(X_8)f_{9,9}(X_9)f_{9,13}(X_{13})f_{9,14}(X_{14})f_{9,15}(X_{15})F_1-f_{9,2}(X_2)\times$$
$$\times f_{9,3}(X_3)(F_3+F_4+F_5+F_6), \tag{10}$$

$$\frac{dX_{10}}{dt} = f_{10,1}(X_1)f_{10,7}(X_7)f_{10,8}(X_8)f_{10,11}(X_{11})f_{10,14}(X_{14})f_{10,15}(X_{15})F_2-(F_4), \tag{11}$$

$$\frac{dX_{11}}{dt} = f_{11,1}(X_1)f_{11,2}(X_2)f_{11,3}(X_3)f_{11,4}(X_4)f_{11,5}(X_5)f_{11,6}(X_6)f_{11,7}(X_7)f_{11,8}(X_8)\times$$
$$\times f_{11,14}(X_{14})f_{11,15}(X_{15})F_2-(F_3+F_4+F_5+F_6), \tag{12}$$

$$\frac{dX_{12}}{dt} = f_{12,1}(X_1)f_{12,2}(X_2)f_{12,3}(X_3)f_{12,4}(X_4)f_{12,5}(X_5)f_{12,6}(X_6)f_{12,7}(X_7)f_{12,8}(X_8)\times$$
$$\times f_{12,9}(X_9)f_{12,10}(X_{10}). \tag{13}$$

The time argument t for all functions in (2)–(13) is omitted for brevity.

2.3. Creation of functional relationships among the internal variables of the model

Expressions in the system of differential equations that are written as $f_{A,B}(X_B)$ indicate the relationship between the variable X_A and X_B and are determined using regression analysis tools.

On the other hand, expressions of the form F_i^{if} for $i = (1, ..., 6)$ represent the dependency of the variable on an external factor, as defined by the predicate:

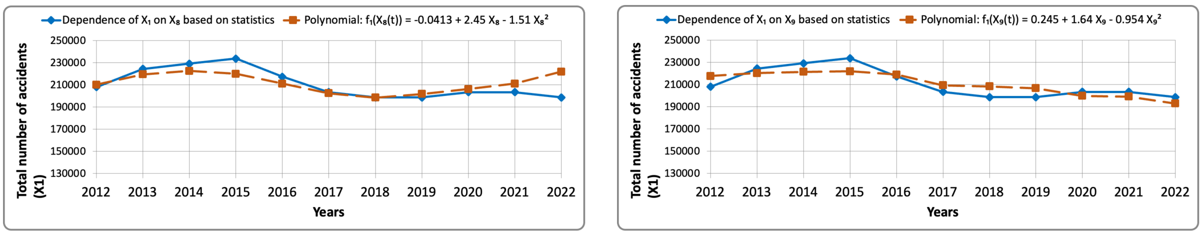
$$F_i^{if} = \begin{cases} -1, & \text{an inverse relationship between the variable and the external factor,} \\ 0, & \text{the variable and the external factor are not related to each other,} \\ +1, & \text{direct proportionality between a variable and a factor.} \end{cases}$$

Each expression F_i^{if} for $i = 1, ..., N$ has its own conditions.

In order to ascertain the nature of $f_{A,B}(X_B)$ expressions, we utilize regression analysis to establish the relationships between the variables. In our notation of expressions $f_{A,B}(X_B)$, the variable X_B is the explanatory variable and X_A is the variable being explained. By employing the least squares method, we identify functional dependencies as 2nd-degree polynomials [9]. For example, in the first equation for X_1 there are dependencies of this variable on variables X_7–X_{12}. These dependencies, determined by the least squares method, have the form:

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

To illustrate, we can demonstrate the relationship between the occurrence of road accidents X_1 and two factors: the number of road accidents caused by intoxicated drivers X_8 (Fig. 3, *a*) and the number of road accidents caused by pedestrian traffic violations X_9 (Fig. 3, *b*). For each polynomial, some characteristics were calculated, for example: for $f_{1,9}(X_9)$: standard deviation = 0.044; regression variance = 0.0029; regression standard error = 0.035; Pearson's test: 0.88. The Pearson criterion, in this case, shows the magnitude of the approximation reliability.



a *b*

Fig. 3. Graph of the functional dependence of the number of accidents (indicator X_1) on the number of accidents due to traffic violations: *a* — by drivers in a state of intoxication X_8; *b* — by pedestrians X_9. The black line represents the graphs of changes in these dependencies; the gray line represents the corresponding statistical data (color online)

3. Solving a system of differential equations numerically

Once the construction of a system dynamics model is complete, it is necessary to define the elements and variables involved in the equations of this system. This task relies on the data obtained from the available statistics on the factors and significant variables of the system [5]. After determining the functional dependencies and coefficients in the equations, and external factors, the resulting system of equations is solved by the numerical methods of the fourth order of accuracy.

