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RESEARCH ARTICLE

A Hybrid Best-Worst Method (BWM)–Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) Approach for Prioritizing Road Safety Improvements

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ABSTRACT The increase in road accidents underscores the urgent need for effective methodologies to evaluate and prioritize road safety improvements. Traditional decision-making processes in road safety management often confront challenges due to the lack of a comprehensive approach, particularly in handling multiple evaluation criteria. This study introduces a novel Hybrid Multi-Criteria Decision-Making approach that amalgamates the Best-Worst Method (BWM), the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), and the Simple Additive Weighting (SAW) method. This approach is designed to prioritize road safety improvements effectively by analyzing various criteria and alternatives in a structured manner. Focusing on a 500-meter road section, the study identifies eight distinct road improvement criteria and divides the road section into five sub-sections for detailed analysis. The BWM is utilized to determine the criteria weights, which are subsequently integrated into the TOPSIS and SAW methodologies for prioritizing improvements in each road subsection. This hybrid approach provides a comprehensive framework for decision makers, including road safety auditors and transportation professionals, facilitating a nuanced and systematic evaluation of safety improvements. The methodology's efficacy is validated through field expert consultations and comparative analysis with standalone SAW results. The validation underscores the potential of the proposed approach as a robust tool for road safety stakeholders, enabling them to make informed decisions based on a detailed, Chainage-wise analysis of road sections. The Python code for TOPSIS is available at https://github.com/kanak02/TOPSIS.

INDEX TERMS Best-worst method (BWM), multi-criteria decision making (MCDM), road safety improvement, simple additive weighting (SAW), technique for order preference by similarity to ideal solution (TOPSIS).

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I. INTRODUCTION

In the realm of decision-making, individuals frequently engage in the process of ranking various options to articulate relative importance, personal preference, or the likelihood of different outcomes. Multi-criteria decision-making (MCDM) has garnered significant attention as an essential facet of decision theory, finding applications across diverse fields such as management, economics, and engineering [1], [2], [3]. MCDMs fundamentally involves arranging a set of available alternatives and then identifying the most optimal choice using specific methodologies and available decision-related data, while considering multiple criteria [4].

Before ranking the alternatives, it is critical to establish a decision criteria system and assign appropriate weights to each criterion. This is followed by evaluating the options against these criteria, a process often referred to as constructing performance assessments. MCDM methods offer a structured framework to ensure the consistency of results.

Among the plethora of MCDM techniques, the Analytic Hierarchy Process (AHP) is renowned for its widespread application. It is recommended to integrate a consistency check within the AHP framework to eliminate inaccurate responses and assess the competency of evaluators [5]. This involves setting a threshold for the consistency ratio (CR) [6], where scores above this threshold deem the respondent as ineligible, and those below as eligible. Over recent decades, extensive research has been conducted to refine the CR consistency metric, yet the metrix remains largely unchanged and extensively used in AHP applications [7].

Apart from AHP, various MCDM methods have been deployed to ascertain effective ranking decisions based on decision-makers' preferences. These include the Analytic Network Process (ANP) [8], Best-Worst Method (BWM) [9], Elimination and Choice Translation Reality (ELECTRE) [10], Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) [11], and VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR) [12]. Notably, both AHP and BWM are based on pairwise comparisons, but BWM requires fewer comparisons ($2n - 3$) compared to AHP's n (n-1)/ 2, showcasing BWM's data efficiency [9].

Evaluating road safety is complex issues as there are multiple factors causing road accidents [13]. In road safety assessment, MCDM techniques play a pivotal role in identifying key factors that influence the safest behaviors among road users [14], [15]. Moreover, these techniques can pinpoint specific geographic boundaries that require substantial safety improvement [7]. Table 1 presents a summary of notable recent works on MCDM application in the area of road safety. As seen from Table 1, there exists a gap in understanding the factors considered by road safety experts when recommending necessary safety enhancements. Further, there is a lack of a decision-support approach that provides a clear prioritization of road safety improvements required within a selected road stretch. Based on the research gaps, the following are the original contributions of the present research:

- The present research contributes to the novel framework of a hybrid BWM-PROMETHEE approach for prioritizing road safety improvements.

TABLE 1. Summary of recent works on application of MCDM for road safety.

Reference	MCDM	Application area	Major Outcome	Shortcoming
Ganji et al. [18]	DEMATEL, ANP, Evidential Reasoning	Vehicle Safety	Identification of the braking system as the most critical vehicle safety factor	Difficulty in evaluating crash causations due to lack of reliable data
Khademi and Choupani [19]	System Thinking Approach, ANP	Road Safety Management System	Identification of major deficiencies in Iran's Road Safety Commission	Overestimated influence of the Road Safety Commission; need for institutional reforms
Nanda and Singh [20]	Fuzzy-AHP	Road Safety in India	Determination of the most crucial factors in road accidents	Methodology may not be generalizable beyond Indian context
Moslem et al. [21]	AHP-BWM	Driver Behavior	Ranking of significant driver behavior factors related to road safety	Complexity in the application of AHP for layman participants; model complexity
Farooq and Moslem [22]	ANP	Driver Behavior	Evaluation of risky driver behavior factors and their ranking in road safety	Focus on subjective expert opinions may not fully capture driver behavior nuances
Sayadinia and Beheshtinia [23]	AHP, ELECTRE, Copeland	Road Maintenance	Prioritization of roads for maintenance based on various criteria	Limited to case study of streets in Tehran; may need adaptation for other contexts
Zagorskas and Turskis [24]	MEW, EDAS, ARAS, SWARA	Pedestrian Bridge Placement	Development of a hybrid MCDM model for bridge location selection	Less focus on displacement strategy and usability
Yakar [25]	Weighted Linear Combination	Road Section Safety	Methodology for determining accident-prone road sections	The methodology's reliance on expert opinion could introduce subjectivity
Martins and Garcez [26]	MCDM/A	Road Safety Performance	Multidimensional and multi-period analysis of road safety	Specific to the road network in the state of Pernambuco, Brazil
Farooq et al. [27]	AHP-BWM	Lane Changing Behavior	Prioritization of factors affecting frequent lane changing	Fewer pairwise comparisons but requires validation for different contexts
Sharma et al. [28]	EWM, TOPSIS	Traffic Safety Evaluation	Ranking of Indian states based on road safety	Potential limitations in the evaluation criteria and their

