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Optimization of the process of forecasting the number of traffic accidents

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Abstract: The primary goal of this paper is to develop a methodology for optimizing the forecasting process of traffic accident occurrence. Traffic accidents remain a critical societal and economic issue, and existing forecasting approaches often fall short when applied to complex, variable, or incomplete datasets. To address this challenge, the paper proposes a structured multi-criteria optimization framework grounded in formal decision theory. The core of the methodology lies in formulating a multi-objective optimization problem (ZO) that includes sets of admissible solutions, vector-valued objective functions, and dominance relations. The proposed model enables both quantitative and qualitative evaluation criteria to be integrated into the forecasting process. The study details an algorithm that identifies dominant, non-dominated, and compromise solutions, using normalization techniques and distance measures to support solution selection. A case study demonstrates the model's ability to determine optimal forecasting solutions based on multiple conflicting criteria. The approach is characterized by flexibility and generalizability, allowing its application in diverse scenarios involving accident prediction. The results confirm that the proposed method improves both the transparency and robustness of traffic accident forecasting. This methodology may support decision-makers and analysts in the development of effective, data-driven strategies for road safety planning and accident prevention.

1 Introduction

Road traffic accidents represent a significant societal challenge faced by all nations. Their occurrence is influenced by numerous factors, including weather conditions, driver intoxication, vehicle speed, and others. According to data from the World Health Organization [1], road crashes claim the lives of over 1.35 million people annually, with many more sustaining serious injuries and long-term health complications. These incidents also contribute to substantial economic losses. Although recent years have seen a downward trend in accident numbers—primarily attributed to the reduced mobility during the COVID-19 pandemic—the figures remain alarmingly high (Figure 1). On average, 62 traffic accidents occur each day, resulting in approximately 6 fatalities and 72 injuries. Such events lead to increased healthcare expenditures, damage to vehicles and road infrastructure, and environmental harm, including fuel and fluid leaks. In response, various strategies have been implemented to minimize road accidents. These include analyzing the factors contributing to accident occurrence and applying forecasting models to predict future trends [2,3].

Research conducted by Zhai et al. [4] and Holland et al. [5] has demonstrated that pedestrians are among the most vulnerable groups in traffic accidents due to the lack of physical protection compared to vehicle occupants. Moreover, injuries sustained by pedestrians tend to be more severe. Their studies also indicated that numerous factors—such as alcohol consumption, driver demographics (including age and gender), road surface conditions, lighting, pedestrian behavior, accident location, vehicle type, speed, and adverse weather—play a critical role in determining the severity of pedestrian injuries [4,5]. Poor lighting, particularly at crosswalks, and unfavorable weather conditions are frequently associated with more serious outcomes [6-8]. However, the impact of weather varies by region. For instance, one study [9] reported minimal influence of weather on accident frequency. A comparable line of inquiry can be found in [10], where the authors proposed a model linking accident probability with driving time and real-time weather data. The correlation between weather and traffic accidents has also been the focus of numerous other studies [11-23].

Beyond environmental conditions, traffic density and human factors—such as drivers' reaction times to dynamic road situations—also contribute to increased accident rates [24,25]. Brodsky and Hakkert [26] similarly observed that rain could double accident risk, while Danish data revealed only a modest 10% increase. Conversely, Fridstrøm et al. concluded that rainfall had no discernible impact in Norway and Sweden. Interestingly, Polish statistics suggest that the majority of road accidents occur during clear weather. Furthermore, elevated temperatures and favorable weather conditions are also associated with higher accident frequencies [3,25,27].

Given these findings, there is a clear rationale for developing a multi-criteria optimization model to support a robust methodology for forecasting the number of road traffic accidents.

