Traffic & Transportation

Study on the Safety Management of Connected and Autonomous Vehicle Test Roads Based on the Evaluation of Traffic Safety Facilities

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Original Scientific Paper
Submitted: 18 Mar. 2023
Accepted: 11 July 2023

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Publisher:
Faculty of Transport and Traffic Sciences, University of Zagreb

ABSTRACT

More and more connected and autonomous vehicle (CAV) open test roads reconstructed on the basis of traditional roads have appeared in China. However, the management policies vary, which makes the traffic environment complicated. This paper takes CAV test road safety management as the research aim and investigates the open test condition through the evaluation of the traffic safety facilities. Indicators were rigorously screened, then the game theory model was used to determine the combination weight of the indicators, and the set pair analysis was applied to solve the uncertain problems. A case study for the CAV test road network of a city in central China was implemented and the results show, regarding the traffic safety facilities' condition, among the 20 sections of the city's CAV test road network, 15% of which are at an excellent level, 75% of which are at a good level and 10% of which are at a moderate level; road signs, guardrail facilities, isolation facilities and road features are the main limiting factors affecting the level of traffic safety facilities. Based on the results, recommendations have been made for the transport management authorities in the aspects of safety management policy-making and facilities maintenance.

KEYWORDS

CAV test road; traffic safety facilities; evaluation; game theory model; set pair analysis; safety management.

1. INTRODUCTION

Road safety has always been a topic of concern to scholars; many related studies were carried out to analyse which are the important influence factors and their effects. By exploring the relationship between different factors and crash rate, previous studies have confirmed that there is a statistical correlation between road environment and the risk of road crashes [1–3].

As a kind of road infrastructure device designed to ensure road safety, traffic safety facilities are an important part of the road environment. They cover a range of safety measures, including pedestrian tunnels, pedestrian bridges, lighting facilities, signs, markings, guardrails, isolation facilities, sight-guiding facilities, anti-glare facilities, deceleration hills and escape lanes. Conducting the evaluation study of the traffic safety facilities to measure their performance will help to reduce road crash risk or severity and improve road safety management levels.

Countries around the world attach great importance to traffic safety facilities and have introduced a series of standards, specifications and manuals to specify their attributes, performance and location, so as to maintain facility consistency and ensure driving safety. For example, America gathered all the requirements for safety facilities in the "Manual on Uniform Traffic Control Devices"; the relevant standards of traffic safety facilities in China were scattered throughout different national standards and industry standards. In the

1980s, research concerned with evaluating road safety had already begun in the United Kingdom, where the road safety evaluation standard was issued in 1990 to standardise the basic content, methods and steps of road safety review. The Australian Road Association published the Road Safety Evaluation Guidelines in 1994 and 2002, and Canada officially promulgated their "Road Safety Review Guidelines" in 2001, which promoted the application of road safety reviews in other countries.

Studies on the evaluation of traffic safety facilities focused mainly on the indicator systems, models and methods, such as the study of Wang et al.; they constructed an effective evaluation indicator system for traffic safety facilities by analysing and evaluating the number of road crashes and traffic violations of road sections [4]. Koscianski et al. constructed an indicator system based on the comprehensive analysis of problems associated with traffic safety facilities and determined an evaluation method based on the analytic hierarchy process (AHP) [5–9]. Wang and Yao et al. used the fuzzy comprehensive evaluation method and set pair analysis to solve some ambiguous problems and applied three major tools of fuzzy theory in the evaluation of complex traffic safety facilities [10–13].

Scholars have achieved certain results in studies related to the evaluation of traffic safety facilities, but most of them were focused on the evaluation and optimal design of highway or urban expressway traffic safety facilities, among which the AHP and the fuzzy comprehensive evaluation method were the most commonly used. With the development of CAV technology, safety management of the CAV test road has become an important issue. For the CAV test road users and the transport management authorities, in the pursuit of absolute safety in human-driven vehicles and CAVs mixed traffic environment, traffic safety facilities are always one of the most important factors to be considered, in spite of the fact that CAVs are equipped with active obstacle avoidance devices. Therefore, in order to understand thoroughly the conditions of the traffic safety facilities system and which are the key indicators for the safety of CAV test roads for the purpose of promoting fine safety management, this paper has conducted an evaluation of the traffic safety facilities to assess the CAV roads' open test condition (or status). Unlike the previous studies, in terms of the evaluation methods, this paper used subjective and objective analysis on the basis of the game theory to determine a combination weight, which could greatly reduce the risk of weight distortion. In addition, the concept of connection degree was introduced during the set pair analysis to deal with the uncertainty in the evaluation, which made the final evaluation model more objective and scientific. A case study was carried out and the results have been obtained.

2. METHODOLOGY

2.1 Determination of the evaluation scope

CAV test road facilities are generally composed of three parts: traditional infrastructures, communication facilities and perception-computing facilities, all of which have the function of ensuring road safety. It is assumed that the technology of the CAV itself is mature, and in a mixed traffic environment, the potential safety hazards for the CAVs on the test road mainly come from the interference of human-driven vehicles, the performances of which depend highly on the condition (or status) of the traditional infrastructure. Therefore, the evaluation in this paper involved only the traditional traffic safety facilities of the CAV test road.

