Istraživanja i projektovanja za privredu
ISSN 1451-4117
DOI:10.5937/jaes0-54057
www.engineeringscience.rs

publishing

Journal of Applied Engineering Science
Original Scientific Paper,
Volume 23, Number 4, Year 2025,
no 1298, pp 621-630

THE TRAFFIC INTENSITY AND THE NUMBER OF TRAFFIC ACCIDENTS BASED ON PROBABILITY THEORY AND MATHEMATICAL STATISTIC FORECASTING

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Based on the collected experimental data on the number of vehicles moving along the street and road network of the urban agglomeration, a theoretical approach to predicting the number of vehicles based on mathematical statistics and probability theory is developed in the article. The obtained results of the intensity of vehicle traffic forecasting, together with the processed statistical data on the number of traffic accidents, make it possible to identify places with increased traffic accident rates for predicting the number of traffic accidents. The results of the predicted values of seasonal vehicle traffic intensity are given in the text (Table 1). The forecast results are within the confidence interval, which theoretically confirms the correctness of the obtained values. The theoretical approach to predicting the number of traffic accidents was obtained on the basis of the two-parameter Weibull distribution law. The results of the obtained numerical parameters of the statistical and theoretical distribution law λ(t) characteristics are shown in Table 3. An additional assessment was carried out when choosing the distribution curve λ(t), which makes it possible to implement the K. Pearson agreement criterion and its properties χ^2*. The theoretical approach allows you to assess the road traffic situation in an urban agglomeration with the subsequent implementation and implementation of organizational and technical measures to reduce road deaths.*

Keywords: traffic intensity, traffic accident, vehicle, probability theory and mathematical statistics, forecasting, mathematical trend, Weibull distribution law, confidence intervals.

HIGHLIGHTS

- Developed a forecasting model for vehicle traffic intensity using statistical trend analysis.
- Applied the two-parameter Weibull distribution to predict traffic accident rates.
- Model identifies high-risk road sections through seasonal and statistical analysis.
- The method enables proactive measures for reducing traffic accidents in urban areas.

1 Introduction

Ensuring traffic safety today is a global problem [30-32]. Despite the progressive development of measures to reduce road deaths, a significant amount of time still has to be devoted to this issue, since the life and health of citizens belongs to the priority direction of the country [5, 33]. One of the main characteristics of the traffic flow is the intensity of vehicle traffic, thanks to which it is possible to assess not only the social, but also the economic development of the region. Increased values of vehicle traffic intensity indicate the congestion of a particular road section, which directly affects the likelihood of an emergency on the roads [6, 7]. In turn, forecasting this indicator will make it possible to implement organizational and technical measures in advance at emergency sites in the agglomerations of the world. Deaths on the country's roads are increasingly forcing scientists to develop and improve methods, techniques and measures aimed at improving traffic safety. Thus, the forecast of the number of traffic accidents, based on the theory of probability and neural networks, makes it possible to assess the road traffic situation at certain hotbeds of traffic accidents [1-4].

Currently, when predicting traffic accidents, statistical methods based on traffic police statistics are chosen, which takes into account the dead and injured [30]. Statistical methods, including the Weibull distribution law, are presented in scientific papers [32, 33]. The most popular methods are extrapolation, which takes into account seasonality and recurring facts of traffic accidents. Linear smoothing extrapolation is the simplest method of processing statistical data. This method is applicable for a short forecasting period, and the trend over the period under review remains unchanged [31]. The main features of these sections of the road network include increased speed, non-stop traffic and high vehicle traffic intensity. This indicates a significant variety of measures that contribute to increase the capacity of the road and reduce probability of occurrence of the accidents. This condition suggests that the accident rate at road network is less dependent on the season and is little affected by weather and climatic factors. The traffic accident rate on the road network sections with an increased number of traffic accidents is most often associated with non-compliance vehicle's speed limit. Therefore, such types of traffic accidents as vehicle crashes, pedestrian collisions, etc. most often occur in such areas.

