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Original Article

RISK ANALYSIS OF ROAD TRAFFIC ACCIDENTS IN UKRAINE

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Highlights:
- developed a structured methodology integrating statistical and risk management theories to identify and mitigate the most critical causes of road traffic accidents in Ukraine;
- analysed 6 years of traffic accident data (2018–2023) to identify patterns and key risk factors, such as speeding and driving under the influence, contributing to 80% of accidents;
- introduced a dynamic risk map model, enabling targeted monitoring and visual representation of accident severity and frequency for improved decision-making;
- utilized advanced probability density estimation and statistical tools to forecast accident risks, offering actionable insights for policymakers and safety practitioners;
- proposed evidence-based safety measures, including improved enforcement strategies, infrastructure enhancements, and public awareness campaigns to reduce accident frequency and severity effectively.

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Abstract. This article presents a comprehensive investigation into the causes of road transport accidents in Ukraine, focusing on the application of risk analysis to minimize economic and human losses. The study begins with a detailed examination of the current road safety scenario in Ukraine, highlighting the alarming statistics of road accidents and their consequences. The central aim is to develop effective strategies for controlling and managing the causes of road accidents. The research identifies the primary factors contributing to road accidents, such as exceeding safe speed limits, driving under the influence of alcohol, etc. A risk management system is proposed, encompassing the creation of a structured risk management framework, development of methodologies, and implementation of information and analytical systems. The article emphasizes the importance of continuous risk monitoring and assessment, including risk identification, analysis, and management. Statistical observations and analysis play a crucial role in diagnosing risks, which are then used to devise risk minimization measures and improve road safety. The study concludes with recommendations for risk-based decision-making and the implementation of targeted interventions to reduce road accidents and associated risks in Ukraine.

Keywords: road transport accidents, risk analysis, traffic safety, risk management, statistical analysis, safety interventions.

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1. Introduction

Road traffic is one of the most characteristic and integral parts of modern civilization. Motor transport, highways, bridges, tunnels fully embody the achievements of scientific and technical progress. In just one century, the complex system "human–vehicle–road" radically changed the living conditions and appearance of not only individual countries, but also humanity in general (Fisa *et al*. 2022). The vehicles themselves have also changed over time. Their speed capabilities, maneuverability and passability have increased, and comfort has improved. Automobilization of the country contributes to the effective development of both economic and social activity, but at the same time, it has a number of negative consequences: the death of people, injuries, economic and social damage caused by traffic accidents (Alhamad *et al*. 2023; Brondum *et al*. 2022).

In the territory of Ukraine, road transport is currently the most dangerous means of transportation. The largest number of traffic accidents that result in injury or death occur with the participation of automobile transport. According to the Ukrainian National Police data, 18628 road accidents resulting in 2791 deaths and 23145 injuries took place in the territory of Ukraine in 2022 (PPU 2023). The current year 2023 has already witnessed 15041 road accidents that have led to the death of 1870 and inflicted injuries to 18986 people. High motorization rates, the inconsistency of the cities' road network with the actual intensity of traffic flows, low technical condition of vehicles add up to these statistics (Alhomaidat *et al*. 2023), but to a large extent, the situation with accidents is determined by the road users' (primarily drivers') competence level and their attitude to the need to comply with current traffic rules (Che *et al*. 2021; Hughes 2022).

Based on the fact that the problem of road safety is of a complex nature, as it is connected with each of the elements of the "human–vehicle–road" complex system, it is necessary to develop new approaches to the comprehensive assessment of the road situation and the causes of road accidents (Jeon *et al*. 2021; Silva *et al*. 2020). One of the approaches to the multifactor evaluation of the system is the use of risk theory methods based on the analysis and management of risks, including the risks of road accidents. In the development of risk management strategies, modern assessment methods, such as numerical simulations and composite material analysis, are increasingly applied to enhance road safety and risk reduction. For example, numerical simulations of vehicle tires under varying load conditions reveal critical insights into tire performance and its impact on road safety (Karpenko *et al*. 2024). Additionally, advanced risk assessment methods, including frequency response analysis, provide precise modeling of composite tires, aiding in optimal tire design for improved transport safety (Karpenko *et al*. 2023). Moreover, multi-criteria risk assessment techniques, such as SWOT (strengths, weaknesses, opportunities, and threats) and TOWS (threats, opportunities, weaknesses, strengths), are widely used in the innovation process to optimize risk management in technical prototypes (Deptuła *et al*. 2023). These methodologies are further complemented by urban road safety assessments, where risk analysis frameworks help improve safety for vulnerable road users through targeted interventions (Demasi *et al*. 2018).

Currently existing practical recommendations and scientifically based risk management methods are clearly insufficient. In this regard, the study of the nature of risk in transport, the classification of factors affecting the level of risks, the assessment of the economic consequences of their occurrence, the development of methods of risk analysis and forecasting, methods of managing and minimizing the consequences of risks are quite important issues.

2. Materials and methods

The development of road transport, the formation of new structures and the implementation of risk management is becoming an urgent task for road transport in Ukraine. Interest in risk management is mainly caused by the need to strengthen control over the causes of road accidents and reduce losses associated with their occurrence (Shah *et al*. 2018). Risk management involves careful analysis of conditions for decision-making. It is a systematic and logical process that can be used to select strategies for further improving the road transport system activities and increasing the efficiency of its functioning.

