STUDY ON CORE TECHNIQUES Of STATIC HIGHWAY OPERATION SAFETY MANAGEMENT SYSTEM

Wang Yan, Guo Zhong-yin, & Kong Ling-qi

Tongji University
School of Transportation Engineering, Tongji University, No.1239 Siping Road
200092 Shanghai, China
Phone: 021-65981430
Fax: 021-65981430
E-mail:Whj98741@126.com, zhongyin@mail.tongji.edu.cn, lingqi@mail.tongji.edu.cn

Abstract

On the basis of numerous research works on road traffic safety and relevant management theories, the objective and function of the static highway operation safety management system were analyzed and the core technologies of the system were studied, including the highway operation safety evaluation, prediction and decision-making technologies. According to the request of static highway operation safety management, considering both pre-accident and post-accident evaluation, the highway operation safety evaluation index system has been established by analyzing the intrinsic relation among accident data, traffic flow characteristics, highway facility characteristics and highway operation safety conditions. Due to the fuzzy character of road safety problem and the limitation of the classic set theory, the fuzzy logic theory was applied to study the highway operation safety evaluation method, combined with advanced data mining and data fusion technologies. Road traffic system has the typical non-linear characteristic for the interaction among inner and outer factors. Thus the highway operation safety prediction model was studied by the application of Markov theory. What’s more, the operation safety condition identification method has been put forward based on quantitative safety evaluation and prediction results. On this basis, the countermeasures and decision-making technology of static highway operation safety mangement have been studied by adopting expert system technology and optimization method.

1. Background

Road accidents and their consequences constitute a serious problem in many countries. China exhibits substantially higher accident rates than average. In spite of such statistics, the systematic safety management technology has not yet been established and implemented, especially in developing countries. In recent years, safety attains increasing consideration among road management agencies under public pressure for a safer road environment. Given the importance of reducing the social and economic costs associated with collisions, most road authorities employ some type of road safety management program, designed to improve the road safety performance for the system users.

However, road management agencies encounter a number of difficulties in safety management decision making that include identification of accident-prone locations, diagnosis of safety problems and treatment selection□prioritization of improvement needs within existing limitations in resource availability. In addition, If the size and various road classes of a typical network are considered, the need for a systematic management methodology becomes imperative.

Generally speaking, road safety management includes two kinds of works: static management and dynamic management. The static management means implementing the management works during the course of road plan, design, construction, operation and maitenance, such as the safety plan of road network, the periodic safety assessment and improvement of road network, safety education and legislation. The dynamic management means the realtime surveillance and control to road safety during the operation period, such as the accident prevention in bad weathers and the succor works after the occurrence of accidents. In this paper, we will discuss the static safety management during the operation period in rural highways, focusing on its core techniques.

2. System Objective and Function

Incorporating knowledge from past research, expert judgments, and available road and accident data, the static safety management of highway operation comprises four basic interrelated functions: identification of sites requiring safety investigation, diagnosis of safety problems, selection of feasible treatments for potential treatment candidates, and prioritization of treatments given limited budgets. Correspondingly, the system has at least three objectives as follows:

1. To solve the safety problem efficiently so as to reduce the accident rate,
2. To implement the safety improvement at the lowest cost, and
3. To optimize the allocation of limited safety management resources.

The implementation of the system depends on the core techniques, which are the safety evaluation technique, the safety prediction technique and the decision technique for highway operation safety management.

The reminder of the paper is organized as follows. In Section 3 the comprehensive safety evaluation index system was presented and the safety evaluation models was established based on the discussion of present safety evaluation methods and their limitations. Moreover, the operation safety condition for rural highwys has been defined according to the evaluation result. In Section 4 the prediction technique of the evalution index was studied so that the future condition of highway operation safety can be estimated,which will provide important information for making decisions. In Section 5 we present the decision technique by adopting the expert system technology and optimization method for highway safety management agency to select the treatment and make the safety improvement strategy, on the basis of the evalution and prediction results for highway operation safety.