TABLE 1. ***(Continued.)*** **Summary of recent works on application of MCDM for road safety.**

			performance	weights
Babaei et al. [29]	DEA, MCDM	Transportation System Performance	Performance evaluation of transportation systems with a focus on safety	Model complexity and need detailed road accident data
Chen et al. [30]	CRITIC-ELECTRE-FCM	Road Safety Attainment	Appraisal of road safety attainment of countries in Southeast Asia	Methodology's adaptability to different regional contexts not discussed
Farooq and Moslem [31]	PF-AHP, Pythagorean Fuzzy ANP	Driver Behavior	Assessment of critical driver behavior using Pythagorean fuzzy sets	Complexity of the method and reliance on data from specific driver groups
Zu et al. [32]	CV-PROMETHEE II-JSS	Road Safety Progress	Road safety development examination of the EU Member States	Focus on EU member states may not reflect conditions in other regions
Yacheur et al. [33]	DRL-based Algorithm	Vehicular Communication	Enhanced reliability in vehicular communication for safety applications	Applicability and performance in diverse real-world scenarios not fully explored
Elshahawy et al. [34]	Neutrosophic MCDM, TOPSIS	Vehicle Malfunction in IOVT	Evaluation of vehicular malfunctions and corresponding danger levels	Application of the model in real-life scenarios not demonstrated
Li et al. [35]	CRITIC-TODIM-NMF	Road Safety Measurement	Measurement of road safety situation of US states	Specific to the United States, may require adjustments for other regions
Li et al. [36]	CRITIC-MOORA-SC	Transport Safety Analysis	Integrated model for safety system analyses in ASEAN countries	Focus on ASEAN countries, adaptability to other regions not discussed
Fawzy et al. [37]	AHP	Pavement Maintenance	Prioritization of maintenance for road network pavement	Based on an Egyptian case study; context-specific methodology

- The elaborated approach incorporates the inputs provided by the road safety experts and clearly delivers the priority of required road safety improvements within a selected stretch. Moreover, the required safety improvements can be further prioritized within a selected part of the road stretch (e.g., Chainage).
- The results provided by the proposed approach are crisp and easy to interpret.

To address inaccuracies, it is crucial to form specialized groups of experts and employ a combination of MCDM methods, given the diverse policy objectives and the varying weights assigned to different factors by these experts. This study introduces a methodology for effectively selecting necessary improvements in road segments to enhance safety. A panel of experts was convened, and visual representations of the research area were used to gather their feedback. Subsequently, the weights of the criteria were calculated using BWM after which TOPSIS and Simple Additive Weighting (SAW) techniques were employed to determine the prioritization of improvements. The results of both methods were compared for validation as per indicated within available literature [16], [17]. Further, the experts are again consulted to review and validate proposed framework.

The rest of the paper is structured as follows: Section II elaborates on the methodology of this study, detailing BWM, TOPSIS and SAW. Section IV presents an in-depth analysis and discussion of the chosen study, utilizing the hybrid BWM-TOPSIS and BWM-SAW techniques. Finally, Section V concludes with a summary of the study's findings and potential directions for future research.

II. METHODOLOGY

A. BEST- WORST METHOD (BWM)

The AHP technique has a notable problem due to the added complexity and inconsistency that arise from the extensive number of pairwise comparisons. Hence, BWM proposes that in evaluating the preference of criterion c_i over criterion c_j with respect to a given standard, decision makers (DMs) are not required to estimate values for all potential comparisons between pairs of criteria. Instead, DMs only needs to focus on comparing the criterion in question to the best and worst criteria in relation to the specific norm being considered. These comparisons, known as reference comparisons, are the primary determinants of the estimation of relative weights. In contrast, secondary comparisons do not play a role in the estimation process. The decision matrix is firstly defined as per equation (7). Following are the further steps of the BWM [38]:

Step 1: Define the best (e.g., most important) criteria (c_b), and the worst (e.g., least important) criteria (c_w) based on the Experts / DMs inputs with respect to decision-making goal.

Step 2: Establish the preference of best criteria (c_b) over all criteria (Best-to-Others) and the preference of all criteria over worst (c_w) using (1)-(9) scale. The resulting preference vectors are represented as per equations (1) and (2):

$$\text{Best}-\text{to}-\text{Others}=[p_{b1}p_{b2}\ldots p_{bn}] \tag{1}$$

where p_{bi} specifies the preference of c_b over c_i. Further, $p_{bb}=1$.

$$\text{Others}-\text{to}-\text{Worst}=[p_{1w}p_{2w}\ldots p_{nw}] \tag{2}$$

where: p_{iw} specifies the preference of c_i over c_w. Further, $p_{ww}=1$.