Figure 4 shows the change in time of the calculated values for all calculated values of the model variables over the interval from 2021 to 2024.

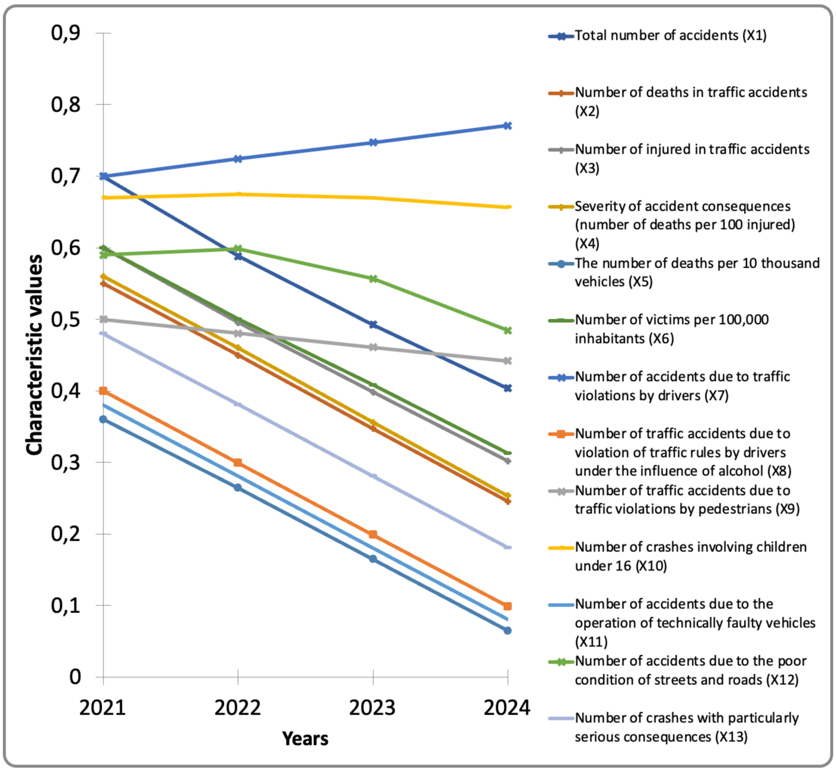
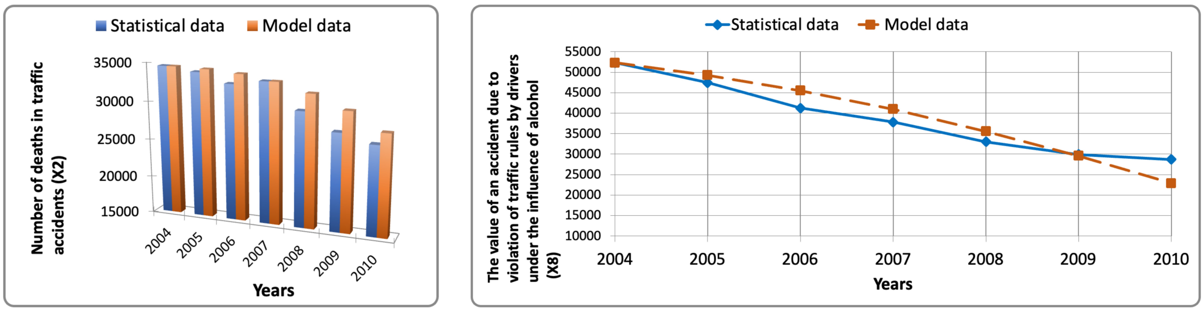


Fig. 4. Forecasting results for each variable for 2021–2024 (color online)

We compared the calculation results with actual statistical data for each variable. For example, let us present graphs comparing statistical and simulated data for 2004–2010 for variables X_2 and X_8. The results are shown in Fig. 5, respectively.

In Fig. 5 *a*, the maximum deviation from statistics was 9.8 percent in 2009; in Fig. 5 *b*, it was 10 percent in 2010.



a *b*

Fig. 5. Comparison of statistical and simulated data for variables X_2 (*a*) and X_8 (*b*) (color online)

4. Correction of the system dynamics model

Correction of the mathematical model is necessary to improve its accuracy and adequacy. Numerous factors come into play when constructing a mathematical model, making certain simplifications and approximations necessary. However, these simplifications and approximations may only sometimes lead to highly accurate predictions of the simulation results.