2.2 Determination of the evaluation indicators

Selection principles

CAV test road is a complex system. In order to ensure a universal applicability of the model, the indicators selected should possess the characteristics of comparability, representativeness and comprehensiveness. Also, the data should be measurable, operable and able to fully and truly reflect the reality of the object studied.

In this paper, the determination of the indicators for the traffic safety facilities of the CAV test road conformed to the following principles:

- System validity. The selected indicators should be able to objectively reflect the level of the safety facilities of the CAV test road, and be universally applicable in the evaluation of the kind.
- Data operability. The selected indicators should be easily observed and comprehended. The description of the indicators should be concise and precise.
- Combination of the qualitative and quantitative parameters. The indicator system should include quantitative indicators and at the same time qualitative indicators which are important.

Selection steps and methods

Indicator primary selection. In order to ensure the integrity of the indicators as much as possible, the first step in the selection process of indicators was to refer to the existing research literature [14–17], relevant norms and standards. In the initial set of indicators, 33 indicators, categorised to reflect the service performance, material quality and environmental and aesthetic effect (see notes below the *Table 1*) of the facilities were identified from 8 sub-systems of the evaluation object. As shown in *Table 1*.

Table 1 – Initial evaluation indicators for the traffic safety facilities of the CAV test road

Sub-system	Indicator
Road sign	"recognise-ability" of road sign*, completeness of road sign*, uniformity of road sign*, consistency of road sign*, legibility of road sign information*, retro-reflectivity of road sign**, breakaway sign usage**, environmental and aesthetic effect of road sign***
Road marking	"recognise-ability" of road marking*, durability of road marking**, slip resistance of road marking**, light-reflecting effect of road marking**
Guardrail facility	stability of guardrail foundation**, anti-collision performance of guardrail*, re-directive performance of guardrail*, environmental and aesthetic effect of guardrail***, structure rationality of guardrail terminal**
Isolation facility	height of isolation facility*, continuity of isolation facility**, environmental and aesthetic effect of isolation facility***
Anti-glare facility	height of anti-glare facility*, continuity of anti-glare facility**, environmental and aesthetic effect of anti-glare facility***
Sight-guiding facility	light-reflecting effect of sight guidance facility**, sight-guiding performance*, reflective film adhesion**
Lighting facility	energy conservation of lighting facility**, light brightness*, consistency of lighting facility*, environmental and aesthetic effect of lighting facility***
Road feature	road surface roughness*, road smoothness*, stability of road foundation**

** service performance, ** material quality, *** environmental and aesthetic effect*

Indicator screening. After the first step, in order to examine whether all the indicators have a significant impact on the evaluation results, and to further rationalise the indicators to be selected, an analysis of the indicators based on the importance measure was carried out by using the Delphi method. In this step, all the indicators about environmental and aesthetic effects and other indicators like breakaway signs usage, structure rationality of guardrail terminal, energy conservation of lighting facility and stability of road foundation were excluded according to experts' advice based on the results of the importance measure.

Indicator streamlining. Since the indicators selected in the previous step reflected the same problem, there was information overlap, which will cause collinearity problems between variables. Therefore, the information redundancy was checked and the principal component analysis (PCA) method was used to combine the indicators with high information overlap and correlation coefficient.

Selection results. Having followed the selection principles and procedures mentioned above, finally, 18 indicators from 8 sub-systems (or dimensions) were selected as the evaluation indicators. Results are shown in *Table 2*.

Description and value determination of the indicators:

– W11 ("recognise-ability" of road sign) – used to evaluate the information transfer function of the sign, it is not only related to the location but also affected by factors such as the font size and the reflective effect, and could be scored according to drivers' actual feelings through the satisfaction survey;
– W12 (completeness of road sign) – used to measure the gap between the actual number of signs and the number that should be set according to norms. It could be scored by the expert assessment on the basis of the data investigated;
– W13 (legibility of road sign information) – affected by the amount of information on the sign, the threshold of which is related to the road speed limit, i.e. when the road speed limit is 60 km/h, it is suggested to provide less than 30 messages/km. Therefore, the legibility could be scored by the expert assessment on the basis of the data investigated;

- W21 (“recognise-ability” of road marking) – referring to the degree to which the driver can clearly recognise the markings on the road when driving. It could be scored based on the drivers’ actual feelings;
- W22 and W23 (durability of road marking and slip resistance of road marking) – reflecting the material properties of the marking, it should be assessed by experts specialised in the material field;
- W31 (anti-collision performance of guardrail) – reflecting the collision energy that the guardrail can withstand, it should be assessed by experts specialised in the material field;
- W32 (re-directive performance of guardrail) – scored by the expert assessment on the basis of the length of different types of guardrails investigated;
- W41 (height of isolation facility) – determined by the average height of the facilities investigated;
- W42 (continuity of isolation facility) – reflecting facilities’ abilities to resist lateral interference, it could be scored according to drivers’ actual feelings;
- W51 (height of anti-glare facility) – determined by the average height of the facilities investigated;
- W52 (continuity of anti-glare facility) – scored according to drivers’ actual feelings as the intermittent setting of anti-glare facilities could cause potential dazzle to drivers;
- W61 (sight-guiding performance) – scored according to drivers’ actual feelings about the effect of delineators, diversion or confluence guiding marks, etc;
- W62 (reflective film adhesion) – assessed and scored by experts specialised in the material field;
- W71 (light brightness) – scored according to drivers’ actual feelings;
- W72 (consistency of lighting facility) – used to measure the gap between the actual number of lighting installations and the number that should be set as defined in norms. It could be scored by the expert assessment on the basis of the data investigated;
- W81 (road surface roughness) – reflecting the vertical deviation of pavement surface relative to ideal surface, it could be measured and scored by experts in the road design field;
- W82 (road smoothness) – reflecting the consistency between road geometric elements and facilities along the line, it could be measured and scored by experts in the road design field.

