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Abstract: This paper presents a robust multi-criteria model for prioritizing highway safety improvement projects, in which a set of criteria related to the project's technical, economic, social and environmental impacts are properly weighted in consideration. The proposed model features an analytical hierarchy process (AHP) framework to tackle the multi-criteria decision making problem. Different from the conventional AHP, this paper adds a fuzzy scale level between the criteria level and the alternative level which offers the advantage of preventing the vagueness and uncertainty on judgments of the decision-maker(s). Such a unique modeling feature is further embedded with a non-linear optimization formulation to maximize the consistency in pair-wise comparison and weight estimation for each criterion. Case study results reveal that the proposed model is efficient not only for selecting the most suitable project for a specific site, but also for determining the priorities for implementation those suitable projects among multiple sites given the budget constraint. Comparative study between the proposed model and the existing ranking methods has also indicated its capability to capture the comprehensive impacts of all contributory factors which have been neglected by most existing approaches during the safety project selection process. The clarity of model inputs, ease of synthesizing the final score of each candidate project, and the interpretation of results with respect to different selection criteria offer its best potential to be used as an effective tool for highway infrastructure manager and transportation authorities to assess and refine the highway safety improvement investments.

Suggested Reviewers:

Opposed Reviewers:

April 13, 2010

Dr. Samer Madanat
University of California, Berkeley

Subject: ASCE Journal of Infrastructure Systems Paper Submission

Dear Dr. Madanat:

Please consider the attached technical paper, "Prioritizing highway system safety improvement projects using the extended analytical hierarchy process with fuzzy logic," for submission to Journal of Infrastructure Systems.

This submission presents a robust multi-criteria model for prioritizing highway system safety improvement projects, to account for the impacts of technical, economic, social and environmental related contributory factors. Grounded on an AHP-based framework integrated with the fuzzy logic, the proposed model offers the advantage of effectively preventing the arbitrariness in determination of the weights for multiple ranking criteria, and easily synthesizing the final score of each candidate project for implementation. Moreover, the clarity of model inputs and its ease of interpreting of the results with respect to different selection criteria offer the best potential for its use in highway infrastructure and safety management. The paper fits squarely within the journal's mission. Please do not hesitate to contact me for further information.

Sincerely,

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PRIORITIZING HIGHWAY SYSTEM SAFETY IMPROVEMENT PROJECTS USING THE EXTENDED ANALYTICAL HIERARCHY PROCESS WITH FUZZY LOGIC

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ABSTRACT: This paper presents a robust multi-criteria model for prioritizing highway safety improvement projects, in which a set of criteria related to the project's technical, economic, social and environmental impacts are properly weighted in consideration. The proposed model features an analytical hierarchy process (AHP) framework to tackle the multi-criteria decision making problem. Different from the conventional AHP, this paper adds a fuzzy scale level between the criteria level and the alternative level which offers the advantage of preventing the vagueness and uncertainty on judgments of the decision-maker(s). Such a unique modeling feature is further embedded with a non-linear optimization formulation to maximize the consistency in pair-wise comparison and weight estimation for each criterion. Case study results reveal that the proposed model is efficient not only for selecting the most suitable project for a specific site, but also for determining the priorities for implementation those suitable projects among multiple sites given the budget constraint. Comparative study between the proposed model and the existing ranking methods has also indicated its capability to capture the comprehensive impacts of all contributory factors which have been neglected by most existing approaches during the safety project selection process. The clarity of model inputs, ease of synthesizing the final score of each candidate project, and the interpretation of results with respect to different selection criteria offer its best potential to be used as an effective tool for highway infrastructure managers and transportation authorities to assess and refine the highway safety improvement investments.

CE Database Subject Headings: Highway safety; Multi-criteria model; Analytical Hierarchy Process; Fuzzy logic; Non-linear optimization

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INTRODUCTION

Over the past several decades, highway safety has emerged as one of the most critical concerns faced by the responsible transportation/highway infrastructure management agencies. In the United States, both federal and local agencies have initiated several programs to address issues related to traffic safety improvement. To ensure such programs implemented as intended, four critical tasks need to be performed. Network screening is the first task aimed to generate a list of hazardous locations ranked in order of priority for the conduct of a more detailed engineering study. The second task addresses the diagnosis of safety problems and selection of a possible array of improvement projects for a specific site. The purpose of task 3 is to generate a priority ranking of "prospectively cost-effective" projects within a series of sites. Then, the before-after study will be conducted as the last task to evaluate the effects of safety projects implemented at specific sites using available data. Many research issues are interlaced with these four tasks, such as estimating accident frequency, identifying high accident locations, and prioritizing candidate improvement projects. This study will propose a new model focused on prioritizing candidate safety improvement projects to assist responsible agencies in achieving better safety improvement results with a limited budget.