The main principle of building a risk management system is a comprehensive account of risk when making decisions both during planning and when evaluating the results of the units responsible for road safety. The implementation of the road transport risk management system involves the following aspects (Barati, Mohammadi 2008; Perera, Holsomback 2005):

- creation of a risk management structure, which includes the formation of specialized functions and procedures in the management of the enterprise and ensuring their effective implementation;
- development of the necessary methodology for risk management;
- creation and implementation of information and analytical systems for risk management.

The road transport risk management system should be based on the following principles:

- constant awareness and monitoring of risks in order to manage them effectively;
- assessment of the probability and possible consequences of the occurrence of various undesirable situations.
- formation and constant updating of risk management tools;
- setting clear risk limits (exact estimation of the maximum permissible level of losses);
- working out recommendations for the formation of strategies and allocation of resources taking into account the level of risk;
- provision of complete and timely information about the level of risk in management information systems.

In the process of auditing and risk management in the operation of road transport networks, the key basis is the qualitative and valuable identification of risk indicators. The risk that can be used to ensure traffic safety, in the context of risk management, can include operational risks.

Diagnostics of risks in road transport means the analysis of processes (Russo, Vitetta 2006). in order to identify risk factors. This process is performed during the risk audit of the road safety direction and includes a comprehensive analysis of parameters in order to identify, describe and classify risks. The most common method of risk diagnosis is statistical observations, which are the most objective and accurate, but often difficult to implement, especially due to the complexity of formalizing historical data and their analytical processing, as well as the lack of necessary historical data (Evans 2003; Delfino *et al*. 2005; Ye, Lord 2011; Kravchenko 2008). Identifying risks is a key stage and the foundation for building a risk management system in road transport. The success of risk management is generally determined by the quality of the analysis of the primary data on the road situation, as it plays a central role in all other risk management procedures (Luk'janova, Golovach 2007).

The process of risk management can be presented in the form of a structural diagram (Figure 1).

Data collection for the organization of risk management. At this stage, an analysis of the functional structure of the process, which will be directly exposed to risk management, its input and output parameters, is performed. Requirements are formulated based on risk assessment criteria, their structure and analysis methods:

- ***risk identification***. At this stage, the risk situation is specified in relation to the achievement of the set goal. A complete list of critical parameters and their risks is formed;
- ***risk analysis***. The level of risk is estimated taking into account the probability of occurrence of the risk and the consequences of the risk situation. The causes and factors of the occurrence of risk as well as its consequences are established, models and methods of risk control are specified and evaluated;
- ***risk assessment***. At this stage, the risk levels of each of the controlled parameters are compared with the established values. An assessment of the scale of management influence on risk and the characteristics of this influence is carried out;
- ***implementation of risk-solution***. Risk minimization measures, aiming at reduction of potential losses in relation to risky situations, are developed and implemented;
- ***monitoring and analysis***. Continuous monitoring and analysis of the risk management process is carried out at each stage of the risk management process to assess the effectiveness of the current risk system and the need for its replacement or renewal;
- ***interaction and consultation***. At each stage of the risk management process, information is exchanged with internal and external participants of this process.

After identifying critical risk factors, the risk management process moves towards a more detailed assessment of the probability of accidents and their potential impact. This approach allows for a structured evaluation of the risks associated with road accidents, focusing on both their frequency and severity. The probability of an accident is evaluated by identifying the modal value of its occurrence:

$$P_{accid_i} = f\left(\text{mod}\left(K_{accid_i}\left(t\right)\right)\right), \quad (1)$$

where: P_{accid_i} is the probability of a specific road traffic accident i occurring within the analysed timeframe; K_{accid_i} is the quantitative measure of the risk factor (e.g., frequency or intensity) contributing to accident i; t is the time interval over which the analysis is conducted; i is the specific road traffic accident.

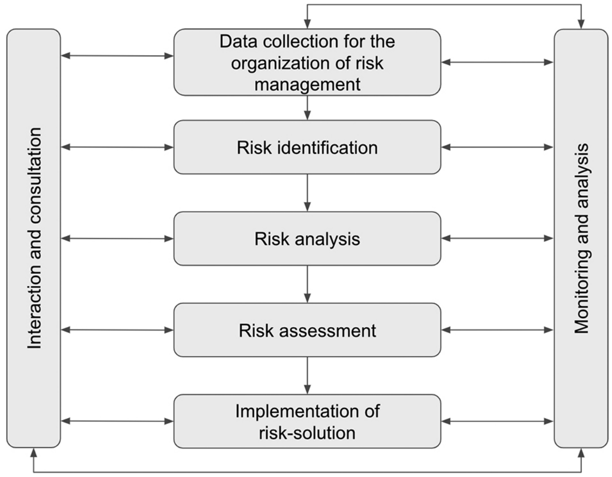

Figure 1. Structural diagram of the risk management process (compiled by the authors)

In the work, according to the theoretical provisions of risk analysis, the quantitative value of risk R is determined on the basis of the basic ratio of risk management theory, where P is the probability of an accident; S is a quantitative indicator of damage from a road accident. At the next stage, we will conduct an assessment of the road accident most likely risks R_{accid_n}, which is defined as the product of the modal probability value and the modal value of this indicator, i.e.:

$$R_{accid_n} = P_{accid_i} \cdot \text{mod}\left(K_{accid_i}\left(t\right)\right), \quad (2)$$

where: R_{accid_n} is the calculated risk level of a specific road traffic accident n.

