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Exploratory Study for the Development of Road Safety Index on Indian Roads

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Abstract

Road Safety has always been a factor of great concern in India as well as across the world. Road Traffic Accidents have been consistently increasing, and to address this issue, the world's governments declared 2021 to 2030 as the 'Decade of Action' for Road Safety. This rise in accidents can be attributed to the increasing motorization escalation, increasing individual modes of transport, soaring speeds, drinking and driving, increasing transportation network patterns and inefficient enforcement, to name a few. If compendiously scrutinized, the losses due to road traffic incidences are wholly avoidable. A comprehensive study was thus conducted to identify the key aspects which can be attributed to road safety. The six key factors were identified, namely the design of roads, the design of vehicles, the role of the law enforcement agency, the part of the Indian judicial system, the function of the Indian medical system, and general public awareness for developing road safety index. Primary data collection among various population segments identified the relative importance of these factors. The weightage based on the importance of these factors was computed using the Logarithmic Goal Programming Model, and thus, the Road Safety Index was developed.

Keywords

safety, logarithmic goal programming, priority point vectors, consistency indicator

1 Introduction

Detailed statistics published by the Ministry of Road Transport and Highways (2021) in the study "Road Accidents in India" reported an alarming death toll of 150,000 and more than 500,000 irreversible severe injuries annually. Despite the global motorisation population increase, the Global Status Report on Road Safety (World Health Organization, 2013; 2015; 2018) shows that the number of road traffic accident deaths in India was 105724, 137572, and 150785, respectively. These numbers have been increasing continuously since 2007. These road traffic injuries cause approximately 3% of GDP loss. It means one serious road accident occurs every minute, and one person is lost every four minutes.

These statistics depict the enormity of the problem. Although there is no reason for any scepticism over the abundant concern shown by those responsible, the results have not been encouraging (Ahmed et al., 2023; Deshpande, 2014). Casualty graphs continue to run on an even keel. These revelations call for an urgent and immediate plan of action. The best way to approach the issue would be to conduct detailed studies that could accommodate all factors governing road safety and then undertake the necessary exercises to resolve the issue.

Although much work has been done to develop utility functions mathematically in several other areas, this paper is possibly one of the first attempts to build the Road Safety Index using the Logarithmic Goal Programming Model. With a possible objective of reducing road traffic injuries, losses of lives, and property damage by identifying the significant factors and generating the relative priorities of the specified attributes through which relevant countermeasures can be contrived. This paper does not consider that road safety depends on only one but several factors, like the design of roads and vehicles, the role of law enforcement, judicial and medical agencies, and awareness of the general public concerning safety (Gupta et al., 2021).

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The present study contributes to the following areas:

1. What are the important factors on which a general road safety index should be based?
2. Based on a small questionnaire survey, what are the relative weights for each factor or attribute?
3. How consistent is our analysis for the variation?

Indian roads are the second largest in the world after the United States, consisting of about 4,700,000 km. It includes 0.04% of Expressways, 2.15% of National Highways, 3.8% of State Highways, 22.4% of PWD roads and 71.61% of rural and other roads (Ministry of Road Transport and Highways, 2021). However, this darker side of development reveals an alarming 137,000 annual death toll and 466,600 serious injuries and disabilities. With an increasing rate of 8% over the past ten years, Road Traffic Injuries (RTIs) are India's 6th leading cause of fatalities. A cyclically modulated risk decay function model presented by Mohan et al. (2009) predicts that countries like India will unlikely see declining death rates before 2030 with the current measures.

An increase in road accidents alleviates the economic cost of each fatality. Based on the willingness to pay approach, the total economic loss due to all fatalities accounted for rupees 1.3 million, about 3.2% of the GDP (Bhattacharya et al., 2007). Assessing the costs of road accident fatalities, injuries, and damage enables the creation of reasonable countermeasures and corroborates the efforts invested (Kanuganti et al., 2017).

Road safety becomes vital since the primary goal of any transportation is safer and higher mobility, not just accessibility (Agarwala and Vasudevan, 2023). Traffic fatalities per unit population is a rough indicator of the health of society at the city, regional and national levels and affect the Happiness Index of the population. The identified four 'E's pertaining to road safety: Education, Engineering, Enforcement and Emergency Care.