4. Evaluation technique of highway operation safety

3.1 Highway section dividing

Considering accident types and patterns as well as roadway and operating characteristics differ among highway sections with different road and traffic characteristics, highway should be divided and classified into different kinds of units according to functional characteristics, e.g., traffic volumes, design features. Each section type is treated separately in highway operation safety management, including safety evaluation, safety prediction, and improvement decisions.

3.2 Systematic evaluation indices

The selection of safety evaluation index is one of the most important aspects of highway operation safety management and has been the subject of considerable research aimed at providing the comprehensive and credible result.

Road accidents are complex events influenced by a variety of factors such as road geometry, pavement condition, traffic level, and existing safety measures. A thorough safety evaluation should ideally consider all or as many parameters as possible. However, this is practically difficult due to the inability to isolate the effect of each parameter. As a result, safety evaluation has typically examined few parameters of the problem. In addition, although there is general agreement upon the major factors affecting traffic accidents, different studies have not always provided consistent results. Most of the previous research focus on using accident data to measure the safety level. But the limitation of accident index is obvious for the following reasons. First, the quantity and quality of accident data is far from enough to reflect the safety level correctly and efficiently due to the lack of a properly detailed and unified methodology to gather data. Second, the potential safety problem can not be identified before the ocurrence of accidents so that proactive countermeasures can't be taken to prevent the collision. To help mitigate this problem, the more recent studies try to develop evaluation techniques that does not rely on collision statistics, but the traffic and road infrastructure characteristics. On the basis of the relevant research works, this paper puts forward systematic evaluation indices for highway operation safety management, which consists of not only accident data, but also the traffic and road infrastructure characteristics. And the corresponding evaluation models could be used to identify and diagnose problematic areas more effectively.

The systematic evaluation indices can be divided into three categories as follows□indices relating to accident characteristics, indices relating to traffic flow characteristics and indices relating to road infrastructure characteristics. The following will describe each index in detail.

3.2.1 Indices relating to accident characteristics

By comparing different accident indices, the Accident Rate(AR), i.e. the accident number occuring on a certain segment per kilometer per year, was selected, which reflects the safety level quantitatively from the post-accident aspect.

3.2.2 Indices relating to traffic flow characteristics

From the macroscopical point of view, the stable and free traffic flow will contribute to the high level of safety, while the turbulence of traffic flow tends to more accidents. From the microcosmicpoint of view, if the driver can run at the expected speed and lane, without need to change lane frequently, there is less possibility for them to make mistakes leading to accidents. On the contrary, in the unsafe traffic flow condition, it's difficult for the driver to achieve their expectation so that they have to follow the foregoing car at the unstable speed and even change the lane frequently. In conclusion, the traffic flow characteristics have much to do with the operation safety.

With the development of traffic conflict technology(TCT), many researchers try to use TCT to study the safety of traffic flow. TCT reflect the extent of disturbance among vehicles in traffic flow. Based on the concept of TCT, a lot of indices was put forward, among which, Unsafety Density(UD) is selected here, considering both the probability and the severity of collisions in traffic flow. We define the indices relating to traffic flow characteristics as Traffic Flow Safety (TFS), which derived from UD. TFS reflects the safety level quantitatively from the pre-accident aspect,

3.2.3 Indices relating to road infrastructure characteristics

Road infrastructure are the important components of road environment, but easier to control, compared with other components such as climate and geography conditions. Road infrastructure includes hardware and software establishments. The hardware establishment includes main body, traffic facility and roadside. The software facility means safety management level. Obviously, road infrastructure with good safety performance contribute to a high level of safety. We define the indices relating to road infrastructure characteristics as Road Infrastructure Safety index(RIS). RIS is a synthetical index derived from the sub-indices listed in Table 1. RIS reflects the safety level quantitatively from the pre-accident aspect.

To sum up, the systematic safety evaluation indices is shown in Table 1.

