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Assessing Critical Road Hazard Factors for Sustainable Development in Cities

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ABSTRACT

Improving road safety is essential for building sustainable and resilient urban infrastructure, in line with the United Nations Sustainable Development Goals (SDGs). This study aims to support sustainable transport policy by evaluating the impact of critical factors on road hazards using an efficient decision-making model. The Fuzzy Analytic Hierarchy Process (FAHP) was applied to manage ambiguity and uncertainty inherent in expert evaluations. A real-world decision-making scenario was analyzed, focusing on factors influencing road safety. The FAHP results for the first level identified "Adverse Geometric Condition" as the most significant factor contributing to road hazards (weight: 0.6811), while "Poor Road Surface Condition" was the least impactful (weight: 0.1332). At the second level, "Improper Road Width" emerged as the top sub-factor (weight: 0.2557), whereas "Excessive Potholes" ranked lowest (weight: 0.0129). These findings provide a structured and data-driven foundation for policymakers to prioritize interventions that promote safer, more sustainable transportation systems.

1. Introduction

Road safety is a critical component of sustainable development. According to the World Health Organization (2016), approximately 1.35 million people die annually due to road traffic collisions—equivalent to about 3,700 deaths per day—while another 20 to 50 million suffer injuries or permanent disabilities. These alarming statistics underscore the urgent need to enhance traffic safety systems, especially in urban environments striving for sustainability [1].

There are numerous probable causal factors to the possibility of happenings of traffic collisions [2, 3]. By means of all potential variables in estimating traffic collision projecting models undercuts the precision of the constraint evaluations to a definite range. Many factors influence the

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road safety. The most important factors are driver behaviour, construction and condition of the vehicle and condition of infrastructure [4].

Analysis of the interaction between elements of the system “driver–vehicle–road–traffic environment” and study their mutual influence help to develop methods of optimization factors of road environment and traffic as well as get solutions that meet the requirements of the safety and comfort of movement [5]. A case study approach is applied to identify and assess potential security risks in a smart city infrastructure. The risk factors used in the study are identified as traffic accidents, flash floods, and transportation security, robbery and public safety threats, health crises and pandemics, cybersecurity threats, and energy infrastructure and outages [6].

The geometry of the roadway plays a significant role in road crash frequencies as well as the crash severity level. Knowledge of roadway parameters affecting road safety can help to plan, design, build and maintain the road infrastructure to facilitate a safe road environment. The design of roads plays a major role in terms of road safety [7].

Acquiring knowledge of the risk factors that contribute to road traffic crashes is important in formulating the priorities of action plans and interventions that can reduce the risks associated with those factors. It is generally recognised that a multi-disciplinary approach is essentially needed in understanding the main causations of RATs and providing better and appropriate solutions [8].

The analytic hierarchy process (AHP) method was created by Saaty and it considers the most used and sustainable decision-making model. Recently, it has been adopted to estimate the transportation complex issues, such as, evaluating the park and ride problem, ameliorating urban transport system, modelling travel mode and estimate the critical factors related to road safety. However, the popularity of AHP has been significantly increased after combining it with fuzzy logic, and it has been applied in many recent different research studies, including transportation [9]. This integration presents complex issues and risks in the various modes, levels, and approaches. The combined method can produce data through risk assessments, which can be realized by inconsistent models. The models generated from the risk assessments are used in various areas, such as in the floor water incursion in coal mines, hazardous substances in transportation, and for the development of information technology. In recent study, the multi-attribute utility theory (MAUT) was applied as a practical multi-objective decision-making method to prioritize 20 bridge networks in Western Turkey [10].

Multi-Criteria Decision-Making Model (MCDM) were used in evaluation of significant factors related to road safety such as driver behavior [11], frequent lane changes [12] and public transport network [13]. Nenadic [14] investigated the road hazardous point using a Multi-Criteria Decision-Making Model (MCDM) considering five quantitative and two qualitative criteria for vehicle traffic safety. First, the criteria’s weight coefficients were defined using the FUll Consistency Method (FUCOM). Then, the hazardous sections of the road were ranked using the Weighted Aggregate Sum Product Assessment (WASPAS) method.

Fernandez *et al.* [15] employed the Analytic Hierarchy Process (AHP) method to analyze the data and prioritize the road accident factors. The results of this study showed that a high level of understanding of traffic signs generally results in a more accurate and reliable prioritization of road accident factors. Moreover, it was found that the factor with the highest rank among road accident factors is lack of knowledge of traffic signs, while the lowest-ranked factor is bad driving behavior.

The following is the order in which the paper is presented: Section 1 includes background studies from the literature covering road accidents, decision making and analytical tools to investigate the drivers’ behavior and their relationships to road safety. Section 2 depicts the methodology of current research is described covering risk perception, critical behavior during driving, and road conditions along with their correlations to traffic congestion, violation, and injuries. The results and key findings with the categorical analysis and factorial prioritization are presented in Section 3. Finally, Section 4 demonstrates the conclusion, limitations, findings of research, and future recommendation.

