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Method of determining weights of subjective evaluation indexes for vehicle handling stability based on fuzzy consistent matrix

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Abstract. Vehicle handling stability evaluation is one of the most important research parts in vehicle dynamics. Currently, the tuning and final sign-off of a vehicle's handling setup relies on subjective evaluation by experienced test engineers on roads and test tracks. The situation of multi-levels and multi-indexes is combined in the subjective evaluation system of vehicle handling stability. It is easy to evaluate one property but difficult to the whole performance of handling stability. In view of this situation, the weights of subjective evaluation indexes are obtained based on fuzzy consistent matrix of fuzzy analytic hierarchy process(FAHP). Three vehicles are carried out subjective evaluation experiment. The underlying indexes scores of the three vehicles are obtained by the vehicle evaluators combining with the identified weight coefficient. Then the results of overall performance are given with weights and scores of single indexes. Through the analysis of the scores of indexes and their weights, the proposal for improving the overall performance is given. The proposed method can provide a scientific reference for the benchmark and chassis turning.

Key words. Handling stability, subjective evaluation, weight, fuzzy analytic hierarchy process, fuzzy consistent matrix.

1. Introduction

Vehicle handling stability contains two interconnected parts: maneuverability and stability. Maneuverability is the vehicle's ability to response to the driver's steering instructions exactly. Stability is the vehicle's ability to recover the vehicle from unsteady state to the steady state and has a direct impact on the maneuverability. Vehicle handling stability is not only an important factor in the evaluation

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of vehicle performance, but also is a main factor in relation to the vehicle safety. Therefore, the subjective evaluation of the vehicle handling and stability is an important part in the process of modern vehicle development, and the evaluation results directly determine the overall performance of the developed model. If the evaluation results can't reflect the vehicle's performance exactly, it will causes big misleading for the subsequent development and calibration[1].

In early vehicle development period, in order to ensure the future development of vehicle models with competitive, the performance of developed models are calibrated according to the level of opponents. The strength of enterprises and suppliers, laws and regulations as well as the cost for the developed models, which means to determine values of these performance indicators. Subjective evaluation is a major means of performance calibration, and it is critical for developing an effective method of subjective evaluation in the earlier period of vehicle development. The handling stability is one of the main performance for vehicle. With the high speed development of modern vehicle, handling stability has received more and more attention and handling stability calibration becomes one of the key content of early development[2].

2. Fuzzy analytic hierarchy process and fuzzy matrix

2.1. The existed problem of traditional analytic process

Analytic hierarchy process is put forward by operational research expert, the professor of the university of Pittsburgh, A.L.Saaty in the early 1970s, which is a systematic and hierarchical analysis method combining with qualitative analysis and quantitative analysis[4-6]. Analytic hierarchy process calculates the weight values of per evaluation indexes for the combination of general objective through five steps, which are defining the problem, establishing analytic hierarchy structure model, building judgment matrix, hierarchy single ranking and hierarchy general ranking. Then it gives comprehensive evaluation values of different feasible plans which provide the bases for choosing the optimal solution. The key lin of AHP is to establish judgment matrix, and whether the judgment matrix is scientific and reasonable directly affects the result of AHP. Through the analysis, we find that:

(1) Whether the judgment matrix is checked consistent is very difficult

Judgment matrix consistency test needs to get the maximum characteristic root of the judgment matrix $\lambda_{\max}$, so as to confirm that whether $\lambda_{\max}$ equals with the matrix dimension n. If $\lambda_{\max} = n$, it has consistency. When the matrix dimension n larger, the accurate calculation of $\lambda_{\max}$ needs significant workload.

(2) When the judgment matrix doesn't have consistency, the judgment matrix elements are needed to adjust to make it possess consistency. The process of adjustment, inspection and readjustment, retest is probably needed to make the judgment matrix with consistency.

(3) Judging criteria of check the consistency of judgment matrix: when $CR < 0.1$, it lacks scientific basis.

