

Evaluation model for freeway incident management system

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Abstract: In order to evaluate the general situation and find special problems of the freeway incident management system, an evaluation model is proposed. First, the expert appraisal approach is used to select the primary evaluation index. As a result, 81 indices and the hierarchical structures of the index such as the object layer, the sub-object layer, the criterion layer and the index layer are determined. Then, based on the fuzzy characteristics of each index layer, the analytical hierarchy process (AHP) and the fuzzy comprehensive evaluation are applied to generate the weight and the satisfaction of the index and the criterion layers. When analyzing the relationship between the sub-object layer and the object layer, it is easy to find that the number of sub-objects is too large and sub-objects are significantly redundant. The partial least square (PLS) is proposed to solve the problems. Finally, an application example, whose result has already been accepted and employed as the indication of a new project in improving incident management, is introduced and the result verifies the feasibility and efficiency of the model.

Key words: freeway incident management system; evaluation model; analytical hierarchical process; fuzzy comprehensive evaluations; partial least square

Recently the freeway incident management system has been widely used and studied all over the world because of the huge social and economic effects of traffic incidents. Many investigators in different countries and districts have established the incident management system with a distinctive feature according to local road conditions, traffic features and so on.

The incident management system is an important subsystem of the freeway management system, which has been in use since the 1960s^[1]. However, the application of the incident management system in China is still at an initial stage which is far behind the rapid development of highway construction^[2]. Facing special domestic situations and tens of newly-built freeways, it is urgent to find some guide lines for incident management.

This paper proposes a method which can synthetically evaluate the efficiency of the old incident management system or the improvement of the new system. The method can also make sure what problems are the most important and how well the system works in given surroundings.

1 Evaluation Index of Freeway Incident Management System

1.1 Selecting primary evaluation index

1.1.1 Primary evaluation index

The incident management system can be described as an

integrated system that uses human resources, laws, emergency equipment and other techniques harmoniously to reduce the traffic incident time and weaken its harmful effects. It should offer effective tools in dealing with different issues, including

- Detecting the incidents;
- Determining the emergency services and resources;
- Dispatching suitable vehicles and determining the best routes to the incident point;
- Coordinating the actions of different agencies in a timely manner;
- Transmitting the traveller information;
- Monitoring the process of management and making new responses if needed;
- Recording important incident data for evaluation and improvement.

The basic flow of the incident management has been widely studied before and it is described in Fig. 1.

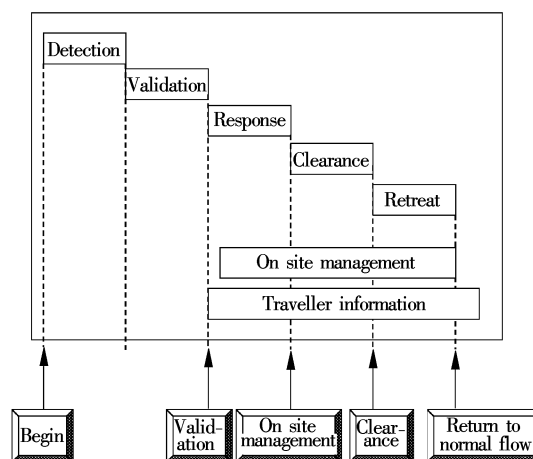


Fig. 1 Flow of incident management

With the full consideration of the construction principles of the evaluation index^[3-4], the basic functions and the flow of incident management, the primary evaluation index is constructed based on the previous studies^[5-12] and practical experience in building the incident management system in Huailian freeway in China. The expert appraisal approach^[13-14] is used to select the index.

1.1.2 Expert appraisal approach

The steps to choose the index are as follows:

1) Organization of the expert team

The choice of expert members is a key issue of this method. Members are required to be authoritative and able to represent a comprehensive part of the incident management. It usually includes domain experts, senior administration experts and decision makers.

2) Pretest and pilot test

A pretest and a pilot test are executed. The test is admin-

Received 2009-09-30.

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Citation: He Ding, Ni Fujian, Yang Shunxin. Evaluation model for freeway incident management system [J]. Journal of Southeast University (English Edition), 2010, 26(1): 126 – 131.

istered to the investigators of incident management at the School of Transportation of Southeast University and some workers in the Operation Center of Huai'an-Lianyungang Freeway. In this process, they can suggest some new necessary indices.

