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Urban Network Risk Assessment Based on Data Fusion Concept using Fuzzy-AHP, TOPSIS and VIKOR in GIS Environment

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Risk assessment of urban network using traffic indicators determines vulnerable links with high danger of traffic incidents. Thus, determination of an appropriate methodology remains a big challenge to achieve this objective. Here, we propose a methodology based on data fusion using fuzzy-AHP, TOPSIS and VIKOR to achieve this aim. The proposed methodology tries to address two main points: first, use of fuzzy AHP for weight estimation of risk indicator to overcome the problem of some famous weighting method such as AHP that uses a limited scale of Saaty. Since a risk assessment decision maker prefer to consider a criterion with in a range, instead of using an exact number, as Saaty's scale, a fuzzy triangular number is proposed in our methodology, and second use of TOPSIS is proposed for risk score estimation respecting estimated weight, because all the input risk data have numerical values. Furthermore, risk evaluation is done using distance from an ideal solution. The output is evaluated in 2 different ways: (1) using sensitivity analysis and (2) *checking the accuracy in comparison with similar numerical results from VIKOR. The proposed methodology is evaluated using a pilot urban link in the state of California in USA.*

Keywords: *Urban network, Risk analysis, TOPSIS, Fuzzy-AHP, VIKOR.*

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1. Introduction

Risk assessment of urban links using traffic indicators helps to determine vulnerable links being in high danger of traffic incidents. The big challenge to achieve this objective is determination of an appropriate methodology. Here, we give a short review of available works on this topic. Several methodologies were used by experts to assess urban network risk. Artificial neural network was considered in [14] and [18] for risk assessment of urban networks. An advantage of this method in comparison with common methods is using historical dataset provided by previous studies or projects to assess risk. Although the proposed methodology is a famous method for risk assessment, the need of having a complete historical data set is the main challenge in using the proposed methodology. Consequently, Multi-Criteria-Decision making (MCDM) concept was proposed by a number of experts to tackle the mentioned problem. Many different MCDM methods were used by experts to assess risk. AHP was used in [19] to assess risk of road respecting accident. The main step in the mentioned methodology is using pairwise comparison of criteria based on Saaty's scales to estimate the overall score for risk assessment. Ordered weighted averaging (OWA) is another MCDM method that was used in [6] for risk assessment. The big advantage of the proposed methodology in comparison with the AHP method is assessing risk using risk accepting concept. Using the concept, a comparison was made using subjective rank of decision maker for assessing

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risk. The authors of [20] proposed using analytical network process (ANP) for risk assessment. These experts believe the dependency concept between alternative and criteria cannot be evaluated in the methods such as AHP and OWA. Although the MCDM concept is a common method for risk assessment, the main problem of the proposed methodology is modeling the uncertainty concept, because of data incompleteness or existence of uncertainty in risk assessment model. Consequently, fuzzy theory was used by some experts to improve efficiency of the risk assessment model. For example, Delphi-AHP-fuzzy method was used in [22], fuzzy continuous-interval-argument ordered weighted average (COWA) was used in [8] and fuzzy analytical hierarchical process was used in [4] to assess urban network risk. As pointed out, AHP is a popular method for risk score assessment, when most input data for risk assessment are qualitative, but in many studies such as our work here, where most risk factors are numeric, using the mentioned method would decrease the accuracy of risk score estimation. Therefore, fuzzy-TOPSIS method was proposed by several experts such as authors of [3] for risk assessment. The main advantage of this method is the calculation of ideal solution for risk score estimation that would be obtained using the worst and best values of risk indicators from among all risk alternatives. Considering the available work, a combination of fuzzy-AHP and TOPSIS was proposed because using fuzzy-AHP tries to overcome the problem of weight estimation in methods such as AHP and TOPSIS was proposed because all input criteria were numeric. Furthermore, for validation of the proposed methodology, these criteria were considered: first, sensitivity analysis evaluates robustness of the output to consider fuzzy numbers and (2) assessment of output using similar numerical method such as VIKOR to evaluate accuracy. Here, we are to propose a new methodology using fuzzy-AHP, TOPSIS and VIKOR to determine vulnerable urban links being in high danger of traffic incidents.

2. Methodology

The main step for urban network risk assessment is determination of appropriate methodology and criteria. Fuzzy based MCDM is a common method being used by many experts to achieve this objective. In this section, integration of fuzzy-AHP and TOPSIS would be used to achieve this objective. Our proposed methodology consists following steps:

1. Identification of effective criteria and normalizing them.
2. Criteria weight estimation using nonlinear fuzzy-AHP based on Mikhailov’s theory.
3. Employing TOPSIS to assess urban links risk respecting the criteria weight.
4. Classification of urban link risks based on the overall scores of TOPSIS to determine vulnerable links.
5. Evaluation of output in 2 different ways: (1) evaluation based on sensitivity analysis and (2) evaluation of output’s accuracy in comparison with results obtained by similar numerical methods such as VIKOR. The general steps of our work are shown in Fig.1.