2. Methodology

2.1 Questionnaire Survey and Factorial model of Road Safety

The current research is intended to conduct a questionnaire-based study by considering a fuzzy scale to estimate the effect of critical factors affecting road hazards. These specified factors are structured in a two-level hierarchical structure as shown in Figure 1. The questionnaire survey was distributed among hundred respondents (drivers with active driving license and studies in Transportation engineering) from the Department of Civil Engineering of Pakistani Universities (UET Taxila, UET Lahore and COMSATS University Wah). Among all the individuals in the locality, only 70% of the respondent's response to the survey and the response rate these participants were analyzed. Solomon (2006) [16] stressed in his study "Wisdom of crowds" that 20 respondents in survey can facilitate a great judgment. In order to gather pertinent data, the questionnaire was split into two sections. The first section includes key information about the respondents, including their gender, age, level of education, and time of driving licenses. The descriptive statistics of the socio-demographic variables are depicted in Table 1. While the second section projected to collect data related to influence of specified factors affecting road hazards as depicted in the results section.

Table 1
Demographic statistics of participants

Variable Details	**Frequency**
Number (N)	70
Age (years)	
18-30	24
31-50	32
51 above	14
Gender	
male	53
	17
female	
Time of driving license **(years)**	
1-5	15
6-15	36
16-25	19
Education	
BS	43
MSC/PhD	27

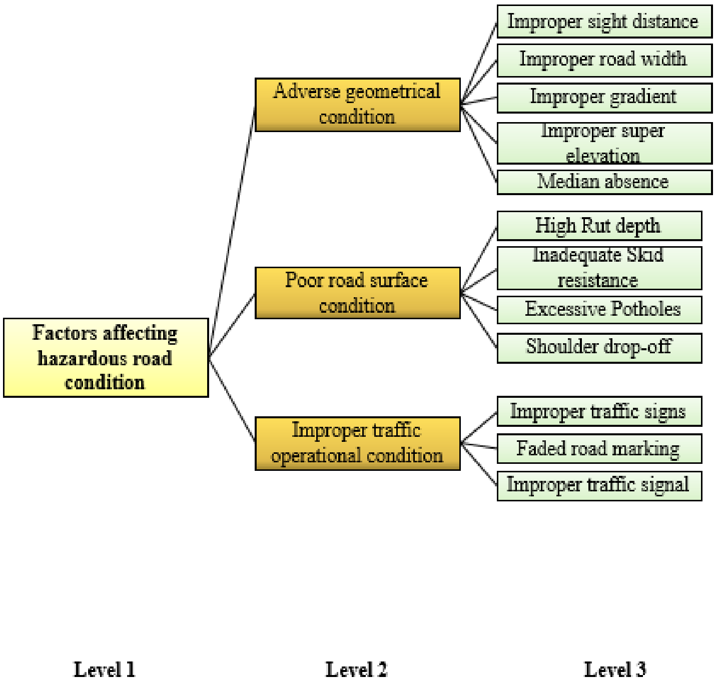

Fig. 1. The hieratical structure of the main factors and sub factors affecting road hazards

2.2 Fuzzy AHP

This basic model of factors affecting road hazards was employed for Pakistani drivers, however to avoid uncertainty of respondents, AHP technique was used under fuzzy environment. In the computation process, fuzzy numbers give the ability to the evaluators to reflect their feelings in pairwise comparisons (PCs) which provide us closer answers to more efficient findings. Thus, the survey was designed on hierarchy and PCs among main factor and sub-factor were developed. After PC estimations final weights have been adopted by rules of F-AHP and consistency was tested.

The concept of mathematical model was used by Sun (2010) [17]. However, the questionnaire was created with triangular fuzzy numbers (TFNs).

S fuzzy number abbreviated $\tilde{S}$ on $\mathbb{R}$ to be a TFN if it has membership function $\mu S(x)\colon \mathbb{R} \to [0.1]$ is similar in value to Eq. (1):

$$\mu\, \tilde{S}(x) = \begin{cases} \frac{x-1}{m-1}, & l \le x \le m \\ \frac{u-x}{u-m}, & m \le x \le u \\ 0. & \text{otherwise} \end{cases} \tag{1}$$

From the previous equation (eq. 1.), l and u express lower and higher limits of fuzzy number $\tilde{S}$, and m is modal value for $\tilde{S}$. TFN can be depicted by $\tilde{S} = (l, m, u)$. Operational rules of TFN $\tilde{S}_1 = (l_1, m_1, u_1)$ and $\tilde{S}_2 = (l_2, m_2, u_2)$ are demonstrated as resulting formula Eqs. (2) – (7).

