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Evaluation Method of Traffic Safety Maintenance of High-Grade Highway

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Abstract

With the evolution of better highway services and larger traffic volume, the traditional maintenance management indicators can no longer satisfy the demands of highway traffic safety. In order to ensure timely, fast, safe, and reliable highway maintenance and repair, this paper proposes a road traffic safety maintenance evaluation method. The fuzzy maintenance evaluation method based on the gray correlation degree is used to construct the safety maintenance evaluation model. The damaged characteristics of the high-grade highway components are analysed. The parameters of the evaluation model are established using the analytic hierarchy process, and the accuracy of the model is verified through experiments. The results show that the safety service level can intuitively measure the maintenance and repair status of various transportation facilities. When the safety level is 1 (above 87 points) or 2 (above 85 points), the road maintenance and repair are in good condition and the road users have a high level of satisfaction on safety; when the safety level is 3 or 4 (80 points or less), it reflects that there are weak links in the road components, and targeted maintenance repairs are required. The results provide references for highway safety maintenance decision-making and improvement of highway traffic safety services to some extent.

Keywords: Traffic safety maintenance, gray correlation degree, safety service level

1 Introduction

As a result of rapid economic development, the length of high-grade highways is increasing annually in China. At the end of 2019, the total length of highways in China was 5.0125 million kilometres, and the length of highways classified to be second-grade and above was 672,200 kilometres, accounting for 13.4%, of which the highway length was 149,600 kilometres. The number of road traffic accidents and deaths in China attracts attention. In 2018, 244,937 road traffic accidents were reported, causing 63,194 deaths and 258,532 injuries, and direct property losses of CNY 1,384,559,000 [1]. There are still many difficulties in improving road traffic safety, and it is necessary to take measures to curb the high incidence rate of traffic accidents in China.

Based on such background, researchers use historical data analysis or conflict analysis methods to research traffic safety in terms of maintenance policy research, maintenance economics, maintenance processes and responsibilities, maintenance automation, etc., to extend the service life of highways, ensure the maintenance of

highways, and upkeep desirable technical conditions of the facilities along the route. Therefore, the urgent questions that remain unanswered are that of how to comprehensively evaluate the potential safety hazards of the road from the perspective of road users and of how to propose corresponding safety maintenance measures.

This paper establishes a gray correlation model of traffic safety maintenance evaluation through the fuzzy grading evaluation method and analyses the damage characteristics of the subgrade and pavement, safety facilities, management facilities, channelling facilities, and greening facilities of high-grade highways. It is a means to predict maintenance and repair effects more accurately to ensure the safety satisfaction of road users and provide a reference for highway safety maintenance decision-making and safety service improvement.

2 State of the art

At present, wide research has been conducted on highway maintenance safety. The American maintenance standards manual *Maintenance Specification* specifies the maintenance measures and maintenance cycles of roads and their auxiliary facilities [2]. The trunk road maintenance manual in the United Kingdom describes trunk road maintenance in detail from the perspectives of traffic maintenance and safety, maintenance management information, and structural maintenance [3]. Siobhan analysed the cases of road maintenance and traffic accidents, and pointed out that continuous collisions often occurred in the accidents caused by large trucks, which leads to serious casualties; however, accidents caused by automobiles was not analysed [4]. Kingsland established a safety evaluation index system for the construction phase of highway maintenance, but failed to provide detailed research and analysis for other phases of highway maintenance [5]. Ray studied the relationship between the form of highway maintenance safety accidents and differentiated safety management strategies. However, the research object did not involve vehicles [6]. In order to evaluate the impact of traffic management such as marking signs on road maintenance construction area accidents, Berkowitz established a regression model for measurement [7]. Pantha et al. developed a road maintenance decision-making model based on GIS, considering the weighted combination of each maintenance component for the maintenance priority of road slope stability, but the use of this model was limited regionally [8]. Bayraktar et al. introduced the Bayesian network model when making road maintenance decisions [9]. Xiuying used a fuzzy comprehensive evaluation method to identify and rank the sensitive factors of highway maintenance risks [10]. Qizhi used a fuzzy analytic hierarchy to evaluate the risk factors of highways and established a matrix of each risk factor to calculate the weight value [11]. Luxin established a traffic management model of highway sections under maintenance through Vissim traffic micro-simulation system software [12]. In their doctoral dissertation, Qing of Chang'an University [13] and Xiang of Southwest Jiaotong University studied pavement performance and obtained a pavement performance attenuation curve, and proposed a decision-making method for expressway maintenance sequence, but there have been few studies on road traffic safety facilities [14]. Chang conducted research on the decision-making associated with highway maintenance time and maintenance investment in his master thesis [15]. Zhigang et al. used dynamic programming methods to establish a dynamic optimisation model for maintenance decision-making to maximise the benefits of maintenance investment [16]. Weiwei analysed the maintenance of highway safety facilities and quality control, but the research of indicator systems was not involved [17].