Table 2 – Evaluation indicators for the traffic safety facilities of the CAV test road

Sub-system	Indicator	Method of measurement
Road sign (W1)	“Recognise-ability” of road sign (W11)	Satisfaction survey
	Completeness of road sign (W12)	Investigation and verification
	Legibility of road sign information (W13)	Investigation and verification
Road marking (W2)	“Recognise-ability” of road marking (W21)	Satisfaction survey
	Durability of road marking (W22)	Expert assessment
	Slip resistance of road marking (W23)	Expert assessment
Guardrail facility (W3)	Anti-collision performance of guardrail (W31)	Expert assessment
	Re-directive performance of guardrail (W32)	Investigation and verification
Isolation facility (W4)	Height of isolation facility (W41)	Investigation and verification
	Continuity of isolation facility (W42)	Satisfaction survey
Anti-glare facility (W5)	Height of anti-glare facility (W51)	Investigation and verification
	Continuity of anti-glare facility (W52)	Satisfaction survey
Sight-guiding facility (W6)	Sight-guiding performance (W61)	Satisfaction survey
	Reflective film adhesion (W62)	Expert assessment
Lighting facility (W7)	Light brightness (W71)	Satisfaction survey
	Consistency of lighting facility (W72)	Investigation and verification
Road feature (W8)	Road surface roughness (W81)	Expert assessment
	Road smoothness (W82)	Expert assessment

2.3 Evaluation model

Determination of the indicator weight

The weight of the indicator is important in the evaluation system. If the weight setting is unreasonable, it cannot reflect the real situation of the evaluation object. In many cases, a simple average-weighted method is used, but it is too rough. The single weight-determination method also has defects, such as strong subjectivity and the inability to take into account the horizontal influence between indicators, which can easily lead to weight distortion. In an attempt to resolve these problems, this paper proposed a method which combined subjectivity and objectivity based on the principle of the game theory, namely, the game theory comprehensive weight method [18, 19].

Supposing $[w_1,w_2,\dots,w_s]$ represents the basic weight vector set, then *Equation 1* represents the linear combination of weight vectors w_k:

$$w=\sum_{k=1}^{s}\alpha_k w_k^T \tag{1}$$

where α_k is the linear combination coefficient, w is a possible weight vector under the basic weight vector set.

In order to find the consistency or compromise of the weight value, the linear combination coefficient α_j is optimised in *Equation 1*, which can minimise the deviation between the weight vector w and each weight vector w_k, *Equation 2* is the introduced countermeasure model:

$$\min\|\sum_{k=1}^{s}\alpha_j w_j^T - w_i^T\| \qquad (i=1,2,\dots,s) \tag{2}$$

The optimal derivative condition of *Equation 2* can be expressed by *Equation 3*:

$$\sum_{j=1}^{s}\alpha_j w_j w_j^T = w_i w_i^T \quad (i=1,2,\dots,s) \tag{3}$$

The weight coefficient vector $(\alpha_1,\alpha_2,\dots,\alpha_s)$ can be obtained by solving *Equation 3*, and then through normalisation, the combination weight is produced and expressed by *Equation 4:*

$$w^*=\sum_{k=1}^{s}\alpha_k^*\cdot w_k^T \tag{4}$$

Regarding the comprehensive weight, in the first stage, the AHP method and the entropy weight method are used respectively to solve the weights of all indicators, and then the collaborative goal of the subjective and objective weight value is found. *Equation 5* represents the linear equation system for solving the weight coefficient vector:

$$\begin{bmatrix} w_1\cdot w_1^T & w_1\cdot w_2^T \\ w_2\cdot w_1^T & w_2\cdot w_2^T \end{bmatrix}\begin{bmatrix}\alpha_1\\ \alpha_2\end{bmatrix}=\begin{bmatrix} w_1\cdot w_1^T \\ w_2\cdot w_2^T\end{bmatrix} \tag{5}$$

Determination of the evaluation level

There are many uncertainties in the evaluation of the traffic safety facilities of the CAV test road. The factors that affect the final evaluation results are not only the weights of the indicators but also the quality of the original data of the indicators, including the consistency, completeness and accuracy of the data. In this evaluation model, the set pair analysis method was used, and the concept of connection degree was introduced to transform the understanding of uncertainty into a specific mathematical problem. It is a new analysis method and uses the degree of connection to deal with the uncertain problems. It has been widely used in decision-making management, engineering technology and traffic engineering [20–23].