Previous research show that, although seven-point likert scales capture more details, it is unlikely that respondents make such fine distinctions during the limited time of survey completion^[15]. The smaller scale creates a more user-friendly survey instrument, and considering the target respondents, an attractive survey instrument is important to gain participation^[16]. All the variables are measured using the five-point likert scales method. The exploratory factor analysis with a cut-off criterion of 0.5 factor-loading is used. The analysis is conducted with a stepwise approach. The index item which has the lowest maximum factor loading is removed. If the lowest maximum factor loading is less than 0.5, factor analysis is repeated until the lowest maximum factor loading is greater than 0.5. The first version of the instrument which has 78 question indices is thus validated.

Tab. 1 Indices of the efficiency of information sharing and transmission

Criterion	Index
Reliability of information channel	Stability of long time work
	Ability of resisting factitious attack
	Efficiency under bad condition(wicked weather, out of electricity...)
Dispatch and feed-back decision information	Communication mechanism of information(voice, photo, video...)
	Real time of information
	Guarantee of institution
Efficiency of information sharing and communication	Communication mechanism of information(voice, photo, video...)
	Real time of information sharing and communication
	Comprehensiveness of information
	Category of units receiving the service

2 Procedure of Evaluation

2.1 Determining weight factor of index and criterion layers

The analytical hierarchical process(AHP) is a structured technique for helping people to deal with complex decisions. Rather than prescribing a “correct” decision, the AHP helps people to determine one. Based on mathematics and human psychology, the AHP was developed by Saaty and it has been extensively studied and refined since then. The general steps are as follows^[17]:

1) Form the comparison matrix

The descriptive preferences between every two factors can be translated into nine scales. Intensities of 1, 3, 5, 7 and 9 represent equal importance, moderate importance, strong importance, very strong importance and extreme importance, respectively. Intensities of 2, 4, 6, and 8 can be used to express intermediate values. Then we can form matrix $A = (a_{ij})_{n \times n}$ $a_{ij} > 0$ and $a_{ij} = 1/a_{ji}$ when $i = j$, $a_{ij} = 1$.

2) Compute the eigenvector

$$\bar{W}_i = \sqrt[n]{\prod_{j=1}^n A_{ij}} \quad i = 1, 2, \dots, n \quad (1)$$

The normalization is

3) Main field test

Sixty-five first responders participate in the main field test. The first-responder community consists of duty officers of the monitor center, decision makers of the incident management, wreckers, highway administrator, traffic polices, firefighters and medical professionals. After the selection process of five-point likert scales method described before, the final result includes 81 indices.

1.2 Hierarchical structure of evaluation index

According to the concept and the structure characters of incident management, it can be easily found that the purposes of incident management have a hierarchical structure, which determines the hierarchical structure of the evaluation index. We consider the incident management system as a complicated system coupled step by step with four hierarchies: the object layer, the sub-object layer, the criterion layer and the index layer. The overall structure and the indices of efficiency of information sharing and transmission are shown in Fig. 2 and Tab. 1.

$$W_i = \frac{\bar{W}_i}{\sum_{i=1}^n \bar{W}_i} \quad i = 1, 2, \dots, n \quad (2)$$

where $W = \{W_1, W_2, \dots, W_n\}$, and W_i is the weight factor of element i .

3) Maximize the eigen value

$$\lambda_{\max} = \sum_{i=1}^n \left[\frac{(AW)_i}{nw_i} \right] \quad (3)$$

4) Check the consistency

We have a measure of consistency, called the consistency index C_1 , as

$$C_1 = \frac{\lambda_{\max} - n}{n - 1} \quad (4)$$

Then we compute the consistency ratio C_R , which is a comparison between the consistency index C_1 and the random consistency index R_1 , as