The above research results were mainly concentrated on the maintenance policy research, economics, processes and responsibilities, automation, etc., and there were few studies on the traffic safety characteristics, especially on the correlation of the maintenance of traffic safety facilities. From the perspective of ensuring the safety of road users, this paper adopts the fuzzy hierarchical evaluation method, which is based on gray correlation degree to discuss the damage characteristics of the components of high-grade highways respectively, and establishes a traffic safety maintenance evaluation model to provide references for the classification of safety maintenance levels.

In this paper, Section 3 analyses common damages of highway components, selects evaluation indicators, and builds evaluation models. Section 4 verifies the objectivity of the evaluation indicators and the rationality

of the evaluation model and divides safety maintenance levels at crossroads and road sections. The last section summarises this paper and provides relevant conclusions.

3 Analysis of influencing factors

In this research, high-grade highways are divided into level crossroads, and road sections are to be evaluated separately. By analysing the components of the subgrade and pavement, safety facilities, management facilities, channelling facilities, and greening facilities this section provides evidence for the selection of evaluation indicators [18].

3.0.1 Subgrade and pavement

This part is mainly composed of road shoulders and pavements, among others. The common damages of road shoulders include poor surface flatness, improper width setting of the shoulders, and staggering. The common damages of road pavements are ruts and breakages on the road surface, insufficient slip resistance, and water accumulation.

3.0.2 Safety facilities

This part is mainly composed of central separation zones, separation zones for motor-driven vehicle and non-motor-driven vehicles, roadside guardrails, crossroad marks, anti-glare facilities, sightline guidance facilities, etc. Common damages mainly include poor sight distance, missing parts, poor reflectivity, poor visibility, weakened retroreflectivity, etc.

3.0.3 Management facilities

This part mainly refers to traffic markings, signs, signal lights, street lights, etc. Common damages are severely worn facilities, insufficient anti-slip resistance, poor retroreflectivity, missing parts, or damaged, tilt, reduced visibility, unreasonable location settings, and insufficient or overloaded information.

3.0.4 Channelling facilities

Channelling is the use of diversion islands or marking lines to separate or control conflicting vehicle flow. The common damages are improper channelling, damages of channelling diversion islands, worn channelling marks, and poor visibility.

3.0.5 Greening facilities

Greening refers to the planting of trees and flowers on both sides or in the middle of the road, aiming to improve the traffic environment. The major common damages are the inappropriate selection of greening tree species which negatively affect the viewing distance.

3.1 Selection of evaluation indicators

Combining the selection principle of evaluation indicators, this research uses a combination of qualitative analysis and quantitative calculation to break down the high-level highway, thereby forming an ordered hierarchical structure, as shown in Tables 1 and 2.

3.2 Selection of evaluation methods and model construction

Considering the multiple levels and complexity of the evaluation object, this research uses the fuzzy hierarchy theory based on gray correlation to construct the evaluation model. This method combines the advantages of the three evaluation methods of gray correlation, hierarchy analysis, and fuzzy theory, which are conducive to solve the problems of complexity, ambiguity, and insufficient information in traffic safety evaluation, so as to obtain more accurate, scientific, and reasonable evaluation results. The specific steps are as follows:

(1) Construct a comprehensive evaluation system framework

Table 1 Evaluation indicator system of the high-grade highway section.