2 Materials and methods

2.1 Forecast of vehicle traffic intensity based on a statistical assessment of changes in the number of vehicles depending on the season

The constantly increasing traffic intensity with lagging infrastructure development in urban agglomerations leads to negative consequences. A low level of traffic regulations entails a problem, one of which is the traffic accident, the severity of their consequences and mortality. If there is a discrepancy between the rapidly growing rate of motorization and an insufficiently developed infrastructure, it becomes difficult to move traffic and pedestrian flows along the street and road network, which in the current road transport situation becomes not convenient, safe and comfortable enough. Also, the traffic safety is negatively affected by high values of traffic intensity during the year in urban agglomerations.

In order to determine the possible number of cars for a projected period of time that is outside the study period, that is, when $t_i > t_n$. When predicting the intensity of traffic, the inertia property of large systems should be taken into account, which make it possible to make such an assumption that the patterns of changes in the intensity of traffic obtained during the analysis persist throughout the found time range. To obtain the values of the point forecast of traffic intensity, an analytical approximation of the occurrence trend of the highest value of traffic intensity was applied [12]. Table 1 contains the results of the values obtained during the mathematical operations.

In order to verify the correctness of the forecast results obtained, it is necessary to build a confidence interval for the trend in question $m_y(t)$, applying confidence probability data. The forecast results are within the confidence interval.

The boundaries of the symmetric confidence interval are denoted a $z_1(t)$, $z_2(t)$ and correspond to the inequality:

$$z_1(t) \leq m_y(t) \leq z_2(t) \tag{1}$$

calculated according to the formula, according to the provisions of probability theory and mathematical statistics [13, 14]:

$$z_k = m_y(t) \mp \sigma\left[m_y(t)\right] \cdot t_{\frac{1+q}{2}(n-2\,p-1)}, \quad (k = 1,2) \tag{2}$$

where p – s the number of terms used in the expression (15); q – probability of confidence intervals; $t_{\gamma(n-2\,p-1)}$ – s the probability of confidence intervals; is the quantile of the student's distribution with degrees of freedom γ and $n-2p-1$.

On the basis of mathematical statistics, according to a special t [15, 16], in which the numbers and are reflected γ and $n-2p-1$, e quantile values are found. The estimate of the time series variance is determined by the formula:

$$\overline{\sigma}^2 = \frac{1}{n-2\,p-1}\sum_{i=1}^{n}\left[y_i - m_y(t_i)\right]^2 \tag{3}$$

where $m_y(t_i)$ – the initial data of the function for the studied time interval [17].

The results of the confidence interval values were obtained for the daily traffic intensity. An analytical expression containing values for the considered as well as the predicted time period, taking into account the results of mathematical expressions (15), (16) and when taking into account (14), in case of p=3, resemble the following:

$$m_y(t) = 985751 - 123{,}098t + 6786{,}9\cos\frac{2\pi t}{72} - 22989\cos\frac{4\pi t}{72} - 18574\cos\frac{6\pi t}{72} - 25586\sin\frac{2\pi t}{72} - 13118{,}5\sin\frac{4\pi t}{72} + 18857{,}2\sin\frac{6\pi t}{72} \tag{4}$$

The results of the trend $m_y(t)$ re shown in the table 1. The function obtained from [18], at p=3 resemble the following:

$$\omega_1^{\cdot}(t) = t - 35{,}5 + \cos\frac{2\pi t}{72} + \cos\frac{4\pi t}{72} + \cos\frac{6\pi t}{72} - 0{,}00006\sin\frac{2\pi t}{72} - 0{,}0001\sin\frac{4\pi t}{72} - 0{,}0002\sin\frac{6\pi t}{72} \tag{5}$$

2.2 The number of traffic accidents forecast based on the two-parameter Weibull distribution

At the moment, statistical methods when predicting traffic accidents based on the State road safety Inspectorate statistics, which takes into account the dead and injured, are chosen [12]. The most popular methods are extrapolation, the forecasting of which takes into account seasonality, recurring facts of traffic accidents that have occurred.

