The Evaluation of the Effectiveness of Existing Safety Facilities in Highway Tunnels

Shuohan1*, Jinliang Xu2, Menghua Yan3, Sunjian Gao4 and Hui Wen5
1School of Highway, Chang’an University, Xi’an, ShanXi, 710000, P.R.China
2School of Highway, Chang’an University, Xi’an, ShanXi, 710000, P.R.China
3School of Highway, Chang’an University, Xi’an, ShanXi, 710000, P.R.China
4School of Highway, Chang’an University, Xi’an, ShanXi, 710000, P.R.China
5CCCC Investment Company Limited, Beijing, 100000, P.R.China
*shuohan@chd.edu.cn
*Corresponding author’s e-mail: hanshuo1110@163.com

Abstract: Known as “the throat of road”, the tunnels endow with semi-enclosed structure, which is a big challenge for the road safety. A large number of safety facilities have been installed in tunnels to raise the driving safety. However, the real effects of these facilities tend to lack of scientific researches and assessments. Therefore, this paper focuses on the evaluation of the effectiveness of several common safety facilities, including variable message boards, flashing lights, over-speed snapshots, and speed-control humps, aiming to provide some technical references for the design of tunnel safety facilities. In this study, the numerous field experiments have been conducted to collect vehicle speed data at four forward and backward sections of safety facilities, selecting the difference in the speed before and after the safety facilities as a major evaluation index. On the basis of improved entropy method TOPSIS, the comprehensive evaluation model is built to evaluate the efficiency of safety facilities in tunnels, and the function characteristics and actual effects of various safety facilities are given.

1. Introduction

At present, the majority of the available evaluation systems are established from the perspective of the design of facilities in tunnels. They tend to build up the analysis and evaluation model through characterization of the design parameters including the appearance of facility, installation conditions, recognizability, and so forth, followed by the attaching corresponding weights and values for evaluation. The subjectivity involved in the aforementioned evaluation process is too large to assess the practical effects of facilities objectively. For example, the actual impact of safety facilities in tunnels on the road safety has not been clearly known yet. Also, the exact influence of safety facilities on coordination ability of road traffic operation remains unrationlized now [1-4].

Herein, we focus on the actual applications of the existing safety facilities in highway tunnels, and the effectiveness of the common safety facilities existed in tunnels has been investigated in this work. It is anticipated that the comprehensive evaluation approach proposed here will shed light on the design and installation of safety facilities in tunnels.
2. Characteristic Analysis on Traffic Accidents in Tunnels

As an important index to evaluate the safety of a specific road segment, the traffic accident rate has been widely used for the safety evaluation of highway. In this work, the characteristics of traffic accident are based on the data collected from the highway tunnel segments in our research project. The highway involved here spans 62.5 km, and it feature bi-directional four-lane standard with the designed speed of 120 km/h. There are 8 tunnels on the whole line, consisted of 4 short and 4 medium tunnels. On the basis of the calculated all-line accident rate, the whole line average accident rate is 1.268 at per million vehicle kilometer during the five years from 2013 to 2017, among which the highest traffic accident rate occurs in 2013 of 1.376 at per million vehicle kilometer. The results of annual accident rate of the typical tunnel segments are listed in Table 1.

Table 1. Traffic accident rate of the tunnels

| Tunnel number | Average annual accident rate during 2013-2017 (at per million vehicle kilometer) |
|---------------|---------------------------------------------------------------------------------|
| 1             | 0.957416                                                                         |
| 2             | 1.523137                                                                         |
| 3             | 0.977269                                                                         |
| 4             | 0.674196                                                                         |

As can be seen from the results obtained above, there is an obvious difference of the accident rates between tunnels and general sections accident rate exists many differences compared to the general road segment. Generally speaking, the linear conditions, flat aspect ratio, as well as combinations of horizontal curves in tunnels are well designed, which are superior to those in general sections. As a consequence, the frequency of the traffic accidents caused by the inferior design of routes is relatively reduced, which is an essential factor for the lower partial tunnels accident rate than that in the whole line. Meanwhile, the semi-enclosed structure and the induced insufficient brightness in tunnel segments would exert adverse influences on drivers in both perception and psychology, misleading them into making incorrect judgments. Hence, the risk of driving safety would be raised a lot, and the accident rates of several tunnels are significantly higher than that in the whole line average level. Taking the difference of accident rates between tunnels and general road segments into consideration, it is vital to set up the various safety facilities in a more reasonable and effective way according to their own characteristics for highway tunnels.