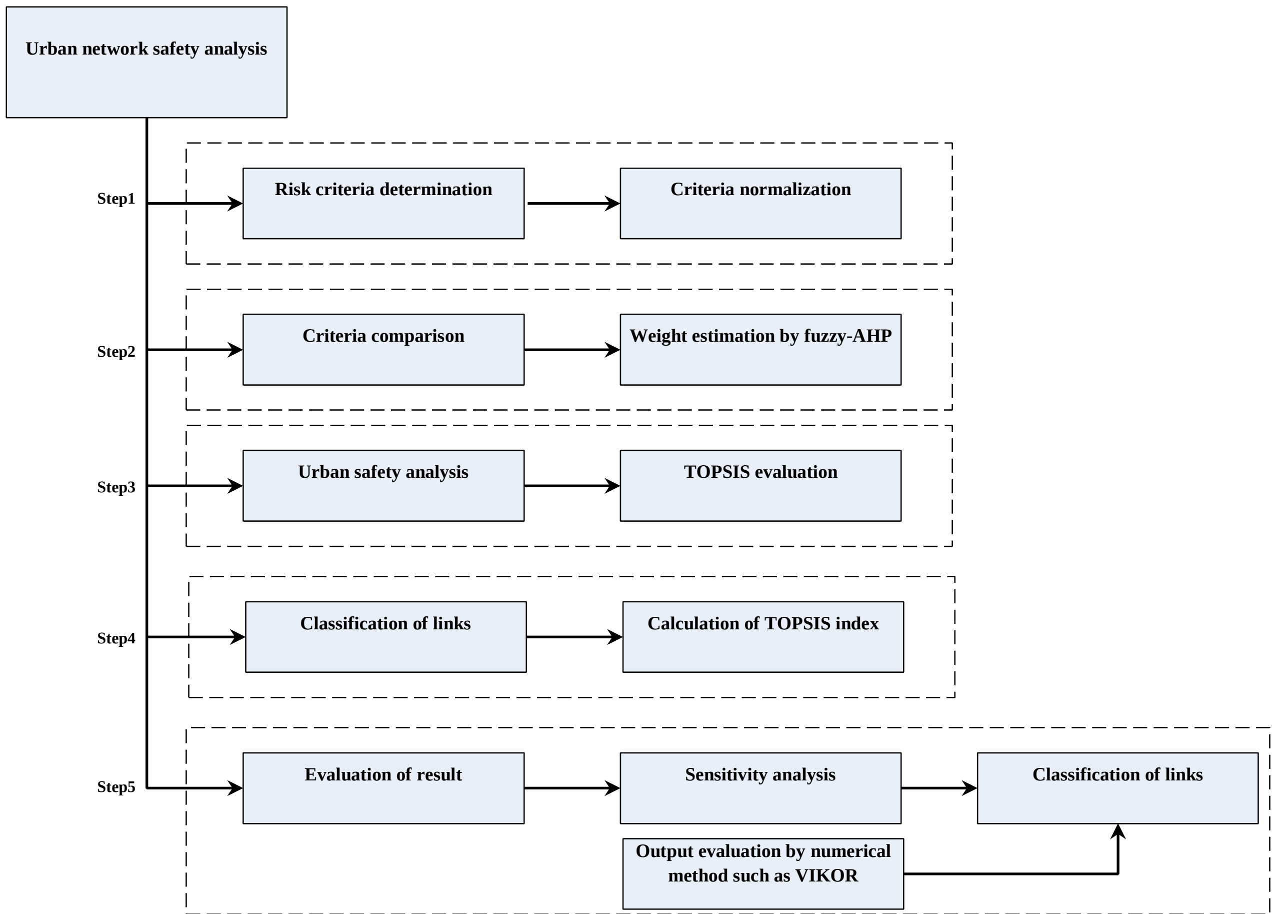


Figure 1. A flowchart of the proposed methodology

2.1. Main Criteria to Evaluate Urban Network Risk

The main step is the determination of effective criteria. Some criteria such as annual average data traffic (AADT), Safety (access to a safety place for driver's or passenger's rest), distance from critical places (such as hospital that need more traffic controlling), and average slope are determined by traffic expert's (see Table1).

