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Vulnerability Evaluation of the Highway Transportation System against Meteorological Disasters

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Abstract

Extreme weather events and meteorological disasters frequently occur owing to continuously changing global climate. These abnormal phenomena further cause increasingly serious traffic problems, such as infrastructure damage, traffic congestion, and traffic accidents, which make the road transport system operation vulnerably. Hence the vulnerability evaluation has recently aroused general interests in transportation research. This study aims to construct an effective methodology used for evaluating road transport system vulnerability against meteorological disasters from the view of risk analysis theory. Firstly, the paper reviews the research state of art of vulnerability and establishes the vulnerability evaluation system, which is based on three aspects including physical exposure, disaster loss sensitivity and resistance ability. Secondly, 13 evaluation indices are elaborately selected and quantified, and then the single vulnerability evaluation index is obtained by the combinational method of analytic hierarchy process and fuzzy comprehensive evaluation theory. Finally, this methodology is applied on Hangzhou regional road network and the results show that Hangzhou road transport vulnerability scores 55.3, and the vulnerability grade belongs to “Middle”, which indicates this road network is lightly vulnerable to meteorological disasters.

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Keywords: meteorological disasters; risk analysis; highway transportation system vulnerability; analytic hierarchy process (AHP); fuzzy comprehensive evaluation (FCE)

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1. Introduction

Global climate change brings about increasing extreme weather events and even meteorological disasters. And those abnormal phenomena further cause serious traffic problems, such as infrastructure damage, traffic congestion, and traffic accidents, which together make the road transport system operation very vulnerable. For example, low temperature, frost and snow disaster of southern China in 2008 blocked highway traffic in several provinces, resulted in direct economic loss up to 159.5 billion Yuan and took away 162 lives (National Bureau of Statistics, 2009). Hence it is very necessary and important to carry on vulnerability evaluation of the highway transportation system against the meteorological disasters at present.

The concept of vulnerability is firstly proposed by geosciences researcher Timmerman and he regards vulnerability as affected degree on system performance caused by disasters and other incidents (Timmerman, 1981). So far vulnerability concept is applied to different research fields, such as social sciences, economics, geophysics, information system and environment science etc. In fact, the concept of vulnerability should deserve redefining to adjust to various research purposes. However there is no fully recognized definition about transport system vulnerability, though the definition given by Berdica has received relatively mach acceptance from researchers. Berdica defines vulnerability as traffic network’s sensitiveness to major incidents which decrease network serviceability (Berdica, 2002), but Husdal thinks vulnerability refers to network non-operation ability and operation reliability in some certain situation (Husdal, 2004). D.Este and Taylor distinguish well the difference between reliability assessment and vulnerability assessment in that the former assessment centers on the probability of traffic incidents and the latter assessment focuses on the consequences caused by abnormal incidents. They also divide general vulnerability concept into two specific definitions: one-node-accessibility vulnerability and two-node-connectivity vulnerability (D. Este & Taylor, 2001). Though vulnerability evaluation has been a research hotspot in other research fields, the highway traffic system vulnerability has just began, exactly as American transportation research board (TRB) says, studies about transport vulnerability against climate change are far from comprehensive development and need more traffic researchers and managers to devote themselves into deep research on wide phases of transport systems (Transportation Research Board of the National Academics, 2008). And the reason why transportation vulnerability is fit for traffic network analysis under natural disasters is that it also considers the consequences of disasters as well as the probability. In contrast, the traffic reliability analysis only concerns about probability but not the consequences (Bureau of Transport Regional Economics, 2002).