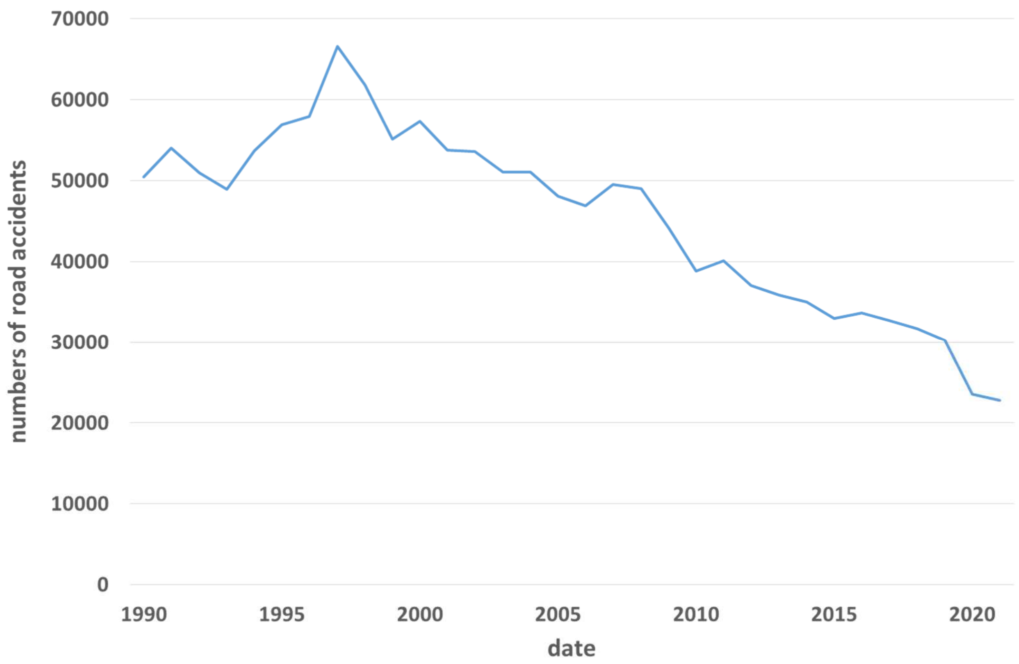

Figure 1 Number of road accidents in Poland between 1990 and 2021 [3]

2 The optimization model

When defining an optimization problem, it is often challenging to express solution quality using a single scalar objective function F. This difficulty arises because the set of feasible solutions X typically exhibits multiple attributes, each of which may contribute differently to the overall assessment of solution quality.Thus, it is necessary in this case to formulate an Optimization Task (ZO) with multiple (e.g., N) quality indicators in the form of a criterion function F [28] (1):

$$F : X \rightarrow R^N \tag{1}$$

This function assigns to each admissible solution $x \in X$ its numerical rating in the form of a vector (2):

$$F(x) = (F_1(x),..., F_n(x),..., F_N(x)) \in R^N \tag{2}$$

where:

N = {1,..., i,..., n} - collection of quality indicator numbers,

$F_n(x)$ - the value of n - this quality indicator (n - this criterion function for the solution $x \in X$).

The formulation of the optimal solution problem is then as follows. Denoting:

a) A – solution space;
b) B – solution evaluation space;
c) $F : A \Rightarrow B$ – criterion function, assigning to each solution $X \subset A$ its grade $Z \in B$ and assuming that the set of possible solutions A is not empty, a certain subset X can be selected (the set of acceptable solutions), whereby (3):

$$Z = F(X) = \{F(x) \in B \mid x \in X\} \tag{3}$$

After determining the set X, the mapping function F and the dominance relation Φ, the optimization task (ZO) is formulated in the form (4):

$$ZO = (X, F, \Phi) \tag{4}$$

where:

$X = \{ x_1,...,x_n \}$ – set of possible solutions;

F – criterion function for selecting possible solutions (5) $F: X \Rightarrow R^N$

$$F(X) = (f_1(X), f_2(X),),..., f_n(x),..., f_N(x)) \tag{5}$$

When considering ZO for R^2 (6):

$$F(X) = (f_1(X), f_2(X)) \tag{6}$$

Where the partial functions $f_1(X)$, $f_2(X)$ can have the preference structure of the dominance relation Φ: MAX or MIN, respectively;

Where the dominance relation Φ has a preference of MAX (7):

$$\Phi = \{ (c_1, c_2, \dots, c_n, \dots, c_N) \in C \times C : c_1^1 \geq c_2^1 \wedge c_1^2 \geq c_2^2 \} \tag{7}$$

where:

C - The image of the set X at the mapping F,
c_1, c_2 - points of space C (8):

$$C = F(X) = \{(f_1(x), f_{1,2}(x)) \in R^2 : x \in X\} \quad (8)$$

Where the dominance relationship Φ has a MIN preference (9):

$$\Phi = \{(d_1, d_2) \in D \times D : d_1^1 \le d_2^1 \text{ i } d_1^2 \le d_2^2\} \quad (9)$$

where:

D - The image of the set X at the mapping F,
d_1, d_2 - points of space D (10):

$$D = F(X) = \{(f_1(x), f_2(x)) \in R^2 : x \in X\} \quad (10)$$

Based on the above, a method of solving a multi-criteria optimization task is presented. Let the optimization task of determining possible solutions be (11):

$$(X_1, F_1, \Phi_1) \quad (11)$$

where:

X_1 - the set of admissible solutions defined as (12)

$$X_1 = \{x_{1,1}, x_{1,2}, x_{1,3}, x_{1,4}\} \quad (12)$$

F_1 - quality indicator defined as (13) $F_1 : X_1 \Rightarrow R^2$

$$F_1(X_1) = (f_{1,1}(x), f_{1,2}(x)) \quad (13)$$

Φ_1 - Dominance relationship with preference, e.g. MAX, MAX.