Table 1. Determined criteria for assessment of risk

Criterion	Calculated index	Detail
Annual average daily traffic	AADT	Total volume of the traffic on highways or roads for in a year divided by 365 days
Safety	Safety	Estimated by access to a safe place for driver's rest
Distance from critical place	Distance from POI	Distance from hospital
Slope	Average slope	The ratio of height difference to link's length

2.1.1. Safety

The safety criterion would be obtained using the position of safe place for rest or staying of passengers or driver. Lack of the criterion would increase the rate of accidents and lead to accident severity. Urban links with more value for the AADT index being far from safety are in high danger of disaster (such as an accident). For estimation of the safety criterion, proximity to urban facilities such as road side rest area is estimated using proximity analysis in GIS.

2.1.2. Annual Average Daily Traffic Index

To evaluate traffic, annual traffic index (AADT) is proposed by traffic experts to be used as an important risk criterion. To estimate this index, the volume of vehicles must be estimated during each period and be divided by the number of days in the considered period see (1) of [12]. In the following equation, the axle parameter converts the counted number of axles to the number of vehicles, ADT is average daily traffic, and SF is seasonal showing the seasonal fluctuation pattern:

$$AADT = ADT * SF * Axle. \tag{1}$$

2.1.3. Distance From POI

The final criterion for evaluation of urban network risk is the distance from critical areas such as hospitals which need more traffic controls. As a result, urban links near critical area must be controlled using appropriate traffic strategies. To obtain the distance of each urban link from hospital, parcel is estimated and to estimate the criterion spatial function in GIS such as near analysis is used.

2.2. Application of Fuzzy-AHP and TOPSIS

In risk assessment, an appropriate methodology must be employed to aggregate the value of inputs corresponding to their weights. Here fuzzy-AHP and TOPSIS are employed. An integration of AHP and TOPSIS is used by several researches; for more information, see [1], [2], [5], [7], [13] [15] and [17]. In these works, fuzzy-AHP or AHP is used to evaluate weights of criteria, and then TOPSIS method is used to assess risk scores of the alternatives using the AHP or fuzzy-AHP weights.

In using the method, the value of input criterion for each urban link is normalized using (2) below. In this formula, x_{ji} is the value of *i*th alternative in *j*th criterion. *i* refers to *i*th and *j* refers to *j*th column of the comparison matrix, *n* is size of comparison matrix. Using this formula, all elements of the decision matrix containing the criteria values are normalized:

$$Normalizing\ value = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}}, i = 1, \dots, m, j = 1, \dots, n. \tag{2}$$

Then fuzzy-AHP method is employed to estimate the weights of the criteria. Estimated weights are used by the TOPSIS method to assess risk of each link. To do this step, closeness coefficient is estimated for each urban link. A high value of closeness index refers to increase of the chance of urban link to be classified as a vulnerable link. Finally, urban links are classified in four different ranks: high risk, middle risk, low risk and lowest risk. Urban links belong to the first rank with high value of closeness coefficient interpreted as vulnerable link being in high danger of traffic incidents. Next, we discuss MCDM method such as Fuzzy-AHP, TOPSIS and VIKOR for evaluation of the output.

2.2.1. Fuzzy-AHP

Although AHP is a famous method for weighting, but the problem with this method is its comparison of criteria using the limited scales of Saaty [16] that leads to decrease the accuracy in the weight estimation process. To overcome this problem, fuzzy-AHP was proposed by some experts such as Mikhailov [9]. In this method, fuzzy triangular numbers are used instead of Saaty's scale for estimation of the criteria weight. First, all elements of the pairwise comparison matrix are expressed using triangular fuzzy numbers (see Table 2) [21].

Table 2. Standard of Fuzzy-AHP

Importance level	**Concept**	$\tilde{a}_{ij}$	$\tilde{a}_{ji}$
1	Equal	(1,1,1)	(1,1,1)
2	Slightly preferred	(1/2,1,3/2)	(2/3,1,2)
3	Important	(1,3/2,2)	(1/2,2/3,1)
4	Relatively important	(3/2,2,5/2)	(2/5,1/2,2/3)
5	Very important	(2,5/2,3)	(1/3,2/5,1/2)
6	Strongly preferred	(5/2,3,7/2)	(2/7,1/3,2/5)

In this method to estimate weights of criteria, nonlinear programming is used (see [9] and [21]). The elements of the comparison matrix ($\tilde{a}_{ij}$) are given by triangular fuzzy number $\left(l_{ij}, \mu_{ij}, u_{ij}\right)$. To estimate the criteria weights, the nonlinear programming problem (3) below is solved using some software such as Lingo. To evaluate accuracy of the process, the inconsistency index (λ) is estimated, (positive value of inconsistency index means that estimation is accepted):

$$
\begin{aligned}
&\text{maximize}\,\lambda\\
&s.t.\\
&\quad \left(\mu_{ij} - l_{ij}\right)\lambda w_j - w_i + l_{ij} w_j \leq 0,\\
&\quad \left(u_{ij} - m_{ij}\right)\lambda w_j + w_i - u_{ij} w_j \leq 0,\\
&\quad Where\ i = 1,2,\dots,n-1, j = 2,3,\dots n, j > i,\\
&\quad \sum_{k=1}^{n} w_k = 1, \qquad w_k > 0, k = 1,2,\dots,n.
\end{aligned}
\tag{3}
$$