Different road network vulnerability evaluation methods are proposed in prior studies. Murray puts those methods into four categories: scenario-based evaluation method, strategy-based evaluation method, simulation-based evaluation method and mathematical model-based evaluation method (Murray et al, 2008). Jenelius maintains that vulnerability consists of probability and consequence, and he appraises road section importance and regional affected degree by observing path cost variation due to road section failure (Jenelius, 2006). Taylor analyzes network vulnerability in terms of accessibility by establishing a new logit choice model to deal with abnormal situation (Taylor, 2008). Chen also introduces travel demand model and use utility-based accessibility as indicator of vulnerability (Chen et al, 2007). Erath considers the direct and indirect consequences by road section failure on Swiss road network, and then constructs a statistical model to identify the main factors affect vulnerability (Erath et al, 2009).

In China, road transport vulnerability research is also paid more attention on, but it is only in the beginning. Tu proposes a new network topology vulnerability indicator by introducing “mincuts frequency vector” assessment index prevailing in the field of telecommunication to determine critical links and appraise how the vulnerability varies with the change of road section resistance ability (Tu et al., 2010). Du instead uses the increased journey travel time to analyze road network vulnerability (Du, 2011). Yin suggests that network efficacy and failure probability may be better for static vulnerability indicator, while travel cost variation due to road section failure in transport network may be better for dynamic vulnerability indicator (Yin, 2011).
As can be seen from research reviews above, most of their studies consider both probability and consequence of traffic incidents, and assess transport system vulnerability from the view of network operation efficiency. The shortcomings of these studies lie in that they pay much more attention on external traffic incidents and ignore the underlying factors, so they are unable to find out the relationship between disastrous incidents and road transport. Hence this paper tempts to appraise road transport system vulnerability from the view of disaster risk analysis, and it also tries to find the inherent relationship between meteorological disasters and road transport system vulnerability. It is not able to instruct transport system planning, design, construct, maintenance and management before the highway transport system vulnerability is well understood and analyzed especially under present continuing climate change. So it is valuable to carry on vulnerability evaluation of the highway transportation system against the meteorological disasters. This paper is organized as follows: vulnerability evaluation system is established and evaluation method is given in section 2. Then 13 evaluation indices are respectively explained and quantified by various means in section 3, which is followed by Hangzhou regional road network vulnerability evaluation as a case application in section 4. Finally the conclusion is drawn in section 5.

2. Vulnerability evaluation system establishment and evaluation method statement

In climate change research field, vulnerability means a system property which is prone to or unable to deal with adverse effects caused by climate change. It is a function of variance characteristics, magnitude, sensitivity and adaptability of a certain climate system.

According to disaster risk management theory, disaster bearers in highway transport system is the objects that meteorological disasters bring to bear on, and here it includes human, vehicle, road etc. The property of disaster bearers in some extent determines the probability and seriousness of meteorological disaster risk and it is very appropriate to be depicted by vulnerability. So the vulnerability used in this study is given by definition as follows: highway network vulnerability is a measure of one property susceptible to meteorological disasters and one inability to resist adverse effects and to restore to initial state. Therefore highway network vulnerability evaluation can be evaluated from the following three aspects: highway network physical exposure, disaster loss sensitivity and resistance ability. Physical exposure measures the ratio of highway network which are exposed to meteorological disasters. The vulnerability is positive proportional to physical exposure, other things being equal. Disaster loss sensitivity reflects whether disaster bearers are sensitive to disasters’ destructive power and vulnerability is also positive proportional to disaster loss sensitivity. Resistance ability shows whether the highway network is robust to resist meteorological disasters and how fast it returns to initial state and vulnerability is negative positive proportional to resistance ability. Disaster bearer vulnerability can be express as a function as follows:

\[ V = f(E, S, R) \]  

Where V denotes vulnerability, E denotes physical exposure, S denotes damage loss sensitivity and R denotes resistance ability.