The unit of measurement of risks coincides with the unit of measurement of this indicator.

The next stage involves the construction of normatively acceptable 90% upper R_{ru} and lower R_{rl} limits of the risk range based on the estimation of risk volatility (mean square deviation) σ_R. Limits are calculated using the expression:

$$R_{ru} = R_n + k \cdot \sigma_R;$$
$$R_{rl} = R_n - k \cdot \sigma_R, \quad (3)$$

where: R_n is the modal risk value, which is the most probable level of risk derived from the dataset; R_{ru} is the upper boundary of the risk range, indicating the maximum acceptable risk level; R_{rl} is the lower boundary of the risk range, indicating the minimum acceptable risk level; σ_R is a standard deviation (volatility) of the normal distribution of road accident risk; k is the coefficient for the corresponding level of confidence probability.

For a significant number of symmetric distributions with a confidence probability of 90%, the coefficient k = 1.6. The most responsible is the calculation of the risk upper limit. Exceeding this limit by the current value of the risk will indicate an unfavorable state of the road situation in relation to the analyzed cause of the accident. It is recommended to use the value k = 0.5...1 as the lower limit of R_{rl}. In this case, the confidence probability is reduced to 80...85%; however, according to Pareto's law, this is sufficient to identify the main number of events and can be of practical application.

3. Results and discussion

According to the presented structural diagram of the risk management process, at the initial stage, an analysis of the causes of road accidents in the territory of Ukraine was performed in the form of quaterly values of the number of road accidents. For this, the number of road accidents for the period January 2018 – December 2023 was analyzed with a classification by the reasons for their occurrence on the basis of road accident statistics according to the National Police of Ukraine data (PPU 2023). A fragment of the results of the analysis of the number and causes of road accidents is given in the Table 1. The dynamics of changes in the number of road accidents for the period 2018–2023 and their main causes are presented in Figure 2.

A deeper analysis of the Table 1 could explore the trends in accident numbers across different quarters, identifying peak periods and discussing seasonal factors. For example, the significant rise in accidents during the summer months may correlate with increased travel activity, requiring further exploration of traffic patterns and road conditions during these periods.

In terms of types of roads of state importance with the highest number of accidents during the analyzed period, the distribution of the number of road accidents is presented in Figure 3.

However, such a large number of road accidents during the analyzed period, which are shown in Table 1, makes it difficult to qualitatively identify and assess the main causes of road accidents (Boo, Choi 2021; Ivančić 2014).

To solve this problem, there are a number of modern methods of process quality assessment theory. They provide simplicity, clarity, and visualization of many statistical methods, turning them into effective tools of operational quality control. One of these methods is the Pareto law (80%|20%), the principle of which is based on the separation of important factors from unimportant and insignificant factors and allows focusing efforts and resources on eliminating the most significant problems (Gądek-Hawlena 2019).

The constructed Pareto diagram of the causes of road accidents, which are listed in Table 1, is presented in Figure 4.

Analysis of the diagram shows that 80% of the causes of road accidents in the territory of Ukraine during the studied period are: exceeding the safe speed, violation of the rules for using external lighting devices of vehicles, violation of the rules of crossing intersections, violation of the rules of driving at pedestrian crossings, failure to maintain the distance and driving the vehicle under an influence of alcohol (DUI – driving under the influence). Exceeding the safe speed (speeding) amounts to 38.5%. The above-mentioned main causes of road accidents are further used to develop a methodology for conducting risk analysis of road accidents.

The next step of the risk analysis is to conduct a statistical assessment of the quaterly number of road accidents according to the main reasons for their occurrence and to construct the probability density of these indicators. The main values of statistical estimates of a number of quaterly causes of road accidents (2018–2023) are presented in the Table 2.

Table 1. The number of road accidents in Ukraine for the period 2018–2023 and their main causes (compiled by the authors)

Quarter of the year	Exceeding the safe speed	Violation of the rules for the use of vehicle external lighting devices	Violation of the intersection crossing rules	Violation of the pedestrian crossings passing rules	Failure to maintain the distance	Driving a vehicle while intoxicated	Pedestrians crossing in an unspecified place	Exceeding the set speed	Entering the oncoming traffic lane	Violation of unobstructed passage provision rules	Unexpected entering the carriageway	Drivers' failure to comply with regulation signal requirements	Violation of overtaking rules
Q1 2018	1169	696	253	192	144	125	97	85	62	41	34	34	32
...	...	...	...	...	...	...	...	...	...	...	...	...	...
Q1 2022	1452	864	314	239	179	155	120	105	77	51	42	42	39
Q2 2022	1816	1081	393	299	224	194	150	131	97	63	53	52	49
Q3 2022	2303	1371	498	379	284	246	190	166	122	80	67	66	63
Q4 2022	1635	974	354	269	202	174	135	118	87	57	48	47	44
Q1 2023	1788	858	343	435	206	171	249	106	101	50	62	43	32
Q2 2023	2160	1429	493	283	280	230	150	171	111	85	56	57	66
Q3 2023	3349	2099	770	464	422	387	183	255	134	82	67	54	63
Q4 2023	1918	805	408	460	240	154	199	110	74	63	48	43	55

Figure 5 shows the probability density of an accident depending on the cause of its occurrence. The abscissa axis shows the quantitative assessment of road accidents and the ordinate axis shows the probability assessment of this indicator, expressed in the number of events that occurred in a quater. Histogram columns show the percentage probability of the indicator numerical value.