To increase accuracy in the weight estimation process, weight estimation is repeated using different $\alpha -$ cuts. An $\alpha -$ cut is defined as follows. For $\tilde{a}_{ij}$, a fuzzy number expressed as a triangular fuzzy number $\left(l_{ij}, \mu_{ij}, u_{ij}\right)$, $\alpha -$ cut is defined as:

$$\tilde{A}_a = [l^{\alpha}, u^{\alpha}] = [l + \alpha(\mu - l), u - \alpha(u - \mu)]. \tag{4}$$

Thus, the weight estimation is repeated using different α values corresponding the $\alpha -$ cuts as follows:

$$\begin{aligned}
&\text{maximize } \lambda \\
&s.t. \\
&(\mu_{ij} - l_{ij}^{\alpha})\lambda w_j - w_i + l_{ij}^{\alpha} w_j \le 0, \\
&(u_{ij}^{\alpha} - m_{ij})\lambda w_j + w_i - u_{ij}^{\alpha} w_j \le 0, \\
&\text{Where } i = 1,2,\dots,n-1; j = 2,3,\dots n, j > i, \\
&\sum_{k=1}^{m} w_k = 1, \qquad w_k > 0, k = 1,2,\dots,n.
\end{aligned} \tag{5}$$

2.2.2. TOPSIS Method

The main purpose of TOPSIS method is to estimation closeness of alternative to ideal solutions in the decision making process. To evaluate the chance of an alternative, the closeness coefficient will be estimated during the process; the higher the value of closeness coefficient, the more the chance of the alternative. To use this method, the following steps are employed ([5] and [10]).

Step 1. Determination of risk criteria respecting the goal.
Step 2. Entering the criteria weights that are estimated using fuzzy-AHP.
Step 3. Determination of worst and best criteria for determination of ideal solution(v_j^+, v_j^-), $j=1,\dots,n$.
Step 4. Calculation of separation of each alternative from ideal solution(d_i^+, d_i^-):

$$d_i^+ = \sqrt{\sum_{j=1}^{n}(v_{ij} - v_j^+)^2}, \qquad i = 1,2,\dots,m, \tag{6}$$

$$d_i^- = \sqrt{\sum_{j=1}^{n}(v_{ij} - v_j^-)^2}, \qquad i = 1,2,\dots,m. \tag{7}$$

Step 5. Calculations of closeness coefficient index (C_i):

$$C_i = \frac{d_i^-}{d_i^+ + d_i^-}, \qquad i = 1,\dots,m. \tag{8}$$

2.2.3. VIKOR

Similar to TOPSIS, VIKOR is designed to determine closeness of alternatives to ideal solutions. To do this, the following are employed [11]:

Step 1: Construction of a decision matrix with each column the values of the alternative criteria.
Step 2: Normalizing the decision matrix.
Step 3: Calculation of the worst and best values of all criteria:

$$f_i^+ = max_j\, f_{ij}, \tag{9}$$
$$f_i^- = max_j\, f_{ij}. \tag{10}$$

Step 4: Calculation of S and R parameters:

$$S_j = \sum_{i=1}^{m} \left[\frac{w_i (f_i^+ - f_{ij})}{(f_i^+ - f_i^-)} \right], \quad j = 1, \dots, J, \tag{11}$$

$$R_j = \max \left[\frac{w_i (f_i^+ - f_{ij})}{(f_i^+ - f_i^-)} \right], \quad j = 1, \dots, J. \tag{12}$$

Step 5: Calculation of the advantage function $\boldsymbol{Q}$:

$$Q_j = \left(\frac{v * (S_j - S^*)}{(S^- - S^*)} \right) + \left(\frac{(1 - v) * (R_j - R^*)}{(R^- - R^*)} \right) \tag{13}$$

$$\begin{cases} S^* = \min S_j \,, S^- = \max S_j \,, \\ R^* = \min R_j \,, R^- = \max R_j . \end{cases} \tag{14}$$