2.2. The concept and properties of fuzzy consistent matrix

Fuzzy analysis hierarchy process (FAHP)[7] which fully considers fuzziness of human's thinking is a combination theory method of fuzzy theory and the traditional analytic hierarchy process. The basic thought and steps of FAHP is basically identical with AHP, but still has the differences of the following two aspects. First, the established judgment matrix is different: AHP establishes the consistent judgment matrix by comparing two elements , But FAHP establishes fuzzy consistent judgment matrix by comparing two elements. Second, the method of solving weights of the relative importance of each element in the matrix is different.

At present, the FAHP is divided into two categories. One is based on fuzzy number, the other is based on fuzzy consistent matrix. This paper chooses a kind of FAHP which is based on fuzzy consistent matrix to determine the subjective evaluation index weight coefficient of vehicle handling stability.

1. Fuzzy consistent matrix and its related concepts

Definition 1

Assuming that matrix $R = (r_{ij})_{n\times n}$ exists, if it meets the condition:

$0 \le r_{ij} \le 1$ $(i = 1, 2, \cdots, n; j = 1, 2, \cdots, n)$

$R$is defined as a fuzzy matrix.

Definition 2

Assuming that fuzzy matrix $R = (r_{ij})_{n\times n}$ meets the condition:

$r_{ij} + r_{ji} = 1$ $(i = 1, 2, \cdots, n; j = 1, 2, \cdots, n)$

Fuzzy consistent matrix $R = (r_{ij})_{n\times n}$ has characteristics as follows:

(1)r_{ii} =0.5.

(2)$r_{ij} + r_{ji}$ =1.

(3)Elements summation in row i and column j of fuzzy consistent matrix R is n.

2.3. Geometry of the plate

Fuzzy consistent judgment matrix R shows the relative importance comparison with the above layer among the elements of current layer. Assuming that elements of the above layer C is associated with elements $a_1, a_2, \cdots, a_n$of next layer, the Fuzzy consistent judgment matrix can be expressed as:

C	$a_1 \cdots a_n$
a_1 $\vdots$ a_n	$r_{11} \cdots r_{1n}$ $\vdots\ \vdots$ $r_{n1} \cdots r_{nn}$

Element r_{ij} possesses practical significance as follows: r_{ij} expresses that element a_i and a_j have a membership degree of fuzzy relations "more important" when compared with element C. Nine scale method of 0.1 ˜ 0.9 scale is used to make any two elements about the relative importance of certain criteria get quantitative description. Table 1 shows the fuzzy scale and its meaning.

With the number scale as above, comparing elements $a_1, a_2, \cdots, a_n$ with last layer element C, the fuzzy judgment matrix is got as follows:

$$R = \begin{pmatrix} r_{11} & \cdots & r_{1n} \\ \vdots & & \vdots \\ r_{n1} & \cdots & r_{nn} \end{pmatrix}$$

Element r_{ij} of fuzzy consistent matrix R_1 usually indicates the relative importance of the factor a_i and a_j.

$$(1) r_{ij} = 0.5, i = 1, 2, \cdots, n.$$

$$(2) r_{ij} + r_{ji} = 1, i, j = 1, 2, \cdots, n.$$

Table 1. Fuzzy Scale and Meaning

Scale	Meaning
0.1	the latter is more extremely important than the former
0.2	the latter is more strongly important than the former
0.3	the latter is more obviously important than the former
0.4	the latter is a little important than the former
0.5	the latter is the same important as the former
0.6	the former is a little important than the latter
0.7	the former is more obviously important than the latter
0.8	the former is more strongly important than the latter
0.9	the former is more extremely important than the latter

Therefore, R is a fuzzy consistent matrix. The consistency of fuzzy judgment matrix reflects the consistency of people's thought and judgment, which is very important in constructing fuzzy judgment matrix. But in the actual decision analysis, because of the complexity of the problem and people's one-sided recognition, the fuzzy complementary judgment matrix obtained from expert judgment is often inconsistent. So how to adjust R to get the fuzzy consistent matrix for calculating weight According to the theorem 2, the fuzzy complementary judgment matrix R can be expressed into a fuzzy consistent matrix.