Assuming that, in an uncertain system, two associated sets X and Y, both have N characteristics, they can be expressed as:

$$X=(x_1,x_2,\dots,x_n),\ \ Y=(y_1,y_2,\dots,y_n) \tag{6}$$

Constructing a set pair of set X and Y, expressed as $H(X,Y)$. According to the relationship between identity, difference and opposition, their connection degree can be expressed as:

$$\mu(X,Y)=\frac{S}{N}+\frac{F}{N}i+\frac{P}{N}j \tag{7}$$

where $\mu(X,Y)$ is the connection degree of the set pair $H(X,Y)$; N is the total number of elements in the set, $N=S+P+F$; S is the number of elements with the same characteristics in the two sets; P is the number of elements with the opposite characteristics in the two sets; F is the number of elements with different characteristics in the two sets; i is the difference coefficient, which can be selected in the interval of (-1,1) according to the specific situation; j is the opposition coefficient and often takes the value -1. If we set

$$a=\frac{S}{N},\ b=\frac{F}{N},c=\frac{P}{N}$$

then *Equation 7* can be simplified as:

$$\mu(X,Y)=a+bi+cj \tag{8}$$

where a+b+c=1, a is the identity degree of two sets, b is the difference degree of two sets, and c is the opposite degree of two sets. Owing to the complexity of the actual problem, the multiple connection degree μ can be obtained. Making $bi=b_1i_1+b_2i_2+...+b_ki_k$, then *Equation 8* can be written as:

$$\mu(X,Y)=a+b_1i_1+b_2i_2+...+b_ki_k+cj \tag{9}$$

According to the normalisation conditions, $a+b_1+b_2+...+b_k+c=1$, considering the weight of each influencing factor or evaluation indicator, the connection degree of the same, opposite and different characteristic weights is:

$$\mu(X,Y)=a+bi+cj=\sum_{k=1}^{N}\omega k+\sum_{k=S+1}^{S+F}\omega ki+\sum_{k=S+F+1}^{N}\omega kj \tag{10}$$

where $\sum_{k=1}^{N}\omega k=1$ and ωj is the weight of each characteristic, which is determined by the analytic hierarchy process, entropy value method, etc. In order to calculate the connection degree μ when considering the weight, the similarity and difference inverse quantity model is introduced, with the form as:

$$\mu=WRE=\left(\omega_1,\omega_2,...,\omega_n\right)\begin{pmatrix}a_1 & b_1 & c_1\\ a_2 & b_2 & c_2\\ \cdots & \cdots & \cdots\\ a_n & b_n & c_n\end{pmatrix}\begin{pmatrix}1\\ i\\ j\end{pmatrix} \tag{11}$$

where W is the weight coefficient vector matrix, R is the similarity, difference and inverse vector matrix, and E is the sameness, difference and inverse coefficient matrix.

Calculation of the connection degree

Supposing Z is the indicators set and L is the level set, and then the evaluation level of the set pair $J(Z,L)$ can be calibrated by the connection degree through the *Equations 12–15*:

$$\mu_{i1}=\begin{cases}-1,\ x_j\in\left[S_{j(0)},S_{j(2)}\right)\\ 1+\dfrac{2\left(x_j-S_{j(3)}\right)}{S_{j(3)}-S_{j(2)}},\ x_j\in\left[S_{j(2)},S_{j(3)}\right)\\ 1,\ x_j\in\left[S_{j(3)},S_{j(4)}\right)\end{cases} \tag{12}$$

$$\mu_{i2}=\begin{cases}-1,\ x_j\in\left[S_{j(0)},S_{j(1)}\right)\\ 1+\dfrac{2\left(x_j-S_{j(2)}\right)}{S_{j(3)}-S_{j(2)}},\ x_j\in\left[S_{j(1)},S_{j(2)}\right)\\ 1,\ x_j\in\left[S_{j(2)},S_{j(3)}\right)\\ 1+\dfrac{2\left(x_j-S_{j(3)}\right)}{S_{j(3)}-S_{j(4)}},\ x_j\in\left[S_{j(3)},S_{j(4)}\right)\end{cases} \tag{13}$$

$$\mu_{i3}=\begin{cases}1+\dfrac{2\left(x_j-S_{j(1)}\right)}{S_{j(1)}-S_{j(0)}}, & x_j\in\left[S_{j(0)},S_{j(1)}\right)\\ 1, & x_j\in\left[S_{j(1)},S_{j(2)}\right)\\ 1+\dfrac{2\left(x_j-S_{j(2)}\right)}{S_{j(2)}-S_{j(3)}}, & x_j\in\left[S_{j(2)},S_{j(3)}\right)\\ -1, & x_j\in\left[S_{j(3)},S_{j(4)}\right)\end{cases} \tag{14}$$

$$\mu_{i4}=\begin{cases}1, & x_j\in\left[S_{j(0)},S_{j(1)}\right)\\ 1+\dfrac{2\left(x_j-S_{j(1)}\right)}{S_{j(1)}-S_{j(2)}}, & x_j\in\left[S_{j(1)},S_{j(2)}\right)\\ -1, & x_j\in\left[S_{j(2)},S_{j(4)}\right)\end{cases} \tag{15}$$

where μ_u is the connection degree of the indicator i corresponding to the grade u; x_j is the actual value of the indicator and $S_{j(0)}$, $S_{j(1)}$, $S_{j(2)}$, $S_{j(3)}$, $S_{j(4)}$ are the thresholds of the evaluation grade, which satisfy $S_{j(0)}<S_{j(1)}<S_{j(2)}<S_{j(3)}<S_{j(4)}$.