Five key directions were identified in the Decade of Action of the U.N. for the road safety route: road safety management, safer roads and transport systems, safer vehicles, road use and improved post-crash care. The above factors appear to be blended with urban planning, novel technologies, and transport policies for advanced mobility.

The concept of total harm, defined by Mohan et al. (2009), road safety as the product of risk, exposure, and consequences. Thus, based on this logical structure, as well as considering the evaluations, six key factors were identified in this study that played a defining role in road safety, namely:

1. The design of roads;
2. Design of vehicles;
3. Part of the Law Enforcement Agency;
4. The function of the Indian Judicial System;
5. Role of the Indian Medical System;
6. General public awareness.

These concepts cover the whole system and aim to evolve an advanced transportation system that is connected, safer, greener, inclusive, and technologically savvy. When brought together, these factors can decrease congestion, conserve energy, enable economic growth, increase transportation efficiency, and enhance the quality of life in general (Kiss et al., 2013).

Although many attempts have been made to study road traffic injury patterns across the globe (Chand et al., 2021; Mekonnen and Sipos, 2022; Mekonnen et al., 2023), the study of the relative importance of each factor, mainly using Logarithmic Goal Programming Model (LGPM), has not been done. Some parallels can be drawn from similar works done in the life insurance sector by Dutta et al. (2010), in which optimisation techniques were used to obtain customer preferences for various insurance product features. An intensive and complete study of the factors concerning road safety in the Indian context is the need of the hour.

2 Methodology and data analysis

Section 2 describes the three significant implementation steps for the subsequent development of the Road Safety Index. Section 2.1 describes the data collection method and the consequent data point analysis. It is followed by Section 2.2, where the entire model is explained using a small data set and a reduced set of factors. Section 2.2 can advocate the reliability of our findings. Section 2.3 deals with the complete implementation of the mathematical model, which is further elucidated in Section 4.

2.1 Data collection method and data point analysis

A comprehensive study of the factors affecting road safety reveals six crucial factors. A survey was conducted to obtain the relative importance of these factors. The study aimed to identify the importance of each element by a comparative rating method, which can be utilised in various studies to minimise fatalities due to road accidents. In the proposed method of generating priority point vectors, respondents were requested to rate the above-stated parameters on a scale of 1 (not at all important) to 100 (exceedingly important).

In the survey, inputs were taken from the respondents about the factor "Design of vehicle" to supply suggestions for improving road safety by instigating road improvements, bringing a change in the laws, or any other innovative manner. Among all the 1170 respondents, a number of 1117 responses were acceptable and considered for further analysis. The principal focus was to explore people's views from varied occupational backgrounds. Methods like meeting individuals, personal calling, mailing, and circulation of Google forms were employed in the survey. The general characteristics of the population surveyed are presented in Fig. 1. The acronyms used to present the data in Fig. 1 are:

- IMS: Indian Medical System;
- LEA: Law Enforcement Agency;
- DOR: Design of Roads Geometry;
- IJS: Indian Judicial System;
- GP: General Public;
- DOV: Design of Vehicle.

2.2 Model explanation with a sample data set

A sample of 100 respondents was randomly taken from the surveyed population of 1117 respondents and computed in Excel Solver. The implementation method is the same as that used in the complete model. The methodology adopted calculates the six attributes' relative importance presented in Table 1.

2.3 Implementation of the mathematical model

The logarithmic Goal Programming Method was applied to the sample data set of 10 responses, where the value of the objective function was realised using weights of various attributes as the decision variable. The solution time in Excel Solver for the same was about 0.1 seconds.

However, using Excel Solver to process our data set of 53 respondents is not feasible. A Mathematical Programming Language (AMPL) is thus employed to formulate large-scale optimisation or mathematical programming problems. Using AMPL, it is possible to communicate with various solvers and examine solutions. MINOS 5.51 Solver has been operated for our data. AMPL's easy syntaxes, model data independence, model solver independence, convenience, speed, flexibility, and reliability make it ideal for developing complex models. Apart from the computations of the relative weighted importance, the consistency analysis has also been done for different segments.

3 Equations

The Road Safety Index can be exploited for a wide range of studies as it presents the priorities of the key factors pertaining to road safety. The Analytic Hierarchy Process (AHP), a technique to address Multiple Criteria Decision-Making Problems (MCDM), is used to obtain the relative weight of child indicators and the relative weight of evaluators. The road safety Index is defined as:

$$S(X) = \sum_i w_i x_i , \tag{1}$$

where:

- w_i: the relative importance (weights) of each attribute;
- x_i: the level of ith factor's importance in affecting road safety.