3. Determine the weight coefficient of subjective evaluation indexes based on the fuzzy consistent matrix

Table 2. Subjective evaluation fuzzy consistent matrix analytic hierarchy structure of vehicle handling stability and scoring results

Target layer	Criteria layer (A_i)	Sub-criteria layer (B_i)	Scheme layer (C_i)	Model A	Model B	Model C
Handling Stability	A_1 Steering performance	B_1Parking performance	C_1 Parking force	8	8	8
			C_2Returnability	7.5	7.5	6.5
			C_3 Mobility	8	7.5	7.5
		B_2Central steering	C_4 Response	7.5	8	8
			C_5Torque feedback	8	8	8
			C_6 Predictability	8	8	8
		B_3Turning corners	C_7 Response	7	7	7.5
			C_8 Torque feedback	8	7	8
			C_9 Steering force	7.5	7.5	8
			C_{10} Returnability	7.5	7.5	6.5
			C_{11} Predictability	8	7.5	7.5
		B_4Steering interference	C_{12} Steering torque	8	7.5	8
			C_{13} Deviation	7.5	7	8
			C_{14} Steering shocks	8	7.5	8
			C_{15} Single wheel impact	7.5	7.5	7.5
	A_2 Stability	B_5 Linear stability	C_{16} Linear deceleration	7.5	8.5	7.5

According to the basic theory of fuzzy consistent matrix and how to establish fuzzy consistent judgment matrix, the subjective evaluation index weight coefficient of the handling stability is gradually determined.

3.1. Establish the fuzzy consistent matrix hierarchy model

With reference to mature evaluation system, the handling stability of subjective evaluation system combined with the actual situation of Chinese domestic enterprises is established, which is of enterprise characteristics and includes project evaluation indexes. This system with self-characteristics includes drivers' operation methods, scoring basis and scoring method, etc. Scoring method uses the system of SAE (Society of Automotive Engineers) 10-point scale method , and fuzzy consistent matrix analytic hierarchy structure model is established based on the evaluation system. In a test site in China, subjective evaluation experiment of handling stability of three kinds of vehicles is conducted by experienced engineers. A subjective mark for the relatively simple underlying individual indicators is given in this experiment. According to this evaluation system, a hierarchical analysis model of fuzzy consistent matrix analysis is set up, as shown in table 2 [3].

3.2. Establish the fuzzy judgment matrix

Three engineers who have more experience in the subjective evaluation test are selected. The construction method of judgment matrix is explained for them. The judgment matrices in which each pair of indicators are comparative are established by the subjective evaluation engineers according to the fuzzy scale of table 1. One engineer's fuzzy judgment matrices are shown in table 3˜12.

Table 3. Judgment matrix of handling stability indicators

Indicators	A_1	A_2
A_1	0.5	0.5
A_2	0.5	0.5

Table 4. Judgment matrix of steering performance indicators

Indicators	B_1	B_2	B_3	B_4
B_1	0.5	0.6	0.8	0.7
B_2	0.4	0.5	0.7	0.6
B_3	0.2	0.3	0.5	0.4
B_4	0.3	0.4	0.6	0.5

Table 5. Judgment matrix of stability indicators

Indicators	B_5	B_6	B_7
B_5	0.5	0.5	0.3
B_6	0.5	0.5	0.3
B_7	0.7	0.7	0.5

Table 6.Judgment matrix of parking performance indicators

Indicators	C_1	C_2	C_3
C_1	0.5	0.3	0.6
C_2	0.7	0.5	0.8
C_3	0.4	0.2	0.5

Table 7.Judgment matrix of turning indicators in the Central

Indicators	C_4	C_5	C_6
C_4	0.5	0.7	0.5
C_5	0.3	0.5	0.3
C_6	0.5	0.7	0.5

Table 8. Judgment matrix of steering indicators

Indicators	C_7	C_8	C_9	C_{10}	C_{11}
C_7	0.5	0.6	0.4	0.6	0.7
C_8	0.4	0.5	0.4	0.4	0.7
C_9	0.6	0.6	0.5	0.7	0.8
C_{10}	0.4	0.6	0.3	0.5	0.6
C_{11}	0.3	0.3	0.2	0.4	0.5