$$C_R = \frac{C_1}{R_1} \quad (5)$$

The value of R_1 is shown in Tab. 2. Then we obtain the C_R

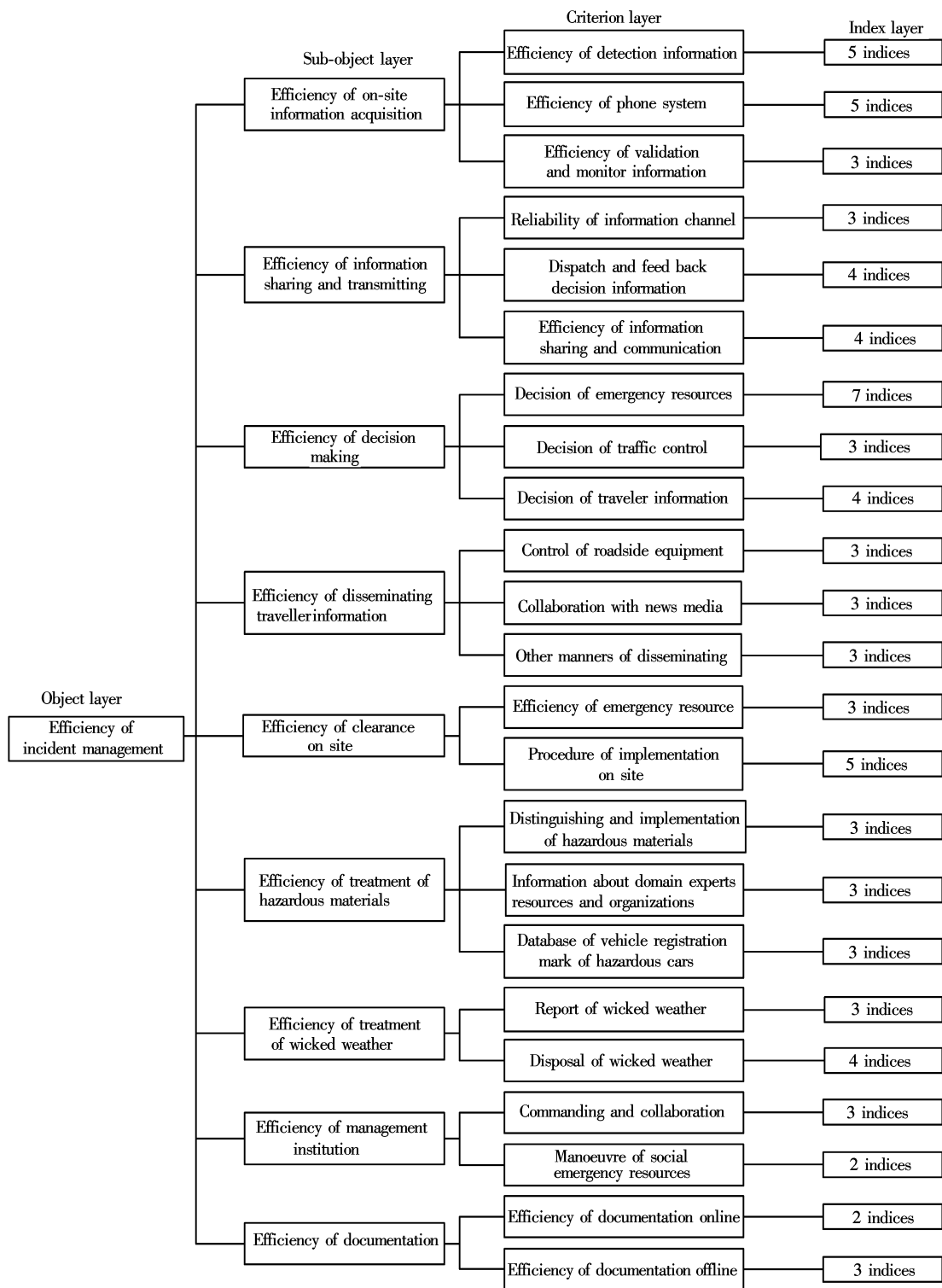


Fig. 2 Hierarchical structure of evaluation index

Tab. 2 Value of R_1

n	R_1
3	0.58
4	0.90
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45

to see whether it is about 0.1 or less. If the $C_R < 0.1$, we can conclude that the consistency is accepted.

5) Compute fuzzy numbers

With a set of judgments from different experts, we face the problem of aggregating them to a group value. Because most decision makers may not have enough knowledge of directly using fuzzy ratios, we apply the concept of fuzzy numbers only to aggregate their individual judgments.