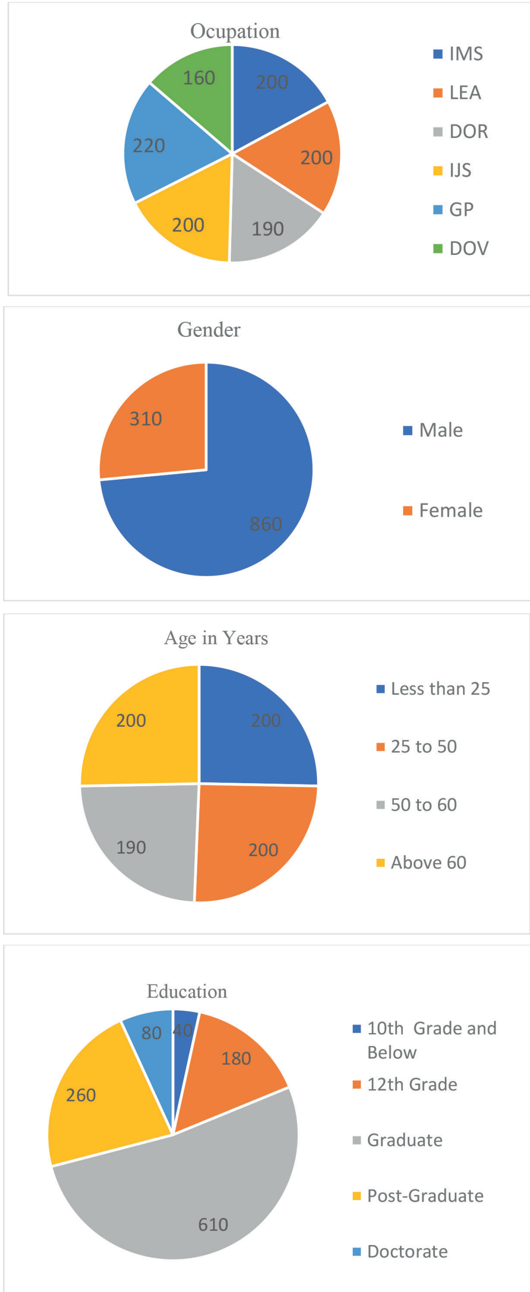

Fig. 1 Demographic description of the survey

The method of generating the consensus priority point vectors (weights) is discussed in this paper by applying the logarithmic goal programming approach developed by Bryson and Joseph (1999). The steps employed for the same are as follows:

1. The complex set of potential road hazards is classified into six major groups to establish a hierarchical structure.
2. A detailed survey covers diverse occupational groups and analyses elements that might affect the survey result. After some iterations, the final results of the attribute comparisons are obtained from the respondents.
3. The priority point vector is calculated as described in the subsequent section.
4. The consistency of the results must be examined, as there might be discrepancies between the effects of attribute comparison and the final decision. The consistency indicator (CI) is established for the same. If the decision makers' estimates are perfectly consistent, the value of CI is 1. However, the anticipation of perfect consistency is impractical as people can be biased and inconsistent in their subjective judgments. Therefore, CI values can range from 0 to 1.

In Section 3.1, the methodology to find the weights is elucidated. The ratings ascribed by different decision-makers to the respective attributes in the survey are used to determine the weights.

3.1 Logarithmic goal programming model

The Logarithmic goal programming model (LGPM) describes the consensus priority point vectors. AHP and LGPM are amalgamated to represent the unanimous opinion of the group from their priorities of decision alternatives. The LGPM method developed by Bryson and Joseph (1999), the AHP method developed by Saaty (1980), and the revised version of Aczél and Saaty (1983) are employed to compute the results. The advantages of using LGPM are stated below:

- It does not require that the pairwise comparison matrix be reciprocal.
- Unlike the Logarithmic Least Square Method (LLSM), it does not require any statistical assumptions.
- LGPM is resistant to outliers as it is mathematically like the Minimum Sum of Absolute Errors (MSAE) regression model.
- Provides an interpretable CI for the group data.
- It is never infeasible.