After calculating the connection degree of each indicator, combined with the combination weight obtained by the comprehensive weight method of the game theory, *Equation 16* is used to calculate the total connection degree of n indicators:

$$\mu_u=\sum_{i=1}^{n}\mu_{iu}w^* \tag{16}$$

where μ_u is the total connection degree of the indicators corresponding to the grade u, μ_{iu} is the connection degree of the indicator i corresponding to the grade u, and w^* is the combination weight.

Note that $\mu_p=\max\left\{\mu_u\right\}, p\in\left[1,2,...,m\right]$, m is the grade number of the evaluation grade, and the traffic safety facilities of the CAV test road can be judged as the grade P.

3. CASE STUDY

3.1 Case description

In a city in central China, the CAV industry has developed rapidly in recent years, and CAV test roads are being gradually opened in batches. Carrying out an evaluation of traffic safety facilities for the CAV test road network is important from the perspective of the safety management.

In order to verify the reliability of the evaluation model, a section Y of the city's CAV test road was firstly selected as the research object. Local transport management authority has organised 9 experts in the field of traffic engineering to carry out an on-the-spot research and measurement analysis. The task force was divided into 3 groups, A, B and C according to the measurement methods of the indicators.

Group A, composed of 2 experts, was in charge of measuring the values for the indicators W11, W21, W42, W52, W61 and W71 through satisfaction survey. The work was organised by the experts with the assistance of the authority personnel during 3 days. By using the traditional roadside inquiry method with the survey stations set up in the road exit, 200 random samples were collected, the results of which were verified in the further reliability and validity analysis.

Group B, composed of 3 experts, was in charge of measuring the values for the indicators W12, W13, W32, W41, W51 and W72. Experts were required to carry out the on-site investigation and verification and then score independently the indicators on the basis of the data investigated. The average values which passed the coefficient of variation test were determined as the final results.

Group C was formed by 4 specific experts, with 2 experts specialised in the material field and others in the road design field. They conducted a specific expert assessment for the indicators W22, W23, W31, W62, W81 and W82, the values of the indicators were commonly determined by the 2 experts who worked together through internal group discussion.

In this case, four levels, namely excellent, good, medium and poor were used to indicate the performance of the facilities. In the process of scoring, to better scale the indicators, the defects were divided into four categories according to the severity of the impact:

1) Critical defect. Defect that may directly threaten personal safety or even lead to death and needs to be dealt with immediately, i.e. warning sign of an important section (like a school) missing, a guardrail of an important section (like a bridge) missing.
2) Serious defect. Defect that may cause serious road crash with injury and temporary prevention measures are needed to ensure safety, i.e. lack of road guide information of the construction area, junction marks missing, serious pavement collapse.
3) Ordinary defect. Defect that may cause slight traffic conflict but with little chance of injury, i.e. junction marks not clear, isolation facility partly missing, information overload of a road sign.
4) Minor defect. Defect that causes little or no threat to road safety, i.e. lights do not work, pits on road pavement.

Experts were asked to find out and categorise the defects based on their experiences and then score the indicators complying with the instructions determined by the authorities, as shown in *Table 3.*

Table 3 – Instruction matrix for scoring

Category of defects	Number of defects			
	Excellent	Good	Medium	Poor
Critical defect	0	0	1	≥2
Serious defect	0	1	2~3	≥4
Ordinary defect	0~2	3~5	Expert decision	Expert decision
Minor defect	0~3	4~6	Expert decision	Expert decision

Table 4 – Survey data of the section Y and grading standard of indicators

Configuration of the section Y		Indicator	Value	Grading and the corresponding threshold			
				Excellent	Good	Medium	Poor
Road sign	category (quantity): warning sign (26), prohibition sign (34), mandatory sign (67), guide sign (40), work zone sign (8)	W11	95	100~90	90~80	80~60	60~0
		W12	88	100~90	90~80	80~60	60~0
		W13	87	100~90	90~80	80~60	60~0
Road marking	width: 15 cm, colour: white and yellow	W21	87	100~90	90~80	80~60	60~0
		W22	91	100~90	90~80	80~60	60~0
		W23	95	100~90	90~80	80~60	60~0
Guardrail facility	waveform guardrail	W31	400	420~300	300~180	180~30	30~0
		W32	84	100~90	90~80	80~60	60~0
Isolation facility	metal mesh	W41	1.9	2.5~2.0	2.0~1.8	1.8~1.0	1.0~0
		W42	75	100~90	90~80	80~60	60~0
Anti-glare facility	anti-glare shield and plant	W51	2.1	2.5~2.2	2.2~2.0	2.0~1.5	1.5~0
		W52	86	100~90	90~80	80~60	60~0
Sight-guiding facility	delineator	W61	95	100~90	90~80	80~60	60~0
	(spacing 50 cm, height 70 cm), pavement raised marker (20 mm)	W62	67	100~90	90~80	80~60	60~0
Lighting facility	height: 10 m, spacing: 30 m	W71	83	100~90	90~80	80~60	60~0
		W72	85	100~90	90~80	80~60	60~0
Road feature	lane width: 3.5 m, pavement: asphalt	W81	64	100~90	90~80	80~60	60~0
		W82	85	100~90	90~80	80~60	60~0

Referring to the references [16, 24–25] and combined with the characteristics of the CAV test road, the grading threshold of the indicators is determined, values and grading threshold of indicators are shown in *Table 4*.