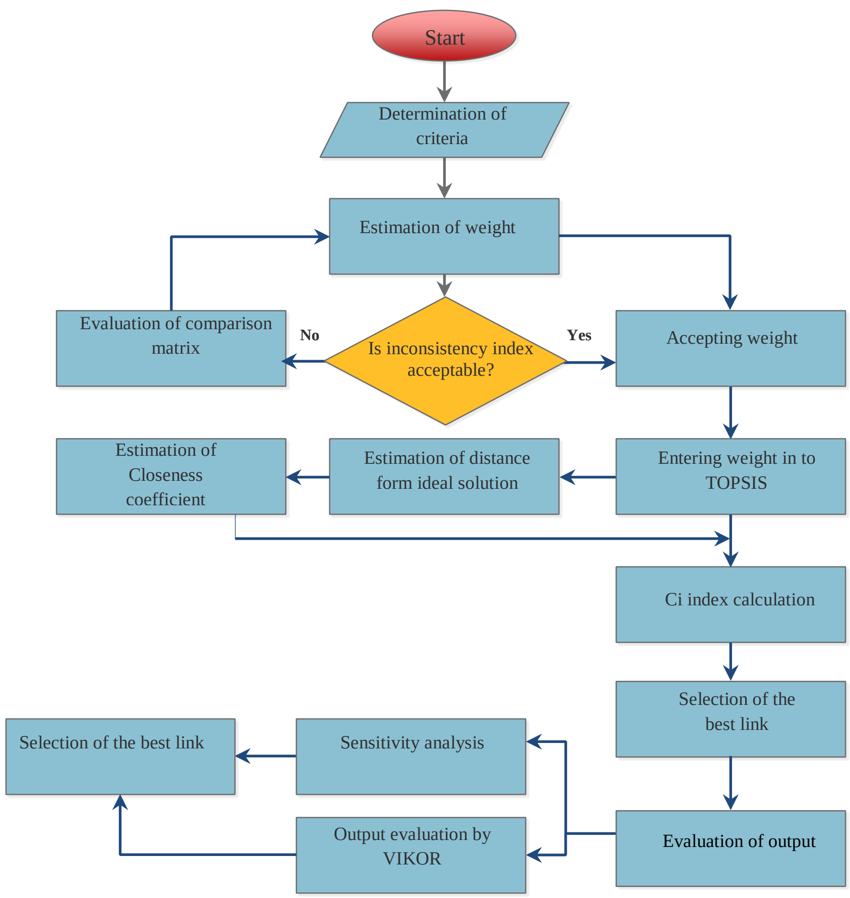


Figure 2. The proposed steps

The less the value of Q_j , the more the change for selection of alternative as the best alternative. The parameter v (maximum group utility) has a value between 0 to 1 and thus alternative evaluation would be made using different value of v.

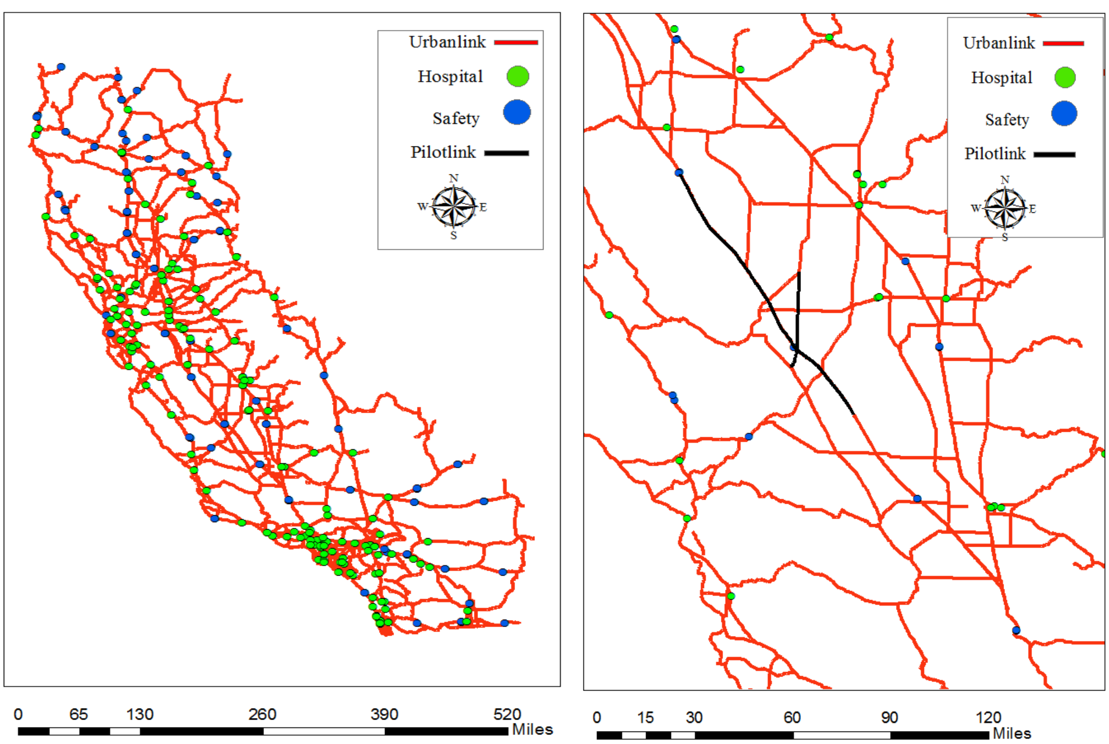
The alternative a', which is the best ranked using Q estimation would be selected as the best alternative if following condition is satisfied ,Where $a"$ is alternative in second position using Q estimation and J is number of criteria.