In addition, the investigation of the accidents black-spots in tunnels was also carried out. Based on the collected information about the installation of safety facilities around accident-prone areas together with the field researches about numerous highways in China, the existing safety facilities in tunnels is classified. Judged by the traffic accident rate, the conclusion can be drawn that the traffic accidents is closely related to the application effectiveness of the variable information versions, flashing lights, snapping overspeed systems and the forced speed bumps, which is in favor of determining the object for this study.

3. Selection of Effectiveness Evaluation Method and Index

Most of the effects of people, cars, roads and environment can be directly reflected on the speed of driving vehicles. And lots of mature theoretical results and the related regulatory standards have already been proposed for the research of vehicle speed and road safety. Thus, the vehicle speed is selected as a major evaluation index, and the method of effectiveness assessment for safety facilities is established in this study [5-8].

Specifications for Highway Safety Audit (JTG B05-2015) proposed definite requirements for the operating speed (85% speed) and the changing value of speed gradient of adjacent segments on road, which can reflect the coordination of road operation. Research results show that there is a closed relationship between the degree of speed deviation and the traffic accident rate, model about which has
been built up [9]. This work is conducted for the purpose of evaluating the effectiveness of the existing safety facilities in highway tunnels, and the practical effect of safety facilities in tunnels has been put emphasis on. The vehicle speed is selected as the main evaluation index, and the effectiveness of safety facilities in influencing the coordination of road operation, regulation of light and heavy vehicle speed, overspeed management and accident rate control is evaluated based on the average speed, 85% speed, speed gradient distribution, and the degree of speed deviation.

4. Effectiveness Evaluation Based on the TOPSIS

Based on the modification of entropy weight, the Technique for Order Preference by Similarity to Ideal Solution (abbreviated as TOPSIS) method, also known as the “ideal point method”, is a sorting method closed to the ideal solution. Principle of this method is to construct the ideal solution via the design of multi-objective evaluation problems, followed by calculation of the distance between each evaluated object and the ideal solution and judgement of the superiority and inferiority orderly. Such method features objective in evaluation, scientific in principle, and clear in results. And most importantly, the evaluation difference caused by the subjective preference can be effectively avoided.

Assuming that the number of safety facilities in tunnel and decision problem of evaluation index are \( n \) and \( m \), respectively, and the decision matrix is \( A = (a_{ij})_{mxn} \), the basic steps are as follows:

- Toward the comprehensive evaluation index systems for the existing safety facilities in tunnels, both positive and negative indexes are included. Specially, only the positive index exists in this study, which is more convenient and available with a simple conversion process of \( a_{ij} = X_{ij} \). So the homotactic decision matrix can be easily obtained as shown in the equation:

\[
X = \begin{bmatrix}
X_{11} & X_{12} & \cdots & X_{1n} \\
X_{21} & X_{22} & \cdots & X_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
X_{m1} & X_{m2} & \cdots & X_{mn}
\end{bmatrix}
\]

The normalized decision matrix is shown in the equation:

\[
Y_{ij} = \frac{X_{ij}}{\sqrt{\sum_{i=1}^{m} (X_{ij})^2}}, (i=1,2,\ldots,m; j=1,2,\ldots,n)
\]