Step 3: Optimal criteria weight are presented as per equation (3):

$$W^* = \left[w_1^* w_{2,}^* \ldots w_n^*\right] \tag{3}$$

It is important to note that the optimal criteria weight (w_i^*) of a criterion c_i has to satisfy the following conditions as per equation (4):

$$\frac{w_b}{w_i} = p_{bi}, \frac{w_i}{w_w} = p_{iw} \tag{4}$$

The following equation (5) has to be solved to satisfy the above conditions for all i:

$$\begin{aligned} & min\xi, \text{ such that} \\ & \left|w_b - w_i p_{bi}\right| \leq \boldsymbol{\xi \forall i} \\ & \left|w_i - w_w p_{iw}\right| \leq \boldsymbol{\xi \forall i} \\ & \sum_{i=1}^{n} w_i = 1, \\ & w_i \geq \mathbf{0}, \forall i \end{aligned} \tag{5}$$

The solution of equation (5) concludes the optimal criteria weights $\left(w_1^*, w_2^*, \ldots, w_n^*\right)$ as well as provides the value of CR.

Step 4: Calculate consistency ratio (CR) as per equation (6), where the values of ξ_{max} varies with the values of p_{bm} as shown in Table 2.

$$CR = \frac{\xi^*}{\xi_{max}} \tag{6}$$

TABLE 2. **Relation between p_{bw} and consistency index [9].**

p_{bw}	1	2	3	4	5	6	7	8	9
ξ_{max}	0	0.44	1	1.63	2.3	3	3.73	4.47	5.23

B. TECHNIQUE FOR ORDER PREFERENCE BY SIMILARITY TO THE IDEAL SOLUTION (TOPSIS)

TOPSIS is introduced within the work of Hwang and Yoon [39] as a very appealing approach for addressing MCDM problems. The fundamental concept behind the TOPSIS method is that the optimal option or alternative should be located at the closest geometric distance to the positive ideal solution while simultaneously being situated at the furthest geometric distance from the negative ideal solution [39]. The positive ideal solution refers to the solution that offers the greatest advantages and lowest cost among all available choices. Conversely, the negative ideal solution pertains to the solution that delivers the lowest benefits at the highest cost. The following section provides an explanation of the primary steps involved in the TOPSIS method [39].

Step 1: Consider a collection A consisting of m options, denoted as $A = \{a_1, a_2, \ldots, a_m\}$, where m is a positive integer. The evaluation of these options must be conducted in relation to a set C consisting of n criteria, where C is defined as $\{c_1, c_2, \ldots, c_n\}$, and n represents a positive integer. Subsequently, the individual responsible for making the choice would proceed to construct a decision matrix denoted as X, as per equation (7), whereby the options are quantitatively evaluated across several criteria.

$$X = \begin{bmatrix} x_{11} & \cdots & x_{1n} \\ \vdots & \ddots & \vdots \\ x_{m1} & \cdots & x_{mn} \end{bmatrix} \tag{7}$$

where x_{ij} specifies the preference score of alternative a_i with respect to criteria c_j.

Step 2: The decision matrix is normalized as per equation (8):

$$y_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \tag{8}$$

where: $i = 1, 2, \ldots, m$ and $j = 1, 2, \ldots, n$. Further, y_{ij} is normalized score of alternative a_i with respect to criteria c_j.

Step 3: The weight assigned to criterion c_j is denoted as w_j, which signifies the comparative significance of c_j in relation to other criteria. The computation of the optimum criterion weights is conducted using the BWM, following the steps outlined in the preceding section.

Step 4: The weighted normalized matrix can be concluded as per equation (9):

$$z_{ij} = w_j y_{ij} \tag{9}$$

where z_{ij} is the normalized weighted score of a_i with respect to criteria c_j.

Step 5: The positive ideal solution v_j^+ and the negative ideal solution v_j^- for every criteria can be concluded as per following equations:

Equations (10) and (11) for beneficial criteria:

$$v_j^+ = max\left\{z_{1j}, z_{2j}, \ldots, z_{mj}\right\} \tag{10}$$

$$v_j^- = min\left\{z_{1j}, z_{2j}, \ldots, z_{mj}\right\} \tag{11}$$

Equations (12) and (13) for non-beneficial criteria:

$$v_j^+ = min\left\{z_{1j}, z_{2j}, \ldots, z_{mj}\right\} \tag{12}$$

$$v_j^- = max\left\{z_{1j}, z_{2j}, \ldots, z_{mj}\right\} \tag{13}$$

Further, the vector of positive ideal solutions V^+ is computed as per equation (14):

$$V^+ = \left[v_1^+ v_2^+ \ldots v_n^+\right] \tag{14}$$

Moreover, the vector of negative ideal solution V^- is computed as per equation (15):

$$V^- = \left[v_1^- v_2^- \ldots v_n^-\right] \tag{15}$$

Step 6: The identification of the Euclidean Distance for every alternative from V^+ and V^- is concluded as per equation (16) and (17).

$$d_i^+ = \sqrt{\sum_{j=1}^{n} \left(z_{ij} - v_j^+\right)^2} \tag{16}$$

$$d_i^- = \sqrt{\sum_{j=1}^{n} \left(z_{ij} - v_j^-\right)^2} \tag{17}$$

where, d_i^+ is the Euclidean distance of alternative a_i from the positive ideal solution V^+ and d_i^- is the Euclidean distance of alternative a_i from the negative ideal solution V^-.

