

Study on evaluation indexes of the full width deformable barrier test

Jialin Yang^{1,a}, Bin Zhang^{1,b}

¹CATARC automotive test center (Tianjin) Co.,Ltd, 300000;

^a yangjialin@catarc.ac.cn, ^b zhangbin@catarc.ac.cn

Abstract. In order to evaluate the crash compatibility of vehicles, the full width deformable barrier is introduced into the vehicle crash test. Real car to car frontal collision is better simulated by installing deformable barrier on the load-cell wall. By the load-cell wall data, the values and distribution of vehicle frontal collision loads can be further obtained. Based on this, the full width deformable barrier tests are conducted for different structural sedans and SUV. The height index, homologous index, horizontal structure interaction index(HSI), vertical structure interaction index(VSI), and minimum load-cell index are analyzed and compared. The results indicate that there is uncertainty when calculating the homologous index RH and the evaluation indexes proposed by FIMCAR repeat the first step of VSI and HSI. Therefore, the height index, VSI, and HSI indexes are selected as effective indexes for evaluating the compatibility of the full width deformable barrier test.

Keywords: Full width deformable barrier; Evaluation indexes; Compatibility.

1. Introduction

In traffic accidents, due to the difference in vehicle mass, front end stiffness or structural dimensions, one side's vehicle is more aggressive, thus causing serious occupant injury to the other side's vehicle. In order to reduce this collision incompatibility and guide the vehicle to carry out targeted development and design, research institutions have successively launched corresponding vehicle compatibility testing evaluation procedures. Among them, the full width deformable barrier test was first proposed by the TRL laboratory in the UK[1]. The test and structural deformation are closer to real traffic accidents and vehicle to vehicle collisions. It also reduce the impact of engine sinking. And the lateral structure of the vehicle's front end also can be evaluated[2].

In 2007, the EEVC Working Group 15 of the European Committee for the Enhancement of Vehicle Safety and in 2012, the Front Impact and Compatibility Assessment Research (FIMCAR) prioritized full width deformable barrier test to evaluate vehicle collision compatibility[3].

In 2014, the European New Car Evaluation Program (Euro NCAP) used full width deformable barrier test to effectively test the frontal crash performance of L7e level vehicles for passenger injury evaluation[4]. Therefore, the following studies will be conducted on the collision compatibility indexes of the full width deformable barrier test. The test indexes will be analyzed through actual vehicle collision tests, providing reference for the development of relevant testing methods.



Figure 1. Euro NCAP L7e model test[4]

2. Full width deformable barrier test setup

The full width deformable barrier test speed is set to $56 \pm 1\text{km/h}$, and the collision barrier is composed of a deformable barrier and a load-cell wall. The deformable barrier is shown in the following figure, consisting of two layers of honeycomb aluminum with a thickness of 150mm and strengths of 0.34MPa and 1.71MPa respectively. The deformable barrier has a width of 2000mm and a height of 1000mm, and is connected to the rear load-cell wall through bolts. The first layer of honeycomb aluminum is mainly used to reduce the impact of engine sinking load in the test, so as to be closer to the vehicle to vehicle collision test. The second layer of honeycomb aluminum is mainly used to prevent the impact of protruding rigid components such as bolts and traction holes. The protruding components have little impact in actual vehicle to vehicle tests.

The load-cell wall consists of 128 force measuring units, each with a size of $125\text{ mm} \times 125\text{ mm}$. The height from the bottom edge of the force wall to the ground is 80mm, and the center is consistent with the centerline of the collision test track, used to collect the front end collision force of the vehicle during the test process.



Figure 2. Honeycomb aluminum and loadcell wall [1]

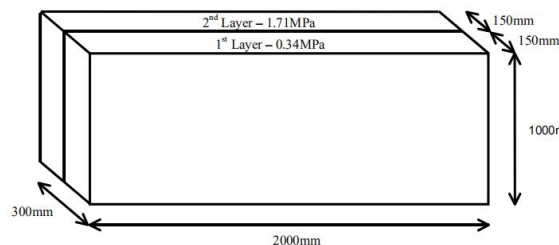


Figure 3. Dimensions and strength of the honeycomb aluminum [1].