Table 1 Systematic evaluation indices of highway operation safety

<table>
<tr><th>Category</th><th colspan="3">Index</th></tr>
<tr><td>Indices relating to accident characteristics</td><td colspan="3">Accident Rate (AR)</td></tr>
<tr><td>Indices relating to traffic flow characteristics</td><td colspan="3">Traffic Flow Safety (TFS)</td></tr>
<tr><td rowspan="9">Indices relating to road infrastructure characteristics</td><td rowspan="9">Road Infrastructure Safety (RIS)</td><td rowspan="2">Main Body Safety(MBS)</td><td>Alignment Continuity(AC)</td></tr>
<tr><td>Pavement Condition Index (PCI)</td></tr>
<tr><td rowspan="5">Traffic facilities Safety(TFS)</td><td>Sign and Mark Safety(SMS)</td></tr>
<tr><td>Safety Facility Safety(SFS)</td></tr>
<tr><td>Illumination Facility Safety(IFS)</td></tr>
<tr><td>Monitor Facility Safety(MFS)</td></tr>
<tr><td>Communication Facility Safety(CFS)</td></tr>
<tr><td colspan="2">RoadSide Safety(RSS)</td></tr>
<tr><td colspan="2">Safety Management Level(SML)</td></tr>
</table>

Indices relating to accident data can reflect the safety level directly, but its randombility leads to the incredible result probably. Numerous research works show the strong relationship between the occurrence of accidents and the traffic and road infrastructure characteristics. In othre words, the indices relating to the traffic and road infrastructure characteristics can reflect the safety level indirectly but effectively. Furthermore, these two kinds of indices are more stable and credible compared with accident index. The systematic indices can provoide the information about operation safety to the road management agency from three different angles. Thus, the comprehensive assessment of highway operation safety level can be achieved by use of three kinds of indices mentioned above.

3.3 Evaluation models of highway operation safety

With respect to evaluation models, previous studies have provided valuable insight regarding the methodologies formulated for accident analysis. Several approaches have been developed and refined to provide safety performance estimates, including historical accident data averages, predictions based on statistical models, results from before-and-after studies, and expert judgments made by experienced engineers. Each of these methods, if used alone, has significant weaknesses. On the contrary, there is an advantage to combining elements of each of these methods. Due to the difference among the three kinds of indices, we should discuss the correspionding models separately in the following section, applying different mathematical theories.

3.3.1 Model for indices relating to accident characteristics

So far, there has been an established consensus among traffic safety researchers that a non-linear, non-Gausian relationship exists between traffic exposure and safety. This relationship is reflected by the Safety Performance Functions (SPF) calibrated for various classes of roads.

Based on substantial empirical evidence derived from observing safety performance of various roads over extended time periods as well as work of other researchers, the following model form for SPF is usually employed.

$$E\{y\} = X^{\beta_0}(1 + \beta_1 X + \beta_2 X^2 \Lambda)$$

Here, E{y} is the annual number of accidents expected to occur on a segment of road(AR), X is the independent variable (AADT), and β are parameters to be estimated. With the poisson distribution assumption of accident, the model parameters were estimated by the maximum-likelihood method.

Safety Performance Function provides a realistic estimate of expected accident frequency per unit of traffic exposure over a unit of time for various types of transportation facilities. If the level of safety predicted by the SPF will represent normal or expected number of accidents at a specific level of AADT, then the degree of deviation from the norm can be stratified to represent specific levels of safety. The delineated boundary line is located 1.5 standard deviations from the mean. Four Levels of Safety (LOS) can be proposed shown in figure 1, and the qualitative descrioption is presented in Table 2.