Extrapolation with linear smoothing refers to the simplest method of processing statistical data. This method is applicable for a short forecasting period, and the trend over the period under review remains unchanged [20].

The main features of these sections of the road network include increased speed, non-stop traffic and high traffic intensity, which indicates a significant variety of measures that contribute to increasing the capacity of the road and reducing the likelihood of the traffic accident. This circumstance allows us to assume that the traffic accident rate at the road network is less dependent on the season and is little affected by weather and climatic factors. Traffic accidents in road network sections with an increased number of traffic accidents are most often associated with non-compliance with the vehicles' speed limit, as a result, such types of traffic accidents as a collision of vehicles, hitting a pedestrian, etc. occur most often.

Thus, the traffic accident rate has a technological character and is associated in most cases with improper actions of the driver. When predicting traffic accidents, the theory of the two-parameter Weibull distribution was chosen, because the statistics of traffic accidents from a physical point of view clearly indicate the type of exponential curve.

Traffic accidents Information in the Belgorod urban agglomeration is presented in Table 2.

Transformation the empirical dependence coordinates of under study in order to bring it to a linear form [21]:

$$y = A + Bx \tag{6}$$

where x = f(t) and y = f(P) – transformation functions, A and B – constant regression equations.

The determination of the constants of the regression equation A and B, as well as the correlation coefficient R_{xy} and relative errors δ_x and δ_y carried out by the least square's method.

At the same time, the correlation coefficient R_{xy} serves as an evaluating criterion the agreement of theoretical and empirical distributions.

The determination of the parameters of the theoretical distribution a and b using constants A and B, the compilation of the desired functions of the theoretical distribution was carried out, followed by the determination of main indicators and the construction of graphs.

To develop a mathematical model based on the Weibull distribution law, it is necessary to perform the following mathematical operations for converting coordinates (x, y), presented below by the formulas [21-23]:

$$x_j = \ln(t_j) \tag{7}$$

$$y_j = \ln\frac{1}{\ln\frac{1}{P_j}}. \tag{8}$$

Auxiliary values are calculated using following formulas:

$$X_{cp} = \frac{\sum_1^N x_j}{N} \tag{9}$$

$$Y_{cp} = \frac{\sum_1^N y_j}{N} \tag{10}$$

$$S_x = \sum_1^N x_j^2 - NX_{cp}^2 \tag{11}$$

$$S_y = \sum_1^N x_j^2 - NX_{cp}^2 \tag{12}$$

$$S_{xy} = \sum_1^N x_j Y_j - NX_{cp}Y_{cp} \tag{13}$$

The obtained values make it possible to calculate the values of the correlation coefficient R_{xy}, relative errors δ_y and δ_x, as well as constants A and B according to the following formulas:

$$R_{xy} = \frac{S_{sy}}{\sqrt{S_x S_y}} \tag{14}$$

$$\delta_y = \sqrt{\frac{(1 - r_{xy}^2)S_y}{N - 1}} \tag{15}$$

$$\delta_x = \sqrt{\frac{(1 - r_{xy}^2)S_x}{N - 1}} \tag{16}$$

$$A = Y_{cp} - BX_{cp} \tag{17}$$

The parameters of the shape b and scale a of the Weibull distribution are calculated using the formulas:

$$\beta = -B \tag{18}$$

$$\alpha = \exp\,(A/B) \tag{19}$$

The values of the numerical characteristics of statistical distributions are obtained using the formulas presented below [23]:

– mathematical expectation:

$$\bar{M}[\lambda(t)] = \frac{1}{n}\sum_{i=1}^{n}\dot{\lambda}(t)_i \tag{20}$$

– statistical variance:

$$\bar{Д}[\lambda(t)] = \left\{\frac{1}{n}\sum_{i=1}^{n}\left[\dot{\lambda}(t_i)\right]^2 - \bar{M}[\lambda(t)]^2\right\}\frac{n}{n-1} \tag{21}$$