Target layer	Criterion layer W_i	Indicator layer W_{ij}	Criterion layer W_i	Indicator layer W_{ij}
High-grade highway road section evaluation index	Subgrade and pavement W_1	Road shoulder safety intactness W_{11}	Management facilities W_3	Traffic marking visibility W_{31}
		Road pavement safety intactness W_{12}		Street light intactness W_{32}
		Central separation zone intactness W_{21}		Traffic sign information W_{33}
	Safety facilities W_2	Separation zone for motor-driven vehicle and non-motor-driven vehicle intactness W_{22}		Traffic sign visibility W_{34}
		Roadside guardrail intactness W_{23}		Traffic sign intactness W_{35}
		Railway crossroad marking intactness W_{24}	Greening facilities W_4	Rationality of greening plants W_{41}
		Anti-glare facilities intactness W_{25}		Line of sight distance adequacy W_{42}
		Line of sight intactness W_{26}		
		Road spike intactness W_{27}		

The high-grade highway maintenance evaluation system is a complex system, with each subsystem depending, influencing, and impacting every other. In the safety evaluation process, if the mutual influence between the relevant subsystems is ignored, the evaluation results will not be comprehensive, objective, or reliable. The comprehensive evaluation system consists of three functional modules, namely the data acquisition module, the subsystem performance evaluation module, and the comprehensive evaluation module, as shown in Figure 1 below.

(2) Determine the comment set and whitening weight function

The comment set is made for each evaluation indicator according to a certain scale. In this research, in order to facilitate calculation and analysis, the vector comment set of each indicator corresponds to and is consistent with the system's safety level. The comment level is shown as $z = (z_1, z_2, z_3, z_4) = (\text{Level 1, Level 2, Level 3, Level 4})$. In order to make the evaluation process rational and reasonable, it is necessary to standardise the sample matrix. In this paper, four gray classes are determined according to the four security levels, and the corresponding whitening weight function is established as shown in Table 3.

(3) Calculate gray evaluation weights

For the evaluation index u_{ij} , the evaluation objects belong to the gray evaluation coefficient of the evaluation

Table 2 Evaluation indicator system of high-grade highway crossroad.

Target layer	Indicator layer W_i	Indicator layer W_{ij}	Criterion layer W_i	Indicator layer W_{ij}
High-grade highway crossroad evaluation index	Subgrade and pavement W_1	Road shoulder safety intactness W_{11}	Management facilities W_3	Traffic marking visibility W_{31}
		Road pavement safety intactness W_{12}		Street light intactness W_{32}
	Safety facilities W_2	Central separation zone intactness W_{21}		Signal lamp brightness W_{33}
		Separation zone for motor-driven vehicle and non-motor-driven vehicle intactness W_{22}		Signal light feasibility W_{34}
		Roadside guardrail intactness W_{23}		Signal intactness W_{35}
		Railway crossroad marking intactness W_{24}		Traffic sign information volume W_{36}
		Anti-glare facilities intactness W_{25}		Traffic sign visibility W_{37}
		Reflecting mirror intactness W_{26}		Traffic sign intactness W_{38}
		Line of sight intactness W_{27}		Channelling facility intactness W_{51}
		Road spike intactness W_{28}		Channelling facility visibility W_{52}
	Greening facilities W_4	Rationality of greening plants W_{41}		Channelling rationality W_{53}
		Line of sight distance adequacy W_{42}		

gray class:

$$X_{ije} = \sum_{n=1}^l f_e(d_{ijn}) \quad (1)$$

For the evaluation index u_{ij} , the evaluation objects belong to the total gray evaluation coefficient of every

Fig. 1 System comprehensive evaluation.

Table 3 Summary of whitening weight function.

Gray class	Comment level	Gray value	Whitening weight function
1	Level 1 (90, 100)	$\theta_1 = [90, \infty]$	$f_1(d_{ijn}) = \begin{cases} d_{ijn} / 90, d_{ijn} \in [0, 90] \\ 1, d_{ijn} \in [90, \infty] \\ 0, d_{ijn} \in (-\infty, 0) \end{cases}$
2	Level 2 (80, 90)	$\theta_2 = [0, 90, 180]$	$f_2(d_{ijn}) = \begin{cases} d_{ijn} / 90, d_{ijn} \in [0, 90] \\ 180 - d_{ijn} / 90, d_{ijn} \in [90, 180] \\ 0, d_{ijn} \in (-\infty, 0) \cup (180, +\infty) \end{cases}$
3	Level 3 (70, 80)	$\theta_3 = [0, 80, 160]$	$f_3(d_{ijn}) = \begin{cases} d_{ijn} / 80, d_{ijn} \in [0, 80] \\ 160 - d_{ijn} / 80, d_{ijn} \in [80, 160] \\ 0, d_{ijn} \in (-\infty, 0) \cup (160, +\infty) \end{cases}$
4	Level 4 (0, 70)	$\theta_4 = [0, 70, 140]$	$f_4(d_{ijn}) = \begin{cases} 1, d_{ijn} \in [0, 70] \\ 140 - d_{ijn} / 70, d_{ijn} \in [70, 140] \\ 0, d_{ijn} \in (-\infty, 0) \cup (140, +\infty) \end{cases}$