Several ranking criteria have been proposed and applied in prioritizing safety improvement projects in the literature, including "the number of accidents reduced", "the number of fatal and injury accidents reduced", "the project cost", "the expected project benefits", "cost-effectiveness of the project", "benefit-cost ratio of the project", and "net project benefits" (Hauer et al, 2002; FHWA, 2002a; Banihashemi, 2007). Using the number of accidents reduced or the number of fatal and injury accidents reduced as the ranking criteria has the advantage of simplicity; however they neglect the estimation of costs or benefits for implementing those improvement projects which sometimes are of the most concern to responsible agencies. To deal with this issue, project costs or expected benefits have been proposed as the alternatives for those simple criteria. However, these criteria can only take into account one aspect of the safety improvement project at a time, which might result in biased ranking due to neglect of other aspects. As an improvement, the criteria of cost-effectiveness, benefit-cost ratio, and net benefits have been proposed to integrate more than one attributes of a project (i.e. cost, expected benefits, or number of accidents reduced) during the ranking procedure. In those ranking methods, the relationship between those attributes is assumed to be linear for integration, which is always not true due to the impacts of other contributory factors.

Despite their simplicity and widely use in ranking safety improvement projects individually, those aforementioned criteria may generate quite different or even contradictory ranking lists compared with each other. It may cause a dilemma for decision makers in selecting efficient projects to best improve overall safety performance. This is probably due to the fact that those criteria do not investigate all the potential contributory factors to evaluate the safety improvement project. Therefore, it is essential to develop a robust multi-criteria ranking model which has the potential to accommodate conflicting, multidimensional, various-unit contributory factors.

AHP, the Analytical Hierarchy Process, has been widely used for tackling multi-criteria decision making problems since developed by Saaty (1980). In recent years, there is an increasing use of the AHP in transportation engineering fields for prioritizing resources. For example, Larson et al. (2007) have applied the AHP to derive the most preferred project scope for video-logging and pavement condition data collection. Filippo et al. (2007) have presented an AHP model for ranking environmentally valid highway restoration by priority. Besides, this subject has attracted the attention of highway safety researchers. Wei et al. (2007) proved that AHP is an effective approach to measure the effect of road factors to driver’s safety perception, and similarly Zhang et al. (2002) have determined the factors affecting driving fatigue by AHP. Despite the successful application of AHP in transportation engineering and highway safety fields, its applications in prioritizing highway safety improvement projects are very limited. Moreover, the following critical issues deserved further investigation during the application of AHP, which are: 1) handling the very unbalanced scale of judgment, 2) proper construction of the pair-wise comparison matrix subject to the biased impacts from the subjective judgment, selection and preference of decision-makers. In view of the literature, the most commonly used approach for constructing the pair-wise comparison matrix in AHP is to rely on the knowledge of specialists, which may sometimes result in arbitrary and biased decisions. In estimating the weights for all criteria, eigenvalue method (Saaty, 1980; Golden et al, 1989), logarithmic goal programming method (Bryson, 1995; Yu, 2002), the geometric mean method (Sudhakar and Shrestha, 2003), and linear programming methods (Mikhailov, 2000; Chandran et al, 2005; Wang et al, 2008) have all been widely used. However, due to the vagueness and uncertainty on judgments of the decision-maker(s), the crisp pair wise comparison by the aforementioned methods in the conventional AHP still remains insufficient and imprecise to capture the right judgments of decision-maker(s). In order to model this kind of uncertainty in human preference, fuzzy sets could be integrated with the pair-wise comparison which enables a more accurate description of the decision making process.

Recent studies (Ayağ and Özdemir, 2006; Jin et al, 2004) have yielded promising results by integrating the fuzzy logic with the AHP to conduct pair-wise comparisons.

Along the line of previous research, this study aims to propose a fuzzy-AHP model embedded with a non-linear optimization formulation to maximize the consistency in pair-wise comparison and weight estimation for multiple criteria, and further employ the enhanced model in ranking highway safety improvement projects. The proposed approach has the potential to capture all the contributory factors during the safety project selection process, and offers an effective tool in practice for highway infrastructure and safety managers to assess and refine the ranking results. The paper will focus on the following critical research tasks:

- Design a hierarchical AHP structure with the goal of significantly improving highway safety performance, in which multiple criteria will be selected to account for the impacts of technical, economic, social and environmental related contributory factors;
- Incorporate the fuzzy logic with the AHP to: 1) normalize the scales of different indicators, 2) construct the matrix of pair-wise comparisons, 3) optimize the weight of each criterion with the objective of minimizing the consistency index of judgment matrix, and 4) synthesize the final priority score for each of the safety improvement projects; and
- Test the proposed AHP model with an illustrative case, and compare the results from the proposed model with the existing ranking methods aforementioned, to assist responsible personnel in best understanding and applying the proposed AHP model.

This paper is organized as follows. Next section will present a 4-level hierarchical AHP structure, and the description for each criterion will also be elaborated. Section 3 will propose an AHP model integrated with the fuzzy logic, which includes four processes: fuzzy scaling, pair-wise comparisons, weights determination, and synthesis of priority scores. A case study will be employed in Section 4 to illustrate the application of the proposed multi-criteria approach, and the output will be compared with the existing ranking methods as well. Concluding comments along with future extensions are reported in the last section.