– standard deviation:

$$\bar{\delta}[\lambda(t)] = \sqrt{\bar{Д}[\lambda(t)]} \tag{22}$$

Refined confidence intervals for numerical characteristics are calculated using expressions [20, 23]:

$$\bar{M}[\lambda(t)] - t_\beta\sqrt{\frac{\bar{Д}[\lambda(t)]}{n}} < \bar{M}[\lambda(t)] < \bar{M}[\lambda(t)] + t_\beta\sqrt{\frac{\bar{Д}[\lambda(t)]}{n}} \tag{23}$$

$$\frac{\bar{Д}[\lambda(t)](n-1)}{X_1^2} < \bar{Д}[\lambda(t)] < \frac{\bar{Д}\{\lambda(t)\}(n-1)}{X_2^2} \tag{24}$$

$$\sqrt{\frac{\bar{Д}\{\lambda(t)\}(n-1)}{X_1^2}} < \bar{\delta}[\lambda(t)] < \sqrt{\frac{\bar{Д}\{\lambda(t)\}(n-1)}{X_2^2}} \tag{25}$$

where t_β – the value determined from tabular data depending on the accepted probability value β and n-1 [11]; χ_1^2, χ_2^2 – values selected from tabular data χ^2 – distributions with n-1 degrees of freedom depending on β [24]. Probabilities of a random variable going beyond the boundary to the right p_1 and to the left p_2 are the incoming data taken from the tables [25].

Figure 3 shows an example of a pedestrian traffic accident histogram approximated by the Weibull distribution law [26]:

$$\lambda(t) = \frac{\beta}{\alpha}(t-\gamma)^{\beta-1}; \qquad t \geq \gamma, \tag{26}$$

where α – a scale parameter indicating the initial period of the traffic accident monitoring on a certain section of road; β – a shape parameter that characterizes the rate of varying intensity of the traffic accident λ(t); γ – position parameter.

Almost always a position parameter γ=0. When the value γ is entered as a negative number, there is no probability of the traffic accident.

Numerical characteristics of the Weibull distribution law at γ=0 expressions that determine the numerical characteristics of the statistical and theoretical distribution have the form [22, 27]:

$$M[\lambda(t)] = \int_0^{t_1}\frac{\lambda(t)dt}{t_1} = \frac{t_1^\beta}{\alpha t_1} = \frac{1}{\alpha}t_1^{\beta-1} = M \tag{27}$$

$$Д[\lambda(t)] = \frac{1}{t_1-1}\int_1^{t_1}[\lambda(t)-M]^2dt + \frac{\dot{\lambda}_0}{t_1} = \frac{1}{t_1-1}\left[\frac{\left(\frac{\beta}{\alpha}\right)^2}{2\beta-1}\left(t^{2\beta-1}-1\right) - M^2t_1 + \frac{2M}{\alpha} - -M^2\right] + \frac{\dot{\lambda}_0(t)}{t_1} \tag{28}$$

where t_1 – the total value of the amount of time for which the traffic accident was observed on the roads; $\lambda_0(t)$ – statistical specific traffic accident rate in the first year of observations.

Using the least squares method, the Weibull parameters are calculated when processing statistical data. Compliance with curve alignment requirements $\lambda(t)=(\beta/\alpha)t^{\beta-1}$ and experimental points λ(t) it is possible if the condition is fulfilled:

$$\sum_{i=1}^{n}\left[\dot{\lambda}_i(t)-\lambda_i(t)\right]^2 = min \tag{29}$$

3 Results and discussion

Table 1 contains the results of the values obtained during the mathematical operations.