evaluation gray class:

$$X_{ij} = \sum_{g=1}^e X_{ijg} \quad (2)$$

The evaluation objects belong to the gray evaluation power of the e-gray class:

$$r_{ije} = X_{ije} / X_{ij} \quad (3)$$

The evaluation index u_{ij} corresponds to the gray evaluation weight matrix of each evaluation gray class:

$$R_i = \begin{bmatrix} r_{i11} & \cdots & r_{ile} \\ \vdots & & \vdots \\ r_{in1} & & r_{ine} \end{bmatrix} \quad (4)$$

Standardise the second-level indicators under the first-level indicators according to the gray evaluation weight vector, and obtain the evaluation vector as $k_{ij} = (k_{ij1}, k_{ij2}, \dots, k_{ije})$, thus forming an evaluation matrix:

$$K_i = \begin{bmatrix} k_{i11} & \cdots & k_{ile} \\ \vdots & & \vdots \\ k_{in1} & & k_{ine} \end{bmatrix} \quad (5)$$

In the formula:

$$k_{ij} = \left\{ \frac{r_{ij1}}{\bar{r}_{ij}}, \frac{r_{ij2}}{\bar{r}_{ij}}, \dots, \frac{r_{ije}}{\bar{r}_{ij}} \right\}, \bar{r}_{ij} = \max(r_{ij1}, r_{ij2}, \dots, r_{ije})$$

(4) Determine the indicator weight set

Subjective weighting method and objective weighting method are commonly adopted to determine the weight value of each indicator, namely: $A = (a_1, a_2, \dots, a_n)$, where $a_i > 1$ and $\sum a_i = 1$. The determination of the weights in this section is still obtained through expert investigation and AHP. In the actual investigation, the judgement matrix returned by some experts cannot pass the consistency test. In this research, an optimisation algorithm was selected to adjust the consistency matrix A .

$$A' = [a'_{ij}]_{n \times n} = \left[\left(\frac{W_i}{W_j} \right)^P \right]_{n \times n} \quad (6)$$

In the formula:

W is the relative weight vector of the original judgement matrix A , $W = (W_1, W_2, \dots, W_n)^T$;

P is solved by the minimum closeness, and the calculation formulas are shown in formulas (7) and (8).

$$\min_P = \min_P \sum_{i=1}^n \sum_{j=1}^n \left[\lg a_{ij} - \lg \left(\frac{W_i}{W_j} \right)^P \right] \quad (7)$$

$$P = \frac{\sum_{i=1}^n \sum_{j=1}^n \lg a_{ij} \cdot \lg \frac{W_i}{W_j}}{\sum_{i=1}^n \sum_{j=1}^n \left(\lg \left(\frac{W_i}{W_j} \right) \right)^2} \quad (8)$$

According to the hierarchical relationship of highway safety maintenance and its subsystems given in Tables 1 and 2 above, the weight of each parameter is summarised and shown in Figures 2 and 3 below. There are 16 sub-indicators in the highway section and 23 sub-indicators in the plane crossroads.

In the actual evaluation process, if there are missing items to be evaluated, the weights are adjusted according to the following formula (9).

$$W_i^n = \frac{W_i}{1 - \sum_j W_j} \quad (9)$$

In the formula:

W_i^n represents the adjusted weights of the i facility;

W_i represents the weights of the original i facility;

Fig. 2 Summary of highway section parameters weights.

Fig. 3 Summary of plane crossroads section parameters weights.

$\sum W_j$ represents the sum of the weights of missing facilities.