3.2 Computational analysis

According to the data collected, the AHP method (represented by weight 1) and the entropy weight method (represented by weight 2) were used. The results are shown in *Table 5*.

Using the game theory model and taking Nash equilibrium as the coordination goal, *Equations 1–3* were used to calculate the comprehensive weight coefficient based on the game theory, the result of the calculation was α_1=0.516, α_2=0.484. Finally, *Equation 4* was used to obtain the combined weight value:

W^*=(0.07258 0.06742 0.07258 0.07242 0.06742 0.065 0.07258 0.06258 0.05258 0.04742 0.05242 0.04742 0.04758 0.03984 0.04016 0.03742 0.045 0.03758).

According to the grading standard mentioned above, *Equations 12–15* were used to calculate the connection degrees between the indicators and the grades. The results are shown in *Table 6*.

Table 5 – Values of the indicator weight

Indicator	W11	W12	W13	W21	W22	W23	W31	W32	W41
Weight 1	0.075	0.065	0.075	0.070	0.065	0.065	0.075	0.065	0.055
Weight 2	0.070	0.070	0.070	0.075	0.070	0.065	0.070	0.060	0.050
Indicator	W42	W51	W52	W61	W62	W71	W72	W81	W82
Weight 1	0.045	0.050	0.045	0.050	0.035	0.045	0.035	0.045	0.040
Weight 2	0.050	0.055	0.050	0.045	0.045	0.035	0.040	0.045	0.035

Table 6 – Connection degree of the indicators with different grades of the section Y

Indicator	Connection degree				Indicator	Connection degree			
	Excellent	Good	Medium	Poor		Excellent	Good	Medium	Poor
W11	1	0	-1	-1	W42	-1	0.5	1	-0.5
W12	0.6	1	-0.6	-1	W51	0	1	0	-1
W13	0.4	1	-0.4	-1	W52	0.2	1	-0.2	-1
W21	0.4	1	-0.4	-1	W61	1	0	-1	-1
W22	1	0.8	-1	-1	W62	-1	-0.3	1	0.3
W23	1	0	-1	-1	W71	-0.4	1	0.4	-1
W31	1	-0.667	-1	-1	W72	0	1	0	-1
W32	-0.2	1	0.2	-1	W81	-1	-0.6	1	0.6
W41	0	1	0	-1	W82	0	1	0	-1

Table 7 – Total connection degree of the sub-systems and the traffic safety facilities of the section Y

Sub-system	Total connection degree			
	Excellent	Good	Medium	Poor
Road sign (W1)	0.142	0.140	-0.142	-0.213
Road marking (W2)	0.161	0.126	-0.161	-0.205
Guardrail facility (W3)	0.060	0.014	-0.060	-0.135
Isolation facility (W4)	-0.047	0.076	0.047	-0.076
Anti-glare facility (W5)	0.009	0.099	-0.009	-0.099
Sight-guiding facility (W6)	0.008	-0.012	-0.007	-0.036
Lighting facility (W7)	-0.016	0.078	0.016	-0.078
Road feature (W8)	-0.045	0.011	0.045	-0.011
Traffic safety facilities of the section Y	0.272	0.533	-0.272	-0.852

Then, using the combined weight of the indicators determined above and *Equation 16*, the total connection degree of the sub-systems as well as the overall evaluation level of the traffic safety facilities of the section Y were calculated. The results are shown in *Table 7.*

3.3 Results

The calculation results in *Table 7* show that the connection degree of the traffic safety facilities of the section Y corresponding to the grade "good" is the largest. According to the aforementioned maximum value function $\mu_p = \max\{\mu_u\}, p \in [1,2,...,m]$, it is concluded that the comprehensive level of the traffic safety facilities of the section Y could be judged as "good". From *Table 6*, it can be seen that 10 of the 18 indicators, accounting for 55.6% of the total are at a good level and the connection degree is bigger than 0.5, which is consistent with the comprehensive evaluation result. Moreover, compared with the study in the reference [17], where the total connection degree is no bigger than 0.5 for the "good" level, we find that the method in this paper is more accurate. Therefore, the evaluation result is satisfactory and the evaluation method using the comprehensive weight is more reliable than that using AHP.

Then, the model was further applied in the evaluation of the traffic safety facilities of the city's CAV test road network, which is composed of 20 road sections (represented by A1~A5, B1~B5, C1~C5 and D1~D5). The results are shown in *Figures 1 and 2*.