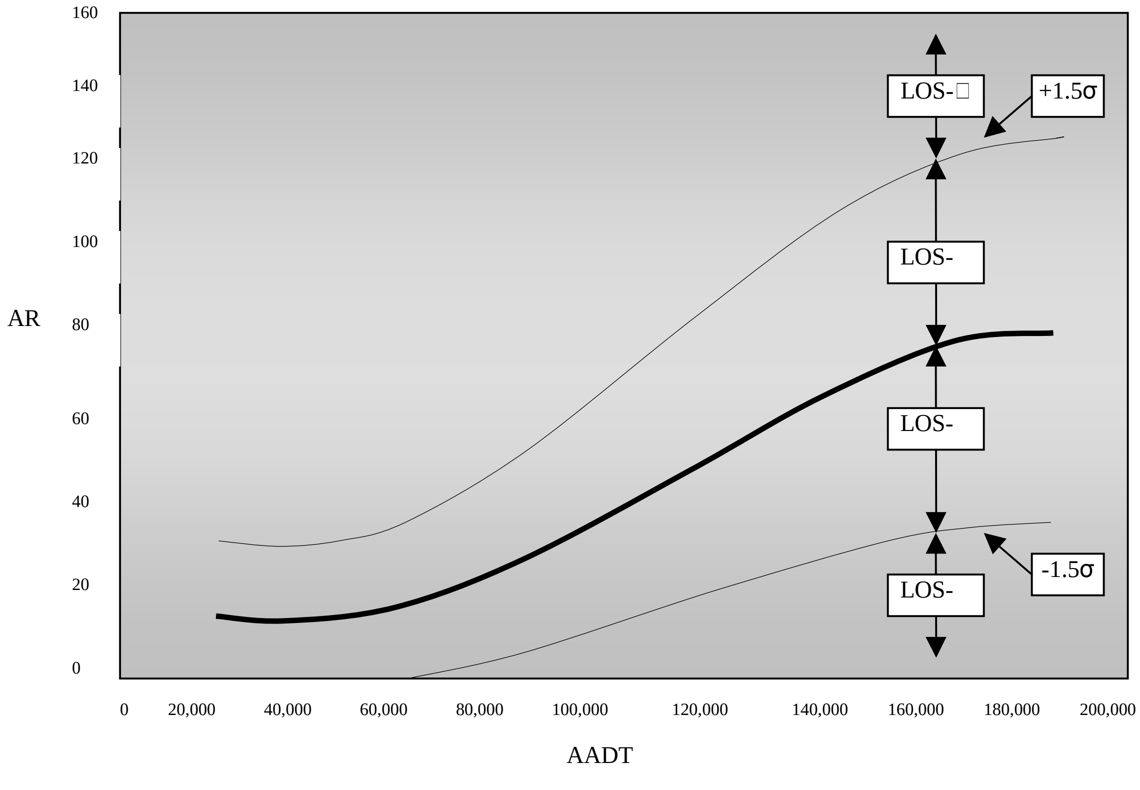

Figure 1 LOS/SPF Graph

Table 2 Qualitative description of LOS based on AR

Level Of Safety	Qualitative description
AR -☐	low potential for accident reduction
AR -☐	better than expected safety performance
AR -☐	less than expected safety performance
AR -☐	high potential for accident reduction

3.3.2 Model for indices relating to traffic flow characteristics

Since Traffic Flow Safety (TFS) derives from Unsafety Density(UD) , we should discuss UD before modeling TFS. UD is the sum of the Unsafety parameter of each vehicle in traffic flow, calculated based on the speed of each vehicle and the following vehicle and the distance between them. UD reflects the potential risk of vehicle following and lane changing behavior in traffic flow. Thanks to the development of image identification technology, it's possible to get the speed and distance information in traffic flow from the visual record shot by video camera. Hence, the calculation of UD will be resolved soon. Of course, we can also adopt the microsimulation technology to get the parameter needed for the calculation of UD.

The risk of traffic flow always exist, so we can get the value of UD at any time, which reflecting the realtime safety of traffic flow. Through analyzing the values of UD in a certain period, we can get the traffic flow safety information in this period. We use 85th percentile UD(UD_{85}) in a certain period as the representative of traffic flow safety. In this way, the value of Traffic Flow Safety(TFS) in a certain period equals the value of UD_{85} during the same time.

Similar to AR, we can propose four levels of safety based on TFS, and the qualitative description of each level is shown in Table 3. It should be mentioned that the quantitative boundary of each level is still on the research.