(5) Determine the evaluation vector

Taking the correlation between the first-level evaluation indicator vector and the relatively most indicator vector as the evaluation indicator, the gray evaluation matrix of the first-level indicator is obtained.

$$C_i = \omega_{i \times n} \cdot T_i = (c_{i1}, c_{i2}, \dots, c_{ie}), \quad i = 1, 2, \dots, m \quad (10)$$

$$C_i = \begin{bmatrix} c_{11} & \cdots & c_{1e} \\ \vdots & & \vdots \\ c_{m1} & & c_{me} \end{bmatrix} = [C_1, C_2, \dots, C_e]^T \quad (11)$$

Obtain the traffic safety service level D of evaluation vector of the first-level indicator U :

$$D = W^\circ \cdot C = (\omega_1, \omega_2, \dots, \omega_m)^\circ [C_1, C_2, \dots, C_e]^T = (z_1, z_2, \dots, z_e) \quad (12)$$

(6) Determine the comprehensive evaluation results

To facilitate analysis, D is normalised, that is:

$$D = \left\{ \frac{D_1}{\sum_{i=1}^e D_i}, \frac{D_2}{\sum_{i=1}^e D_i}, \frac{D_3}{\sum_{i=1}^e D_i}, \dots, \frac{D_e}{\sum_{i=1}^e D_i} \right\} \quad (13)$$

According to the principle that evaluating and analysing is based on the maximum degree of membership, the comments of corresponding $\max_i D$ are the final comprehensive evaluation results.

Table 4 Indicator deduction standard.

Sub-feature indicator	Investigation content	Maintenance status (/point/place)		
		Safe	Moderately safe	Unsafe
Road shoulder safety intactness	Road shoulder flatness, gutter cover intactness, and subgrade drainage	Deduct 0–5	Deduct 5–10	Deduct 10–20
Road pavement safety intactness	Pavement flatness and damage	Deduct 0–5	Deduct 5–10	Deduct 10–20
Central separation zone intactness	Central separation zone type, broken end treatment, and intactness	Deduct 0–5	Deduct 5–10	Deduct 10–20
Separation zone of motor-driven vehicle and non-motor-driven vehicle intactness	Damage, incline, excessively high kerbstones, etc.	Deduct 0–5	Deduct 5–10	Deduct 10–20
Roadside guardrail intactness	Guardrail structure intactness, end treatment, and appropriate setting	Deduct 0–5	Deduct 5–15	Deduct 15–30
Railway crossroad marking intactness	Defect, tilt, visibility, and reflectivity	Deduct 2 for tilting and deformation, deduct 5 for massing and damage, and deduct 5 for loss of reflectivity		
Anti-glare facilities intactness	Missing of anti-glare effect	Deduct 0–5	Deduct 5–10	Deduct 10–20
Reflecting mirror intactness	Improper position, improper angle, an inclination of a pillar, and damaged mirror surface	Deduct 5 for any of these situations		
Line-of-sight intactness	Defects, deformation, poor reflectivity, poor visibility, and blocked	Deduct 5 for the former, deduct 10 for the latter		
Road spike intactness	Missing or poor reflection	Deduct 2		
Traffic marking visibility	Worn condition	Deduct 2 for minor cases, deduct 5 for severe cases		
Street light intactness	Insufficient brightness or damaged components	Deduct 3		
Signal brightness	Fuzzy situation	Deduct 10 for minor cases, deduct 20 for severe cases		
Signal visibility	Obscured or confusing background	Deduct 15		
Signal intactness	Damaged or incomplete components	Deduct 5		
Traffic sign information	Overload or wrong information	Deduct 10 for overloaded information, deduct 15 for wrong information		
Traffic sign visibility	Blocked or too small font	Deduct 10		
Traffic sign intactness	Panel deformation, cracks, corrosion, loose deformation of support, etc., no fragile design or flexible design	Deduct 5 for the former, deduct 10 for the latter		
Rationality of greening plants	Plant height does not meet requirements	Deduct 5–10		
Line-of-sight sufficiency	Does not meet line-of-sight requirements	Deduct 15–20		
Channelling facility intactness	Worn facilities or breakage	Deduct 5 for minor cases, deduct 10 for severe cases		
Channelling facility visibility	Poor	Deduct 5–15		
Channelling rationality	Unreasonable and excessive channelling	Deduct 10–20		

4.2 Reasonable verification of evaluation model

Common methods for model rationality verification include subjective evaluation, fitting test, residual plot method, regression analysis, etc. In this research, the score of the plane crossroads section and road section used

Table 5 Deduction of test indicators.