To determine the set of dominant solutions $X_D^{\Phi1}$ of the optimization task, find the product of the following sets X_1^1 and X_1^2 (14), (15):

$$X_1^1 = \{x^* \in X_1 : f_{1,1}(x^*) = \max_{x \in X_1} f_{1,1}(x)\} \quad (14)$$

$$X_1^2 = \{x^* \in X_1 : f_{1,2}(x^*) = \max_{x \in X_1} f_{1,2}(x)\} \quad (15)$$

Where the quantities $f_{1,1}(x)$, $f_{1,2}(x)$, are defined by appropriate relations, e.g. as (16):

$$f_{1,1}(x) = e_j(x) \text{ i } f_{1,2}(x) = r_j(x) \quad (16)$$

Therefore, two tasks need to be solved:

a) maximize function (17):

$$f_{1,1}(x) = e_j(x),\ x \in X_1;\ j = 1,\dots,n \quad (17)$$

b) maximize function (18):

$$f_{1,2}(x) = r_j(x),\ x \in X_1;\ j = 1,\dots,n \quad (18)$$

Then determine the sets of X_1^1 i X_1^2 (19), (20):

$$X_1^1 = \{x^* \in X_1 : e_j(x^*) = \max_{x \in X_1} e_j(x)\} \quad (19)$$

$$X_1^2 = \{x^* \in X_1 : r_j(x^*) = \max_{x \in X_1} r_j(x)\} \quad (20)$$

and the set of dominant solutions as the product of the sets of X_1^1 i X_1^2 (21):

$$X_D^{\Phi1} = X_1^1 \cap X_1^2 \quad (21)$$

If the set $X_D^{\Phi1}$ is empty, the set of non-dominated solutions $X_N^{\Phi1}$ and the set of compromise solutions $X_K^{\Phi1}$ are determined.

According to the remarks made above, the maximum value of the function (19) and the maximum value of the function (20) determine the coordinates of the ideal point $c^* = (c_1^*, c_2^*)$ (22):

$$c_1^* = \max_{x \in X_1} e_j(x); \qquad c_2^* = \max_{x \in X_1} r_j(x) \quad (22)$$

From the adopted form of the criterion function $F_1 = \{f_{1,1}, f_{1,2}\}$ it follows that for c* the maximum value of e_j is demanded and the maximum value of r_j is demanded.

In further considerations, the normalized index of the quality of the solution of the task (5,6) will be used, which is proposed to be (23):

$$F_1^*(x) = \{f_{1,1}^*(x), f_{1,2}^*(x)\} \quad (23)$$

Where (24):

$$f_{1,1}^*(x) = \frac{f_{1,1}(x)}{c_1^{max}},\quad f_{1,2}^*(x) = \frac{f_{1,2}(x)}{c_2^{max}} \quad (24)$$

whereby (25):

$$c_1^{max} = \max_{x \in X_1} f_{1,1}(x),\quad c_2^{max} = \max_{x \in X_1} f_{1,2}(x) \quad (25)$$

The advantage of this method of normalization is that the ratio is preserved after normalization. The highest value of the ratio is 1, and the lowest is greater than or equal to 0. The normalized ideal point then has coordinates (26):

$$c^{**} = (c_1^{**}, c_2^{**}) \quad (26)$$

Due to the form of the set of admissible solutions X_1 (discreteness) for determining the set of its non-dominated solutions $X_N^{\Phi1}$ and compromise solutions $X_K^{\Phi1}$, a method is proposed to determine the approximate result (and therefore the solution) of the compromise for the norm $|\bullet|$, which is a measure of the distance of the results c* ∈ C* from the ideal point c** [29].

Let c** denote the ideal point determined by relation (29) and C* the known set of normalized results (27):

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$$C^* = \{c^{*i}\},\ i = 1,\dots,n \tag{27}$$

where $c^{*i} = (c_1^{*i}, c_2^{*i})$, whereby (28):

$$c_1^{*i} = \frac{c_1^i}{c_1^{max}},\ c_2^{*i} = \frac{c_2^i}{c_2^{max}} \tag{28}$$

In order to determine the compromise results, it is proposed to calculate the value of the $|\bullet|$ standard with the parameter p = 2 (29):

$$r_i = |c^{**} - c^{*i}|^2 = \sqrt{(c_1^{**} - c_1^{*i})^2 + (c_2^{**} - c_2^{*i})^2} \tag{29}$$

and selecting such a result c^o (30), which would minimize the calculated values of r_i norms. e.g. $x_1^o = x_{1,3}$

$$x_1^o = c^o = \min r_i \tag{30}$$

An interpretation of the above method is shown in Figure 2.