The evaluation system should be organized in a tree shape with the top indicator being abstract and the bottom indicators being specific. Besides, many evaluation indicators are deterministic while others are not, and the relationships between the indicators and the boundary of each level of the vulnerability are not very clear. These two questions or difficulties are always shown up in comprehensive evaluation study. After second thoughts about research object and research purpose, the combinational method of analytic hierarchy process (AHP) and fuzzy comprehensive evaluation (FCE) method is brought up to evaluate the vulnerability. AHP method can be used for dividing single vulnerability index evaluation into several different layers from the top to the bottom and very instructive to select feasible and concise sub indicators. FCE method is good at simultaneously dealing with multi influence factors, and the principle of fuzzy transformation and weighted average method ensure that the vulnerability evaluation is reasonable. In one word, the combinational method of AHP and FCE solves the two
questions mentioned above very well, so it is very suitable for this study. Details of AHP method and FCE method is demonstrated in case study.

In sum, the highway network vulnerability evaluation question is a process which firstly respectively evaluates highway network physical exposure, disaster loss sensitivity and resistance ability using FCE method, and integrates three sub indictors into one single vulnerability indictor using AHP method. Hence the complete evaluation system of highway transport system against meteorological disasters is shown in Table 1.

Table 1 Evaluation system of highway transport system against meteorological disasters

<table>
<thead>
<tr>
<th>Objective layer</th>
<th>Principle layer</th>
<th>Sub principle layer</th>
<th>Scheme layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vulnerability</td>
<td>Physical exposure (U₁)</td>
<td>Infrastructure exposure</td>
<td>Road section physical exposure index (U₁₁)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Vehicle exposure</td>
<td>Vehicle physical exposure (U₁₂)</td>
</tr>
<tr>
<td></td>
<td>Disaster loss sensitivity (U₂)</td>
<td>Highway sensitivity</td>
<td>Highway technical grade index (U₂₁)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Highway physical structure index (U₂₂)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Node connectivity degree index (U₂₃)</td>
</tr>
<tr>
<td></td>
<td>Resistance ability (U₃)</td>
<td>Traffic sensitivity</td>
<td>Traffic composition index (U₃₁)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Design speed index (U₃₂)</td>
</tr>
<tr>
<td></td>
<td>Pre-disaster precaution</td>
<td></td>
<td>Meteorological disaster monitoring and forecasting index (U₃₃)</td>
</tr>
<tr>
<td></td>
<td>Emergency response</td>
<td></td>
<td>Disaster early-warning index (U₃₄)</td>
</tr>
<tr>
<td></td>
<td>Post-disaster recovery</td>
<td></td>
<td>emergency plan index (U₃₅)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Emergency work forces index (U₃₆)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Emergency goods and materials index (U₃₇)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>disaster-relief financial resources index (U₃₈)</td>
</tr>
</tbody>
</table>
3. Description of Evaluation index

It is a hard work to evaluate highway network vulnerability against meteorological disasters unless effective evaluation method is found and the chosen evaluation index is representative and feasible. Hence thirteen evaluation indexes are determined as the sound base of vulnerability evaluation. They are explained and qualified one by one in the below context.

3.1. Physical exposure

Highway network physical exposure measures the quantity of highway network which are exposed to the influence scope of meteorological disaster drivers, such as quantity or value of highway transport system disaster bears. It further contains physical exposure of infrastructure network, and physical exposure of vehicles in highway network.

- Road section physical exposure index ($U_{11}$)
  
  Road section physical exposure index is the ratio of road section length affected by disaster drivers to the total road length, and is calculated by given formula as follows:
  
  \[ E_r = \frac{L_r}{L} \]  
  
  Where $E_r$ denotes road section physical exposure, $L_r$ denotes road section length affected by disaster drivers (km), and $L$ denotes road total length (km).