The triangular fuzzy numbers (a_{1j}, a_{2j}, a_{3j}) for representing the group weight of element $C_j(j = 1, 2, \dots, n)$ assessed

by all decision makers $DM_d (d = 1, 2, \dots, s)$ are given as

$$\left. \begin{aligned} a_{1j} &= \min\{w_{1j}, w_{2j}, \dots, w_{dj}\} \\ a_{2j} &= \left(\prod_{d=1}^s w_{dj}\right)^{1/s} \\ a_{3j} &= \max\{w_{1j}, w_{2j}, \dots, w_{dj}\} \\ \sum_{j=1}^n w_{dj} &= 1 \\ d &= 1, 2, \dots, s \end{aligned} \right\} \quad (6)$$

where $w_{1j}, w_{2j}, \dots, w_{dj}$ are the normalized global weights of element $C_j (j = 1, 2, \dots, n)$ given by the decision makers $DM_d (d = 1, 2, \dots, s)$, respectively.

With the concept of α -cut in the fuzzy set theory (The α -cut of a fuzzy set is the ordinary (crisp) set that contains all the values with a membership degree (possibility) of at least $\alpha, 0 \leq \alpha \leq 1$), we can calculate the group weight x_α^λ as

$$x_\alpha^\lambda = \lambda x_r^\alpha + (1 - \lambda) x_l^\alpha \quad (7)$$

where α represents the decision makers' degree of confidence about their assessments of criteria weights; λ can be used to reflect the decision makers' attitudes towards risk; x_l^α and x_r^α are the average of the lower bounds and upper bounds of the crisp intervals.

2.2 Fuzzy comprehensive evaluations

2.2.1 Fuzzy transformation

After setting up the laying structure and computing the weights of sub factors, the fuzzy comprehensive evaluation (FCE) is used to do the evaluation on each level of the structure. Since an important issue in the risk analysis is to handle imprecise or incomplete human expertise and knowledge that the evaluation involves, the FCE is used to better deal with the vagueness^[18].

When evaluating a subject, let the set of evaluation factors of the FCE be $U = \{u_1, u_2, \dots, u_m\}$. Let $V = \{v_1, v_2, \dots, v_n\} = \{\text{very bad, moderately bad, medium, moderately good, very good}\}$, which represents the satisfaction of the index, be the set of evaluation remarks (The fuzzy value of $V = \{0.1, 0.3, 0.5, 0.7, 0.9\}$). Let $W_a = \{w_{a1}, w_{a2}, \dots, w_{am}\}$, acquired in AHP, be the relative weights of the elements of fact or set U corresponding to a subject. Let $B = \{b_1, b_2, \dots, b_n\}$ be a fuzzy subset on V . B is the membership degree of the remark v_j . In fact, B is the measure of the possibilities of various remarks in the remark reference set V .

The FCE can be implemented by a fuzzy transformation,

$$B = W_a \circ R$$

which can also be expressed as

$$\{b_1, b_2, \dots, b_n\} = \{w_{a1}, w_{a2}, \dots, w_{am}\} \circ \begin{bmatrix} r_{11} & r_{12} & \dots & r_{1n} \\ r_{21} & r_{22} & \dots & r_{2n} \\ \vdots & \vdots & & \vdots \\ r_{m1} & r_{m2} & \dots & r_{mn} \end{bmatrix} \quad (8)$$

where $R = (r_{ij})_{m \times n}$, $b_j \leq 1 (j = 1, 2, \dots, n)$.

The evaluation matrix is a fuzzy relation on $U \times V$. $r_{ij} \in$

$[0, 1]$ is the membership degree of the subject to remark v_j from the viewpoint of factor u_i . In order to obtain the fuzzy evaluation matrix R , suitable membership functions of different evaluation factors to risk remarks are used according to the characteristics of the factors. Here r_{ij} is obtained by dividing the number of people who agree with the corresponding value by the total number of people who evaluate the item.

2.2.2 Aggregating results through the hierarchy

The composite evaluation of the risk remarks is then determined by aggregating the results through the hierarchy. This is done by following a path from the bottom of the hierarchy to each subject at the above level and multiplying the weights vector by the fuzzy relation matrix along each segment of the path.

2.2.3 Overall fuzzy evaluation at top level

The outcome of this aggregation is a normalized vector of the overall weights of the risk remark,

$$O = \frac{\sum_{i=1}^n v_i b_i}{\sum_{i=1}^n b_i} \quad (9)$$

We follow the nearest principle to select the risk remarks with the nearest value of O as the result of the evaluation.