Step 7: The closeness coefficient r_i is concluded as per equation (18):

$$r_i = \frac{d_i^-}{d_i^- + d_i^+} \tag{18}$$

Step 8: Finally, the alternative with the highest value of r_i needs to be concluded as the best alternative.

C. SIMPLE ADDITIVE WEIGHTING (SAW)

The Simple Additive Weighting (SAW) technique is a MCDM method in which the performance values of an option across multiple evaluation criteria are combined into a single scalar score by adding the weights given to each evaluation criterion. By considering $\boldsymbol{W^*}$ as the vector that represents the weights of the evaluation criteria and $\boldsymbol{A} = \{\boldsymbol{a_1}, \boldsymbol{a_2}, \ldots, \boldsymbol{a_m}\}$ as the vector of the scores of the alternative over all criteria, where a_i represents the score of the alternative with respect to criterion $\boldsymbol{c_i}$, then the cumulative score, $\boldsymbol{z}$ can be computed as per equation (19) [40].

$$z = W^*A = \sum_{i=1}^{n} w_i a_i \tag{19}$$

III. PROPOSED HYBRID MCDM APPROACH

The proposed hybrid MCDM methodology used in this paper is shown in Figure 1.

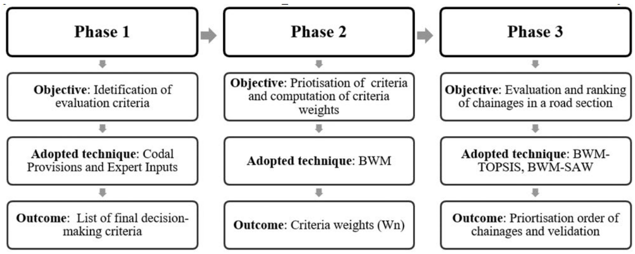

FIGURE 1. **Proposed hybrid MCDM approach.**

Phase 1: Identification of evaluation criteria

Based on the codal provisions of Indian Road Congress (IRC), eight decision-making criteria has been finalized for further analysis [41]. Different road safety professionals and researchers are contacted to be provide their inputs for the present study. Later, five road safety professionals—two from academia (a professor and a road safety researcher) and three from government departments (a police officer, a road engineer, and a road safety consultant)—understood the aim of this research and were consulted to finalize the decision-making criteria and provide the comparative importance scores of the criteria. The selected experts have at least five years of field experience in road safety.

Phase 2: Prioritisation of evaluation criteria and computation of criteria weights

This step evaluates the relative significance and the weights assigned to the completed decision-making criteria, as shown in Table 3. The current study focuses on a specific road portion of 500 m. To facilitate the analysis, a comprehensive video recording and photographs of the chosen length have been provided to a team consisting of five road safety experts. Initially, experts have determined the best criteria (criteria with the highest priority for improvement) and worst criteria (criteria with the least priority for improvement). Subsequently, each expert has been requested to provide their note on comparative improvements of best criteria over other as per Table 4. The structure outlined in Table 5 and Table 6 has been utilized to note the expert inputs. The experts are asked to select the best and worst criteria and further asked to provide the importance score as per the formats of Table 5 and Table 6. The BWM has been employed to determine the weights of all eight criteria based on the inputs provided by individual experts. The criterion weights obtained from each expert's contributions were further examined for consistency, and only those that demonstrated consistency were further taken into consideration. Many available literature provided different weights to each experts based on relevant aim of study [42], [43]. However, the present research proposes a

TABLE 3. **Decision making criteria for road safety improvements.**

Criteria	Names of Criteria	Definition
Criteria 1 (C1)	Improvement in cross-sectional elements	Criteria evaluate the improvement required in geometric design elements of a road section, such as the width of the carriageway, the width of the median opening, the width of the median, etc.
Criteria 2 (C2)	Improvement in pedestrian facilities	Criteria evaluate the improvement required in available pedestrian facilities, such as the provision of a footpath, pedestrian crossings, etc.
Criteria 3 (C3)	Improvement in roadside encroachment and hazard	Criteria evaluate the improvement required in roadside encroachment and hazards present over footpaths, roadways, or even shoulders, such as the removal of on-road parking of vehicles, food stalls, etc.
Criteria 4 (C4)	Improvement in Signs, Pavement Marking, Dealination	Criteria evaluate the improvement required within existing road signs, pavement marking, and dealination.
Criteria 5 (C5)	Improvement in access to nearby property	Criteria evaluate the improvement required to ensure safe access to properties near a road section.
Criteria 6 (C6)	Improvement in road surface	Criteria evaluate the improvement required to ensure the quality of the road surface.
Criteria 7 (C7)	Improvement in lighting and night time issue	Criteria evaluate the improvement required to ensure the proper lighting conditions as well as night time visibility.
Criteria 8 (C8)	Improvement in speed calming measures	Criteria evaluate the improvements required to ensure the presence of proper speed claiming measures such as speed humps, speed tables, etc.

TABLE 4. Linguistic importance and score.

Linguistic Importance	Score
Equal importance	1
Somewhat between Equal and Moderate	2
Moderately more important than	3
Somewhat between Moderate and Strong	4
Strongly more important than	5
Somewhat between Strong and Very strong	6
Very strongly important than	7
Somewhat between Very strong and Absolute	8
Absolutely more important than	9

TABLE 5. Formate of scoresheet for experts to note the improvement score of best criteria over other criteria.

