

A MCDM Based Approach to Prioritizing National Highways for Road Safety Improvements



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Abstract Selection of the most vulnerable alternative for implementation of road safety projects considering financial and technical availability often put the road authorities in dilemma. This paper proposes a two-step approach based on multi-criteria decision-making methods to overcome the difficulties in location prioritization. The objective of this study was to rank the national highways based on their vulnerability in terms of road safety and identify the location that requires the most attention. The study area covered Cumilla-Feni section of N1 national highway, Gazipur-Elenga section of N4 national highway, Natore-Nawabganj section of N8 national highway, and Barisal-Madaripur section of N8 national highway. These four alternatives were evaluated under five criteria- average annual daily traffic (AADT), crash per thousand vehicles, percentage of corridor without median, heavy vehicles percentage in the corridor, and percentage of non-motorized vehicles in the corridor. The required data for analysis were collected from some secondary sources along with drive-through video footage from a probe vehicle. To evaluate the relative importance of each criterion, criteria weights were calculated using the Analytic Hierarchy Process (AHP). AHP uses pair-wise comparison based on subjective judgment to establish relative importance and the consistency ratio provides a measure of the consistency of the judgment. Here, the consistency ratio was found 0.02 which does not exceed $CR = 0.1$, indicative of consistent judgment. The criteria weights and the criteria values were combined using the Technique for Order Preference

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by Similarity to Ideal Solution (TOPSIS) and ranks of alternatives were achieved. The analysis identified Natore-Nawabganj (N6) as the most vulnerable alternative followed by Gazipur-Elenga (N4), Cumilla-Feni (N1), and Barisal-Madaripur (N8). This study proposes a framework for evaluation of alternatives that is reliable, and data driven. The results indicate that the proposed framework possesses replicability and promises effective decision-making based on scientific approach.

Keywords MCDM · AHP · TOPSIS · Road safety · Ranking · Prioritization

1 Background

An acceptable approach to ensure efficient allocation of limited resources which also imparts maximum benefit to the society often puts the decision makers in disarray. A prioritization framework that is technically sound and easily understandable by the stakeholders can aid decisionmakers in numerous ways. This type of framework is more suitable for safety improvement projects where benefits of project implementation are immeasurable in most cases. Where economic viability of a project can be the most important metric for the selection of a general development project, safety improvement project's feasibility may depend on many more important factors such as- current crash statistics, demography of the road users, existing road safety features, speed differential in the corridor etc.

The application of multi-criteria-decision-making (MCDM) methods in project appraisal or location prioritization is not a very new concept in the transportation research domain. The pragmatic and inclusive nature of the framework has made MCDM methods a top pick for decision makers. Use of MCDM methods such as Analytic Hierarchy Process (AHP), Analytic Network Process (ANP), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), Best Worst method, Decision Making Trial and Evaluation Laboratory (DEMATEL), Preference Ranking Organization Method for Enrichment of Evaluations (PROMETHEE) are evident in the existing works of literature [1–9]. However, the Analytic Hierarchy Process (AHP) proposed by Saaty [10] is considered the pioneer of all MCDM methods. In AHP, alternatives are evaluated based on several criteria. Later, the weight of each criterion is obtained through a pair-wise comparison matrix developed by experts' consultation. The application of AHP in solving transportation related issues has become very prevalent in recent years [11]. Use of AHP specially in the road transportation mostly encompassed decision and planning related problems [11–14]. From literature, Agarwal et al. [6] proposed an AHP based methodology for ranking hazardous locations. They divided the hazardous condition into different factors and applied the AHP to evaluate the weightage of each factor. Jun et al. [15] assessed the variables involved in virtual road safety audit using AHP. The experts were asked to take survey on AHP based questionnaire based on which the pair-wise comparison matrix was developed. Results indicated that the suggested strategy gave valuable guidance on creating an appropriate experiment for a road safety audit.

The AHP methodology is often presented in conjunction with other approaches to bolster the scientific acceptance of the framework. Fancello et al. [8] aimed to rank road intersections for road safety improvements using Electre III and concordance analysis. For further analysis, the authors used Vikor and TOPSIS and compared the two methods. They found TOPSIS performing the best in determining critical road intersection. Pal et al. [7] considered several techno-economic factors for prioritizing among fifteen state highway sections. They determined the weightage of the factors using AHP and ranked the highway sections using TOPSIS and RIDIT. In this study, AHP has been proposed in conjunction with Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). The AHP was used to evaluate the criterion weights whereas TOPSIS was used to rank the alternatives based on overall score.