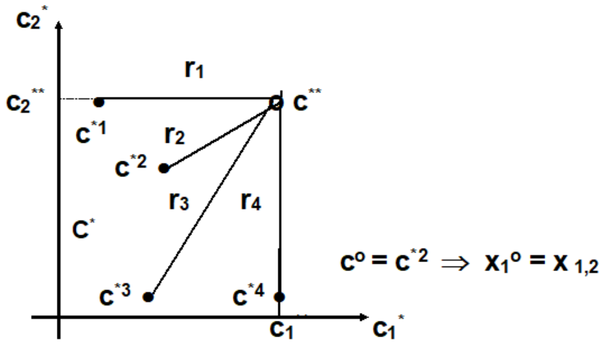

Figure 2 Graphical interpretation of the solution to the optimization task [28]

Based on the aforementioned insights, the following section outlines an algorithm that supports the proposed methodology for optimizing the traffic accident forecasting process (Figure 3).

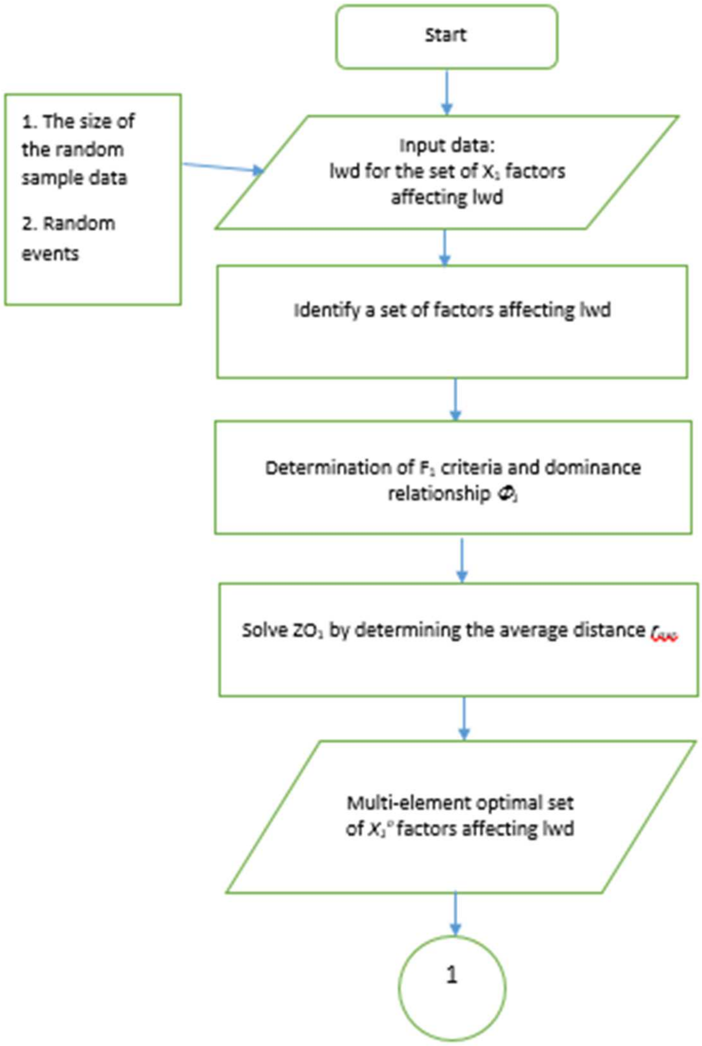

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Figure 3 Schematic diagram of the methodology for optimizing the process of forecasting the number of road accidents

3 Conclusion

This study presents a methodological framework for optimizing the forecasting of road traffic accidents using a multi-criteria decision-making approach. The complexity of the problem, stemming from the multifactorial nature of road accidents and the limited quality of available data, necessitates a solution that can incorporate both quantitative and qualitative criteria. The proposed model formulates the forecasting process as a multi-objective optimization task, introducing sets of admissible solutions, partial objective functions, and dominance relations.

The developed algorithm enables the identification of dominant, non-dominated, and compromise solutions through normalization and distance-based evaluation, ensuring the adaptability of the method to varying data structures and decision-making preferences. The flexibility of the approach allows it to be applied in different contexts and with diverse sets of forecasting indicators.

The main advantage of the proposed methodology lies in its universality and scalability. It can be adapted to various forecasting challenges where both numerical and categorical indicators are relevant. Furthermore, the presented optimization framework provides a structured basis for supporting data-driven decisions in traffic safety management.

Future research may extend this approach to real-time data environments, include dynamic factors (e.g., weather or traffic flow), and integrate machine learning techniques to enhance predictive accuracy and operational efficiency.

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