- Vehicle physical exposure index ($U_{12}$)
  
  Vehicle physical exposure index is the ratio of number of vehicles affected by disaster drivers to road network capacity, and is calculated by given formula as follows:
  
  \[ E_v = \frac{C_r}{C} \]  
  
  Where $E_v$ denotes vehicle physical exposure, $C_r$ denotes number of vehicles affected by disaster drivers (pcu/h), and $C$ denotes road network capacity (pcu/h).
3.2. disaster loss sensitivity

Highway network disaster loss sensitivity characterizes the highway network’s damage hardness by certain intensity of disasters or disturbances. And it affects vulnerability by highway transport system inherent physical properties. Obviously, the sensitivity varies with different meteorological disasters, such as extreme precipitation, ice and snow, fog, extreme temperature, strong wind, sandstorm etc. and secondary hazards, such as landslides, collapses, debris flow etc. It further contains highway network sensitivity and traffic sensitivity. And the highway network sensitivity consists of highway technical grade index, highway physical structure index, and highway node connectivity degree index. The traffic sensitivity consists of traffic composition index and design speed index.

- **highway technical grade index** \(U_{21}\)
  
  The technical grade of highway is related with highway network sensitivity, generally speaking, the higher the highway technical grade is, the lower the disaster loss sensitivity is. However, the different kinds of meteorological disaster should not be neglected in sensitivity evaluation. For example, though the expressway has higher technical grade, its sensitivity to heavy fog is also very high, compared to lower technical grade roads. When judging the sensitivity level of one road section or one path, its technical grade is main consideration; while judging sensitivity level of regional network, average technical grade, percent of second and second-above technical grade road, and percent of expressway are taken into consideration together.

- **highway physical structure index** \(U_{22}\)
  
  Highway physical structure refers to the physical structure forms of highway road section, including steep slope ratio, percent of bridge and culvert, unfavorable geology road section ratio, mountainous road ratio etc. They are weighted average value and can be calculated with the help of geographic information system database. Notably particularly, sensitivity of physical structure also varies from different meteorological disasters shown in table 2, and needs treating separately to choose different evaluation index in practice.

<table>
<thead>
<tr>
<th>Meteorological disaster</th>
<th>Recommendation index of highway physical structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>extreme precipitation</td>
<td>ratio of deep excavation, low subgrade, waterfront road, unfavorable geology road section</td>
</tr>
<tr>
<td>ice and snow</td>
<td>ratio of road section with slope more than 5%; percent of bridges</td>
</tr>
<tr>
<td>fog</td>
<td>ratio of road section having fog frequently; ratio of expressway</td>
</tr>
<tr>
<td>extreme temperature</td>
<td>highway grade; pavement structure</td>
</tr>
<tr>
<td>strong wind</td>
<td>ratio of road located at wind gap or col; ratio of high subgrade road; percent of bridges</td>
</tr>
<tr>
<td>sandstorm</td>
<td>highway greenery condition; percent of desert road</td>
</tr>
<tr>
<td>secondary geological hazards</td>
<td>ratio of unfavorable geology road section ratio, ratio of mountainous road</td>
</tr>
</tbody>
</table>

- **highway node connectivity degree index** \(U_{23}\)
  
  Highway node connectivity degree refers to the connection intensity among nodes in a regional road network, and it reflects highway network’s layout characteristics in some extent. Generally speaking, damage loss sensitivity is negative proportional to highway node connectivity degree. It is calculated by formula as follows:

\[
C = \frac{L/\xi}{H \cdot N} = \frac{L/\xi}{\sqrt{A \cdot N}}
\]
Where C denotes highway network connectivity degree, L denotes highway network total length (km), H denotes straight-line distance of two adjacent nodes (km), A denotes area of zone (km²), N denotes number of connected nodes, ξ denotes line nonlinear factor, which means the ratio of actual distance to straight-line distance between every two nodes.

- traffic composition index ($U_{24}$)

Different type of vehicle has different sensitivity to meteorological conditions. For example, vehicles with good mechanical performance is less sensitive to icy and snowy pavement than vehicles with bad mechanical performance, and multi-layer vehicles are more sensitive to strong wind weather than single-layer vehicles. So traffic composition is taken into consideration in evaluation disaster loss sensitivity, and the percent of every vehicle type can be obtained by traffic survey.