After we tested the model on statistical data, it may become clear that it does not correspond to reality in some aspects. In this case, correcting the model can improve its accuracy and reliability. The mathematical model can be corrected by adding new parameters or variables and adjusting the parameters. As a result of model correction, it is possible to obtain a more accurate forecast of the dynamics of the main characteristics of the road transport system, which can help make decisions in the field of accidents.

We used statistical data from 2004 to 2020 to predict system behaviors as part of the modeling process. For instance, Fig. 6 illustrates the system behavior during the period from 2004 to 2010 [10].

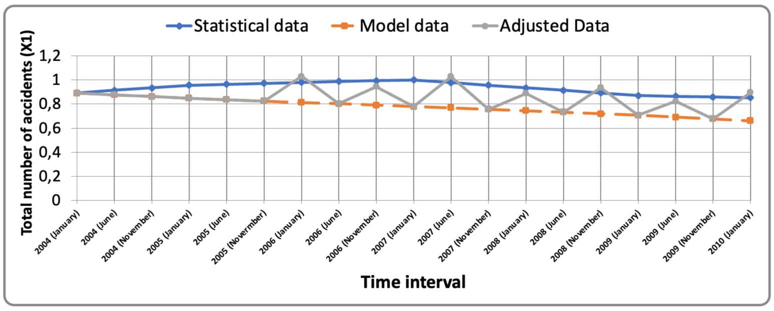


Fig. 6. The state of the system for 2004–2010 (color online)

We correct the mathematical model if the difference between the model and statistical data exceeds 10%. Figure 5 indicates that the model did not require any corrections from January 2004 to November 2005. However, corrections were made to the model during the remaining time interval. The developed models accurately align with the statistical data recorded between 2021 and 2022, indicating that the number of accidents from these models closely matches the actual figures. As a result, the developed software can be confidently recommended for practical application in simulating the primary safety metrics of the Russian road transport system.

5. Actions of the decision maker when the model variables go beyond the allowable values

In the decision-making sphere, when the main characteristics of the road transport system reach or exceed permissible values, a number of measures are required to return the variable's value to the acceptable zone. These are the points where serious decisions are made to restore the model's stability. Often, acceptable values are set in advance based on relevant safety documents so that they can be considered when making decisions [2].

The mathematical complex can build petal diagrams and compare the obtained values with the maximum allowable. This functionality will be recommended for use by the decision-maker. Figure 7 shows radar diagrams that characterize changes in the main safety indicators of the road transport system in the time interval of 2021 to 2023. The red line shows the limit values of these characteristics.

Figure 7 shows that the characteristic X_7 goes beyond the allowable zone, and this is a signal for the decision-maker to make a decision.

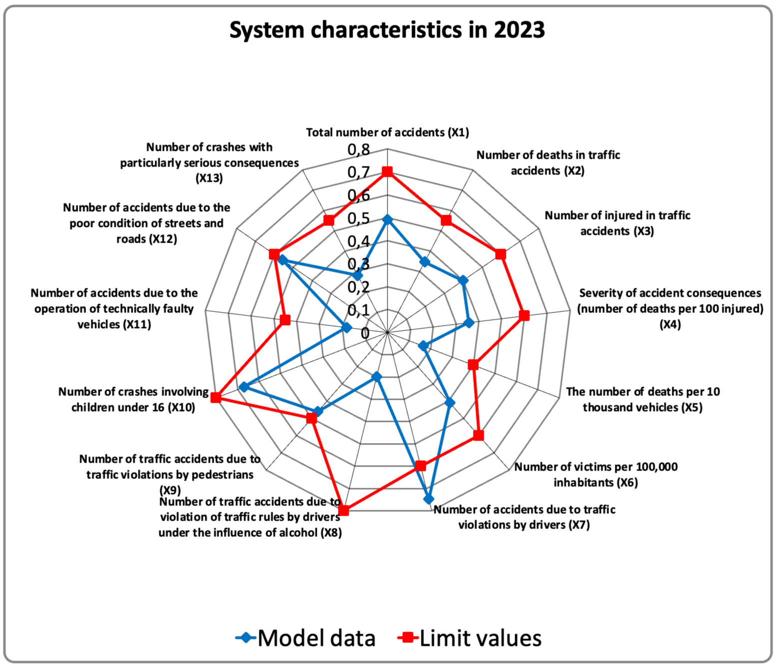


Fig. 7. Changes in key safety indicators in 2023

Conclusion

We created a set of system dynamics models that enable the prediction of key safety indicators related to the operation of the road transport system. By utilizing the suggested approach, we also designed a non-linear differential equation system, the solution of which enables the determination of fluctuations in safety indicator values during various time intervals. A proposed procedure has been suggested to enhance the accuracy and reliability of the forecasting results by making corrections to the model.

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