The results in *Figure 1* show that, regarding the traffic safety facilities' condition, among the 20 sections of the city's CAV test road network, 15% are at an excellent level, 75% are at a good level and 10% are at

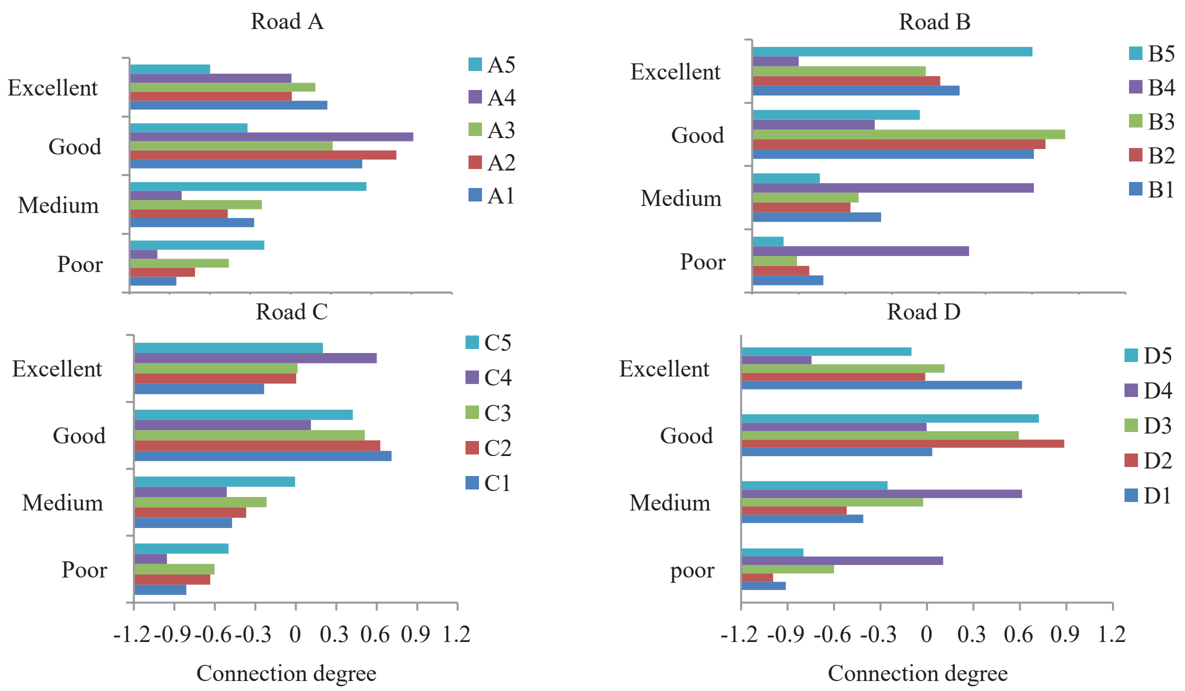

Figure 1 – Grading distribution of the traffic safety facilities of the roads A, B, C and D

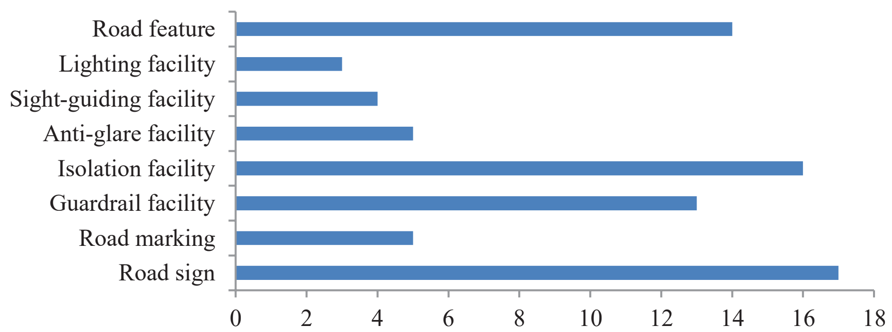

Figure 2 – Distribution of the limiting factors for the level of the traffic safety facilities

a moderate level. The results in the *Figure 2* show that road sign, guardrail facility, isolation facility and road feature are the main limiting factors affecting the evaluation level of traffic safety facilities.

4. DISCUSSION

The policy-making for the safety management of the CAV test road has been an important issue since the coming of the autonomous driving; many interesting findings related to the impact of infrastructure on CAVs could provide useful reference for policymakers. Reference [26] presented an overview of the interaction between road infrastructures and automated driving systems (ADS) and found out that international harmonisation of traffic signs and road markings is one of the challenges that must be faced in order to cope with future mobility. The results of the reference [27] showed that, with the increase of markings' retro-reflection, the detection quality and the range of view of Mobil-eye increase. Reference [28] focused on novel smart road geometric design and review criteria to evaluate the impact of the novel system on road capacity and safety, and the case study results indicated that the expected potential percentage improvement in the lane capacity may reach values up to 205% with respect to the current lane capacity. In the reference [29], the impact of the location of the smart road side units (RSUs) on avoiding potential collisions was evaluated for vehicles with different sensor configurations and the results showed that with the support of smart RSUs, the collisions with vulnerable road users (VRUs) can be reduced.

There is no doubt that the above representative findings could offer policymakers with renewed sense of the implications of new technologies on the infrastructures for ensuring CAV road safety as well as the coming challenges. However, all of these should be based on the systematic knowledge of the traffic safety facilities. Hence, it is essential to carry out evaluation research from a system point of view to get a better understanding of its condition. In this study, set pair analysis was used to deal with the uncertainty, and game theory was used to enhance the accuracy of the evaluation.