- design speed index ($U_{25}$)

Highway design speed not only has impact on highway traffic operation state, but also influences meteorological disaster sensitivity. For example, the road with high design speed, such as expressway, is more sensitive to heavy fog. So design speed should be divided into several intervals according to present highway design guide, and is further considered into sensitivity evaluation by using FCE method.

### 3.3. Resistance ability

Resistance ability shows the ability of highway transport system to resist meteorological disaster’s influences. It can be further divided into three aspects: pre-disaster precaution ability, emergency response ability and post-disaster recovery ability. Pre-disaster precaution ability consists of meteorological disaster monitoring, forecasting index, disaster early-warning index, and emergency plan index. Emergency response ability consists of emergency work forces index, emergency goods and materials index. Post-disaster recovery ability is measured mainly by disaster-relief financial resources index.

- meteorological disaster monitoring and forecasting index ($U_{31}$)

Meteorological disaster monitoring and forecasting index means the hardwares and softwares configuration used for monitoring and forecasting weather condition. More and more traffic metrological monitoring stations along expressway and corridor in many provinces provide a large amount of support for meteorological information monitoring, analyzing and disseminating. This index is scored by experts and front-line staff from highway meteorological industries who totally understand current development of regional highway meteorological monitoring and forecasting.

- disaster early-warning index ($U_{32}$)

Disaster early-warning index is ability to take advantage of the collected information to make precise early-warning judgment before the disaster develops in future. Precise and reliable early-warning may greatly enhance resistance ability of highway network. This index is also scored by experts and front-line staff from highway meteorological industry, and they score according to current development of response time, information disseminating and early-warning mechanism.

- emergency plan index ($U_{33}$)

It is well known that practicable emergency plan is very helpful to resist disaster for highway network. This index is also scored by experts and front-line staff from highway meteorological industry who judge according to current development of institution completeness, emergency mechanism construction and plan implementation.

- emergency work forces index ($U_{34}$)
Emergency work forces index refers to the number of disaster-relief work forces devoted per highway mileage unit. Humans are playing a principle role in resisting disasters and they should have good professional skills for emergency rescue.

- emergency goods and materials index\((U_{35})\)
  Emergency goods and materials index refers to the quantity or value of disaster-relief goods and materials devoted per highway mileage unit. Besides, different type of disaster requires different kind of emergency goods and materials. For example, secondary geological hazards require excavating machinery and carrier vehicles, while ice and snow disasters require sandy soil, snow-melting agent, and snow clearer etc. So evaluation of this index should consider the type of disaster.

- disaster-relief financial resources index\((U_{36})\)
  Post-disaster recovery ability mainly refers to the amount of disaster-relief financial resources, that is, disaster-relief financial resources index, which is the quantity of financial resources devoted per highway mileage unit. Disaster-relief financial resources index is a representative indicator for measuring post-disaster recovery ability. If the disaster-relief money is timely and plentiful, the recovery ability will be improved tremendously.

4. Case study

The Hangzhou regional highway network, including national and provincial highways, is used as a case to apply the proposed evaluation method. It is prone to be influenced by extreme precipitation and secondary geological disasters, such as landslides and collapse. So Hangzhou highway transport system vulnerability against those disasters is evaluated here.

The steps of FCE method include the establishment of the factor set, judgment set, and weight vector, single factor evaluation and multivariate comprehensive evaluation, etc.

- Determination of evaluation object
  The evaluation object here is Hangzhou regional highway network, and as a system, its vulnerability is our research objective. The network is denoted by \(X\) as follows:
  \[X = \{x_0\}\]
  Where \(x_0\) is the overall highway network in Hangzhou.

- Establishment of factor set
  Based on the comprehensive evaluation index system in table 1, the following factor set is as follows.
  Level 1 \(U = \{U_1, U_2, U_3\}\);
  Level 2 \(U_1 = \{U_{11}, U_{12}\}\),
  \(U_2 = \{U_{21}, U_{22}, U_{23}, U_{24}, U_{25}\}\),
  \(U_3 = \{U_{31}, U_{32}, U_{33}, U_{34}, U_{35}, U_{36}\}\).