Table 1. Projected values of seasonal traffic intensity

Month	Traffic intensity, vehicle/month	Point forecast	Trend results $m_y(t)$	Standard deviations $\sigma[m_y(t)]$	The boundary of the confidence interval	
					$z_1(t)$	$z_2(t)$
January	1008348	1035457	1079574	88102,5	901607	1257541
February	864522	1037287	1072189	88390,92	893639	1250739
March	861150	1039032	1063177	92964,19	875389	1250964
April	1016361	1040680	1053072	78705,91	894086	1212058
May	864958	1042231	1042435	84735,76	871269	1213601
June	1145120	1043693	1031846	64812,5	900925	1162767
July	1074728	1045086	1021870	59693,42	901289	1142451
August	1169546	1046437	1012998	100467,8	810053	1215943
September	941604	1047775	1005642	103140	797299	1213985
October	1008002	1049133	1000116	89192,08	819948	1178501
November	893996	1050541	996600,9	92144,59	810469	1182733
December	991427	1052020	995149,8	89072,61	815223	1175076

Checking the results for statistical significance showed a 5% significance level.

The first trend is based on the data obtained during the time period under study, the second trend is based on the forecast values. On the curve reflecting the forecast values, it can be seen that there is a discrepancy between trends in the segment of the forecast curve in terms of supplementing the time interval. This process has patterns and depends on the predicted time period (Figure 1).

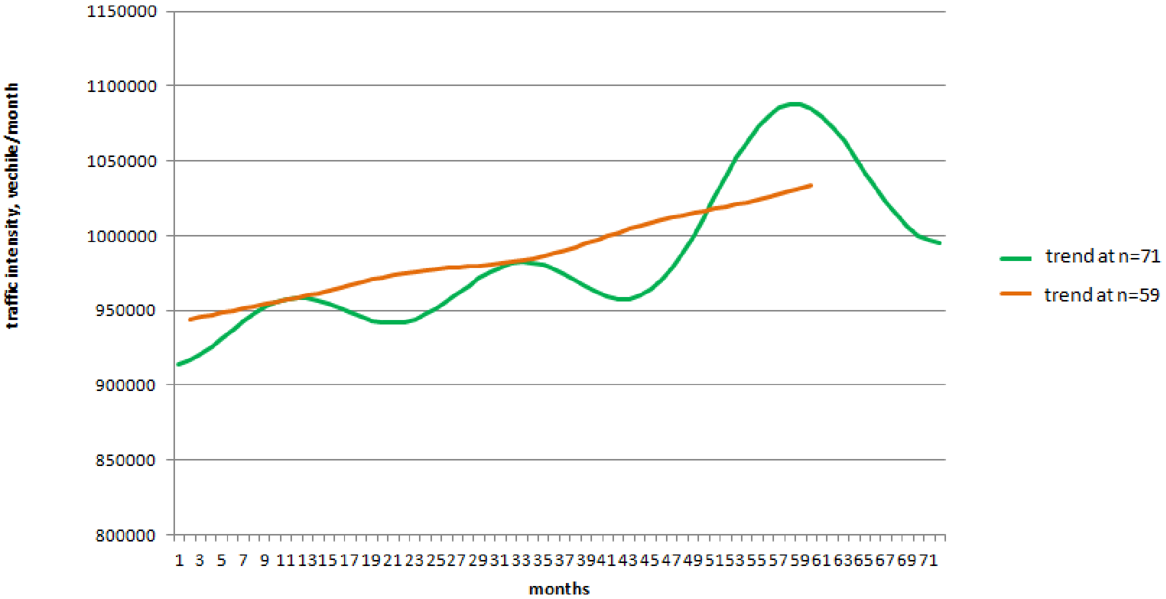

Fig. 1. Seasonal traffic intensity trends, taking into account the forecast

Figure 2 reflects the results obtained during the processing of statistical values of traffic intensity during the implementation of the forecast. Some points of the calculated values go beyond the boundaries of the symmetric confidence interval. In accordance with the system of equations, a smoothing operation was performed [19]. The resulting pattern remains and manifests itself at other points. This situation arises during the change of experimental results and takes into account the possible increase values of traffic intensity in the event of an traffic accident.