Following the above steps, we can obtain the value of the sub-object.

2.3 Computing final object

With the consideration of judgment consistency, the number of elements in a group for pairwise comparisons should be no more than seven. And we notice that nine elements are significantly redundant.

The PLS is used to construct predictive models when the factors are too many and highly collinear^[19]. It can be effectively utilized with smaller sample sizes. Obviously, this method meets our needs.

Partial least square regression is an extension of the multiple linear regression model. In its simplest form, a linear model specifies the (linear) relationship between a dependent variable Y and a set of predictor variables X , so that

$$Y = b_0 + b_1 X_1 + b_2 X_2 + \dots + b_p X_p \quad (10)$$

where b_0 is the regression coefficient for the intercept. If we standardize the data, $b_0 = 0$. b_i values are the regression coefficients (for variables 1 to p) computed from the data.

Both the principal component regression and the partial least square regression produce factor scores as linear combinations of the original predictor variables, so that there is no correlation among the factor score variables used in the predictive regression model. For example, if we have a data set with response variables Y (in matrix form) and a large number of predictor variables X (in matrix form), some of which are highly correlated, a regression using factor extraction can be used to compute the factor score matrix $T = XW$ for an appropriate weight matrix W . And then we can consider the linear regression model $Y = TQ + E$, where Q is a matrix of regression coefficients (loadings) for T , and E is an error (noise) term. Once the loadings Q are computed,

the above regression model is equivalent to $Y = XB + E$, where $B = WQ$, which can be used as a predictive regression model (see Fig. 3).

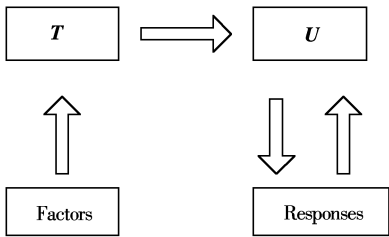


Fig. 3 Transform of PLS

We use the concept of the cross validation test to check the number of factor t . If the cross validation $Q_i^2 \geq 0.0975$, it can be concluded that the number of t is suitable. Furthermore, we can infer the importance of each independent variable from the parameter called $VIP^{[20]}$.

A survey sheet is designed to use the informants marks of

1 to 5, which means {very bad, moderately bad, medium, moderately good, very good}, to express the satisfaction to the nine sub-objects and the object. Then the relationship between the sub-objects and the object can be found with PLS.

3 Introduction of Application

3.1 Testing freeway and system

Fig. 4 demonstrates the actual freeway network, and the black points represent toll stations. The development of this emergency system focusing on emergency incidents in Huai'an- Lianyungang freeway considers the Huai'an-Lianyungang freeway, partial network of its neighboring freeways and provincial highways. Within the partial network, Huai'an-Lianyungang freeway, Lianyungang-Xuzhou freeway, Fen Shui-Guanyun freeway, provincial highway 235 and 236, state highway 204 and other local highways are included.

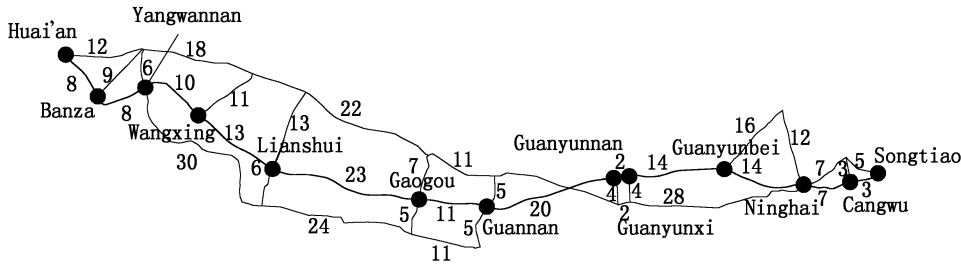


Fig. 4 Actual freeway network

The incident management system mentioned here is developed by the School of Transportation of Southeast University and the Operation Center of Huai'an-Lianyungang Freeway. After almost three years of actual use, it is widely accepted.