The entropy index and index weight are given in the following equation, respectively:

\[
p_j = \frac{\frac{1}{m} \sum_{i=1}^{m} p_i \ln p_i, i=1,2,\ldots,m; j=1,2,\ldots,n;}
\]

\[
H_j = -\frac{1}{n} \sum_{i=1}^{n} p_i \ln p_i, i=1,2,\ldots,m; j=1,2,\ldots,n;
\]

\[
\omega_j = \frac{1-H_j}{n-H_j}, j=1,2,\ldots,n;
\]

\[
W = \begin{bmatrix}
\omega_1 & 0 & L & 0 \\
0 & \omega_2 & L & 0 \\
M & M & O & 0 \\
0 & 0 & L & \omega_n
\end{bmatrix}
\]

The normalized weighted decision matrix is constructed and shown in the equation:

\[
Z_{ij} = Y_{ij}W_{ij}, i=1,2,\ldots,m; j=1,2,\ldots,n
\]
The ideal solution $Z^+$ and the negative ideal solution $Z^-$ are denoted as $Z^+ = \left(z^*_1, z^*_2, ..., z^*_n \right)$ and $Z^- = \left(z^-_1, z^-_2, ..., z^-_n \right)$, respectively. Among them, the basic factors are defined and shown in the equation:

$$z^*_i = \max \{y_{ij}\}, z^-_i = \min \{y_{ij}\}, i = 1, 2, ..., n, j = 1, 2, ..., m$$

Calculation of the distance $D$ between various safety facilities and “ideal solution” as well as the negative ideal solution, and the degree of relative proximity $C$ of safety facilities with the ideal solution. The calculated results for the parameters of $D$ and $C$ are shown in the equation, where the larger the degree of relative proximity is, the better the comprehensive evaluation of the effectiveness of safety facilities in tunnels will be.

$$C = \frac{D}{D + D^-} = \frac{\sqrt{\sum (x_i - z^*_i)^2}}{\sqrt{\sum (x_i - z^-_i)^2}}$$

The ranking of tunnel safety facilities is based on the value of relative proximity in the order of $C = \max \{C_i\}$ Combined with the effectiveness comprehensive evaluation index system of the existing safety facilities in tunnel, the related indicators of the four evaluated safety facilities are shown in Table 2. And the comprehensive evaluation results of the effectiveness of safety facilities in highway tunnels are listed in Table 3.

| Categories | Variable information boards | Flashing lights | Snapping overspeed systems | The forced speed bumps |
|------------|-----------------------------|-----------------|---------------------------|-----------------------|
| Mean value of light vehicles | 2.6344 | 9.4396 | 4.4527 | 8.7401 |
| Mean value of heavy vehicle | 5.9445 | 8.0171 | 1.6269 | 12.9842 |
| Decrease in overspeed rate | 5.8300 | 13.8200 | 21.4700 | 3.5700 |
| Decrease in dispersion for light vehicles | 1.0478 | -1.5320 | -1.7076 | -5.8230 |
| Decrease in dispersion for heavy vehicles | 1.5435 | 2.2876 | 0.6555 | -6.2426 |
| Decrease in dispersion for all vehicles | -0.0622 | 0.0128 | 0.1647 | -1.4649 |

| Safety facilities in tunnels | The optimum proximity |
|-------------------------------|------------------------|
| Variable information boards   | 0.6630                 |
| Flashing lights               | 0.5934                 |
| Snapping overspeed systems    | 0.5499                 |
| The forced speed bumps        | 0.0784                 |

5. Conclusions
In summary, the larger the comprehensive effectiveness is, the better the overall performances will be in ensuring the safety of tunnel operation. However, it should be paid much attention on the difference of various safety facilities in different aspects. For example, although the forced speed bumps does not
Perform well in reducing the speed dispersion, they are prominent in the speed control especially for heavy vehicles. Therefore, the featured characteristics of various safety facilities should be fully taken into account before installation in highway tunnels. On the basis of certain functional properties, it is more reasonable and effective to set up safety facilities in the corresponding positions with target to the specific characteristics of traffic accident in tunnels. It is anticipated that the optimal effectiveness stands out for the safety facilities to be installed, facilitating the tunnel segments keeping in safe operation.

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