$$Q(a") - Q(a') \geq \frac{1}{J-1} \tag{15}$$

Fig.2 shows general steps integrating fuzzy-AHP and TOPSIS.

3. Case Study

The proposed methodology was evaluated using the urban network in a part of California. Studied area is located in the latitude range of $(114°8'W,\ 124°26'W)$ and longitude range of$(32°32'N,\ 42°00'N)$. All estimation was done using the Lambert projection system. Nad-1938 was defined as a datum for the studied area. The Meta data information is shown on Fig.3. For information about metadata, see Table 3. For analyzing the project, the position of urban links and POI parcels such as rest area and hospital were obtained from the base map acquired from the USA transportation department. The positions of the places were stored as a shape file in the arc GIS software package. The shape file contains all the required data, such as slope and traffic. For the analysis, Matlab software packages were used.



(a) . Pilot area in California **(b). Pilot links in studied area.**

Figure 3. Urban network data in California

Table 3. Metadata information

Pilot area information	
Studied area	State of California
Datum	NAD1983
Projection system	UTM (Universal Transversal Mercator)

4. Results and Discussion

To assess the risk of urban links in the pilot area, an integration of fuzzy-AHP, TOPSIS and VIKOR method was employed as explained in see Section 2. The following steps have been taken:

A. Identification of effective criteria and normalization.
B. Criteria weight estimation using fuzzy-AHP method.
C. Evaluation ranks of urban links using TOPSIS.
D. Evaluation of final result in two different ways using sensitivity analysis and comparison of the output with a similar method such as VIKOR.

4.1. Identification of Effective Criteria and Normalization.

The main step for our work is determination of input criteria. Here, input criteria such as safety, annual average traffic, average slope and distance from the critical place (needing traffic control such as a hospital) were determined as important criteria for the analysis (see Section 2). In the next step, the value of each urban link in pilot is normalized using the methodology explained in Section 2.

4.2. Criteria Weight Estimation Using Fuzzy-AHP Method.

The main step for urban network's risk analysis is the determination of the weights of input criteria for inclusion of their importance in the analysis. In this step, fuzzy-AHP method based on Mikhailov's theory is used. In comparison with other fuzzy-AHP methods such as Chung's this method does not allow traffic experts to do pairwise comparison of the input criteria, because of not being reliability for criteria comparison. In this method, traffic experts express their ideas for criteria comparison using triangular fuzzy numbers. Table 4 shows comparison matrix of the input criteria used for the input criteria weight estimation. To increase accuracy of weight estimation, the estimation was done using different $\alpha -$ cuts. Consequently, the final estimated weight was determined averaging all the output results. Table 5 shows the final estimated weights. The comparison matrix of criteria being a symmetric matrix, only in the upper triangle of the matrix is shown in Table 4, with triangular numbers to be used in the weight estimation process. In the weight estimation process, inconsistency index was estimated. The result shows inconsistency index to be about 0.57, and thus the positive value of the index shows acceptance of the weigh estimation process. The estimated weigh would be used in the next step for risk assessment.

Table 4. Importance of criteria in fuzzy-AHP expressed by triangular fuzzy numbers

Criterion	Safety	Annual average daily traffic	Distance from hospital	Slope
Safety	(1,1,1)	(1/2,1,3/2)	(1,3/2,2)	(3/2,2,5/2)
Annual average daily traffic	-	(1,1,1)	(1/2,1,3/2)	(1,3/2,2)
Distance from hospital	-	-	(1,1,1)	(1/2,1,3/2)
Slope	-	-	-	(1,1,1)

Table 5. Estimated weights based on Mikhailov's theory.