3. Full width deformable barrier test evaluation indexes

The indexes of full width deformable barrier test mainly analyzes the interaction between the front end structure of the vehicle, evaluates the load action of the front end structure of the vehicle through the combination of full width honeycomb aluminum and load-cell wall. The level of front end load-cell and its distribution in the horizontal and vertical directions are also evaluated. The main compatibility evaluation indexes are as follows:

3.1 AHOF400 indexes

AHOF400 is the height of the average collision force when the displacement reaches 400mm in the process of vehicle collision[2]. The AHOF400 index is to control the vertical height of the front structure of the vehicle by calculating the average height of the load-cell when the displacement is 25mm to 400mm from the beginning of the collision. It should fall in the area of joint action of vehicle collision. Its recommended limit is the FMVSS Part581 area, and the height from the ground is 406mm to 508mm. The specific calculation formula is as follows:

$$\text{HOF}(d) = \frac{\sum_{i=1}^n Fi(d) * Hi}{\sum_{i=1}^n Fi(d)} \quad (1)$$

$$AHOF400 = \frac{\sum_{25}^{400} HOF(d) * F(d)}{\sum_{25}^{400} F(d)} \quad (2)$$

In the formula, d is the vehicle displacement; $F_i(d)$ is the load-cell corresponding to the force measuring unit; H_i is the height from the corresponding force measuring unit to the ground; N is the number of force measuring units for the load-cell wall; $F(d)$ is the corresponding load-cell wall resultant force.

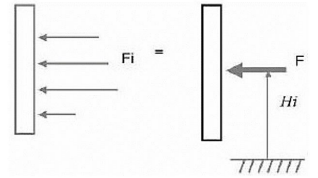


Figure 4. AHOF400 Calculation Diagram

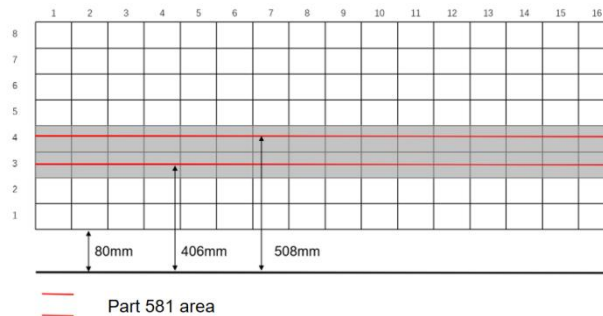


Figure 5. Schematic diagram of FMVSS Part 581 area

3.2 Homogeneity indexes

Based on the structure and geometric dimensions of the vehicle, the evaluation area is determined on the load-cell wall, and the homogeneity index calculation formula is as follows[2]:

$$H = \frac{\sum_{i=1}^n (L - f_i)^2}{n} \quad (3)$$

$$RH = \frac{H}{L^2} \quad (4)$$

In the formula: L refers to the average force of the peak values of each unit in the evaluation area; f_i is the peak force of each unit in the evaluation area; N refers to the number of units within the evaluation area; H is the homogeneity index; RH is a relative homogeneity index. The homogeneity index reflects the distribution of load-cells within the evaluation area, and the smaller its value, the more uniform the distribution of collision force.

3.3 Structural Interaction Index SI

The structural interaction index SI assesses the distribution of force in the horizontal (bumper crossbeam) and vertical directions of the vehicle by calculating the change in load-cell within 40ms before the collision process[1]. At the same time, it is required to meet the minimum collision force requirement in the joint action area, which is divided into the vertical structure interaction index VSI and the horizontal structure interaction index HSI .

3.3.1 VSI evaluation index (vertical structure interaction index)

(1) The first step is to calculate the difference between the actual collision force and the target collision force in the vertical direction, as follows:

If $F_i > F_{\text{target}}$, then the deviation is 0, If $F_i \leq F_{\text{target}}$, then

$$VSI_1 = \sum_{i=3}^4 (F_{target} - F_i) \quad (5)$$

In the equation, F_i is the peak collision force within the first 40ms on lines 3 and 4; F_{target} is the target collision force.

(2) Step 2, meet the requirements for minimum collision force and collision load distribution on lines 2, 3, 4, and 5, VSI_2 refers to the sum of the weighted normalized homogeneity index (Load balance) and the weighted normalized minimum collision force index (Minimum support).

$$VSI_2 = \alpha * CV_n + \beta * NDev_n \quad (6)$$

wherein

$$CV_n = \frac{\sigma_{row(2to5)}}{\bar{F}_{row(2to5)} * CV_{range}} \quad (7)$$

$$NDev_n = \frac{\sum_{i=2}^5 F_{target} - F_i}{NDev_{range}} \quad (F_i \leq F_{target}) \quad (8)$$

In the equation, α and β Is the weighting coefficient, usually 1; CV_n is the coefficient of variance within the evaluation range; $NDev_n$ is the negative deviation of the collision force within the evaluation range; $\sigma_{row(2to5)}$ is the standard deviation of the 40ms peak value before the second to fifth rows of the force wall; $\bar{F}_{row(2to5)}$ is the average peak value of 40ms before the second to fifth rows of the force wall; CV_{range} is the range of CV values from the second to fifth rows of the force wall; F_{target} is the target collision force; F_i is the peak collision force within the first 40ms on each line of force measuring units; $NDev_{range}$ refers to the range of negative deviation $NDev$ from the second to fifth lines. The scope of VSI evaluation is shown in Figure 6.