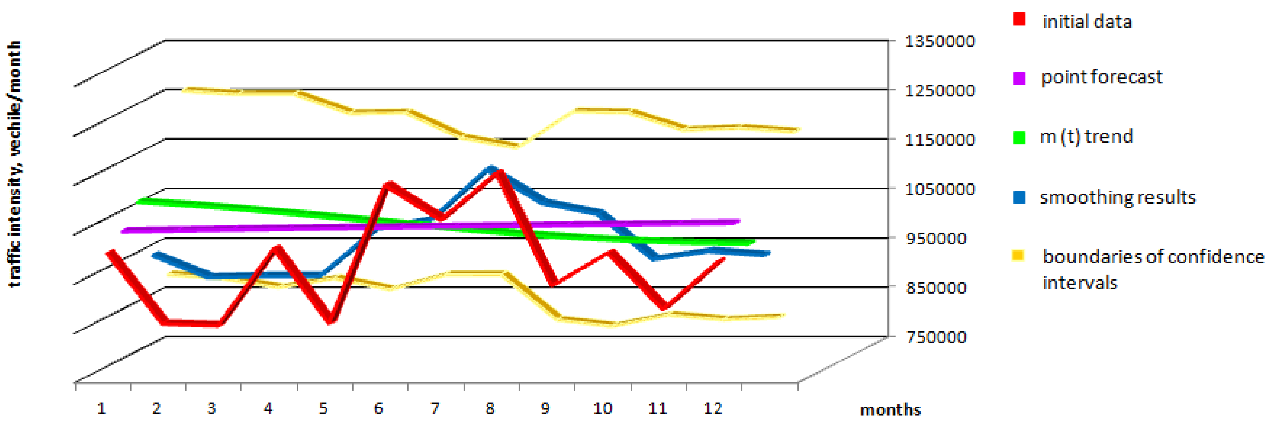

Fig. 2. The seasonal traffic intensity forecast results

Similarly, the traffic intensity is predicted for the following days, weeks, months and years, depending on the set purpose and tasks.

Traffic accidents Information in the Belgorod urban agglomeration is presented in Table 2.

Table 2. The number of traffic accidents over 10 years

Year	The number of traffic accidents		
	Pedestrians	Children	Drivers
2012	451	178	110
2013	436	169	101
2014	421	154	105
2015	415	144	109
2016	397	163	112
2017	438	168	106
2018	369	147	107
2019	354	173	101
2020	311	156	101
2021	253	158	91

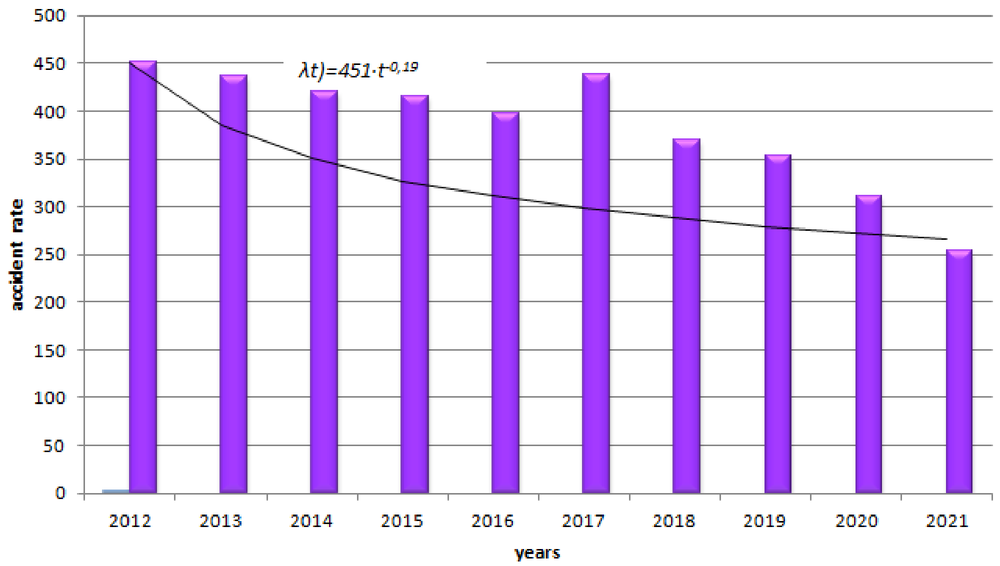

Fig. 3. The intensity of the traffic accident occurrence with the pedestrian's participation histogram