At the next stage, we evaluate the highest probability by identifying the modal value of the occurrence of an accident according to the Equations (1)–(3).

It is advisable to obtain an estimate of the highest probability on the basis of the constructed probability density of the distribution of road accidents (Table 2, Figure 5). On the example of the "Exceeding the safe speed" cause of the road accident with a total number of observations of 34 and the largest number of 8 events according to the theoretical distribution law (Figure 5a), the highest probability is P = 0.24.

Table 2. Statistical assessment of road accidents in Ukraine for the period 2018–2023 (compiled by the authors)

Cause of road accident	Number of measurements	Number of road accidents	Average value	Median *Me*	Min	Max
Exceeding safe speed	80	270621	3383	4056	439	7011
Violation of the rules for using vehicle external lighting devices	80	161153	2014	2416	230	4175
Violation of the intersection crossing rules	80	58576	732	878	95	1518
Violation of pedestrian crossing passage rules	80	44514	556	667	72	1153
Failure to maintain distance	80	33385	417	500	54	865
Driving a vehicle while intoxicated	80	28869	361	433	47	748

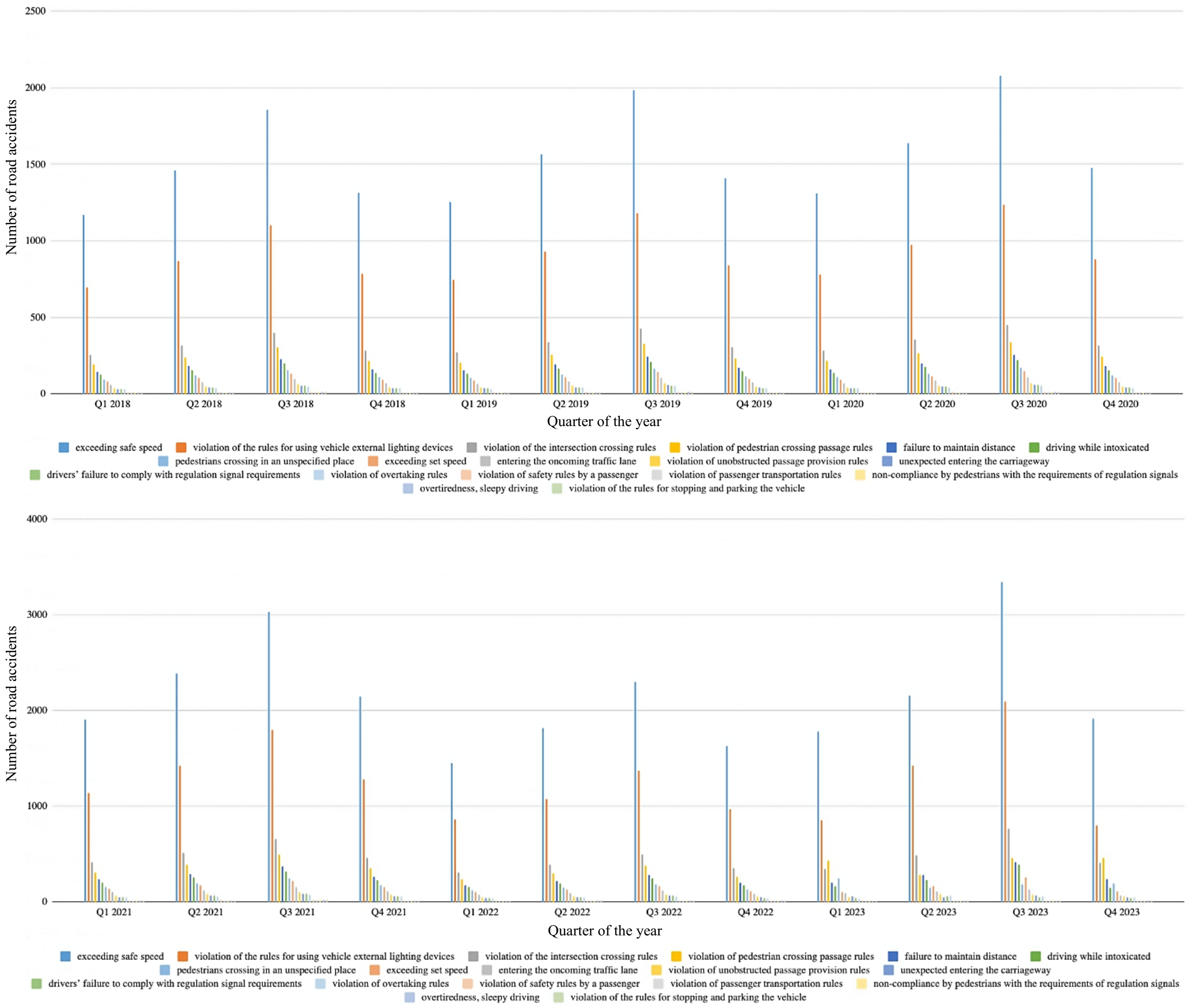

Figure 2. Dynamics of changes in the number of road accidents in Ukraine for the period 2018–2023 (compiled by the authors)