3.2 Demographics

Survey questionnaires are distributed to 84 first-responders in the Huai'an-Lianyungang freeway(5 managers in the operation department, 12 operators in the monitor center, 20 wreckers, 15 traffic police, 10 road administrators, 12 fire fighters, 10 medicine personnel) and 12 domain experts in Southeast University who have had close collaboration with Huai'an-Lianyungang freeway for more than two years.

3.3 Computing weight factor of index and criterion layer

Following the above descriptions, we compute the related values. When calculating fuzzy numbers, we set $\alpha = 0$, $\lambda = 0.5$. Finally we obtain the regression formula(take Y as the efficiency of the incident management system and standardize the data):

Y=0.102 4X1+0.215 57X2+0.157 8X3+0.043 997 3X4+0.108 679X5+0.103 57X6+0.132 5X7+0.196 2X8+0.064 501 5X9=3.218 5

where $X_1, X_2, X_3, X_4, X_5, X_6, X_7, X_8, X_9$ represent efficiency of information acquisition, information sharing and transmitting, decision making, disseminating traveller in-

formation, clearance on site, treatment of hazardous materials, treatment of wicked weather, management institution and documentation, respectively.

From Fig. 5, we can see the degree of importance of each factor through the value of VIP. X_2 and X_8 are very important to the final result according to Fig. 5.

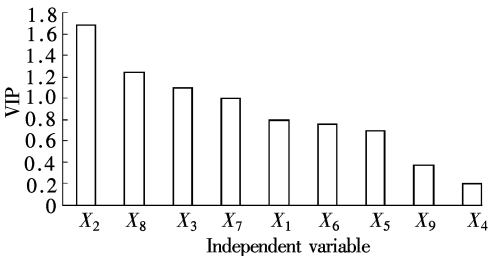


Fig. 5 VIP of each independent variable

3.4 Results

1) The general status of the incident management of the road section is medium (The final score is 3.218 5). This result was agreed on by most of the participators and the leaders of the Operation Center of the Freeway of Jiangsu Province.

2) From the VIP index, we can conclude that X_2 (the efficiency of information sharing) and X_8 (the efficiency of management institution) contribute most to the whole incident management. In most areas of Jiangsu Province, these two are nearly the greatest factors in incident management according to current situations.

3) Several sub-objects obtained the lowest scores, only 2; they are the efficiency of disseminating traveller infor-

mation, treatment of wicked weather and management institution. This means these three items need to be improved immediately.

4) We submitted an analysis report of the weight and satisfaction of the index layer and the criterion layer to the operation center of Huai'an-Lianyungang freeway. It is well adopted and a reformative project to make better incident management based on its current situation.

4 Conclusions

In this paper, the complete theory, method and realization framework for generating the evaluation model of incident management are proposed. The expert appraisal approach, the AHP, the PLS and the fuzzy comprehensive evaluation are used. The proposed model can be applied in different districts or road sections and it is suitable for local conditions to solve regional problems. The model is approved to be positive in the evaluation of Huai'an-Lianyungang freeway. Some projects are implemented in several freeways in Jiangsu Province, China, such as Huai'an-Lianyungang freeway, which can provide beneficial help to some future directions:

- 1) Get more samples to improve the PLS model;
- 2) More meticulous and embedded investigations are needed to modify the idiographic evaluation index;
- 3) The model is formed based on domestic conditions in China, and more surveys and research should be done to fit other countries.
- 4) The prior and the following tests of implementation of the new incident management system should be studied.

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高速公路事件管理系统评价模型

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摘要: 为了评测高速公路事件管理系统的基本状况并发现其中的特别问题, 提出了一种评价模型. 首先使用专家评估法筛选了初始评价指标系, 确定了 81 个指标和指标系的线性层次结构, 如总目标层、子目标层、标准层和指标层. 然后, 在指标系各层模糊性特征基础上, 用层次分析法和模糊聚合法得到指标层和标准层的权重及满意度. 在分析总目标层和子目标层的关系过程中, 容易发现子目标数量过多且有冗余性问题, 并应用了偏最小二乘法进行解决. 最后, 介绍了一个结果已经得到认可并已用来指导新事件管理改进工程的应用实例, 其结果验证了模型的可行性和有效性.

关键词: 高速公路事件管理系统; 评价模型; 层次分析法; 模糊聚合评价; 偏最小二乘法

中图分类号: U491.31