- Establishment of the judgment set
  We choose triangular fuzzy numbers as the membership functions, and discretize the universe of discourse \([0,100]\) into 4 fuzzy linguistic terms (low, middle, high, very high). The threshold of evaluation standard for the vulnerability against disasters of highway network is determined using triangular fuzzy numbers combined with relevant research results of the evaluation method for highway network (see Table 3 and Fig. 1).

<table>
<thead>
<tr>
<th>Score</th>
<th>Fuzzy linguistic term</th>
</tr>
</thead>
<tbody>
<tr>
<td>(S &lt; 40)</td>
<td>Low</td>
</tr>
</tbody>
</table>

Table 3 Threshold of evaluation standard for highway transport system vulnerability
After the threshold of evaluation standard is determined, we can obtain the score whose fuzzy membership degree is 1 according to the membership functions and define the judgment set $V$, $V = \{ v_1, v_2, v_3, v_4 \} = \{ 30, 50, 70, 100 \} = \{ \text{low vulnerability}, \text{middle vulnerability}, \text{high vulnerability}, \text{very high vulnerability} \}$.

- Establishment of the weight vector

The weight vector is determined by expert decision along with field investigation and other related research results at home and abroad.

Level 2 $A_1 = (a_{11}, a_{12}) = (0.6, 0.4)$;

$A_2 = (a_{21}, a_{22}, a_{23}, a_{24}, a_{25}) = (0.3, 0.3, 0.2, 0.1, 0.1)$;

$A_3 = (a_{31}, a_{32}, a_{33}, a_{34}, a_{35}, a_{36}) = (0.1, 0.1, 0.2, 0.2, 0.2, 0.2)$.

Level 1 $A = (a_1, a_2, a_3) = (0.3, 0.3, 0.4)$.

- Fuzzy comprehensive evaluation of Level 2

- Single factor evaluation

Establish a fuzzy mapping from $U$ to $F(V)$, $f: U \rightarrow F(V)$

$$\forall u_i \rightarrow f(u_i) = \frac{r_{i1}}{v_1} + \frac{r_{i2}}{v_2} + \ldots + \frac{r_{in}}{v_n}$$

(5)

where $r_{ij}$ is the membership degree of factor $u_i$, to grading $v_j (i=1, 2, \ldots, m; \ j=1, 2, \ldots, n)$.

Hence the single factor appraisal sets are obtained.

$$R_i = (\gamma_{i1}, \gamma_{i2}, \ldots, \gamma_{in})$$

(6)
The single factor appraisal matrix $R$ is also obtained whose rows are the single factor appraisal sets; the matrix is a fuzzy one.

$$
R = \begin{bmatrix}
  r_{11} & r_{12} & \cdots & r_{1n} \\
  r_{21} & r_{22} & \cdots & r_{2n} \\
  \vdots & \vdots & \ddots & \vdots \\
  r_{m1} & r_{m2} & \cdots & r_{mn}
\end{bmatrix}
$$

(7)

The membership degrees of sub-factors to grading are obtained according to the different degrees of vulnerability against disasters combined with the membership functions quantitatively or qualitatively.

When evaluating the factors of Level 2, quantitative evaluation and qualitative evaluation are unified. And each of the 13 evaluation index has its own calculation method and level standards in Table 4.