The calculations made it possible to obtain the results of the coefficients α, β theoretical distribution λ(t), according to which it is determined that the law of the two-parameter Weibull distribution for three traffic accident groups in the Belgorod region takes the form: λ(t)=451t-0,19, λ(t)=178-0,22, λ(t)=110-0,15.

Table 3 presents the results of the statistical and theoretical distributions of Weibull's law calculated numerical characteristics.

Comparing statistical and theoretical values, it can be argued that the values of the theoretical distribution do not exceed confidence intervals' boundaries [22].

Table 3. Obtained numerical parameters of the characteristics of the statistical and theoretical distribution results λ(t)

Parameter	Statistical distribution			Theoretical distribution				Confidence intervals, 1/100
Element	M*[λ(t)] 1/100	D*[λ(t)] (1/100)²	δ*[λ(t)] 1/100	λ(t) 1/100	M[λ(t)] 1/100	D[λ(t)] (1/100)²	δ[λ(t)] 1/100	
Pedestrians	384,5	4024,5	63,44	$451t^{-0,19}$	318,586	2883,71	53,7	[339,12; 429,88] [2140,69;10877] [46,27; 104,29]
Children	161,0	124,2	11,15	$178\ t^{-0,22}$	141,127	1264,14	35,6	[153,03; 168,97] [66,08;335,74] [8,13; 18,32]
Drivers	104,3	37,1	6,09	$110\ t^{-0,15}$	92,15	677,77	28,8	[99,9; 108,65] [19,75;100,33] [4,44; 10,01]

Note: The values of the obtained results according to the statistical and theoretical Weibull distribution law λ(t) are calculated from the expressions (22), (23). An additional assessment when choosing the distribution curve λ(t) will allow to implement the criterion of K. Pearson's agreement and its properties X^2 [28]:

$$x^2 = \sum_{i=1}^{k} \frac{\left[\dot{\lambda}_i(t) - \lambda_i(t)\right]^2}{\lambda_i(t)} \tag{30}$$

where k – the number of study intervals; $\lambda_i(t)$ – statistical specific traffic accident rate for i-th interval; λ(t) – the theoretical specific traffic accident rate for i–th interval [22].

When making a forecast based on the two-parameter Weibull distribution law, firstly, a large amount of data is not required, secondly, high forecast accuracy, and thirdly, exponential curves characterize two parameters: a scale parameter that has a physical meaning of traffic accident occurrence in the initial period of monitoring the probability of the traffic accident in the studied area of the road network; a shape parameter, which characterizing the rate of change of the traffic accident λ(t).

Table 4. Information on traffic accidents in the Belgorod urban agglomeration, taking into account the forecast for the subsequent period of time

Year	Number of traffic accidents		
	Pedestrians	Children	Drivers
2012	451	178	110
2013	436	169	101
2014	421	154	105
2015	415	144	109
2016	397	163	112
2017	438	168	106
2018	369	147	107
2019	354	173	101
2020	311	156	101
2021	253	158	91
2022	227	112	94
2023	221	109	89