2 Study Area and Data Collection

The study area covered Cumilla-Feni section of N1 national highway, Gazipur-Elenga section of N4 national highway, Natore-Nawabganj section of N8 national highway, and Barisal-Madaripur section of N8 national highway. These four alternatives were evaluated under five criteria- average annual daily traffic (AADT), crash per thousand vehicles, percentage of corridor without median, heavy vehicles percentage in the corridor, and percentage of non-motorized vehicles in the corridor. The required data for analysis were collected from some secondary sources along with drive-through video footage from a probe vehicle as shown in Table 1.

3 Methodology

3.1 Analytic Hierarchy Process (AHP)

The AHP methodology adapts the eigenvector method to determine criteria weights [10]. The Perron-Frobenius theory serves as the foundation for this strategy, according to which the greatest eigenvalue may be found given a positive matrix with the weights vector as its associated eigenvector. The eigenvector contains nonnegative entries, and after being normalized, the sum of its parts equals one, resulting in a vector of relative weights [15]. The simple step by step approach within the AHP methodology is described here.

Step 1: Determining the criteria and alternatives for evaluation.

Step 2: Preparing comparison matrix based on experts' opinion.

Table 2 Saaty’s nine-point scale of preference [10]

Verbal preference	Numerical score
Extremely preferred	9
Very strongly preferred	7
Strongly preferred	5
Moderately preferred	3
Equally preferred	1

Here, $[c_1, c_2, \dots, c_n]$ indicate the criteria for evaluation and $[a_1, a_2, \dots, a_n]$ indicate the alternatives that are to be ranked and prioritized. The pair-wise comparison matrix is developed complying with 9-point Saaty scale (Table 2).

Step 3: Developing normalized matrix and calculating priority vectors. As per the Perron-Frobenius theory, the greatest eigenvalue may be found given a positive matrix with the weights vector as its associated eigenvector. In simple words, the sum of rows of the squared comparison matrix are normalized to obtain the priority vectors/ vector of weights.

Step 4: Checking for inconsistency in the subjective judgement. Since the pair-wise comparison matrix is developed by experts’ opinion, and the judgement is bound to be kept within the discrete nine-point Saaty scale, inconsistency in the judgement may arise. Hence, Consistency Index (CI) is measured.

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{2}$$

Here, λ_{max} is the indicator of highest eigenvalue and the number of criteria is represented by n . Consistency Ration (CR) can be calculated further comparing with the Random Index (RI) where if $CR < 0.1$, the results must be rejected. Random index is the consistency index of a randomly generated pair-wise comparison matrix (Table 3).

$$CR = \frac{CI}{RI} \tag{3}$$

Table 3 Random Index for different number of criteria [16]

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

3.2 Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS)

Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) was initially presented by Chen and Hwang [17] in 1992. The fundamental tenet of this approach is that the optimal compromise alternative should be the furthest away from the negative-ideal solution and the closest to the ideal solution [8]. Simple steps followed in TOPSIS to complete alternative ranking are shown here [18].

Step 1: Formation of a decision matrix.

Step 2: Normalized decision matrix development. If the normalized value is r_{ij} .

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^n x_{ij}^2}}$$

Here, x_{ij} indicates the objective function value i for an alternative.

Step 3: Developing a weighted normalized decision matrix.

$$v_{ij} = w_{ij}r_{ij}$$

Here, i th objective function's weight is w_i

Step 4: Generation positive ideal and negative ideal solution. Here, $A^* = \{(\max v_{ij}|j \in J), (\min v_{ij}|j \in J')\}$ and $A^- = \{(\min v_{ij}|j \in J), (\max v_{ij}|j \in J')\}$

Here, $J = 1, 2, 3, \dots, n$; J indicates benefit criteria and $J' = 1, 2, 3, \dots, n$; J' indicates disbenefit criteria.

Step 5: Determining the separation of each alternative from positive and negative ideal solution.

Here, $D_i^* = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^*)^2}$ is the separation from positive ideal solution and, $D_i^- = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^-)^2}$ is the separation from negative ideal solution.

Step 6: Finding the ideal closeness.

$$C_j^* = \frac{D_j^-}{(D_j^* + D_j^-)}$$

C_j^* ranges between 1 and 0 and it the measure of ranking alternatives. The larger C_j^* indicates better performance.