Table 4 evaluation method of highway traffic vulnerability evaluation index against meteorological disasters

<table>
<thead>
<tr>
<th>Evaluation index</th>
<th>Index property</th>
<th>Calculation method and level standards</th>
</tr>
</thead>
<tbody>
<tr>
<td>Road section physical exposure index</td>
<td>Quantitative</td>
<td>The value of formula (2) multi 100 as fuzzy evaluation value</td>
</tr>
<tr>
<td>Vehicle physical exposure index</td>
<td>Quantitative</td>
<td>The value of formula (3) multi 100 as fuzzy evaluation value</td>
</tr>
<tr>
<td>Highway technical grade index</td>
<td>Quantitative</td>
<td>It scores 0 if highway network average technical grade is 2.5 and 100 if 4.5; It scores 0 if percentage of highway with technical grade two and above is 50% and 100 if 0%. The evaluation scores are determined using the interpolation method; the comprehensive score of highway network technical grade index is calculated using the weighted average method.</td>
</tr>
<tr>
<td>Highway physical structure index</td>
<td>Quantitative</td>
<td>100 multi the ratio of low subgrade road or waterfront road or unfavorable geological road section or percent of bridges as fuzzy evaluation and the comprehensive score of highway network physical structure index is calculated using the weighted average method.</td>
</tr>
<tr>
<td>Node connectivity degree index</td>
<td>Quantitative</td>
<td>It scores 0 if network connectivity degree is 5 and 100 if 0. The evaluation scores are determined using the interpolation method</td>
</tr>
<tr>
<td>Traffic composition index</td>
<td>Quantitative</td>
<td>It scores 0 if percent of small vehicles is 100% and 100 if 0%. The evaluation scores are determined using the interpolation method</td>
</tr>
<tr>
<td>Design speed index</td>
<td>Quantitative</td>
<td>It scores 0 if design speed is 0 km/h and 100 if 120 km/h and above. The evaluation scores are determined using the interpolation method</td>
</tr>
<tr>
<td>Meteorological disaster monitoring and forecasting</td>
<td>Qualitative</td>
<td>It is scored by experts and front-line staff according to current development of regional highway meteorological monitoring and forecasting. The range is from 0 to 100.</td>
</tr>
<tr>
<td>Disaster early-warning index</td>
<td>Qualitative</td>
<td>It is scored by experts and front-line staff according to current development of response time, information disseminating and early-warning mechanism. The range is from 0 to 100.</td>
</tr>
<tr>
<td>Emergency plan index</td>
<td>Qualitative</td>
<td>It is scored by experts and front-line staff according to current development of institution completeness, emergency mechanism construction and plan implementation. The range is from 0 to 100.</td>
</tr>
<tr>
<td>Emergency work forces index</td>
<td>Quantitative</td>
<td>It scores 0 if 100 persons per 100 km road is assigned and 100 if 0. The evaluation scores are determined using the interpolation method</td>
</tr>
</tbody>
</table>
After the membership degrees of sub-factors to grading are calculated, the single factor appraisal matrixes $R_1$, $R_2$, and $R_3$ are obtained by arranging. In this case:

$$R_1 = \begin{bmatrix} 0.37 & 0.47 & 0.11 & 0.05 \\ 0.26 & 0.29 & 0.32 & 0.13 \\ 0.22 & 0.45 & 0.26 & 0.07 \\ 0.16 & 0.23 & 0.38 & 0.23 \end{bmatrix}$$

$$R_2 = \begin{bmatrix} 0.76 & 0.18 & 0.04 & 0.02 \\ 0.57 & 0.36 & 0.07 & 0 \\ 0.22 & 0.32 & 0.23 & 0.23 \\ 0.28 & 0.36 & 0.23 & 0.13 \\ 0.26 & 0.28 & 0.29 & 0.17 \\ 0.11 & 0.32 & 0.26 & 0.31 \\ 0.27 & 0.29 & 0.23 & 0.21 \\ 0.31 & 0.25 & 0.26 & 0.18 \\ 0.33 & 0.32 & 0.22 & 0.13 \end{bmatrix}$$

- Multivariate comprehensive evaluation

When we have determined the single factor appraisal matrixes and weight vectors, we can express the fuzzy comprehensive evaluation as follows.