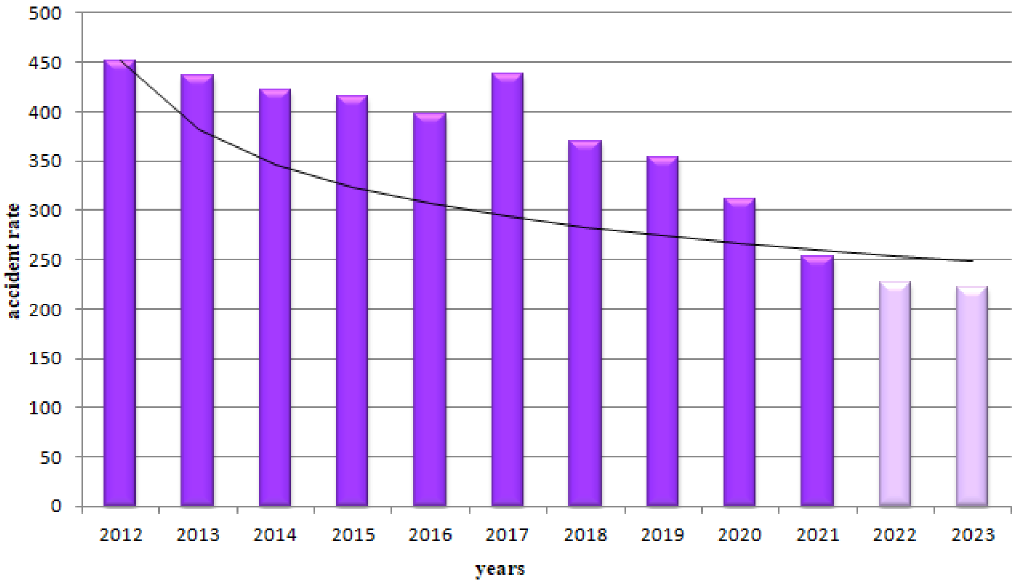

Fig. 4. Forecast of the number of traffic accidents involving pedestrians

According to formula (25), the criteria of agreement are calculated, which make it possible to give a final assessment: if the obtained results of the probabilities of agreement are within 0.3<p<0.999, then the choice of the theoretical distribution law λ(t)=(β/α)tß-1 must be considered correct. This confirms the fact that coordination is taking place from a physical point of view [22].

Thus, the two-parameter Weibull distribution allows to take into account two parameters: the scale parameter, which has a physical meaning of the traffic accident rate in the initial period of monitoring the probability of the traffic accident in the studied section of the road network; the shape parameter characterizing the rate of change in the traffic accident rate λ(t). Depending on the histogram and the angle of the exponential curve, you can see the real traffic accident rate on the roads, taking into account caused it causes. Depending on the histogram and the angle of the exponential curve, it seems possible to establish the real traffic accident rate on the roads, taking into account the causes that caused it. The usual exponential curve does not take into account changes in road transport infrastructure, which in turn allows to take into account the Weibull distribution.

4 Conclusions

Thus, firstly, a theoretical approach has been developed to predict the intensity of vehicle traffic based on mathematical statistics and probability theory. The calculated method confirmed the reliability of the results obtained for the predicted values of vehicle traffic intensity. Secondly, a theoretical approach was developed to predict the number of traffic accidents based on the two-parameter Weibull distribution, which allows to assess the road traffic situation in an urban agglomeration. The obtained forecasting results of the number of traffic accidents involving drivers who were intoxicated, pedestrians, and children, approximated by the Weibull distribution law, took the following form, respectively: λ(t)=110·t-0,15, λ(t)=451·t-0,19, λ(t)=178·t-0,22.

5 Acknowledgement

This work was realized in the framework of the Program «Priority 2030» on the base of the Belgorod State Technological University named after V.G. Shukhov. The work was realized using equipment of High Technology Center at BSTU named after V.G. Shukhov.

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7 Conflict of interest statement

The authors declare that there is no conflict of interest regarding the publication of this paper.

8 Author contributions

Kushchenko L: Investigation, supervision, methodology, writing, review and editing. Kushchenko S: Conceptualization, visualization, supervision, investigation, translation, writing, review and editing. Novikov A: Conceptualization, formal analysis and writing – original draft preparation. Eremin S: Conceptualization, formal analysis and writing – original draft preparation.

9 Availability statement

There is no dataset associated with the study or data is not shared.

10 Supplementary materials

There are no supplementary materials to include.

Paper submitted: 10.11.2024.
Paper accepted: 28.10.2025.