THE HIERARCHICAL AHP STRUCTURE

Typically, the AHP allows decision makers to decompose a complex problem into three hierarchical levels: the goal, criteria, and alternatives. Different from the conventional AHP structure, this paper added a fuzzy scale level between the criteria level and the alternative level to facilitate the normalization of different indicator scales. Figure 1 outlines a graphical view of the designed hierarchical AHP structure including four levels:

- **Goal**: As the first level of the hierarchy, the goal initially established by decision makers is to prioritize safety improvement projects from a predefined set of alternatives;
- **Criteria**: Six criteria related to a broad range of safety improvement concerns, economic concerns, as well as social and environmental importance concerns constitute the second level of the hierarchy. Detailed descriptions for these criteria can be found in Table 1;
- **Fuzzy scale**: The fuzzy membership functions are employed to normalize the scales of different indicators so as to represent the satisfaction of each criterion with respect to each alternative;
- **Alternatives**: The last level of the hierarchy represents a series of predefined safety improvement projects to be ranked.

Insert Figure 1 here

Insert Table 1 here

THE PROPOSED FUZZY-AHP MODEL

In the previous section, this study has proposed a set of 6 critical criteria for highway safety improvement projects. In order to perform a comprehensive ranking, this section will detail the fuzzy-AHP model to integrate those criteria effectively into a single performance index. To facilitate the model presentation, all definitions and notations used hereafter are summarized in Table 2.

Insert Table 2 here

The proposed fuzzy-AHP model can be stated as the following four steps:

Fuzzy Scaling

Due to the fact that different indicators have various types of units, the fuzzy scaling proposed here functions to employ a set of fuzzy membership functions to normalize the scales of different indicators for comparison. The following terms "the-lower-the-better", "the-medium-the-better" and "the-higher-the-better" are used to normalize x_{ik} with their fuzzy sets modeled as follows:

For the-lower-the-better indicators:

$$\mu_{ik} = [x_{i(\max)} + x_{i(\min)} - x_{ik}] \big/ [x_{i(\max)} + x_{i(\min)}] \tag{1}$$

For the-medium-the-better indicators:

$$\mu_{ik} = \begin{cases} x_{ik} \big/ [x_{i(mid)} + x_{i(\min)}],\, x_{i(\min)} \le x_{ik} < x_{i(mid)} \\ [x_{i(\max)} + x_{i(mid)} - x_{ik}] \big/ [x_{i(\max)} + x_{i(mid)}],\, x_{i(mid)} \le x_{ik} \le x_{i(\max)} \end{cases} \tag{2}$$

For the-higher-the-better indicators:

$$\mu_{ik} = x_{ik} \big/ [x_{i(\max)} + x_{i(\min)}] \tag{3}$$

Pair-wise Comparisons

After normalization of all the indicators by fuzzy sets, it is noticeable that, if the deviation of one data set $\left\{\mu_{ik} \,\middle|\, k = 1\cdots m, \forall i\right\}$ is larger than that of the other data set $\left\{\mu_{jk} \,\middle|\, k = 1\cdots m,\, j \ne i\right\}$, criterion *i* must be more influential than criterion *j* when calculating the priority score of alternative *k*. It enables us to employ the indicator of "standard deviation" to make judgments on which of the two criteria is more important and in what proportion. The formulation of "standard deviation" s_i is given in Eq. (4).

$$s_i = \sqrt{\sum_{k=1}^{m} (\mu_{ik} - \bar{\mu}_i)^2 / (m-1)} \tag{4}$$

Then, a pair-wise comparison matrix $A = \left(a_{ij}\right)_{nxn}$ is created to measure the relative weights of each criterion, as shown in Eq. (5).

$$a_{ij} = \begin{cases} \dfrac{s_i - s_j}{s_{\max} - s_{\min}}(a_m - 1) + 1, & s(i) \ge s(j) \\[2ex] 1 / \left[\dfrac{s_j - s_i}{s_{\max} - s_{\min}}(a_m - 1) + 1 \right], & s(i) < s(j) \end{cases} \tag{5}$$

Here, $a_m = \min\left\{9, \mathrm{int}\left[s_{\max} / s_{\min} + 0.5\right]\right\}$ is a comparison scale for all of the criteria recommended by Jin et al (2004).

Weights Determination

Ideally, if a_{ij} can consistently or correctly reflect the importance of criterion *i* over criterion *j*, we will have $a_{ij} = w_i / w_j$. Then, the following three laws can be deducted: (a) $a_{ii} = w_i / w_i = 1$; (b) $a_{ij} = w_i / w_j = 1/a_{ji}$; and (c) $a_{ij} a_{jk} = (w_i / w_j) \cdot (w_j / w_k) = w_i / w_k = a_{ik}$. Therefore, one can obtain the weight for each criterion by solving the following linear equations:

$$\sum_{i=1}^{n} \sum_{j=1}^{n} \left| a_{ij} w_j - w_i \right| = 0 \qquad \text{(6-a)}$$

$$w_i > 0 \qquad i = 1, \cdots, n \qquad \text{(6-b)}$$

$$\sum_{i=1}^{n} w_i = 1 \qquad \text{(6-c)}$$

However, as mentioned in many previous studies (Saaty, 1980; Bryson, 1995; Yu, 2002; Sudhakar and Shrestha, 2003; Jin et al, 2004), it is practically impossible to obtain a completely consistent pair-wise comparison matrix that satisfies the aforementioned three laws. To contend with this problem, this study proposed the following non-linear optimization model to estimate the weights $\{ w_i | i = 1, \cdots, n \}$ from the inconsistent a_{ij} :

$$\min C.I.C.(n) = \sum_{i=1}^{n} \sum_{j=1}^{n} \left| y_{ij} - a_{ij} \right| / n^2 + \sum_{k=1}^{m} \sum_{l=1}^{m} \left| y_{ij} w_j - w_i \right| / n^2 \qquad (7)$$

s.t.