Criteria with the highest priority for improvement (Best criteria)	Score ↓
Improvement in best criteria over Cross Sectional elements (C1)	
Improvement in best criteria over Pedestrian Facilities (C2)	
Improvement in best criteria over Roadside Hazard (C3)	
Improvement in best criteria over Signs, Pavement Marking, Dealination (C4)	
Improvement in best criteria over Access to Near property (C5)	
Improvement in best criteria over Road Surface (C6)	
Improvement in best criteria over Lighting and Night time visibility (C7)	
Improvement in best criteria over Speed calming measure (C8)	

TABLE 6. Formate of scoresheet for experts to note the improvement score of other criteria over worst criteria.

Criteria with least priority for improvement (worst criteria)	Score ↓
Improvement in Cross Sectional elements (C1) over worst criteria	
Improvement in Pedestrian Facilities (C2) over worst criteria	
Improvement in Roadside Hazard (C3) over worst criteria	
Improvement in Signs, Pavement Marking, Dealination (C4) over worst criteria	
Improvement in Access to Near property (C5) over worst criteria	
Improvement in Road Surface (C6) over worst criteria	
Improvement in Lighting and Night time visibility (C7) over worst criteria	
Improvement in Speed calming measure (C8) over worst criteria	

decision-making approach for road safety improvements that has to be applied to actual field conditions. Generally, the field practices represent that a road safety team with experts from different backgrounds and expertise represents a quality outcome [44]. Therefore, it becomes significant to incorporate every expert's input with equal importance. By doing so, the relevance of each expert's inputs becomes equally significant with multi-dimensional perspective. Therefore, it becomes important to incorporate every expert's inputs with equal importance. Consequently, the calculation of the final average value of consistent criteria weights has been completed, and these findings have been designated as the global criteria weights.

TABLE 7. Sample scoresheet for experts to note the priority score of a road section.

	Priority Score for a road segment							
Chainage	C1	C2	C3	C4	C5	C6	C7	C8
0- 100 m (A1)								
101-200 m (A2)								
201- 300 m (A3)								
301- 400 m (A4)								
401- 500 m (A5)								

Phase 3: Evaluation and ranking of chainage in a road section Phase 3 of the proposed methodology effectively hybridizes the BWM-concluded criteria weights with TOPSIS and SAW methods. The 500-metre study stretch has been divided into five sections of 100-metre chainage length for this research. Here, it is important to note that one can select and divide the length of chainage (e.g., alternatives) based on their requirement (i.e., a total length of 10 kilometers can be selected, and alternatives are considered every 1 kilometer of chainage). Therefore, TOPSIS can be a good-fit solution to prioritize any selected number of alternatives. Moreover, a research team has visited this study stretch and provided a priority score for each 100- meter section of the study stretches on a scale of 0-3 for every decision-making criterion as per Table 7. These scores have been provided individually for both sides of the carriageway (i.e., from point A to B and from point B to A). Finally, the chainages have been ranked by hybridizing the priority scores and BWM-generated criteria weights by applying the TOPSIS and SAW methods, and the final ranking by BWM-TOPSIS and BWM-SAW has been compared to validate the approach.

IV. RESULTS AND DISCUSSION

A 500-meter stretch on National Highway (NH) 3 in Hathijan, Ahmedabad district, India, was selected for this study. This particular stretch features a four-lane divided carriageway. As per the inputs provided by local residents and police officers, road accidents are being noted on this selected stretch. Therefore to facilitate a thorough analysis, the stretch was divided into five 100-meter chainages as illustrated in Figure 2. This division may provide a clear answer about "where improvements are required?" and the chainage-wise weighted priority score provide a clear answer about "what type of improvements are required?". To achieve this, a detailed videography and photographic survey of the stretch was conducted and subsequently shared with a team of five road safety experts. The inputs provided by these experts were based solely on their interpretation of the videography and photography evidence. The methodology followed was as outlined in the previous section.

Table 8 presents the best and worst criteria as selected by each expert. It is seen that all expert rate C6 as the criteria with least priority for improvement. 2 out 5 experts' rate C8 as the criteria with highest priority for improvement whereas the other 3 experts' rate C2 as the criteria with highest priority.

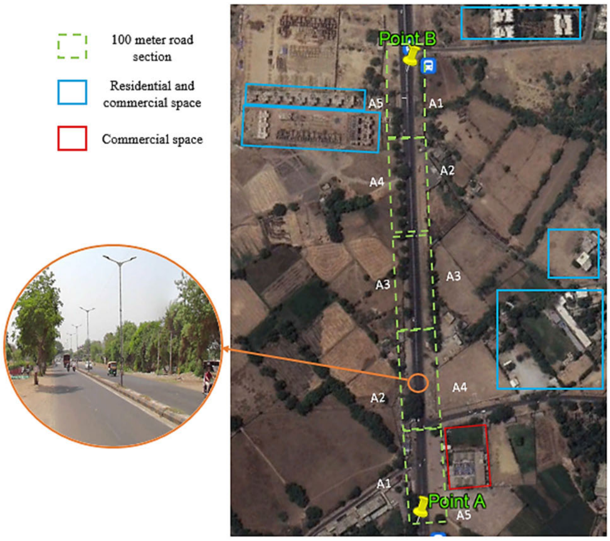

FIGURE 2. Graphical representation of study stretch.

TABLE 8. Selection of best and worst criteria for study stretch by the experts.