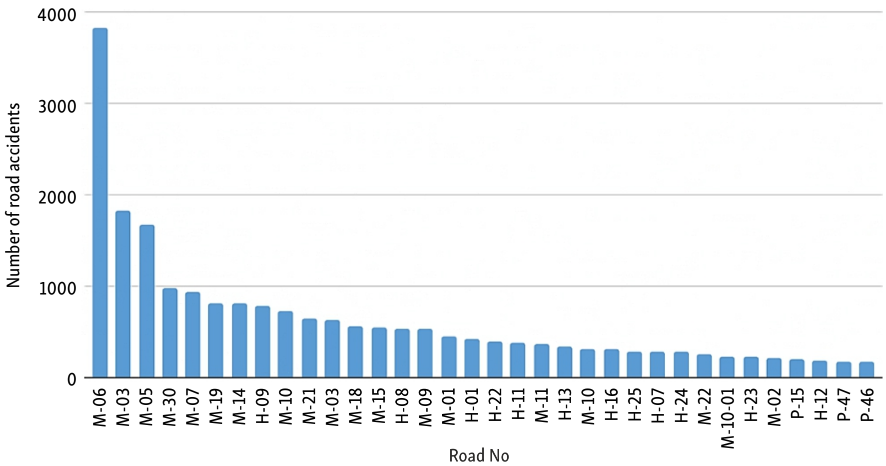

Figure 3. Dynamics of the number of road accidents on roads of state importance in Ukraine for the period 2018–2023 (compiled by the authors)

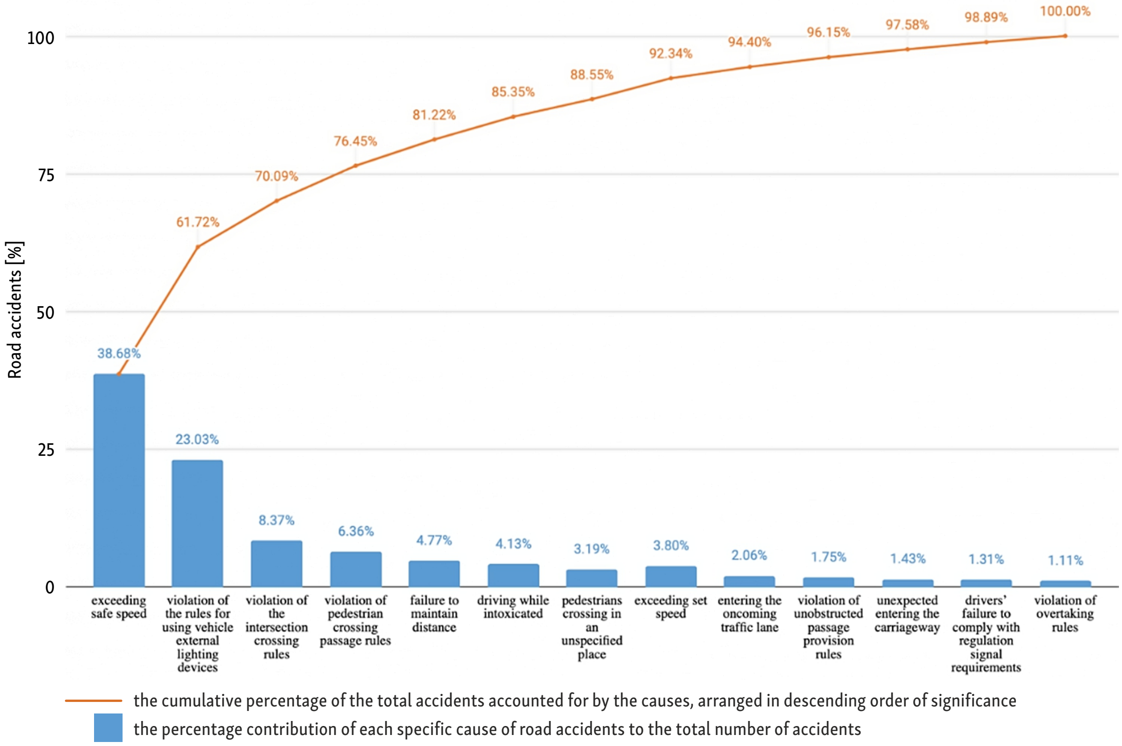

Figure 4. Causes of road accidents in Ukraine for the period 2018–2023 (compiled by the authors)

The modal value of the indicator is estimated on the basis of the constructed road accident distribution probability density (Table 2, Figure 5a). For the "Exceeding the safe speed" indicator $\text{mod}\left(K_{accid_i}\right) = 8$. Hence, the most likely risk for the "Exceeding the safe speed" indicator is $R_{accid_n} = 165$.

The next stage is the construction of a risk map. The risk map is the final analytical product of the risk diagnosis stage and is a graphically arranged display of risk factors or objects according to the magnitude and probability of possible damage to the enterprise. The risk map visually illustrates the severity and frequency of accidents. More detailed interpretation could highlight the specific factors contributing to risk spikes, such as poor road conditions or inadequate enforcement of traffic laws. Additionally, comparing the risks of different causes (e.g., speeding vs. driving under the influence) can provide insight into which factors should be prioritized for intervention.