Lower and higher limits accumulation of fuzzy number $\oplus$

$$S_1 \oplus \tilde{S}_2 = (l_1, m_1, u_1) \oplus (l_2, m_2, u_2) = (l_1 + l_2, m_1 + m_2, u_1 + u_2) \tag{2}$$

Lower and higher bounds multiplication of fuzzy number $\otimes$

$$\tilde{S}_1 \otimes \tilde{S}_2 = (l_1, m_1, u_1) \otimes (l_2, m_2, u_2) = (l_1 l_2, m_1 m_2, u_1 u_2) \text{ for } l_1, l_2 > 0; m_1, m_2 > 0; u_1 u_2 > 0 \tag{3}$$

The lower and higher limits subtraction of the fuzzy number $\ominus$

$$\tilde{S}_1 \ominus \tilde{S}_2 = (l_1, m_1, u_1) \ominus (l_2, m_2, u_2) = (l_1 - u_2, m_1 -, m_2, u_1 - l_2) \quad (4)$$

The lower and higher limits division of a fuzzy number $\emptyset$

$$\tilde{S}_1 \emptyset \tilde{S}_2 = (l_1, m_1, u_1) \emptyset (l_2, m_2, u_2) = \left(\frac{l_1}{u_2}, \frac{m_1}{,m_2}, \frac{u_1}{l_2}\right) \text{for } l_1, l_2 > 0; m_1, m_2 > 0; u_1 u_2 > 0 \quad (5)$$

Reciprocal of fuzzy number

$$\tilde{S}^{-1} = (l_1, m_1, u_1)^{-1} = \left(\frac{1}{u_1}, \frac{1}{m_1}, \frac{1}{l_1}\right) \text{ for } \; l_1, l_2 > 0; m_1, m_2 > 0; u_1 u_2 > 0 \quad (6)$$

Gumus [18] and Sun [17] proposed Table 3 to be used in evaluating PCs.

Table 2
Fuzzy scale based on TFN

Number	Linguistic	TFN
9	Perfect	(8, 9, 10)
8	Absolute	(7, 8, 9)
7	Very good	(6, 7, 8)
6	Fairly good	(5, 6, 7)
5	Good	(4, 5, 6)
4	Preferable	(3, 4, 5)
3	Not bad	(2, 3, 4)
2	Weak advantage	(1, 2, 3)
1	Equal	(1, 1, 1)

Linguistic conditions were employed to estimate PCs by examining which factor is the more significant, as S (5 × 5) is the biggest matrix in our work.

$$\tilde{S} = \begin{bmatrix} 1 & \tilde{s}_{12} & \tilde{s}_{13} & \tilde{s}_{14} & \tilde{s}_{15} \\ \tilde{s}_{21} & 1 & \tilde{s}_{23} & \tilde{s}_{24} & \tilde{s}_{25} \\ \tilde{s}_{31} & \tilde{s}_{32} & 1 & \tilde{s}_{34} & \tilde{s}_{35} \\ \tilde{s}_{41} & \tilde{s}_{42} & \tilde{s}_{43} & 1 & \tilde{s}_{45} \\ \tilde{s}_{51} & s_{52} & \tilde{s}_{53} & \tilde{s}_{54} & 1 \end{bmatrix} = \begin{bmatrix} 1 & \tilde{s}_{12} & \tilde{s}_{13} & \tilde{s}_{14} & \tilde{s}_{15} \\ 1/\tilde{s}_{12} & 1 & \tilde{s}_{23} & \tilde{s}_{24} & \tilde{s}_{25} \\ 1/\tilde{s}_{13} & 1/\tilde{s}_{23} & 1 & \tilde{s}_{34} & \tilde{s}_{35} \\ 1/\tilde{s}_{14} & 1/\tilde{s}_{24} & 1/\tilde{s}_{34} & 1 & s_{45} \\ 1/\tilde{s}_{15} & 1/\tilde{s}_{25} & 1/\tilde{s}_{35} & 1/\tilde{s}_{45} & 1 \end{bmatrix} \quad (7)$$

Where;

$$s_{ij} = \begin{cases} \tilde{9}^{-1}, \tilde{8}^{-1}, \tilde{7}^{-1}, \tilde{6}^{-1}, \tilde{5}^{-1}, \tilde{4}^{-1}, \tilde{3}^{-1}, \tilde{2}^{-1}, \tilde{1}, \tilde{2}, \tilde{3}, \tilde{4}, \tilde{5}, \tilde{6}, \tilde{7}, \tilde{8}, \tilde{9}, \; 1, & i \neq j \\ 1 & i = j \end{cases}$$

For accumulating the fuzzy scores, the fuzzy geometric mean was employed.