Some useful definitions:

- T: a set of decision-makers (respondents) indexed by t, such that $T = (1, 2 \ldots t \ldots T_{\max})$;
- I: the set of first attribute $I = (1, 2, 3, i \ldots I_{\max})$ indexed by i;
- J: the set of second attribute $I = (1, 2, 3, i \ldots I_{\max})$ indexed by j;
- L: pair of criteria (i, j) where $i \in I, j \in J$ and $i \neq j$;
- N: number of attributes to be taken into consideration;
- $\boldsymbol{w^t}$: the priority point vector or weight vector of different attributes.

Such that, $\boldsymbol{w^t} = \left(\boldsymbol{w_1^t},\ \boldsymbol{w_2^t},\ \ldots,\ \boldsymbol{w_N^t}\right)$, where $\sum_j w_j = 1$; $w_j > 0$ for $j = 1, 2, \ldots, N$:

- $\boldsymbol{A^t}$: pairwise comparison matrix of $\left\{a_{ij}^t\right\}$;
- a_{ij}^t : indicates the relative importance of factor i when compared to factor j, where $t \in T$ and $(i, j) \in L$;
- p_{ij}^t : the value generated by the methodology used for the respondent $t \in T$ and $(i, j) \in L$.

It is calculated as follows:

- if $\left(v_i/v_j\right) \times a_{ij}^t > 1$, then $p_{ij}^t = \left(v_i/v_j\right) \times a_{ij}^t$; else $p_{ij}^t = 1$;
- q_{ij}^t : the value generated by the methodology used for the respondent $t \in T$ and $(i, j) \in L$.

It is calculated as follows:

- if $\left(v_i/v_j\right) \times a_{ij}^t > 1$, then $q_{ij}^t = 1$; else $q_{ij}^t = 1 \big/ \left(v_i/v_j\right) \times a_{ij}^t$;
- v_i: the un-normalised decision values (weights) of the LGPM computation;
- w_i: the normalised decision values (weights) of the LGPM computation.
- $\log \theta$: the objective function to be minimised.

Six attributes are taken into consideration, as discussed in Section 1 to 2. Based on the values obtained from the respective stakeholders, a pairwise comparison matrix $\boldsymbol{A^t} = \left\{a_{ij}^t\right\}$ is computed.

$a_{ij}^t = \left(w_i/w_j\right)^t$, which signifies the relative importance of factor i over factor j for each respondent. The data set is perfectly consistent if $a_{ij}^t = a_{ik}^t\ a_{kj}^t$. Discrepancies occur in the relative comparison methods, which can be accounted for incongruous subjective judgements. Therefore, an estimate of the relative consistency has been established, as it is unreal to expect perfectly consistent results. It can proceed if the degree of inconsistency, measured by various indicators (Golden and Wang, 1989), is acceptable.

Let T be the entire set of respondents and $M = |T|$. The main objective of the task is to minimise the difference between the ratio $(w_i/w_j)^t$ and the specified as a_{ij}^t. Assume real numbers p_{ij}^t and q_{ij}^t such that $p_{ij}^t,\ q_{ij}^t \geq 1$ and satisfy:

$$\left(\frac{w_i}{w_j}\right) \times \left(\frac{p_{ij}^t}{q_{ij}^t}\right) = a_{ij}^t. \quad (2)$$

Therefore, if $p_{ij}^t = q_{ij}^t = 1$, $\left(w_i/w_j\right) = a_{ij}^t$. Hence, when $p_{ij}^t > 1$, $\left(w_i/w_j\right) < a_{ij}^t$ and when $q_{ij}^t > 1$, $\left(w_i/w_j\right) > a_{ij}^t$.

Because our values are inconsistent, $p_{ij}^t \neq q_{ij}^t \neq 1 \forall t \in T$, the objective function is the minimisation of the product.

$$\prod\nolimits_{t \in T} \prod\nolimits_{i \in I} \prod\nolimits_{j \in I} p_{ij}^t q_{ij}^t \quad (3)$$

In conventional goal programming, the underachievement and overachievement (in linear form) from the required goal are minimised. The conventional method is analogous to and minimising the logarithms of the product of the variables (underachievement and overachievement). It can be depicted as follows:

1. Minimise:

$$\left(\frac{1}{M}\right) \sum\nolimits_t \log \theta^t. \quad (4)$$

2. Subject to:

$$\begin{aligned} &\log v_i - \log v_j + \log p_{ij}^t - \log q_{ij}^t \\ &= \log a_{ij}^t \forall t \in T;\ i,\ j \in I, \end{aligned} \quad (5)$$

$$\begin{aligned} &\left(\frac{1}{K}\right) \sum\nolimits_{i \in I} \sum\nolimits_{j \in I} \left(\log p_{ij}^t + \log q_{ij}^t\right) - \log \theta^t \\ &= 0 \forall t \in T, \end{aligned} \quad (6)$$

where:

- $K = N \times (N - 1)$;
- $I = \{1, 2, 3 \ldots N\}$;
- $\boldsymbol{v}_i$ or $\boldsymbol{v}_j$: the un-normalised priority point vectors, and all variables are non-negative.