4 Analysis and Result

This study aimed to identify the most vulnerable highway intersection from road safety perspective base on five assessment criteria: Average Annual Daily Traffic (AADT), Crash per thousand vehicle, percentage of corridor without median, percentage of heavy vehicle in the corridor and percentage of non-motorized vehicle in the corridor (Table 4).

The criteria selection was done through extensive literature review and suggestion from the stakeholder organizations- World Bank (WB), Dhaka Transport Coordination Authority (DTCA), Roads and Highways Department (RHD), and Accident Research Institute (ARI). Due to the absence of authentic safety critical data, AADT was considered as a measure of traffic exposure in the corridor. Crash data provided by the ARI for selected highway chainage was converted into crash per thousand vehicles for gaining consistency among the alternatives. Absence of median, percentage of heavy and non-motorized vehicles were included into the analysis because of the safety threats posed by speed variation in the multi-modal carriageway and chance of head on collision. Accident reports showed that 77% of the highway accidents had involvement of heavy vehicles such as bus or truck and 50% of the accidents were associated with pedestrians, cyclists, motorcyclists or NMVs [19].

4.1 Determination of Criteria Weights

In this study, AHP was used for determining the weights of each criterion. A pair-wise comparison matrix was developed by consulting with the stakeholders. Prior briefing sessions were arranged to ensure that the stakeholders are familiar with AHP framework and can deliver consistent judgement. Lastly, the matrix was finalized by the authors after consulting with the transportation safety experts with know-how in ranking, prioritization, and road safety (Table 5).

The comparison scale proposed by Saaty [10] was used to develop the comparison matrix. From the matrix we can see that, AADT is three times less preferred than crash per thousand vehicles. In a similar process, through consultation and surveys, comparison scores were assigned to other pairs. Once the pair-wise comparison

Table 4 Criteria names and criteria codes

Criteria name	Criteria code
Annual average daily traffic	AADT
Crash per thousand vehicles	CPTV
Percentage of corridor without median	% CWM
Percentage of heavy vehicle in the corridor	% HV
Percentage of non-motorized vehicle in the corridor	% NMV

Table 5 The pair-wise comparison matrix for AHP

	AADT	CPTV	% CWM	% HV	% NMV
AADT	1	1/3	1/2	1/2	1/2
CPTV	3	1	2	3	3
% CWM	2	1/2	1	2	2
% HV	2	1/3	1/2	1	1
% NMV	2	1/3	1/2	1	1

matrix was formed, priority vectors/eigen vectors were calculated by simple matrix operations through trial and error (Tables 6 and 7).

The trial-and-error approach to determine priority vector was stopped after second trial as no major difference among the priority vectors were observed. The AHP methodology identified crash per thousand vehicles (CPTV) as the most important criteria (weightage = 40%) followed by percentage of corridor without median (weightage = 24%), percentage of heavy vehicle in the corridor (weightage = 14%),

Table 6 First trial of priority vector determination

Trial-1

	AADT	CPTV	% CWM	% HV	% NMV	Sum of row of squared matrix	Priority vector
AADT	4.99	1.24	2.16	3.49	3.49	15.37	0.09
CPTV	22	4.97	8.5	14.5	14.5	64.47	0.4
% CWM	13.5	2.98	5	8.5	8.5	38.48	0.24
% HV	7.99	1.9	3.16	4.99	4.99	23.03	0.14
% NMV	7.99	0.66	3.16	4.99	4.99	21.79	0.13
Total						163.14	1

Table 7 Second trial of priority vector determination

Trial-2

	AADT	CPTV	% CWM	% HV	% NMV	Sum of Row of Squared Matrix	Priority vector
AADT	137.11	27.722	54.175	88.585	88.585	396.1773	0.1
CPTV	565.58	114.431	223.905	365.805	365.805	1635.526	0.4
% CWM	336.255	68.211	133.21	217.655	217.655	972.986	0.24
% HV	204.07	41.542	80.745	132.095	132.095	590.5473	0.14
% NMV	176.79	5.273	70.205	114.115	114.115	480.4983	0.12
Total						4075.7349	1

Table 8 Consistency ratio determination

	AADT	CPTV	% CWM	% HV	% NMV	Row avg.
AADT	1	0.33	0.5	0.5	0.5	0.566
CPTV	3	1	2	3	3	2.4
% CWM	2	0.5	1	2	2	1.5
% HV	2	0.33	0.5	1	1	0.966
% NMV	2	0.33	0.5	1	1	0.966
Row avg.	Priority values			Priority value/row avg. (X)		Avg. (X) λ_{max}
0.566	3.074			5.431		5.094
2.4	12.894			5.373		
1.5	7.696			5.131		
0.966	4.606			4.768		
0.966	4.606			4.768		
CI	0.0235	RI	1.12	CR	0.02	

percentage of non-motorized vehicles in the corridor (weightage = 12%) and lastly Average Annual Daily Traffic (weightage = 10%).