The risk map has the form of a 2-dimensional diagram. The value expression of the estimated loss under the influence of the considered factor is located on the abscissa axis, and the probability of the realization of the corresponding event is located on the ordinate axis. The most common type of risk map is its construction by risk factors. We build a risk map by determining the most probable (modal) risk curve based on the expression $R_n = P_n \cdot S_n = \text{const}$ (where: R_n is the modal risk value associated with a specific type of accident or risk factor n; P_n is the probability of a particular accident occurring, calculated based on historical data and statistical models; S_n is the sever-

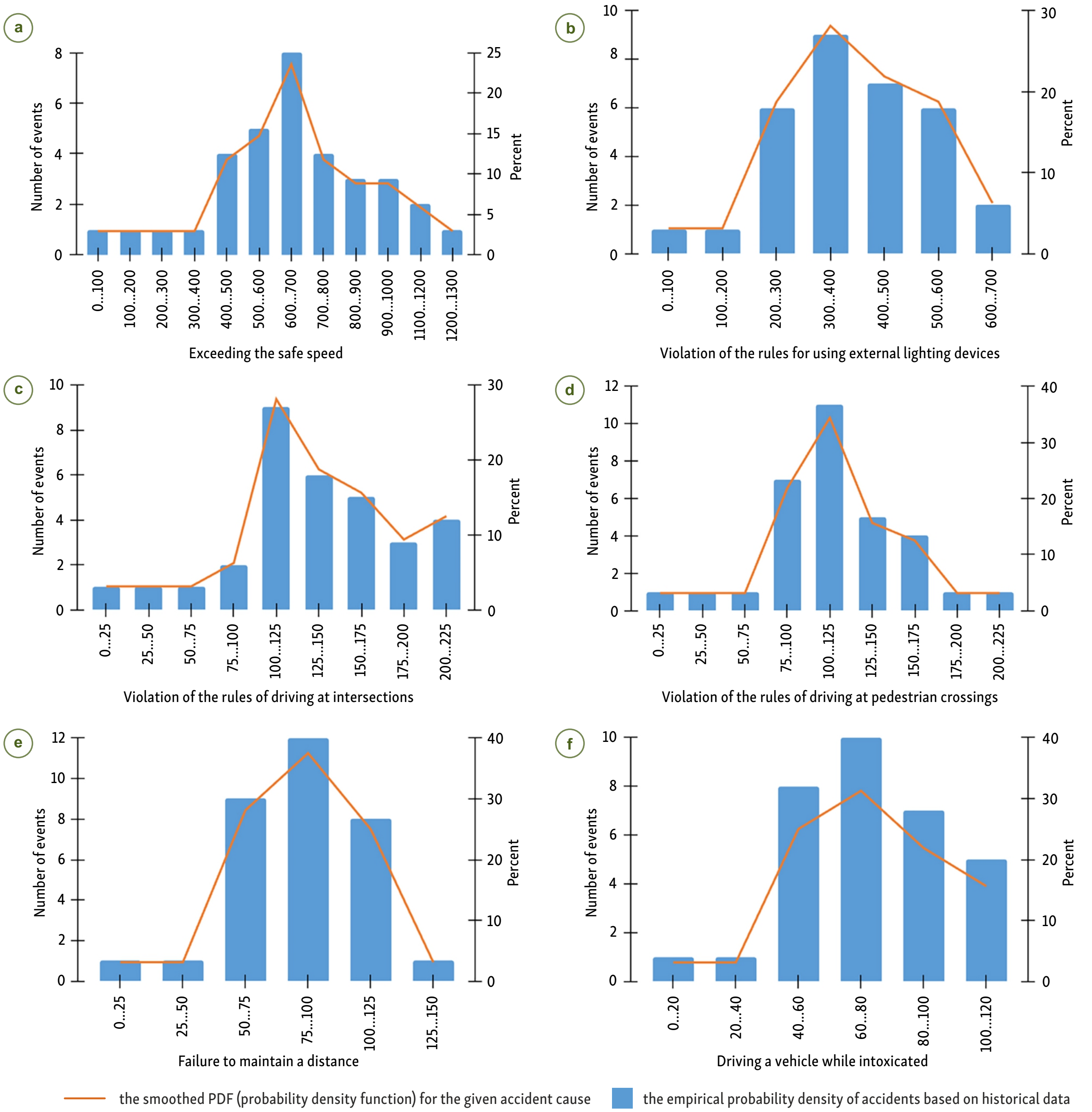

Figure 5. Density of the probability of committing a traffic accident by its cause (compiled by the authors):
(a) – exceeding the safe speed; (b) – violation of the rules for using external lighting devices;
(c) – violation of the rules of driving at intersections; (d) – violation of the rules of driving at pedestrian crossings;
(e) – failure to maintain a distance; (f) – driving a vehicle while intoxicated

ity or impact of the accident, often measured in terms of economic losses, injuries, fatalities, or damage) with the variable values of the probability P of an accident occurrence and the severity S of an accident. We use the same method to build the normatively permissible upper R_{ru} and lower R_{rl} curves of the limits of the risk range (where: R_{ru} is the upper boundary of the risk range; R_{rl} is the lower boundary of the risk range). In the risk map, the abscissa shows the accident values K (quantitative representation of accidents), and the ordinate shows the probability of an accident. Figure 6 shows maps of the risks of road accidents depending on the reasons for their occurrence.