The solution to this problem, after being run on AMPL, yields values of the un-normalised vectors $\boldsymbol{v} = v_1, v_2, v_3, \ldots, v_N$ from which we obtain the normalised weights $w = \{w_1, w_2, w_3, \ldots, w_N\}$ where $(v_i/v_j) = (w_i/w_j)$ for each (i, j).

Dominance is observed when one option is equally suited for some cases and strictly outranks others in another case. When the stakeholders rank different attributes, it is to be checked if any attribute strictly dominates the others. In actuality, it is less likely that one factor pertaining to road safety dominates all other factors in every case. Hence, based on observations, it can be proved or reasonably assumed that the attributes are independent. That is, the linear model can be applied, and uncertainty is not to be incorporated into the model, according to Cochrane and Zeleny (1973). Add the product of the value score of each criterion and their respective weight to form the linear additive model. This model combines the consensus opinions on the six different factors to give one overall value, which is the Road Safety Index:

$$S(X) = \sum\nolimits_i w_i x_i. \quad (7)$$

A multiplying factor is required to make the pairwise comparison matrix consistent because the outcomes obtained are not perfectly consistent. θ, obtained from the objective function log θ, is the minimum average value that needs to be multiplied.

Let the CI be defined as the moderate consistency of the comparisons. It is computed by the formula: $\sigma = 1/\theta$.

When $p_{ij}^t > q_{ij}^t$, CI is the average of the fraction w_{ij}^t / a_{ij}^t and if $p_{ij}^t < q_{ij}^t$, CI is the average of the fraction a_{ij}^t / w_{ij}^t. $\sigma = 1$ implies perfect consistency, and it ranges in the interval [0, 1].

3.2 Model findings

The key factors for road safety have been identified and are listed below. A comprehensive study of these factors and a thorough understanding of their complex interactions can most certainly help to reduce road accident fatalities:

1. the DOR;
2. DOV;
3. role of the LEA;
4. part of the IJS;
5. the function of the IMS;
6. GPA.

The LGPM Model yielded the priority point vectors shown in Table 1.

This study discerns that general public awareness is the most important factor for road safety, followed by the design of roads and the role of the law enforcement agency. Moreover, it is observed that vehicles' design is considered

Table 1 Priority point vectors

Serial number	Attributes	Relative importance weights (W_i)
1	The design of roads	0.1722
2	Design of vehicles	0.1507
3	Role of the Law Enforcement Agency	0.1697
4	Role of the Indian Judicial System	0.1584
5	Role of the Indian Medical System	0.1635
6	General public awareness	0.1856

to be the least important, even though numerous technological interventions can help plummet fatalities to a considerable extent. Demographic-based relative importance weights (W_i) are presented in Table 2 to Table 5.

The distribution of weights (W_i) was somewhat similar. However, several differences in their respective consistencies were observed and presented in Table 6. Therefore, using the aggregate value and not the specific weights of each segment is suitable.

Table 2 Classification based on genders

Attributes		Relative importance weights (W_i)	
No.	Particulars	Female	Male
1	The design of roads	0.16981	0.17226
2	Design of vehicles	0.14859	0.1516
3	Role of the Law Enforcement Agency	0.17924	0.16875
4	Role of the Indian Judicial System	0.14151	0.162
5	Role of the Indian Medical System	0.16981	0.16243
6	General public awareness	0.19104	0.18296

The number of decision-makers in each segment is not homogeneous, so the consistency analysis may not be 100 percent accurate. A more targeted survey is required to obtain precise results.