$$y_{ii} = 1 \qquad i = 1, \cdots, n \qquad (8)$$

$$1 / y_{ji} = y_{ij} \in [a_{ij} - da_{ij}, a_{ij} + da_{ij}] \qquad i = 1, \cdots, n; \; j = i+1, \cdots, n \qquad (9)$$

$$w_i > 0 \qquad i = 1, \cdots, n \qquad (10)$$

$$\sum_{i=1}^{n} w_i = 1 \qquad (11)$$

In the above formulation, $Y=\left(y_{ij}\right)_{nxn}$ is defined as the consistency judgment matrix, which is adjusted based on $A=\left(a_{ij}\right)_{nxn}$ during the minimizing process of the consistency index coefficient, denoted by $C.I.C.(n)$. It consists of the following two parts:

- minimization of $\sum_{i=1}^{n}\sum_{j=1}^{n}\left|y_{ij}-a_{ij}\right|/n^2$, functions to match the judgment matrix $Y=\left(y_{ij}\right)_{nxn}$ with the original comparison matrix $A=\left(a_{ij}\right)_{nxn}$ as closely as possible so that $Y=\left(y_{ij}\right)_{nxn}$ can reflect the original comparison information to the maximum extent; and
- minimization of $\sum_{k=1}^{m}\sum_{l=1}^{m}\left|y_{ij}w_j-w_i\right|/n^2$, functions to ensure that $Y=\left(y_{ij}\right)_{nxn}$ could be as consistent as possible to satisfy Eqns. (6a-6c).

Constraints (8) and (9) limit that all the elements in $A=\left(a_{ij}\right)_{nxn}$ should satisfy the first two laws aforementioned. (The third law is not included in the constraints since it is taken care of by the second part of the objective function). Besides, constraint (9) introduces a non-negative parameter *d* to measure the deviation degree between $Y=\left(y_{ij}\right)_{nxn}$ and $A=\left(a_{ij}\right)_{nxn}$. Constraint (10) ensures the non-negative weights, and constraint (11) limits the sum of all weights equal 1.

Solving the proposed optimization model will yield two types of information: 1) the judgment matrix $Y=\left(y_{ij}\right)_{nxn}$, and 2) the vector of weights $\left\{w_i\left|i=1,\cdots,n\right.\right\}$. However, the global optimal solutions are not assured for the proposed optimization model due to its non-convexity attribute. Thus, this study has employed the convergence criterion of $C.I.C(n)\le 0.1$ to ensure that the obtained judgment matrix $Y=\left(y_{ij}\right)_{nxn}$ is consistent, as recommended by Jin et al (2004), based on extensive numerical experiments.

Synthesis

After obtaining the weights for all criteria, the priority score of each alternative *k* will be synthesized by Eq. (12), stated as:

$$S_k = \sum_{i=1}^{n} \mu_{ik} \cdot w_i \qquad (12)$$

The synthesis results will indicate the overall preference or rank for an alternative with respect to the goal, which includes the following two types of information: 1) the most suitable project for a specific site; and 2) the priorities for implementation those suitable projects among multiple sites given the budget constraint.

CASE STUDY

To assist highway infrastructure and safety managers in best understanding and applying the proposed model, the presentation hereafter will include the following parts:

- Evaluate the applicability of the proposed AHP model with an illustrative case; and
- Compare its outputs with the existing ranking methods.

Test Case Preparation

In this study, *SafetyAnalyst* (A software Federal Highway Administration developed to address site-specific safety improvements) was employed to identify sites and potential improvement alternatives for case study (FHWA, 2002b, 2002c). A series of sites (intersections) are derived from *SafetyAnalyst*, and one or more projects are selected for possible implementation at each specific site. All of the input information required by the proposed AHP model is given in Table 3.

Insert Table 3 here

Application of the Proposed AHP Model

To illustrate the applicability of the proposed AHP model for ranking safety improvement projects, the aforementioned four steps were implemented as follows:

Step 1: Fuzzy scaling

Fuzzy membership functions aforementioned are used to normalize the scales of all the crisp values $\left\{ x_{ik} \middle| i = 1 \cdots 6 \right\}$ derived from Table 3. According to the description of each criterion in Table 1, "project construction costs" is considered as the-lower-the-better index, which is processed by Eq. (1). While the remained five indices, i.e. “number of total accidents reduced”, “number of fatal and injury accidents reduced”, “service life”, “AADT”, and “growth factor of AADT” are taken as the-higher-the-better ones, thus computed by Eq. (3). All of the fuzzified values, denoted as $\left\{\mu_{ik} \left| i = 1 \cdots 6\right.\right\}$, can be found in Table 4.