Table 3 Qualitative description of LOS based on TFS

Level of safety	Qualitative description
TFS-☐	Very low and acceptable risk exist in traffic flow
TFS-☐	Low and conditionally acceptable risk exist in traffic flow
TFS-☐	Hign and unexpected risk exist in traffic flow
TFS-☐	Vey high and unacceptable risk exist in traffic flow

3.3.3 Model for indices relating to road infrastructure characteristics

Considering the fuzzy character of indices relating to road infrastructure characteristics, a fuzzy model of the safety assessment for road infrastructure was established by applying the fuzzy set theory. The facilities that affect highway safety have been hierarchically divided, and fuzzy judgment matrix has been established on the basis of specifications and certain statistic data. Then Two-level fuzzy comprehensive judgment is made to assess safety rank of rural highway infrastructure, obtained through weights and scores assigned to different kinds of facilities. The relative weights were estimated by professionals in the field of road safety using the hierarchical analysis method. The scores assigned to the road facilities result from field inspections.

According to the evaluation result, four levels of safety based on RIS has been proposed and the qualitative description of each level is shown in Table 4.

Table 4 Qualitative description of LOS based on RIS

Level of safety	Qualitative description
RIS -□	Safety performance of road infrastructure is enough, low potential for improvement
RIS -□	Safety performance of road infrastructure is better than average
RIS -□	Safety performance of road infrastructure is less than average
RIS -□	Safety performance of road infrastructure is not enough, high potential for improvement

The model of AR reflects how the highway section is performing in regard to its expected accident frequency at a specific level of AADT. It only provides an accident frequency comparison with the expected norm, it does not, however, provide any information related to the nature of the safety problem itself. The model of TFS reflects the nature of accidents occurrence, but it still does not provide treatment for safety improvement. The model of RIS estimates not only the integrated safety performance of road infrastructure as a whole, but also the safety performance of every single facility. Therefore, it allows the identification of the main safety deficiencies present in highways and provides reference to problem diagnose and treatment selection.

3.4 Identification of highway Operation Safety Condition(OSC)

3.4.1 Vector form of OSC

Highway operation safety condition(OSC) consists of many attributes, e.g. accident rate, traffic flow characteristics, road infrastructure characteristics. Each of them reflect the operation safety level from the different angle. In order to define the highway operation safety condition more exactly, the vector form of OSC is recommended.

According to the evaluation results attained from the systematic indices and models, shown in Table 5, AR, TFS and RIS were selected as elements of the OSC vector.

Table 5 Classification of OSC vector

Class	AR	TFS	RIS
1	AR -□	TFS-□	RIS -□
2	AR -□	TFS-□	RIS -□
3	AR -□	TFS-□	RIS -□
4	AR -□	TFS-□	RIS -□

Each element of OSC vector has four classes, so the combination of different classes of three elements has 4×4×4=64 kinds of conditions in all. Hence, OSC has 64 kinds of states. Each state can be represented as the following vector form.

$$OSC_i = \left(AR_j, TFS_k, RIS_m\right)$$ □i=1,64; j, k, m =1,4□

3.4.2 Integrated index of OSC

The integrated index of OSC is defined as:

$$OSC_i = a_1 \frac{AR_i}{AR_0} + a_2 \frac{TFS_i}{\overline{TFS}} + a_3 \frac{RIS_i}{\overline{RIS}}$$

where

AR_i ——the value of AR in section i;

AR_0 ——the expected AR decided by SPF;

TFS_i ——the value of TFS in section i□

$\overline{TFS}$ ——the average of TFS of all sections;

RIS_i ——the value of RIS in section i□

$\overline{RIS}$ ——the average of TFS of all sections□

a_1, a_2, a_3 ——the weight decided by hierarchically analytical method.

The vector form of OSC can present the information of each attribute of OSC, so it helps to diagnose the safety problems and select treatments. However, it's easy to compare the safety level of different sections and prioritize the improvement projects using the integrated index of OSC. We use both of them in highway operation safety management.

5. Prediction technique of highway operation safety

4.1 Time-sequence prediction model

Time-sequence prediction model is a popular prediction model used in many different fields. The state of OSC is changing as time going, so the model is also suitable in prediction of highway operation safety. In this model, each evaluation index in table 1 is predictied by analyzing its movement rules. Then the future state of OSC can be evaluated with the future value of each evaluation index.