Evaluation indicator	No. Type	No.	No.	No.	No.	No.	No.
		1	2	3	4	5	6
Rationality of channelling	Driver	9	5	6	4	5	6
	Maintenance personnel	5	9	7	6	4	4
	Researcher	8	6	4	5	4	5

the subjective evaluation method, while the linear correlation between the model's score and the subjective score used regression analysis. The rationality of the model is verified by the results.

(1) Verification test

The test section is selected first, which mainly includes two parts, namely model calculation and subjective scoring. Among them, the model calculation is to access the evaluation indicator scores of the selected test sections, and to score each evaluation object and comprehensive evaluation object according to the above safety maintenance evaluation model; the subjective scoring is to organise a batch of experienced experts in safety maintenance evaluation to make a subjective and quantitative evaluation of the safety maintenance quality of the test section, for which the specific deduction criteria are shown in Table 6.

In order to verify the effectiveness of the model, the expert scoring panel offers each indicator's score and the total score on the road section every 2 km on the S321 test highway. Validation data of rationality of road section evaluation model is shown in Figures 4 and 5 below.

Fig. 4 Model scoring value. **Fig. 5** Subjective score.

(2) Model rationality verification

By analysing the correlation between Figures 4 and 5, it can be seen that the absolute error of most validation data is within 5 points, as shown in Figures 6–10. The result is indicating that the model has strong rationality,

Fig. 6 Evaluation correlation analysis of subgrade and pavement.

Fig. 7 Evaluation correlation analysis of safety facilities.

4.3 Division of safety grades

In order to make the scoring results of the above model reflect the safety and service status of the high-level highways of the evaluation object in a more visual manner, this research uses the cumulative frequency curve method to divide the safety service level. The research selects 50 sections and 40 crossroads of high-grade highways in Jiangsu Province for data collection, using the model to score and accumulating frequencies in an order from low to high. Points with a cumulative frequency of 0~15% are selected as the classification criteria for grade 4; points with a cumulative frequency of 15–50% as the classification criteria for grade 3; points with a cumulative frequency of 50–85% as the classification criteria for grade 2; and points with a cumulative frequency of 85–100% as the classification criteria grade level 1. The results are shown in Table 6.

Fig. 8 Evaluation correlation analysis of management facilities.

Fig. 9 Evaluation correlation analysis of greening facilities.

Fig. 10 Correlation analysis of comprehensive evaluation of road safety maintenance.

5 Conclusion

In order to accurately predict the effect of maintenance and repair and improve the safety satisfaction of road users, this paper analyses the damage characteristics of the subgrade and pavement, safety facilities, manage-

Table 6 Interval partition of grade.

Type	Grade	Score	Type	Grade	Score
Road section	Grade 1	87–100	Crossroad	Grade 1	89–100
	Grade 2	85–87		Grade 2	87–89
	Grade 3	83–85		Grade 3	84–87
	Grade 4	0–83		Grade 4	0–80

ment facilities, greening facilities, and channelling facilities of high-grade highways, establishing a traffic safety maintenance evaluation model and drawing the following conclusions:

- (1) The evaluation indicator system for plane crossroad and road section safety maintenance is established from the five aspects of subgrade and pavement, traffic safety facilities, management facilities, channelling, and road-side greening.
- (2) According to the constituent characteristics of each evaluation indicator, a high-grade highway safety maintenance evaluation indicator scoring standard is established.
- (3) A high-grade highway traffic safety maintenance evaluation model is established using the fuzzy hierarchical evaluation method of gray correlation degree.
- (4) The cumulative frequency curve method is used to divide the safety level of high-grade highways, and the standard method and interval for each safety maintenance level are provided.

This research gives the safety level of each road component according to its safety status, which points out the weak links of road components in a visual manner, leading to more target decisions of highway safety maintenance and providing a reference for highway safety maintenance. The determination of indicators in this study also has certain limitations. In the follow-up study, we will further expand the scope of highway distribution, increase the regional factors of severe weather, and incorporate bridge and culvert structures and other components, so as to improve the indicator system.

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