3. Results

The aim of this study was to effectively evaluate factors affecting road hazards for road safety using the Fuzzy AHP. Based on the measured weights for the first level, the results showed that 'Adverse geometric condition' is the most significant factor affecting road hazards, while 'Improper traffic operation condition' was identified as the second most significant factor. Previous study investigated that road geometry play an important role in road traffic crashes [19]. While 'Poor Road surface condition' is observed as the last ranked factor which affect road hazards as presented in Table 3.

Table 3
The significant Pedestrian behavior factors related to road safety

Factor	Weight	Rank
Adverse geometric condition (F1)	0.681147513	1
Poor road surface condition (F2)	0.133258017	3
Improper traffic operation condition (F3)	0.185594471	2

Similarly, the ranking of sub-factors in level 2 affecting road hazards was determined based on global weights. Based on measured weights, the results showed that ' Improper Road width ' is the most significant factor affecting road hazards, followed by 'Improper traffic signal' as compared to other specified factors. A study revealed that when the traffic volume is higher and the lane width is less, the probability for crashes, especially crashes like head-on or run-off the road, are greater [7]. Also a study highlighted that poorly illuminated signs can lead to reduced visibility, confusion, and increased accident risks [20]. The lowest-ranked factor was 'Excessive potholes' followed by 'Shoulders drop-off' as shown in Table 4.

Table 4
The significant Pedestrian behavior factors related to road safety

Factor	Global-Weight	Rank
Improper sight distance (F11)	0.06841987	4
Improper road width (F12)	0.25566994	1
Improper gradient (F13)	0.06421537	5
Improper super elevation(F14)	0.05534679	6
Median absence (F15)	0.04643102	8
High rut depth (F21)	0.17284233	3
Inadequate skid resistance (F22)	0.04850252	7
Excessive potholes (F23)	0.01287744	12
Shoulders drop-off (F24)	0.01485608	11
Improper traffic signs (F31)	0.02753039	10
Faded road marking (F32)	0.04380487	9
Improper traffic signal (F33)	0.19109147	2

The analysis ranks critical road hazard factors based on global weights using the FAHP method. Improper road width (F12) is the most significant factor, with a weight of 0.2557, highlighting its major impact on traffic safety. This is followed by improper traffic signal (F33) at 0.1911, and high rut depth (F21) at 0.1728, emphasizing infrastructure-related issues. Improper sight distance (F11) ranks fourth, while excessive potholes (F23) and shoulders drop-off (F24) are the least influential. The results underscore the need for targeted improvements in road design, traffic control, and maintenance to enhance sustainable road safety.

4. Conclusions

In general, it can be concluded that further efforts should be undertaken for setting and enforcing effective traffic laws and road safety legislations alongside with promoting public awareness on traffic safety. The issue of improving the quality of roads and all related traffic safety equipment's is also a critical factor of reducing road hazards.

The evaluation and prioritization of critical factors affecting road hazards has been identified as an important and multifaceted issue to resolve road safety problems due to complex data and its deviation. The study utilized the driver behavior questionnaire designed on 'Fuzzy scale' to estimate road safety data from drivers having driving license.

The FAHP results showed that 'Adverse geometric condition' is the most significant factor affecting road hazards, while 'Improper traffic operation condition' was identified as the second most significant factor. While 'Poor Road surface condition' is observed as the last ranked factor which affect road hazards. For level 2, the results showed that ' Improper Road width ' is the most significant factor affecting road hazards, followed by 'Improper traffic signal' as compared to other specified factors. The lowest-ranked factor was 'Excessive potholes' followed by 'Shoulders drop-off'.

By advancing to further research, many other MCDM applications are required to get familiar to analyze different real-world features, for instance the following new MCDM extension can be adopted, Parsimonious Best Worst Method [21], analytic hierarchy process and half-quadratic programming [22], parsimonious spherical fuzzy analytic hierarchy process [23], and parsimonious full consistency method [24]. The objectives of integrated model are clear, as it provides cheaper and faster survey procedure, and certainly the survey configuration can more easily be enhanced by this method than utilizing the conventional AHP with multifaceted PC questionnaire. However, this paper simply provided one example, but many other uses can validate the method ultimately.

Author Contributions
For research articles with several authors, a short paragraph specifying their individual contributions must be provided. The following statements should be used "Conceptualization, Danish Farooq and Hafiz Waheed Iqbal; methodology, Danish Farooq; validation, Danish Farooq and Asim Farooq; formal analysis, Asim Farooq; investigation, Asim Farooq; resources, Hafiz Waheed Iqbal.; data curation, Muhammad Awais; writing—original draft preparation, Danish Farooq; writing—review and editing, Muhammad Awais; visualization, Hafiz Waheed Iqbal; All authors have read and agreed to the published version of the manuscript." Authorship must be limited to those who have contributed substantially to the work reported.

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No data was used in this study.

Conflicts of Interest
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper."

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