Criterion	Total weight
Safety	0.32
Annual average daily traffic	0.26
Distance from hospital	0.22
Slope	0.18

4.3. Evaluation of Urban Links Risk Rank Using TOPSIS

To evaluate urban risk, TOPSIS was employed. The result shows classified pilot links in four classes. Table 6 shows the ranges of TOPSIS scores for all classes. As illustrated, the links belonging to the first class should be signified as vulnerable links meaning to be in high danger of traffic incidents. Table 6, 7 show the input criteria values and risk levels corresponding to the closeness coefficient values.

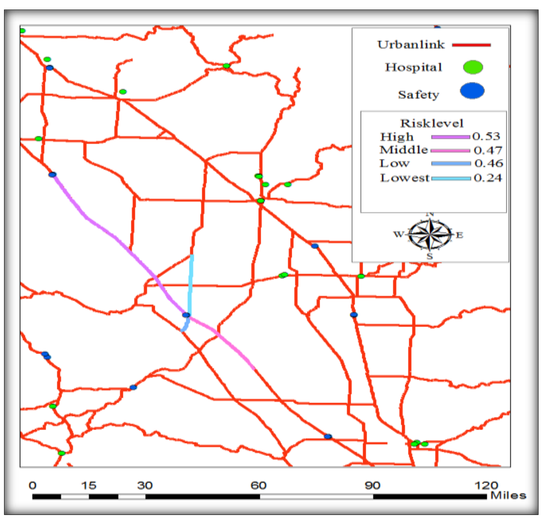


Figure 4. Classified links using TOPSIS method

Table 6. Input criteria for links

Link	Safety	Annual average daily traffic	Distance from hospital	Slope
1	0.0330	0.9947	0.3020	0.5
2	0.3007	0.0097	0.4853	0.5
3	0.6953	0.0069	0.5976	0.5
4	0.6518	0.1017	0.5621	0.5

Table 7. Closeness-coefficient value for pilot links

Link	Risk rank	Detail	Closeness coefficient range
1	1	High risk	0.53
2	4	Lowest risk	0.24
3	3	Low risk	0.46
4	2	Middle risk	0.47

4.4.1. Evaluation of Final Result Using Sensitivity Analysis.

In this step the sensitivity of final result to change of input parameters is investigated. To do this, we, make sensitivity analysis due to change of the fuzzy domain. The domains of fuzzy numbers were decreased (see Table 8) and consequently estimation of weight was repeated using the new fuzzy domain (see Table 9). Table 10 shows the final estimated weights using the new fuzzy domains. Next, classification of urban links was repeated using the new estimated weights and the weights were given to TOPSIS. Fig. 5 shows the urban risk classifications and Table 11 shows the closeness coefficients corresponding to the limited fuzzy range.

Table 8. New fuzzy-AHP standard for weight estimation

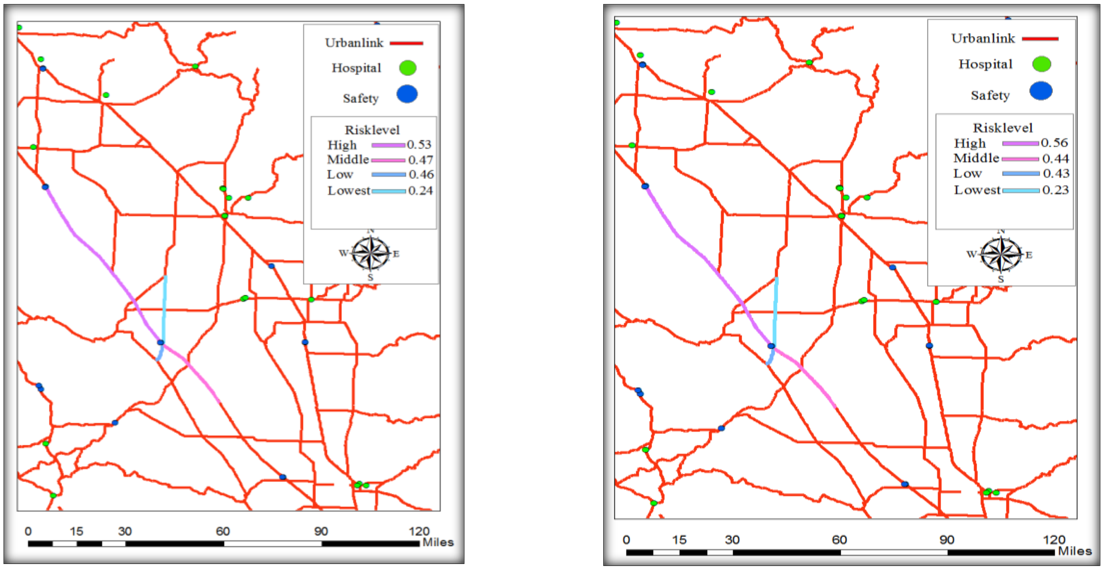
Importance level	Concept	$\tilde{a}_{ij}$	$\tilde{a}_{ji}$
1	Equal	(1,1,1)	(1,1,1)
2	Slightly preferred	(3/4,1,5/4)	(4/5,1,4/3)
3	Important	(1,5/4,3/2)	(2/3,4/5,1)
4	Relatively important	(5/4,3/2,7/4)	(4/7,2/3,4/5)
5	Very important	(3/2,7/4,2)	(1/2,4/7,2/3)
6	Strongly preferred	(7/4,2,9/4)	(4/9,1/2,4/7)