4.2 Markov prediction model

Markov model is a dynamic random model based on the system state and the transition among different states. According to the assumption of Markov theory, if the original state of OSC is determined by investigation and evaluation, and the state transfer probability matrix for different classes of sections is decided, the future state of OSC can be estimated by Markov prediction model.

4.2.1 Prediction process using Markov prediction model

There exist 64 kinds of states of OSC, as mentioned in secion 3. According to evaluation result, the present probability distribution of each state of OSC $\{p_i\}$ is determined as follows:

$\{p_i\}$=the number of sections in the state of OSC_i/the number of sections in all □i=1,64□

The state transfer probablity matrix **P** is calculated as follows:

$P = \{p_{ij}\}$ = the number of sections transfering from the state of OSC_i to the state of OSC_j/ the number of sections in the state of OSC_i □i,j=1,64□

$\sum_{j=1}^{64} p_{ij} = 1$, for i=1□64.

Following this, the futrure state of OSC can be estimated as follows:

$$\{p_{i+1}\} = \{p_i\} \cdot \{p_{ij}\}.$$

4.2.2 State transfer probability matrix

State transfer probability matrix is the core of Markov prediction model, determining the tranfer probability from one state to another state. Obviously, the state transfer probability matrix differ among different type of section, thus we should establish state transfer probability matrix for each type of section.

There are three methods to estimate the state transfer probability matrix: expert judgement, statistics and regression analysis. Since the data on highway operatiion safety is not enough to take statistical analysis, we use expert judgement and regression analysis to get the state transfer probability of each element of OSC. The state transfer probability of OSC can be obtained as follows:

$$p_{s_{n_1,n_2}} = p^{AR}_{i_1,i_2} \times p^{TS}_{j_1,j_2} \times p^{FS}_{k_1,k_2}$$

Where

$p_{s_{n_1,n_2}}$ ——The transfer probability of OSC from state n_1 to state n_2 □

$p^{AR}_{i_1,i_2}$ ——The transfer probability of AR from class i_1 to class i_2 □

$p^{TS}_{j_1,j_2}$ ——The transfer probability of TFS from class j_1 to class□

$p^{FS}_{k_1,k_2}$ ——The transfer probability of RIS from class k_1 to class□

n_1 —— the sate of OSC when AR is in class i_1, TFS is in class j_1 ,and RIS is in class k_1, n_1 =1□64□

n_2 ——the sate of OSC when AR is in class i_2, TFS is in class j_2 ,and RIS is in class k_2, n_2 =1□64.

6. Decision technique of highway operation safety management

5.1 Feasible treatment selection

After identification of the problematic sections, the more important thing is to reveal existing inadequacies in the road environment that may induce accident generation and propose the feasible treatment during static highway safety management.

Based on past experience and expert judgments, a knowledge base has been developed to analyze the nature of the safety problem and provide the feasible treatment. The knowledge base consists of typical treatments base and a number of rules. through the rules, accident, traffic flow and road environment characteristics are examined to identify specific deficiencies. Following this, remedial treatments in typical treatments base are selected to remove or diminish the effect of observed deficiencies. Rules may include single or multiple if-then statements. The rules require a qualitative assessment for a parameter (e.g.the pavement condition is good, fair, or poor). Most rules refer to the characteristics of the specific road section, while others request information from neighboring sections. A rule outcome may be a single treatment or a number of alternative treatments with variable effectiveness that can be applied individually or in combination.

The output of the knowledge base is a list of likely measures for safety improvements. The highway safety management agency can examine the list and make the final decision considering the particular characteristics of the section under investigation. Single or multiple treatments may be selected depending on the magnitude of the problem and estimated treatment effectiveness as well as technical and economic considerations.