Insert Table 4 here

Step 2: Pair-wise comparisons

After normalization of all the indicators by fuzzy sets, the deviation indicators $\left\{s_i \left| i = 1, \cdots, n\right.\right\}$ were calculated by Eq. (4), as shown in the second last row of Table 4. Then, the matrix of pair-wise comparison matrix $A = \left(a_{ij}\right)_{nxn}$ was obtained though Eq. (5) (Here, we set $a_m = 9$ by $\min\left\{9, \operatorname{int}\left[s_{\max} / s_{\min} + 0.5\right]\right\}$):

$$A = \begin{bmatrix} 1.000 & 1.199 & 0.454 & 1.729 & 1.153 & 6.732 \\ 0.834 & 1.000 & 0.417 & 1.530 & 0.956 & 6.533 \\ 2.202 & 2.401 & 1.000 & 2.931 & 2.355 & 7.934 \\ 0.578 & 0.654 & 0.341 & 1.000 & 0.635 & 6.003 \\ 0.867 & 1.046 & 0.425 & 1.576 & 1.000 & 6.579 \\ 0.149 & 0.153 & 0.126 & 0.167 & 0.152 & 1.0000 \end{bmatrix}$$

Step 3: Weights Determination

The proposed non-linear programming model was implemented in the LINGO Solver with systematic variation of parameter *d*, and the judgment matrix $Y = \left(y_{ij}\right)_{nxn}$ reached consistency as shown below with $C.I.C(n) = 0.051$ and $d = 0.04$:

$$Y = \begin{bmatrix} 1.000 & 1.247 & 0.472 & 1.798 & 1.199 & 7.001 \\ 0.802 & 1.000 & 0.433 & 1.591 & 0.994 & 6.794 \\ 2.117 & 2.308 & 1.000 & 3.048 & 2.449 & 8.251 \\ 0.556 & 0.628 & 0.328 & 1.000 & 0.660 & 6.243 \\ 0.834 & 1.006 & 0.408 & 1.515 & 1.000 & 6.842 \\ 0.143 & 0.147 & 0.121 & 0.160 & 0.146 & 1.000 \end{bmatrix}$$

The weights $\left\{w_i \left| i = 1, \cdots, n\right.\right\}$ for all criteria were also obtained, as shown in the last row of Table 4.

Step 4: Synthesis

Finally, the priority scores are synthesized in the last column of Table 4, which can provide the following two types of decision supports for safety project managers:

- For a specific site with more than one candidate projects, the priority score can assist managers in identifying the most suitable project, as highlighted in Table 5 with shaded cells (e.g., P1 is selected as the suitable project at Site 3); and
- Given the project budget constraint, the above selected projects can be further ranked among multiple sites for making the final implementation plan. For example, Table 6 recommends three implementation plans taking into account different budgets with $30,000, $60,000, and $90,000, respectively.

Insert Table 5 here

Insert Table 6 here

Comparison with Existing Ranking Criteria

In this section, the ranking results obtained from the proposed fuzzy-AHP model are compared with those from existing ranking methods (see Table 7), including:

- Fatal and Injury Accidents Reduced (FI)
- Total Accidents Reduced (TOT)
- Construction Cost (CC)
- Safety Benefit (SB)
- Cost Effectiveness (CE)
- Cost Effectiveness Equivalent-Property-Damage-Only (CE_EPDO)
- Benefit cost ratio (BC _ratio)
- Net benefit (NB)

Insert Table 7 here

A glance at Table 7 reveals that there exists inconsistency among the ranking results obtained by the different methods. To further investigate this issue, Spearman’s rank correlation coefficient (Myers and Well, 2003) is employed in this section to analyze the correlation between various ranking results, since it has been widely adopted by researchers in transportation field as a measure of association between the rankings of two variables on

N individuals (Khattak et al, 2004; Cafiso et al, 2007). The magnitude of the correlation coefficient indicates the strength of the variations with respect to one another, with a value of 1.0 indicating a perfect correlation.

Let $\{x_i \,|\, i = 1 \cdots n\}$ and $\{y_i \,|\, i = 1 \cdots n\}$ be the vectors of ranks for sample set 1 and 2, respectively. The mathematical formulation for Spearman's rank correlation coefficient is stated as:

$$r_s = \frac{1}{n-1} \sum_{i=1}^{n} \left(\frac{X_i - \overline{X}}{s_X} \right) \cdot \left(\frac{Y_i - \overline{Y}}{s_Y} \right) \tag{13}$$

$$X_i = \sum_{k<i} x_k + \frac{(x_i + 1)}{2}, \qquad i = 1 \cdots n \tag{14}$$

$$Y_j = \sum_{k<j} y_k + \frac{(y_j + 1)}{2}, \qquad j = 1 \cdots n \tag{15}$$

Where, r_s is the Spearman's correlation coefficient; ($\overline{X}$, $\overline{Y}$) and (s_X , s_Y) represent mean values and standard deviations for $\{X_i\}$ and $\{Y_i\}$, respectively. With the ranks from AHP as the basis, the Spearman's correlation coefficients among different ranking methods as well as the corresponding confidence levels are listed in Table 8.