The results show that the performance of the facilities of the section Y is good. Among the 20 sections of the city's CAV test road network, 90% are at a good or higher level and road sign is a core factor. This conforms to the reality as most of the roads have been well constructed and most of the traffic safety facilities are in good condition. However, it is not sufficient for the transport management authorities to pursue absolute safety. They have to identify as much as possible the defects from a feel-good surface with the aid of a scientific study.

This paper has presented a new approach to the empirical study of the evaluation of traffic safety facilities. The proposed evaluation method provided not only the overall system performance but also the most significant factors which affect the system performance; these basic findings are consistent with the results in previous similar reports [11], [16] and [25].

As mentioned, finding the hidden defects is important. Unlike previous studies, the results of this study show quantitatively the performance of each indicator through the connection degree, it is therefore convenient to measure the importance of an indicator's impact. For example, the results in *Table 7* indicate that the facilities of section Y are graded "good" but not "excellent", and then turn to consult *Table 6*, it is easy to find that the condition of the W42, W62 and W81 is not well, so more attention should be paid accordingly to reduce the defects. In this way, the related authorities can not only understand the system as a whole but also identify more exactly the key indicators in the safety management of the CAV test road, so it is of great significance for the implementation of facilities maintenance and test road openness policy-making.

Nevertheless, some limitations should be noted:

1) In the determination of the indicators, public users of the CAV test road were not invited to directly give their opinions; this may degrade the representativeness of the indicator.
2) The drivers investigated were mostly commuters in the course of the satisfaction survey, which may cause sample bias due to the homogenisation problem.
3) There were not many experts included in the determination of the indicator values and the measurement of some indicators relied on the experiences of the specific experts in a certain field, while we were unable to assess completely the experts' abilities to avoid the deviation, this may influence the evaluation accuracy.

Despite these limitations not affecting the accuracy of the results, attention should still be paid to reducing the impact in future work.

Currently, as there is no specific norm for the traffic safety facilities of the CAV test road, for the indicator system, which is similar to that of the highway or urban expressway, no adaptation problems have been shown. However, if a new regulation appears, the indicator system should be adjusted accordingly. Also, this paper takes the traditional traffic safety facilities as the research object, if the intelligent facilities are involved, then the selection and measurement of the indicators should be treated differently in the model.

5. CONCLUSION

For the CAV test road users and the transport management authorities, in the pursuit of an absolute safety in a human-driven vehicles and CAVs mixed traffic environment, traffic safety facilities are always one of the most important factors to be considered. However, there are many uncertainties in the evaluation of the traffic safety facilities of the CAV test road. In this paper, the indicator system was established in three steps to make sure that the indicators possess the characteristics of comparability, representativeness and comprehensiveness. Then the game theory model was used to determine the combination weight of the indicators, and the set pair analysis was applied to solve the uncertain problems in the evaluation. Based on the case study results, the main conclusion can be summarised as follows:

1) The indicator system could be established by 18 key indicators from 8 sub-systems of the traffic safety facilities of the CAV test road, which are respectively road sign, road marking, guardrail facility, isolation facility, anti-glare facility, sight-guiding facility, lighting facility and road feature.
2) The case study shows that the method of the set pair analysis combined with the comprehensive weight based on the game theory is more reliable than that combined with AHP in terms of evaluation accuracy.
3) Although the overall performance of the traffic safety facilities is at a good or higher level, there are always defects hidden in a feel-good surface. The method in this paper can identify quantitatively the performance of each indicator through connection degree, so it is effective in finding out the safety-related problems.

Therefore, in practice, the results of this study can provide the transport management authorities a guide (or reference) to:

1) Implement fine safety management. With the comprehensive evaluation result of the traffic safety facilities of the CAV test road, transport management authorities can make a risk-based hierarchical safety management policy for the openness of the test roads. For example, if the traffic safety facilities of a road are assessed at an "excellent" condition level, then it can be open all day. On the contrary, if at a "poor" condition level, then it should not be open before the defects are eliminated.
2) Carry out high-efficiency facility maintenance. The maintenance personnel is recommended to pay more attention to the limiting factors affecting the evaluation level of traffic safety facilities so as to quickly identify the defects of the facilities.

The adaptability of the selected indicators needs to be further studied to meet the requirements of the new management regulation and changing technology of CAVs. Especially, the specifications of the intelligent elements of the traffic safety facilities should be put into consideration in future studies.

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基于交通安全设施评价的智能网联汽车测试道路的安全管理研究

摘要：
中国各地出现了越来越多在传统道路基础上改造的智能网联汽车（CAV）开放测试道路。然而，管理政策各异，导致交通环境复杂化。本文以CAV开放测试道路安全管理为研究目的，通过对交通安全设施的评价，调查道路开放测试条件。首先对指标进行严格筛选，然后利用博弈论模型确定指标的组合权重，并应用集对分析来解决不确定性问题。对中部某市CAV开发测试路网进行案例研究，结果表明，在交通安全设施状况方面，该市20个CAV开发测试道路路段中，有15%的路段达到优秀水平，75%的路段处于良好水平，中等水平路段占10%；道路标志、护栏设施、隔离设施和道路特征是影响交通安全设施水平的主要限制因素。根据研究结果，为交通运输管理部门在安全管理政策制定和设施维护等方面提出了建议。

关键词：
智能网联汽车测试道路；交通安全设施；评价；博弈论模型；集对分析；安全管理。