Based on the construction of the risk map, operational monitoring of the actual risk level $R(t)$ at a specific time t and their placement on the risk map is carried out. At the same stage, the values of the target risk indicators R_t, chosen within the range $R_{tl} \leq R_t \leq R_{tu}$ (where: R_t is the desired risk level for a given time period t; R_{tl}, R_{tu} are target lower and upper boundaries of risk define the acceptable fluctuation range of risk indicators for a given time period R_r), are selected or adjusted. When the normatively permissible upper R_{ru} and lower R_{rl} curve limits of the risk range are exceeded by any of the controlled indicators (causes of road accidents), a decision is made to carry out a more thorough analysis of the road situation, which could have caused an increase in the risk indicator, with further development of measures to reduce accidents and the risk of causing a road accident due to a specific cause.

After calculating the modal values for each risk factor and building risk maps, it becomes essential to interpret these values in a practical context. The identification of the highest probability accident causes allows for targeted interventions. For example, the most frequent risk factors, such as exceeding speed limits or driving while intoxicated, indicate areas where enforcement measures could be most effective. By prioritizing these factors, policymakers can allocate resources more efficiently, focusing on the most critical risks to improve road safety outcomes.

As an example of the use of the risk analysis method, let us represent the risks of road accidents due to speeding in 2023 (Table 3) on the risk map (Figure 7) and analyze the obtained results. In order to assess the current risks, we will put the values for the period January–August 2023 on the map of the risks of road accidents due to speeding.

From the obtained risk map, it can be seen that the values of R_{feb} and R_{mar} are smaller than R_{tgt}, that is, they are in the acceptable range. R_{jan}, R_{apr} and R_{may} exceed the target values of R_{tgt}, and the values of R_{jun}, R_{jul} and R_{aug} are bigger than 90% of the maximum allowable values of R_{ru} risk (where: R_{tgt} is a target risk level representing the desired or acceptable risk threshold for a given accident scenario; R_{jan}, R_{feb}, R_{mar}, R_{apr}, R_{may}, R_{jun}, R_{jul} and R_{aug} are the calculated risk values for specific months, i.e., for January, February, March, April, May, June, July and August respectively; R_{ru} is the upper boundary of the risk range). According to the provisions of the risk analysis method-