Insert Table 8 here

As indicated in Tables 7 and 8, one can reach the following findings:

- Consistent results can be obtained if FI, SB or NB is employed as the ranking method, as evidenced by the high correlation coefficients between them (highlighted in Table 8 at a 99% confidence level). Similar consistency also exists between the methods of CE_EPDO and BC_Ratio. However, big discrepancy exist for other ranking methods, such as TOT, CC and CE;
- The ranking list from AHP seems not consistent with any of other existing ranking methods (See the first column in Table 8). However, for some specified sites, the ranking result by AHP would be relatively consistent with that from other ranking methods (e.g., P1 & P2 at Site 4 and P2 at Site 3 in Table 7), or appear as a compromise between the low and high ranks from other methods (e.g., P3 at Site 8 in Table 7). This is probably due to the fact that the proposed AHP approach has the capability of capturing multiple criteria employed by other methods and balancing their conflicts; and

Note that, with AHP, Site 1 is assigned to a higher rank (highlighted in Table 7) compared with most of other methods, due to its highest AADT (highlighted in Table 4), while Site 2 get a lower rank because of its lowest AADT (see highlighted cells in Tables 4 and 7). The reason for such discrepancy could be that AADT is employed as one evaluation criterion of AHP and takes a fair weight to reflect social and environmental importance, which has not been considered by any other existing methods yet.

CONCLUSIONS

This paper presents a robust multi-criteria approach for prioritizing safety improvement projects, to account for the impacts of technical, economic, social and environmental related contributory factors. Grounded on an AHP-based framework integrated with the fuzzy logic, the proposed model offers the advantage of effectively preventing the arbitrariness in determination of the weights for multiple ranking criteria, and easily synthesizing the final score of each candidate project for selection. Moreover, the clarity of model inputs and its ease of interpreting of the results with respect to different selection criteria offer the best potential for its use in highway infrastructure and safety management. The model was successfully applied to an illustrative case in obtaining the priority score for each candidate project. Comparative studies between the ranks by the proposed AHP model and existing ranking methods are also performed through statistical correlation tests, which provide vital information for responsible personnel in best selecting the ranking method for safety improvement projects.

Note that this paper has presented preliminary evaluation and comparative analysis results for the proposed model through a case study. More extensive tests or evaluations will be essential to assess the effectiveness of the proposed model by using larger data samples and accounting for more complicated impact indicators.

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LISTS OF TABLES AND FIGURES

Table 1 Detailed description for each criterion

No.	Criteria	Descriptions
1	Total accidents reduced	1) Number of total accidents reduced during the service life due to implementing the proposed improvement project. 2) The higher this indicator, the higher safety performance improvements.
2	Fatal and injury accidents reduced	1) Number of fatal and injury accidents reduced during the service life due to implementing the proposed improvement project. 2) The higher this indicator, the higher severe-accidents-related safety performance improvements.
3	Project construction costs	1) Construction monetary value of the proposed improvement project. 2) The lower this indicator, the more economical the proposed improvement project.
4	Project service life	1) Service life of the proposed improvement project. 2) The higher this indicator, the longer service provided by the proposed improvement project.
5	Annual Average Daily Traffic (AADT) of implementation year	1) Annual Average Daily Traffic involved in highway entities (such as section, intersection, and ramp) in implementation year. 2) The higher this indicator, the higher social and environmental importance due to implementing the proposed improvement project (i.e. this indicator could measure how many traffic can benefit and how many delay time can be saved within the highway system).
6	AADT Growth factor	1) Growth factor of AADT to reflect the change trend along the service life of the proposed improvement project. 2) The higher this indicator, the higher social and environmental importance for implementing the proposed improvement project.

Table 2 Notation of key parameters used in the proposed model

i	Index corresponding to criterion ($i = 1 \cdots n$)
k	Index corresponding to alternative ($k = 1 \cdots m$)
x_{ik}	Indicator representing the alternative *k* being evaluated by criterion *i*
μ_{ik}	Fuzzy membership value corresponding to indicator x_{ik}
$\overline{\mu}_i$	Average fuzzy membership value for criterion *i*
$x_{i(\min)}$	The minimal crisp value for criterion *i*
$x_{i(mid)}$	The medium crisp value for criterion *i*
$x_{i(\max)}$	The maximal crisp value for criterion *i*
s_i	Standard deviation of indicator values corresponding to criterion *i*
$s_{\min}$	$\min\left\{s_i \middle| i = 1, \cdots, n\right\}$
$s_{\max}$	$\max\left\{s_i \middle| i = 1, \cdots, n\right\}$
$A = \left(a_{ij}\right)_{nxn}$	Pair-wise comparison matrix
a_m	Comparison scale for the pair-wise comparison matrix
w_i	Weight for criterion *i*
$Y = \left(y_{ij}\right)_{nxn}$	Consistency judgment matrix
C.I.C.(n)	Consistency index coefficient
S_k	The synthesized ranking score of alternative *k*