5.2 Decision models for safety resource allocation

5.2.1 Weighted-objective linear programming model

Decisions for resource allocation are based on the priority list, the set of alternative treatments in each case, and the budget constraints. Here, the integrated index of OSC can be regarded as priority index. A goal programming technique could be used. More specifically, if y_{ik} is a zero-one variable that indicates whether or not treatment *k* is applied to section i, c_{ik} is the corresponding cost, and a_{ik} is an index representing the effectiveness of treatment *k*, then a weighted-objective linear programming model of the following form can be employed:

$$\max \sum_i \sum_k OSC_i (a_{ik} + b) y_{ik}$$

Subject to

$$\sum_i \sum_k c_{ik} y_{ik} \le B$$

$$\sum_k y_{ik} \le 1, \forall i$$

where

OSC_{ik}——priority index for section i□

a_{ik}——index representing the effectiveness of treatment *k*,□

c_{ik}——the corresponding cost of treatment *k*□

y_{ik}——zero-one variable that indicates whether or not treatment *k* is applied to section i□

b——weighting coefficient□Low values of *b* would result in high-effectiveness treatments in a limited number of sections with high priority. High values of *b* would lead to an increased number of sections treated but with less-effective treatments.

B——available budget.

5.2.2 Markov decision model

By use of Markov prediction model in section 4, the transfer probability of OSC from state i to state j ($p_{ij}(a_k)$)can be determined after the implementation of a certain treatment a_k. In consequence, the future OSC can be estimated according to the present OSC and the treatment selected. If the management objective is determined and the cost of treatment is calculated, then the decision can be made to meet the object at the lowest cost using Markov decision model. The state transfer probability matrix can be obtained through expert judgement, statistics and regression analysis.

In Markov decision model, the decision variable is the proportion of sections in the state of OSC$_i$, i.e. W_{ik}, after implementing treatment a_k. If q_i means the proportion of sections in OSC$_i$ after making decisions, i.e. implementing a series of treatments, then $q_i = \sum_k W_{ik}$. C_{ik} means the cost of implementing treatment a_k in the sections in the state of OSC$_i$. The objectives are to realilze the lowest proportion of sections in the permitted state of OSC and the highest proportion of sections in the unaccepted state of OSC. The target function is to minimize the management cost in the next period. The model is as follows:

$$\min : \sum_{ik} W_{ik} C_{ik}$$

Subject to

$$W_{ik} \geq 0$$

$$\sum_{k} W_{jk} = \sum_{i,k} W_{ik} \cdot p_{ij}(a_k) = q_j$$

$$\sum_{i,k} W_{ik} = 1$$

$W_{ik} = 0$ □if a_k is not siutable to OSC$_i$□

$\sum_{s,k} W_{ik} \geq \varepsilon \quad (i \in s)$ —— s means the permitted OSC

$\sum_{u,k} W_{ik} \leq \gamma \quad (i \in u)$ ——u means the unaccepted OSC

7. Conclusions

In recent years, increasing public pressure for a safer road environment has led to a more systematic consideration of accident causes and remedial measures. However, highway management agencies encounter a number of difficulties in decision making that include identification of problematic sections, treatment selection and resource allocation among competing objectives within resource availability.

In this paper, the core techniques of static highway safety management during operation period were discussed. The systematic evaluation indices of highway operation safety has been established, which includes not only accident data, but also traffic flow and road infrastructure characteristics. The corresponding evaluation models has been presented. On the basis of evaluation results, the state of highway operation safety was defined, represented as two forms: the vector form and the integrated index. The identification of the state of highway operation safety provide more information to highway managers from different angles so as to help diagnose the safety problem and propose treatments. Following this, the prediction technique was studied and two prediction models were introduced, which are Time-sequence prediction model and Markov prediction model. The prediction information also helps highway managers to make decisions. Last but not least, the decision technique of highway operation safety management was presented. A knowledge base was developed to provide feasible treatments. And two decision models, Weighted-objective linear programming model and Markov prediction model, were provided.

Future research is directed toward enhancing data collection for improving evaluation and prediction models and the knowledge base both quantitatively and qualitatively. In another direction, an effort to establish treatment costeffectiveness estimates would lead to an integrated approach to highway safety management and resource allocation.

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