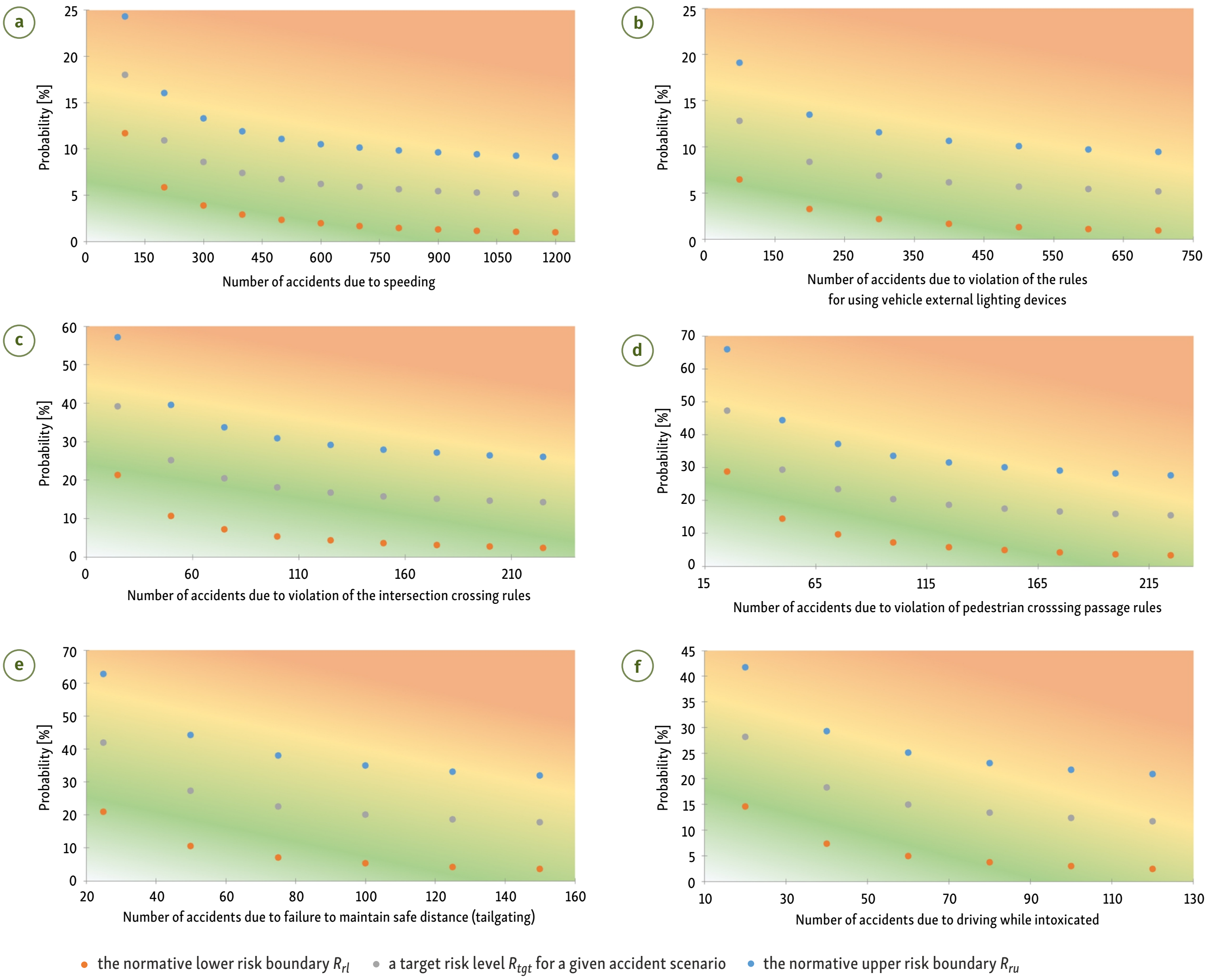

Figure 6. Risk maps by the causes of road accidents (compiled by the authors):
(a) – exceeding the safe speed; (b) – violation of the rules for using external lighting devices;
(c) – violation of the rules of driving at intersections; (d) – violation of the rules of driving at pedestrian crossings;
(e) – failure to maintain a distance; (f) – driving a vehicle while intoxicated

Table 3. Statistics of the risks of speeding-caused road accidents in Ukraine for the period of 2023 (compiled by the authors)

Observation period	Number of road accidents	Risk of road accidents
January 2023	656	74.04
February 2023	567	55.31
March 2023	565	54.93
April 2023	615	65.08
May 2023	721	89.44
June 2023	824	116.82
July 2023	924	146.90
August 2023	940	152.03

ology, if the current maximum permissible indicators are exceeded, it is necessary to carry out measures to identify the causes of the deviation, followed by their elimination or reduction of their impact on accidents. At the same time, during the analysis of the road situation, it is advisable to detail the cause of road accidents in individual locations (region–district–city/village–street), for which exceeding the risk indicator of road accidents is critical.

Further development of the road map to reduce the risk of road accidents should include measures aimed at minimizing the very indicator (cause), the risk of which has reached a critical value. Such measures may include the following:

- arrange pedestrian crossings;
- install "Pedestrian crossing" signs;
- equip underground pedestrian crossings;
- improve road maintenance in winter;
- perform pruning of trees in places where road signs are installed;
- organize comprehensive preventive measures to promote traffic rules among road users;
- improve the effectiveness of supervision to detect cases of operating vehicles by drivers under the influence of alcohol;
- ensure control over the technical condition of the road, using a special laboratory;
- etc.

4. Conclusions

The research has successfully developed a comprehensive methodology for risk analysis specifically aimed at assessing the causes of road traffic accidents in Ukraine. This methodology is instrumental in identifying key risk factors and strategizing preventive measures. The main provisions of risk theory and its application to road traffic safety in Ukraine have been detailed, with the proposed method offering an effective assessment of accidents on highways. The research contributes to the understanding of how risk

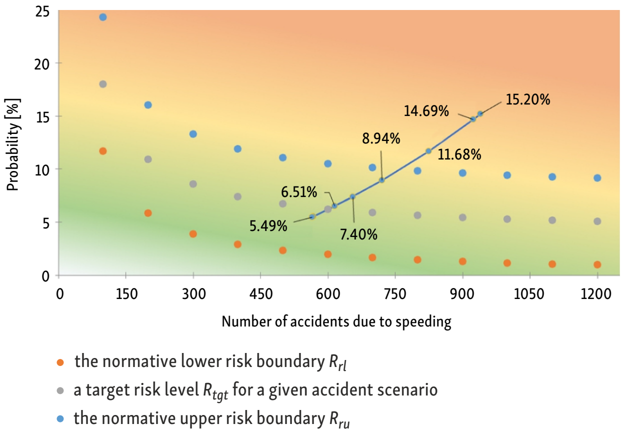

Figure 7. Map of the risks of road accidents due to speeding for the year 2023 (compiled by the authors)

management systems can be structured and integrated with information and analytical tools to improve road safety.

The core contribution of this work is the creation of a structured risk management framework that utilizes statistical data to identify and mitigate the most significant causes of road accidents. The novelty lies in its application of risk management theory to real-world transport challenges, particularly focusing on the Ukrainian context, where road safety issues are critical.

Developed framework is designed for practical use by policymakers, traffic safety authorities, and urban planners. By identifying the most critical risks and offering targeted interventions, this research paves the way for safer road networks and more effective accident prevention strategies. The risk management system proposed in this study can be directly applied to monitor and reduce accident risks, improving both human and economic outcomes.

Future work should expand the risk management framework to include more advanced analytical tools, such as machine learning for predictive accident modeling, and extend the analysis to cover other regions and types of transportation. Furthermore, deeper exploration into the long-term impact of implemented safety measures could refine the framework, leading to more accurate risk forecasts and better prevention strategies.

Author contributions

Oleg Lyashuk, *Dmytro Mironov* and *Pavlo Maruschak* conceived the study and were responsible for the design and development of the data analysis.

Dmytro Mironov, *Volodymyr Martyniuk* and *Viktor Aulin* were responsible for data collection and analysis.

Oleg Lyashuk and *Oleg Tson* were responsible for data interpretation.

Dmytro Mironov wrote the 1st draft of the article.

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