Table 3 Input information for the case study

Site ID	AADT of Implementation Year (vpd)		AADT Growth Factor	Candidate Projects	# Total Accidents Reduced	# FI Accidents Reduced	Construction Costs	Service Life
	Major Rd	Minor Rd					($)	(yrs)
1	55,102	31,012	1.031	P 1	63.75	21.5	10000	10
2	5,900	3,003	0.814	P 1	171.65	144.65	80000	20
3	12,293	8,575	1.1005	P 1	17.82	14.79	5000	10
				P 2	14.69	16.93	60000	20
4	9,036	6,867	0.853	P 1	22.46	9.12	10000	10
				P 2	32.62	12.18	30000	20
5	49,682	27,852	1.0937	P 1	50.64	47.96	5000	5
				P 2	25.32	35.97	30000	20
6	25,085	8,634	0.9587	P 1	33.94	15.09	20000	15
				P 2	30.36	16.68	5000	5
7	41,899	10,814	0.9963	P 1	199.7	102.75	80000	20
				P 2	44.73	23.87	30000	20
8	44,528	10,442	0.9808	P 1	54.69	30.74	10000	10
				P 2	48.61	44.71	30000	20
				P 3	106.34	103.38	60000	20

Note: # Total Accidents Reduced – Number of Total Accidents Reduced; # FI Accidents Reduced – Number of Fatal and Injury Accidents Reduced; P i – Project i

Table 4 Priority scores obtained by the proposed AHP model

Site ID	Projects	# TOT accidents reduced		# FI accidents reduced		Construction costs		Service life		AADT		AADT growth factor		Priority score
		x_{1k}	μ_{1k}	x_{2k}	μ_{2k}	x_{3k}	μ_{3k}	x_{4k}	μ_{4k}	x_{5k}	μ_{5k}	x_{6k}	μ_{6k}	
1	P 1	63.75	0.30	21.50	0.14	10000	0.88	10	0.40	86114	0.91	1.031	0.54	0.592
2	P 1	171.65	0.80	144.65	0.94	80000	0.06	20	0.80	8903	0.09	0.814	0.43	0.439
3	P 1	17.82	0.08	14.79	0.10	5000	0.94	10	0.40	20868	0.22	1.101	0.57	0.464
	P 2	14.69	0.07	16.93	0.11	60000	0.29	20	0.80	20868	0.22	1.101	0.57	0.276
4	P 1	22.46	0.10	9.12	0.06	10000	0.88	10	0.40	15903	0.17	0.853	0.45	0.428
	P 2	32.62	0.15	12.18	0.08	30000	0.65	20	0.80	15903	0.17	0.853	0.45	0.399
5	P 1	50.64	0.24	47.96	0.31	5000	0.94	5	0.20	77574	0.82	1.094	0.57	0.600
	P 2	25.32	0.12	35.97	0.23	30000	0.65	20	0.80	77574	0.82	1.094	0.57	0.528
6	P 1	33.94	0.16	15.09	0.10	20000	0.76	15	0.60	33719	0.35	0.959	0.50	0.455
	P 2	30.36	0.14	16.68	0.11	5000	0.94	5	0.20	33719	0.35	0.959	0.50	0.473
7	P 1	199.70	0.93	102.75	0.67	80000	0.06	20	0.80	52713	0.55	0.996	0.52	0.483
	P 2	44.73	0.21	23.87	0.16	30000	0.65	20	0.80	52713	0.55	0.996	0.52	0.485
8	P 1	54.69	0.26	30.74	0.20	10000	0.88	10	0.40	54970	0.58	0.981	0.51	0.545
	P 2	48.61	0.23	44.71	0.29	30000	0.65	20	0.80	54970	0.58	0.981	0.51	0.517
	P 3	106.34	0.50	103.38	0.67	60000	0.29	20	0.80	54970	0.58	0.981	0.51	0.504
	s_i	0.260		0.267		0.314		0.267		0.261		0.048		
	w_i	0.157		0.189		0.361		0.189		0.158		0.023		

Note: # Total Accidents Reduced – Number of Total Accidents Reduced; # FI Accidents Reduced – Number of Fatal and Injury Accidents Reduced; P i – Project i;

Table 5 The most suitable project selection at each site

Site ID	Candidate Projects	Priority Score	Rank
1	P 1	0.592	1
2	P 1	0.439	1
3	P 1	0.464	1
	P 2	0.276	2
4	P 1	0.428	1
	P 2	0.399	2
5	P 1	0.600	1
	P 2	0.528	2
6	P 1	0.455	2
	P 2	0.473	1
7	P 1	0.483	2
	P 2	0.485	1
8	P 1	0.545	1
	P 2	0.517	3
	P 3	0.504	2

Note: (1) P i – Project i

Table 6 Implementation plans for the case study within different budgets

Site ID	Preferred Projects	Cost	Priority Score	Rank
1	P 1	10000	0.592	2
2	P 1	80000	0.439	7
3	P 1	5000	0.464	6
4	P 1	10000	0.428	8
5	P 1	5000	0.600	1
6	P 2	5000	0.473	5
7	P 2	30000	0.485	4
8	P 1	10000	0.545	3
Implementation Plans	(1) Budget $30,000: P1 at Site 5, P1 at Site 1, P 1 at Site 8. (2) Budget $60,000: P1 at Site 5, P1 at Site 1, P 1 at Site 8, P 2 at Site 7. (3) Budget $90,000: P1 at Site 5, P1 at Site 1, P 1 at Site 8, P 2 at Site 7, P2 at Site 6; P1 at Site 3.			