4.2 Consistency of Judgement

Consistency Ratio is the measure of consistency of the judgement in AHP. The developed matrix is compared with the consistency index of a randomly developed one to determine the consistency ratio. If $CR < 0.1$, the developed comparison matrix cannot be claimed any better than a randomly developed matrix (Table 8).

From analysis, the consistency ratio was found $CR = 0.02 < 0.1$, indicative of a consistent judgement by the stakeholders.

4.3 Ranking of the Alternatives

The weight of the criteria obtained from AHP analysis were applied in the TOPSIS framework to rank the highway sections (Table 9).

The TOPSIS analysis identified Natore-Nawabganj section of N6 national highway as the most vulnerable highway section among the four alternatives. This highway corridor had zero percent road median coverage, remarkably high NVM volume with a moderate crash record. With a score very close to the N6 national highway, Gazipur-Elenga section of N4 national highway was identified as the second

Table 9 Determination of the rank of alternatives by TOPSIS

Alternative/Criteria	AADT X1	CPTV X2	% CWM X3	% HV X4	% NMV X5
Cumilla-Feni (N1)	13995	0.93	0	51.61	1.41
Gazipur-Elenga (N4)	30409	0.62	10.39	73.08	3.65
Natore-Nawabganj (N6)	21446	0.33	100	8.38	23.44
Barisal-Madaripur (N8)	8533	0.23	99.5	38.33	1.79
Normalized Decision Matrix	NDX1	NDX2	NDX3	NDX4	NDX5
Criteria Weights From AHP	0.1	0.4	0.24	0.14	0.12
Cumilla-Feni (N1)	0.3442	0.7829	0	0.5283	0.0592
Gazipur-Elenga (N4)	0.7479	0.5219	0.0735	0.7481	0.1532
Natore-Nawabganj (N6)	0.5274	0.2778	0.707	0.0858	0.9836
Barisal-Madaripur (N8)	0.2099	0.1936	0.7034	0.3924	0.0751
A*	0.0748	0.3132	0.1697	0.1047	0.118
A-	0.021	0.0774	0	0.012	0.0071
Relative Closeness	D*	D-	C	Rank	
Cumilla-Feni (N1)	0.2088	0.9335	0.8172	3	
Gazipur-Elenga (N4)	0.2095	1.1378	0.8445	2	
Natore-Nawabganj (N6)	0.2234	1.3249	0.8557	1	
Barisal-Madaripur (N8)	0.27	0.8326	0.7551	4	

most vulnerable location with very high traffic volume in the corridor, relatively high accident record and extremely high heavy vehicle movement.

5 Conclusions and Policy Implications

The goal of this study was to develop a data driven location prioritization framework for road safety improvement projects that can guide policymakers in the decision-making process. The proposed framework adapted a two-step approach based on multi-criteria decision-making methods to overcome the difficulties in location prioritization. In the initial stage, decisions were made by the major stakeholders to evaluate the candidate highway sections based on five important criteria. The AHP methodology was followed to determine the weightage of each criterion through developing pair-wise comparison matrix. Once the criteria weightage was achieved, state of the art ranking method TOPSIS was employed to rank the alternatives. Results showed that the Natore-Nawabganj section of N6 national highway was the most vulnerable location as this highway corridor had zero percent road median coverage, very high NVM volume with a moderate crash record. Furthermore, Gazipur-Elenga section of N4 national highway was identified as the second most vulnerable location with very high traffic volume in the corridor, relatively high accident record and extremely high heavy vehicle movement.

The proposed framework, if adapted by the transportation professionals and the decision-makers, can reduce significant delay in determining suitable candidate for project implementation. Besides, the common issues faced at the policy level such

as lack of safety critical data, incorporating stakeholders input into the decision-making process, overcoming delay in the decision-making process etc. can be easily marginalized by this framework. Overall, the proposed methodology provides decision-makers with a tool that is data driven, intuitive and adjustable to user's demand.

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