Experts	Criteria with the highest priority for improvement (best criteria)	Criteria with least priority for improvement (worst criteria)
Expert 1	C2	C6
Expert 2	C8	C6
Expert 3	C8	C6
Expert 4	C2	C6
Expert 5	C2	C6

TABLE 9. The comparative improvement score of the best criteria over other criteria provided by the experts.

Criteria with the highest priority for improvement = C2	C2 over C1	C2 over C2	C2 over C3	C2 over C4	C2 over C5	C2 over C6	C2 over C7	C2 over C8
Expert 1	6	1	2	3	3	9	4	2
Expert 4	5	1	3	5	5	8	5	3
Expert 5	5	1	4	4	3	9	3	3
Criteria with the highest priority for improvement = C8	**C8 over C1**	**C8 over C2**	**C8 over C3**	**C8 over C4**	**C8 over C5**	**C8 over C6**	**C8 over C7**	**C8 over C8**
Expert 2	5	5	4	7	4	9	5	1
Expert 3	4	5	4	5	4	9	5	1

TABLE 10. The comparative improvement score of the best criteria over other criteria provided by the experts.

Criteria with least priority for improvement = C6	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5
C1 over C6	4	5	6	5	3
C2 over C6	9	7	6	9	9
C3 over C6	7	7	6	8	6
C4 over C6	8	6	6	6	8
C5 over C6	7	6	6	6	7
C6 over C6	1	1	1	1	1
C7 over C6	3	5	5	4	2
C8 over C6	8	9	9	8	7

TABLE 11. BWM based criteria weights with consistency ratio (CR).

Expert	C1	C2	C3	C4	C5	C6	C7	C8	CR
Expert 1	0.056	0.271	0.169	0.113	0.113	0.023	0.085	0.169	0.068
Expert 2	0.096	0.096	0.120	0.069	0.120	0.029	0.096	0.372	0.109
Expert 3	0.113	0.090	0.113	0.090	0.113	0.030	0.090	0.361	0.090
Expert 4	0.086	0.336	0.144	0.086	0.086	0.030	0.086	0.144	0.096
Expert 5	0.079	0.304	0.099	0.099	0.132	0.024	0.132	0.132	0.091
Average	0.086	0.220	0.129	0.091	0.113	0.027	0.098	0.236	
Rank	7	2	3	6	4	8	5	1	

Table 9 and Table 10 represents the improvement rating of best criteria over other criteria and others to criteria with least priority provided by each experts. It is important to note that experts have provided their improvement scores considering both sides of the carriageway, while the research team has provided chainage-wise priority scores for individual sides of the carriageway.

Criterion weights were determined using the BWM technique, based on the improvement scores from Tables 9 and 10. Each expert contributed unique scores, resulting in varying criterion weights. The consistency of these weights was assessed as per Table 11.

The criterion weights, determined based on the approved consistency ratio (CR) value referenced in [9], took into account the average weights assigned to each criterion: $W_{C1} = 0.086, W_{C2} = 0.220, W_{C3} = 0.129, W_{C4} = 0.091, W_{C5} = 0.113, W_{C6} = 0.027, W_{C7} = 0.098$, and $W_{C8} = 0.236$. These weights indicate that improvements in speed calming measures (C8) are of the highest priority. Similarly, improvements in Pedestrian Facilities (C2) and Roadside Hazard (C3) follow in priority. The criterion for the improvement in road surface (C6) received the lowest weight, suggesting that this aspect of the study area is already in good condition. Figure 3 further reinforces these findings by depicting the cumulative criterion weights as a percentage, indicating that the top three weighted criteria constitute over 58% of the necessary improvements.

TABLE 12. Chainages-wise priority scores.

Chainage	Priority Score from Point A to B								Priority Score from Point B to A							
	C1	C2	C3	C4	C5	C6	C7	C8	C1	C2	C3	C4	C5	C6	C7	C8
0- 100 m (A1)	3	3	3	3	1	2	3	3	3	3	3	3	2	1	2	3
101-200 m (A2)	2	3	2	3	3	1	1	0	0	2	1	2	1	2	1	0
201- 300 m (A3)	2	2	1	2	0	1	2	0	1	1	2	2	0	0	1	0
301- 400 m (A4)	0	2	1	2	0	0	1	3	3	3	2	3	2	2	2	3
401- 500 m (A5)	3	3	3	3	1	1	2	3	2	3	3	2	3	2	3	2

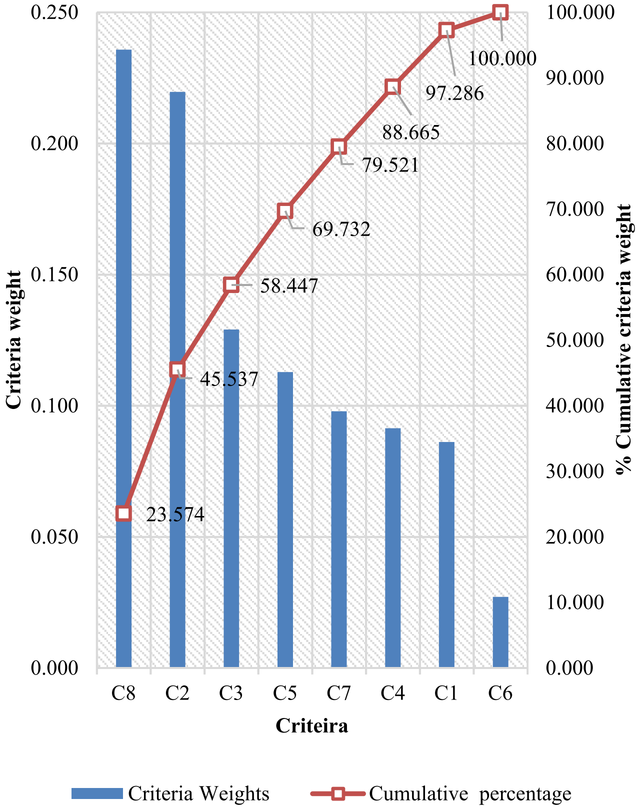

FIGURE 3. Percentage cummlative criteria weight distribution.