$$B = AR = (a_1, a_2, \ldots, a_i, \ldots, a_m) \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{bmatrix} = (b_1, b_2, \ldots, b_n)$$

where $B$ is a fuzzy comprehensive appraisal set; $b_j (j=1,2,\ldots,n)$ is a fuzzy comprehensive appraisal indicator whose meaning is the membership degrees of the objectives being evaluated to grading $j$ of the judgment set considering all influences of factors. By calculating, $B_1$, $B_2$, and $B_3$ can be obtained. In this case:

$$B_1 = \begin{bmatrix} 0.33 & 0.40 & 0.19 & 0.08 \end{bmatrix}$$

$$B_2 = \begin{bmatrix} 0.35 & 0.31 & 0.23 & 0.11 \end{bmatrix}$$
After obtaining the fuzzy comprehensive evaluation result of Level 2, physical exposure, disaster loss sensitivity, and resistance ability are considered as the single factors. Their respective evaluation results of Level 2 are considered as the single factor appraisal sets which constitute the single factor appraisal matrix of the fuzzy comprehensive evaluation of Level 1.

The fuzzy comprehensive evaluation result of Level 1 is obtained by the single factor appraisal matrix and weight vector $B = [0.31 \ 0.33 \ 0.22 \ 0.14]$. According to the above judgment set $V$, $V = \{v_1, v_2, v_3, v_4\} = \{30, 50, 70, 100\}$. The membership degree $b_j$ as weights, the comprehensive score of the objective being evaluated as follows.

$$V = \frac{\sum_{j=1}^{4} b_j v_j}{\sum_{j=1}^{4} b_j}$$
Using above comprehensive evaluation model, the evaluation result of highway network vulnerability against disasters of regional highway network can be calculated. Combined with the threshold of evaluation standard, the evaluation level of vulnerability can be obtained.

Ultimately the comprehensive score of Hangzhou highway transport system vulnerability against meteorological is 55.3, and belongs to the "Middle" level. In terms of membership degree, its membership degree to "Low" level is 0.31; compared to the membership degree to "High" level is 0.22, and the membership degree to "Very high" level is 0.14, which implies that the vulnerability of Hangzhou highway network against meteorological is relatively low. Compared with the actual situation of Hangzhou highway network, this conclusion is reliable.

5. Conclusions

Global climate change results in more and more extreme weather events and meteorological disasters. And these disasters further make highway transport system very vulnerable, and bring about many transportation hazards such as traffic congestion and traffic accidents. To adapt to climate change and mitigate its adverse effects, it is worthy to carry on researches on highway transport system vulnerability. However road transport vulnerability research just begins, and is far from achieving thorough theory system and evaluation method. Besides, most of prior studies stand on the view of transport system operational efficiency and critical link identification, and they also lack much consideration about the causes underlying in vulnerability, so it is unable to make a comprehensive and precise evaluation.

This study constructs an effective methodology used for evaluating road transport system vulnerability under meteorological disasters. Firstly, it establishes the vulnerability evaluation system based on three aspects including physical exposure, disaster loss sensitivity and resistance ability from the view of risk analysis theory. Secondly, 13 evaluation indices are selected and quantified and then the single vulnerability evaluation index is obtained by the combinational method of Analytic Hierarchy Process and fuzzy comprehensive evaluation theory. Finally, this methodology is applied to Hangzhou regional road network and the results show that Hangzhou road transport vulnerability scores 55.3, and the vulnerability grade belongs to “Middle”, which indicates this road network is lightly vulnerable to meteorological disasters.

To sum up, the proposed evaluation system stems from meteorological disasters and takes more consideration about function mechanism between meteorological disaster and highway transport system. In addition, the selected evaluation indices with clear logic relationship and simple computation have good operability. Lastly, the proposed evaluation method can be used for assessing vulnerability of highway transport system at different levels such as road section, route and regional network etc. This study makes a good experiment in evaluating highway transport system vulnerability, but also needs some improvements in future research.

References