Note: P i – Project i

Table 7 Comparisons between Different Ranking Methods

Site ID	Projects	AHP	FI	TOT	CC	SB	CE	CE_ EPDO	BC_ Ratio	NB
1	P 1	2	9	4	4	9	5	7	7	9
2	P 1	12	1	2	14	1	1	3	4	1
3	P 1	10	13	14	1	13	6	4	3	13
	P 2	15	10	15	12	11	15	15	15	11
4	P 1	13	15	13	4	15	12	13	13	15
	P 2	14	14	10	8	14	13	14	14	14
5	P 1	1	4	6	1	5	2	1	1	5
	P 2	4	6	12	8	4	14	9	10	4
6	P 1	11	12	9	7	12	9	12	12	12
	P 2	9	11	11	1	10	7	10	9	10
7	P 1	8	3	1	14	2	4	8	8	2
	P 2	7	8	8	8	8	11	11	11	8
8	P 1	3	7	5	4	7	3	2	2	7
	P 2	5	5	7	8	6	10	6	6	6
	P 3	6	2	3	12	3	8	5	5	3

Note: P i – Project i

Table 8 Spearman's Correlation Coefficients, Based on AHP

Ranking Criterion	AHP	FI	TOT	CC	SB	CE	CE_ EPDO	BC_ Ratio
FI	0.493*							
TOT	0.464*	0.761						
CC	0.307	0.522*	0.382					
SB	0.493*	0.989**	0.779**	0.518*				
CE	0.575*	0.386	0.671**	0.316	0.400			
CE_ EPDO	0.664**	0.632**	0.568*	0.195	0.621*	0.764**		
BC_ Ratio	0.654*	0.571*	0.529*	0.267	0.564*	0.786**	0.993**	
NB	0.493*	0.989**	0.779**	0.518*	1.000**	0.400	0.621**	0.564*

NOTE: (1) Cells in shade represent value of correlation coefficient of 0.800 and above.
(2) *: Correlation is significant at the 0.05 level (1-tailed).
(3) **: Correlation is significant at the 0.01 level (1-tailed).

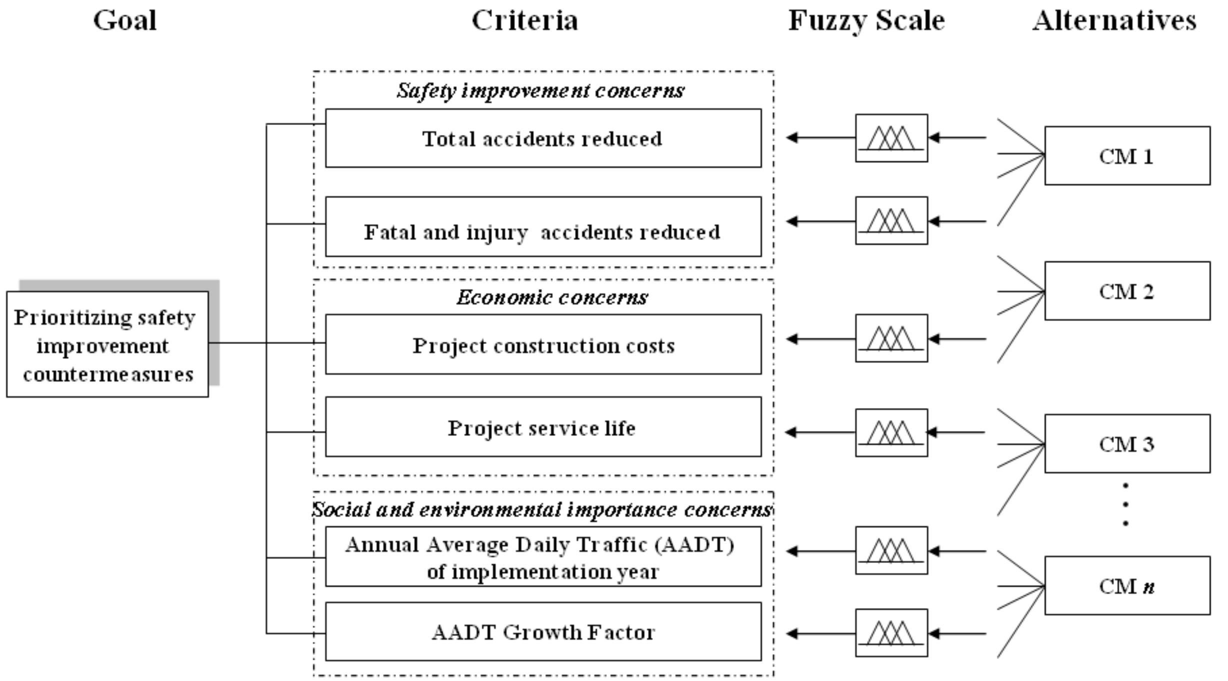

Figure 1 The proposed hierarchical AHP structure