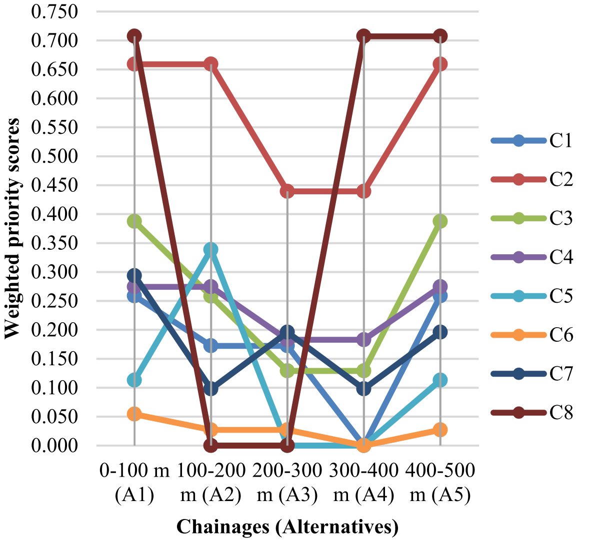

FIGURE 4. Chainage-wise weighted priority scores for every criteria (from point A to B).

TABLE 13. Weighted normalised decision matrix.

	C1	C2	C3	C4	C5	C6	C7	C8
A	0.00	0.01	0.01	0.00	0.00	0.00	0.01	0.02
1	8	6	3	7	8	6	3	2
A	0.00	0.01	0.00	0.00	0.02	0.00	0.00	0.00
2	6	6	9	7	4	3	4	0
A	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00
3	6	1	4	4	0	3	8	0
A	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.02
4	0	1	4	4	0	0	4	2
A	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.02
5	8	6	3	7	8	3	8	2

Subsequent analysis of the chainages utilized these final criterion weights. Table 12 displays the priority scores in both directions (from point A to B and B to A). For an accurate representation, the priority scores from A to B were considered for further analysis. These scores were integrated with the final criterion weights from BWM to create a weighted normalized decision matrix, as shown in Table 13. Table 14 provided the positive and negative ideal solutions, v_j^+ and v_j^-, respectively. The Euclidean distance values (d_i^+ and d_i^-) for each chainage were calculated and used to determine the closeness coefficient r_i and the final priority ranking of each chainage, as shown in Table 15. The chainage with the higher r_i value received a higher rank. This analysis was repeated for the direction from B to A.

It is evident that the 0-100m chainage (A1) for both A to B and B to A directions was prioritized as needing the most immediate improvements. These rankings were further validated using the SAW methodology, where the BWM-generated criterion weights were multiplied with the priority scores from Table 12, and final rankings were concluded as shown in Table 16.

The rankings produced by the hybrid BWM-TOPSIS and BWM-SAW methods showed complete similarity, indicating that both hybrid approaches corroborate each other's findings. This mutual reinforcement underlines the accuracy of the current method in evaluating road safety, integrating diverse expert opinions.

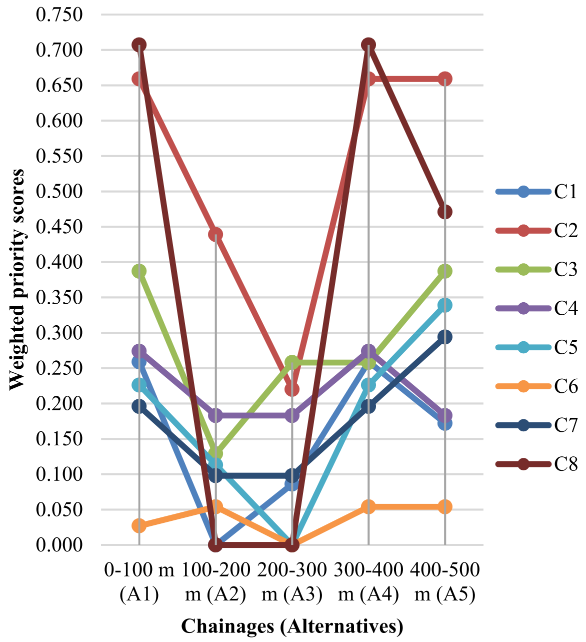

FIGURE 5. Chainage-wise weighted priority scores for every criteria (from point B to A).

TABLE 14. The positive ideal solution v_j^+ and the negative ideal solution v_j^- for every criteria.

	C1	C2	C3	C4	C5	C6	C7	C8
v_j^+	0.008	0.016	0.013	0.007	0.024	0.006	0.013	0.022
v_j^-	0.000	0.011	0.004	0.004	0.000	0.000	0.004	0.000

TABLE 15. Euclidian distance and final ranking of chainages.