4 Conclusions

The world is moving from being fully connected to being hyper-connected. Still, with this alarming death rate, the decision-makers of middle-income countries should work to identify ingenious solutions. City planning and infrastructure design are of utmost importance to lessen the need to travel and to control heavy traffic flow. Space should be created for Non-Motorised Transport in India, like in Beijing and Portland. Homogeneity, thus instilled, will help escalate the safety standards substantially. Potential technological innovations, like connected mobility systems, should be implemented for an intelligent Transport system. Also, as road calamities are a hidden epidemic, a Road Safety Department should be included in the National Institute of Disaster Management.

A framework was constructed that pronounces the road safety index based on the linear additive model, which is the function of six key attributes. Our work realises that general public awareness weighs 0.186, after which is the DOR and the role of LEA at 0.172 and 0.170, respectively, the medical system weighs 0.164 and the judicial system weighs 0.158, followed by the DOR at 0.151 consensus priority weight. The overall consistency of the works' findings lies at 53.5%. Other useful results are illustrated in Table 6.

Table 3 Classification based on age

Attributes		Relative importance weights (W_i)			
No.	Particulars	Less than 25	25 to 50	50 to 60	Above 60
1	The design of roads	0.16893	0.1741	0.16811	0.18811
2	Design of vehicles	0.15855	0.14999	0.14282	0.16721
3	Role of the Law Enforcement Agency	0.16893	0.17009	0.17208	0.1693
4	Role of the Indian Judicial System	0.15203	0.16494	0.16475	0.11497
5	Role of the Indian Medical System	0.16912	0.16322	0.16181	0.15603
6	General public awareness	0.18244	0.17766	0.19043	0.20437

Table 4 Classification based on education qualification

Attribute		Relative importance weights (W_i)				
No.	Particulars	10^{th} grade or below	12^{th} grade	Graduate	Master	Doctorate
1	The design of roads	0.19576	0.17932	0.16673	0.17052	0.17762
2	Design of vehicles	0.14389	0.15312	0.14494	0.16565	0.15816
3	Role of the Law Enforcement Agency	0.17401	0.16429	0.17599	0.16363	0.16696
4	Role of the Indian Judicial System	0.14544	0.14411	0.16426	0.1551	0.15986
5	Role of the Indian Medical System	0.16102	0.16968	0.16173	0.16105	0.16519
6	General public awareness	0.17987	0.18949	0.18635	0.18405	0.17221

Table 5 Classification based on occupation

Attribute		Relative importance weights (W_i)					
No.	Particulars	DOR	DOV	LEA	IJS	IMS	GAP
1	The design of roads	0.18085	0.17477	0.17323	0.16716	0.16726	0.17557
2	Design of vehicles	0.16542	0.16557	0.14033	0.14922	0.13799	0.1511
3	Role of the Law Enforcement Agency	0.15976	0.16296	0.17864	0.16915	0.1746	0.17269
4	Role of the Indian Judicial System	0.15629	0.15802	0.17191	0.15787	0.15638	0.14446
5	Role of the Indian Medical System	0.16046	0.16208	0.15545	0.17644	0.17144	0.1619
6	General public awareness	0.17723	0.17661	0.18044	0.18016	0.19234	0.19428

Table 6 Demographic-based CI

Demographic description		Number of respondents	Consistency indicator
Gender	Female	860	0.562
	Male	310	0.528
		1170	
Age	Less than 25	340	0.511
	25 to 50	320	0.634
	50 to 60	390	0.505
	Above 60	120	0.542
		1170	
Education	10^{th}	40	0.524
	12^{th}	180	0.542
	Graduate	610	0.527
	Post-graduate	260	0.543
	Doctorate	80	0.646
		1170	
Occupation	DOR	190	0.469
	DOV	160	0.584
	LEA	200	0.556
	IJS	200	0.534
	IMS	200	0.587
	GP	220	0.544
		1170	
Overall		1170	0.535

This linear model assumption of this study can be corrected by adding higher-order terms of the non-linear model, which is beyond the scope of this paper.

Moreover, the road safety evaluator can be exploited to compare the levels of safety for a plethora of diverse sets. Safety Indexes can be developed for different nations, states and districts; based on rural and urban locations or depending upon the general behavioural and lifestyle patterns of specific regions. After this ethnographic research, the Index can be used to build precise and substantially more effective countermeasures.

Further, this model can be extended to study other natural or man-made disasters. The linear additive model can be applied after identifying relevant attributes and their corresponding weights. The logarithmic goal programming model has not been employed to study disasters in the Indian context.

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