Table 9. Judgment matrix of steering interference indicators

Indicators	C_{12}	C_{13}	C_{14}	C_{15}
C_{12}	0.5	0.7	0.3	0.3
C_{13}	0.3	0.5	0.2	0.2
C_{14}	0.7	0.8	0.5	0.5
C_{15}	0.7	0.8	0.5	0.5

Table 10. Judgment matrix of straight line stability indicators

Indicators	C_{16}	C_{17}	C_{18}
C_{16}	0.5	0.5	0.7
C_{17}	0.5	0.5	0.7
C_{18}	0.3	0.3	0.5

Table 11. Judgment matrix of cornering stability indicators

Indicators	C_{19}	C_{20}	C_{21}	C_{22}	C_{23}	C_{24}
C_{19}	0.5	0.4	0.4	0.6	0.3	0.6
C_{20}	0.6	0.5	0.4	0.7	0.4	0.6
C_{21}	0.6	0.6	0.5	0.7	0.4	0.6
C_{22}	0.4	0.3	0.3	0.5	0.3	0.4
C_{23}	0.7	0.6	0.6	0.7	0.5	0.6
C_{24}	0.4	0.4	0.4	0.6	0.4	0.5

Table 12. Judgment matrix of shift-line stability indicators

Indicators	C_{25}	C_{26}	C_{27}
C_{25}	0.5	0.7	0.4
C_{26}	0.3	0.5	0.2
C_{27}	0.6	0.8	0.5

3.3. Checking and adjusting fuzzy judgment matrix consistency

Fuzzy judgment matrix which is created in Section 3.1 is consistency inspected. According to the definition 1 and 2, fuzzy complementary matrices can be obtained as shown in table 3˜12. Whether they are consistent matrices is determined by the definition 3. If fuzzy judgment matrices in table 3˜12 are consistent matrices, there is no need to adjust them. Otherwise, fuzzy judgment matrices are adjusted to consistent matrices by using definition 2.

Table 13.Consistent matrix of cornering stability indicators

Indicators	C_{19}	C_{20}	C_{21}	C_{22}	C_{23}	C_{23}
C_{19}	0.5000	0.6429	0.5538	0.5806	0.5217	0.5000
C_{20}	0.3571	0.5000	0.4082	0.4348	0.3774	0.3571
C_{21}	0.4462	0.5918	0.5000	0.5273	0.4677	0.4462
C_{22}	0.4194	0.5652	0.4727	0.5000	0.4407	0.4194
C_{23}	0.4783	0.6226	0.5323	0.5593	0.5000	0.4783
C_{24}	0.5000	0.6429	0.5538	0.5806	0.5217	0.5000

3.4. Calculating element weight with fuzzy consistent matrix

Fuzzy consistent matrices are obtained in Section 3.3. Subjective evaluation index weights of fuzzy consistent matrices are calculated by using the square root method.

$$w_i = \frac{\overline{S_i}}{\sum_{i=1}^{n} \overline{S_i}}, \overline{S_i} = (\prod_{l=1}^{n} f_{il})^{\frac{1}{n}}$$

Table 14.Weight coefficient calculation results based on fuzzy consistent matrix method

Target layer	First-level indicators	Weight	Second-level indicators	Weight	Relative weight	Third-level indicators	Weight	Relative weight
Handling Stability	A_1 Steering performance	0.5000	B_1Parking performance	0.3351	0.16755	C_1 Parking force	0.3183	0.1067
						C_2 Returnability	0.4544	0.1523
						C_3Mobility	0.2273	0.0762
			B_2Central steering	0.2865	0.14325	C_4 Response	0.3719	0.1065
						C_5 Torque feedback	0.2484	0.0712
						C6 Predictability	0.3797	0.1088
			B_3Turning corners	0.1500	0.0750	C_7 Response	0.2140	0.0321
						C_8 Torque feedback	0.1835	0.0275
						C_9 Steering force	0.2525	0.0379
						C_{10} Returnability	0.2112	0.0317
						C_{11}Predictability	0.1388	0.0208
			B_4Steering interference	0.2284	0.1142	C_{12} Steering torque	0.2283	0.0521
						C_{13}Deviation	0.1560	0.0356

The relative weight of each indicator of the other two engineers under a single factor can be adjusted and calculated in the same way. The same indicator weight of three engineers is obtained by the arithmetic mean. Shift-line stability weights of three engineers are 0.4259, 0.4814, 0.4523 and the arithmetic mean is 0.4532. Other indicators is the same available. Weight coefficient calculation results are shown in table 14.