Chainage	from Poin A to B				from Point B to A			
	d_i^+	d_i^-	r_i	Rank	d_i^+	d_i^-	r_i	Rank
A1	0.016	0.029	0.646	1	0.007	0.033	0.831	1
A2	0.024	0.026	0.513	3	0.033	0.008	0.204	4
A3	0.034	0.007	0.179	5	0.035	0.005	0.127	5
A4	0.029	0.022	0.431	4	0.008	0.033	0.810	2
A5	0.017	0.027	0.624	2	0.010	0.029	0.752	3

TABLE 16. Weighted priority scores and Z values.

Weighted priority scores and z values (from Point A to B)										
Chainage	C1	C2	C3	C4	C5	C6	C7	C8	z	Rank
0-100 m (A1)	0.259	0.659	0.387	0.274	0.113	0.054	0.294	0.707	2.747	1
101-200 m (A2)	0.172	0.659	0.258	0.274	0.339	0.027	0.098	0.000	1.827	3
201-300 m (A3)	0.172	0.439	0.129	0.183	0.000	0.027	0.196	0.000	1.147	5
301-400 m (A4)	0.000	0.439	0.129	0.183	0.000	0.000	0.098	0.707	1.556	4
401-500 m (A5)	0.259	0.659	0.387	0.274	0.113	0.027	0.196	0.707	2.622	2
Weighted priority scores and z values (from Point A to B)										
Chainage	C1	C2	C3	C4	C5	C6	C7	C8	z	Rank
0-100 m (A1)	0.259	0.659	0.387	0.274	0.226	0.027	0.196	0.707	2.735	1
101-200 m (A2)	0.000	0.439	0.129	0.183	0.113	0.054	0.098	0.000	1.016	4
201-300 m (A3)	0.086	0.220	0.258	0.183	0.000	0.000	0.098	0.000	0.845	5
301-400 m (A4)	0.259	0.659	0.258	0.274	0.226	0.054	0.196	0.707	2.633	2
401-500 m (A5)	0.172	0.659	0.387	0.183	0.339	0.054	0.294	0.471	2.559	3

Figure 4 and Figure 5 graphically represent the weighted priority scores for each 100-meter chainage in both directions, illustrating the prioritization of necessary improvements. The results indicate the paramount importance of implementing speed calming measures, particularly in the 0-100m, 300-400m, and 400-500m segments. Conversely, the improvement of road surface quality (C6) was assigned the lowest priority, indicating satisfactory conditions in this aspect. Experts, upon reviewing these findings along with the videographic and photographic evidence, acknowledged the potential of the current technique to serve as a robust decision support system for road safety professionals and researchers.

V. CONCLUSION

This research culminates in establishing a robust Hybrid Multi-Criteria Decision-Making approach, which innovatively combines the Best-Worst Method (BWM), the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), and the Simple Additive Weighting (SAW) method, for prioritizing road safety improvements. The approach's application to a 500-meter road section, dissected into five subsections and evaluated against eight road improvement criteria, demonstrates its practical effectiveness in a real-world setting. Results of the study underscore the nuanced prioritization capabilities of the proposed approach. The BWM was instrumental in objectively determining the weights of various safety improvement criteria, which were then seamlessly integrated into the TOPSIS and SAW methods. This integration yielded a comprehensive ranking of the road subsections, highlighting specific areas that require immediate attention. Notably, the study revealed that improvements in speed calming measures, pedestrian facilities, and roadside hazard mitigation emerged as top priorities. These findings align with the current trends in road safety management, emphasizing the need for targeted interventions in these areas.

The validation of the approach through expert consultations and a comparative analysis with the standalone SAW method further solidifies its reliability and applicability. The concurrence of results from both the hybrid BWM-TOPSIS and BWM-SAW methodologies further indicates a high level of accuracy and consistency in the approach. Further, the results are shared with the selected experts with the elaboration of proposed the framework as part of face validation process [16]. The experts are highly convinced with ease of application and interpretation of results provided by this research. These aspects are particularly crucial for road safety stakeholders who rely on precise and dependable practices to formulate safety strategies.

The study's analysis also revealed the dynamic nature of road safety issues, underscoring the importance of a flexible and adaptable decision-making framework. One can utilize the potential of proposed framework over any selected stretch and further divide the selected stretch into different chainage and prioritize the chainage-wise safety improvements quickly. The proposed approach addresses this need by providing a scalable and versatile hybrid MCDM framework that can be adjusted according to specific road safety scenarios and requirements. Thus, this study marks a step forward in the journey towards safer roadways, offering a strategic tool to reduce accidents and enhance the overall safety of road users.

At present, this research considers all expert inputs to have equal weight. This can be consider as limitation of present study as the weight difference provided to every expert may differ the results. It means that the present framework finalized criteria weights takes an arithmetical mean of every expert's individual consistent criteria weight. If some experts are not satisfied with the arithmetic mean of the criteria weight, it may create a conflicting situation. On the other hand, a well-integrated and supportive team of experts may be able to accept the final criteria weight computed through the proposed approach, although it slightly differs from their individual perspective of the road safety situation.

A mobile-based decision support application can be developed for road safety professionals based on the elaborate research. This application may support the road safety audit and improvement process at the time of the field visit. A team of stakeholders may select the best and worst criteria within the said application and provide the chain-wise priority score for the successful evaluation. The future study in a similar direction may consider more criteria for road safety improvements and may build a multi-level decision-making hierarchy. Further work in a similar direction may provide different weights to experts based on different criteria such as seniority, field experience, etc. Also, Fuzzy-BWM can be combined within future study to evaluate the criteria weights.

CONFLICT OF INTEREST

The authors certify that they have NO affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

DATA AVAILABILITY

All data generated or analysed during this study are included in this published article.

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