Table 9. Importance of criteria in fuzzy-AHP expressed by new fuzzy domain

Criterion	Safety	Annual average traffic	Distance from hospital	Slope
Safety	(1,1,1)	(3/4,1,5/4)	(1,5/4,3/2)	(5/4,3/2,7/4)
Annual average traffic	-	(1,1,1)	(3/4,1,5/4)	(1,5/4,3/2)
Distance from hospital	-	-	(1,1,1)	(3/4,1,5/4)
Slope	-	-	-	(1,1,1)

Table 10. Weight calculation based on Mikhailov's method with new fuzzy domain

Criterion	Total weight
Safety	0.29
Annual average daily traffic	0.27
Distance from hospital	0.22
Slope	0.20



(a) Output result (b) Output with new fuzzy range

Figure 5. Sensitivity of algorithm to change of fuzzy domain

Table 11. Closeness-coefficient in limited fuzzy range

Link	Risk rank	Detail	Closeness coefficient range
1	1	High risk	0.56
2	4	Lowest risk	0.23
3	3	Low risk	0.43
4	2	Middle risk	0.44

4.4.2. Evaluation of Final Result Using VIKOR

Here, evaluation of output is made using a numerical method, VIKOR. This step gives more accuracy for selection of the risky links. VIKOR is used because all the criteria are numeric. The comparison with VIKOR was done using an advantage function. The less value of Q corresponds to more chance for selection of link as a risky link. Table12 shows VIKOR's advantage function for links and risk levels.

Table 12. Advantage function in VIKOR method in different V parameters

Link	V=0	V=0.3	V=1
1	1(Lowest)	0.981(Lowest)	0.938(Low)
2	0.548(Middle)	0.683(Low)	1(Lowest)
3	0.564(Low)	0.395(Middle)	0(High)
4	0(High)	0.022(High)	0.076(Middle)

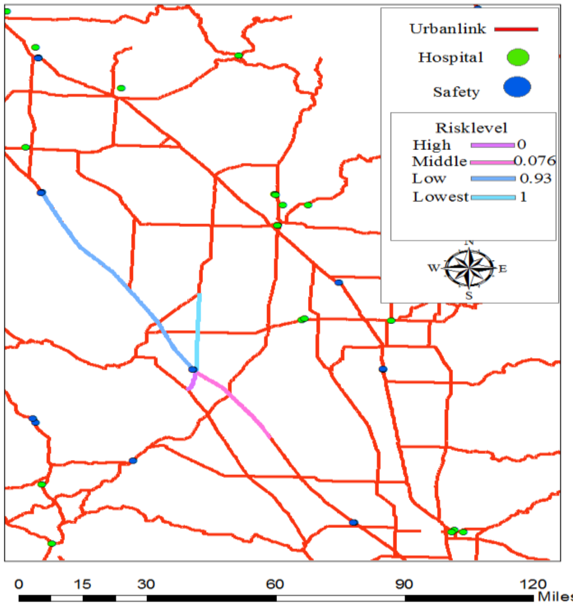


Figure 6. Checking output's accuracy using VIKOR (V=1)

5. Conclusion and Directions for Further Research

Risk assessment of urban network using traffic variables determines vulnerable links that are in high danger of traffic incidents. Big challenges facing this task are determination of an appropriate methodology and appropriate risk indicators. Here, an integration of fuzzy-AHP, TOPSIS and VIKOR was used. In first step, weights of criteria were estimated using fuzzy-AHP. Then the estimated weights were entered to TOPSIS to assess risk of each link in the pilot area. Input criteria such as annual average daily traffic (AADT), safety, average slope of urban link and distance from POI (such as hospital) parcel were determined by traffic experts. Then, using the proposed method, urban links were classified in different risk ranks. The output was checked by 2 different ways: first, sensitivity analysis was done and then comparison was made with similar method such as VIKOR. Finally, we determined vulnerable link being in high danger of traffic incidents.

Although our proposed methodology considers model's uncertainty in the weight estimation process, but uncertainty due to data incompleteness cannot be modelled, in general. Consideration of such uncertainty in the model would be useful.

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