4. The application and analysis of evaluation index weight coefficient

According to the calculated weight coefficient of each index, the score of each vehicle model indicators which are higher than 2 layer can be get by combining with the engineers' subjective assessment[15-16]. For example, the weight of parking force, returnability and mobility of vehicle model A parking performance are respectively 0.3183, 0.4544, 0.2273, and three performance value are respectively 8, 7.5, 8. So parking performance value of vehicle model A is:

$$8 \times 0.3183{+}7.5 \times 0.4544 + 0.2273 \times 8 = 7.7523$$

Other indicators' total values can be got by the same way which are shown in table 15.

Table 15. Subjective evaluation total value of performance indicators

Evaluation project	Model		
	A	B	C
Subjective evaluation total score S of handling stability	7.7793	7.4477	7.7402
Steering performance A_1	7.7523	7.6490	7.6259
Parking performance B_1	7.7728	7.6592	7.2048
Central steering B_2	7.8141	8.0000	8.0000
Turning corners B_3	7.5542	7.3013	7.5068
Steering interference B_4	7.7746	7.4220	7.8526
Stability A_2	7.8062	7.2463	7.8545
Linear stability B_5	7.5693	8.3103	7.6898
Cornering stability B_6	7.7240	7.1992	7.7789
Shift-line stability B_7	8.0000	6.6231	8.0000

The results of the weight show that: steering performance and stability have the same weight in the first-level indicators. Relative to the overall handling stability, shift-line stability is very important in the second-level indicators, and the weight coefficient is 0.2266. In addition, the abilities of parking performance and central steering are relatively important, which weight coefficient are respectively 0.16755 and 0.14325. Then linear stability, cornering stability, steering interference, and turning corners are the same important. In the third-level indicators, predictability and stability of shift-line stability and returnability of parking performance are the most important, which weight coefficient are respectively 0.1853, 0.1564 and 0.1523.

To be sure that 5 points is the critical value in the grade standard. It is generally believed the performance indicators'value can't be equal to or less than 5, otherwise the vehicle will have a fatal weakness and need to be redesigned and improved.

From the table 15, overall rating of three types vehicle handling stability: Model A hold the highest value (7.7793), in other words, the handling stability of model A is the best, then comes model C (7.7402) and model B (7.4477). The handling stability of model B is worse than model A and C.

The result of table 15 shows clearly that model A has the highest score and its each performance is very good. Although the linear stability of model B stands very well, the score is poorer relatively to the other two models in cornering stability and shift-line stability. It mainly because that in the process of cornering and shifting lines overshoot is obvious and stability is bad. The ability of turning corners and steering interference of model B in steering performance get poor value relative to the other two models. Therefore, the performance of vehicle B in steering and stability needs to be improved. The handling stability overall performance of model C is very good, the overall rating of the indicators are around 7.7, especially its stability value is highest in the second-level indicators. But the parking performance of model C is not very well, only 7.2048. If the vehicle can improve returnability which takes the larger weight coefficient, the overall handling stability will be a greater increase in performance.

5. Conclusions

In view of the present China subjective evaluation inaccurate problem on overall performance ratings, the vehicle handling stability subjective evaluation system is established by using the method of fuzzy consistent matrix of fuzzy analytic hierarchy process. The overall score of the vehicle handling stability is determined with the underlying subjective ratings of single index by the driver.

By analyzing the determined weight coefficient and vehicle evaluation test results, the direction of the vehicle to improve is put forward, which provide the scientific basis and reference for vehicle development in the process of calibration, the calibration of standard and adjustment of sample vehicle.

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