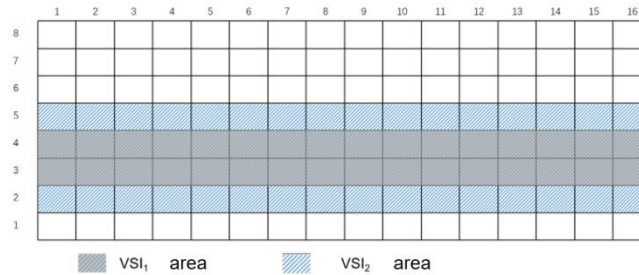


Figure 6. Schematic diagram of VSI evaluation area

3.3.2 HSI evaluation indexes (horizontal structure interaction index)

HSI examines the homogeneity distribution of collision force in the width direction of vehicles, divided into indexes that only consider the middle crossbeam part HSI_1 . Considering both the middle crossbeam and the structures on both sides HSI_2 . The specific situation is as follows:

(1) Only consider the middle crossbeam section HSI_1

For collision units in rows 3, 4, columns 7 to 10, only when $x_{ij} \leq TC_i$, participated in the calculation

Then

$$HSI_{1-step1} = NDev_{centre(n)} = (\sum_i \sum_j TC_i - x_{ij})/4 \quad (9)$$

For collision units in rows 2 to 5, columns 7 to 10, only when $x_{ij} \leq TC_i$, participated in the calculation

Then

$$HSI_{1-step2} = NDev_{centre(n)} = (\sum_i \sum_j TC_i - x_{ij})/4 \quad (10)$$

$$\text{当} \sum_{j=1}^{16} x_{ij} * \frac{125}{W} \leq 20 \text{ 时}$$

$$TC_i = 20 + (\sum_{j=1}^{16} x_{ij} * \frac{125}{W} - 20) \quad (11)$$

$$\text{当} \sum_{j=1}^{16} x_{ij} * \frac{125}{W} > 20 \text{ 时}$$

$$TC_i = 20 \quad (12)$$

In equations (9) to (12), $NDev_{centre(n)}$ is the negative deviation of the collision force on the middle structure of the vehicle; x_{ij} refers to the collision force on the force measuring unit; TC_i is the target collision force; W is the width of the vehicle.

(2) Considering both the middle crossbeam and the structure on both sides HSI_2

According to the survey conducted by the VC COMPAT project, a range of 80% of the vehicle width was selected to evaluate the load-cell distribution of the unit structures on both sides, and to define the number of columns j, k that need to be selected for the unit

$$m = (\frac{W*0.8}{250}) \text{ rounding} \quad (13)$$

$$n = \frac{W*0.8}{250} - m \quad (14)$$

j represents columns (9-m) to 5, and columns 12 to (8+m)

k is the (8-m) and (9+m) columns

If $x_{ij} \leq TC_i$, $x_{ik} \leq TC_i * n$, then

$$NDev_{outer(n)} = \left\{ \sum_i [\sum_j (TC_i - x_{ij}) + \sum_k (TC_i * n - x_{ik})] \right\} / (2m - 6) \quad (15)$$

In equations (13) to (15), $NDev_{outer(n)}$ is the negative deviation of the collision force between the structures on both sides of the vehicle; x_{ij} refers to the load-cell on the force measuring unit; TC_i is the target collision force; W is the width of the vehicle.

Select the units from line 3 to line 4, and the units from line 2 to line 5 as the evaluation area to calculate HSI . The evaluation area is shown in Figure 7.

$$HSI_2 = \alpha * NDev_{centre(n)} + \beta * NDev_{outer(n)} \quad (16)$$

In the equation α and β Is a weighted coefficient, usually 1.

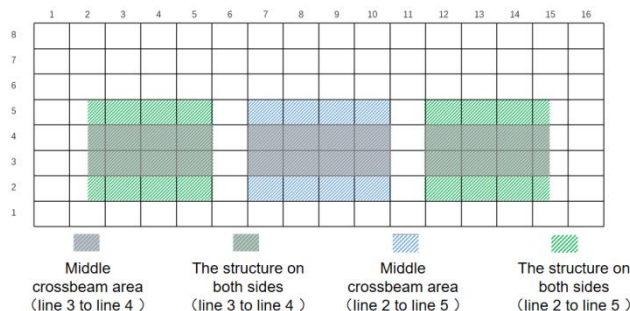


Figure 7. Schematic diagram of HSI evaluation area

3.4 FIMCAR evaluation indexes

The "Frontal Collision Compatibility Research Working Group" FIMCAR mainly evaluates the positions and interactions of the main energy absorbing structures in the front of the vehicle. The collision force in the rating area is used to guide the matching of the front end force during vehicle to vehicle collisions. The simplicity of the indexes and the impact of vehicle weight are considered. The following evaluation indexes are proposed[2]:

$$F3 \geq [MIN(100, 0.2F_{T40})] \quad (17)$$

$$F4 \geq [MIN(100, 0.2F_{T40})] \quad (18)$$

In the equation, F_{T40} refers to the peak value of the combined force of the internal force in the 40ms after the collision occurs; $F3$ and $F4$ are the peak collision force in the third and fourth rows of the 40ms after the collision occurred.

4. Real vehicle test analysis

On the basis of the compatibility evaluation indexes mentioned above, real vehicle collision tests are conducted for analysis. Typical SUV and sedan for full width deformable barrier tests are selected. The test and vehicle information is shown in Table 1 below.

Table 1. Test and Vehicle Information

vehicle	Test speed	Vehicle width
SUV	56km/h	1850mm
Sedan	56km/h	1700mm

The sedan in Table 1 is equipped with a sub-frame, but it does not extend to the front end and has more connections in the lateral structure. The SUV model has a sub-frame that extends to the front and has a high-strength crossbeam in the transverse structure. The structures of the two vehicle models are shown in Figure 8.

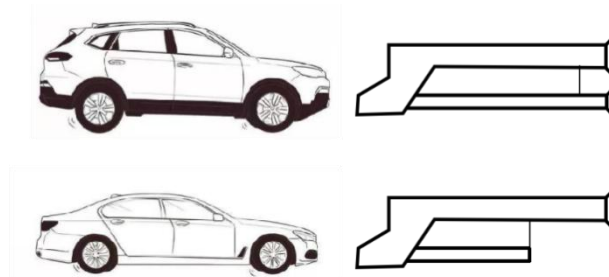


Figure 8. Diagram of the front end structure of the vehicle

The load-cell wall cloud diagrams of SUV and sedan are shown in Figures 9 and 10, and it can be clearly seen that the load-cell wall recognizes and detects the sub-frame structure of the vehicle. The following is an analysis of collision compatibility evaluation indexes based on the real vehicle test results.

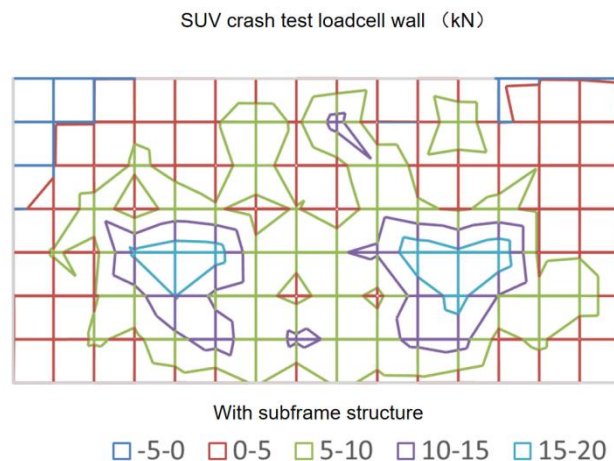


Figure 9. Figure of SUV Loadcell Wall

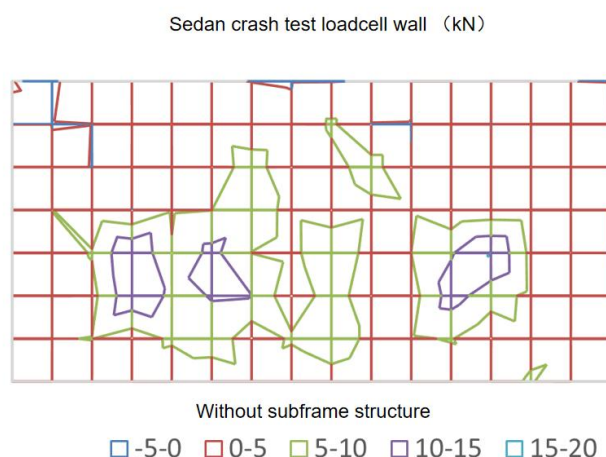


Figure 10. Figure of Sedan Loadcell Wall

4.1 Analysis of the evaluation indexes

4.1.1 AHOF400 index

The AHOF400 index represents the impact height of the average collision force. According to equations (1) and (2), the AHOF400 indexes for the SUV and sedan are calculated, resulting in an SUV AHOF400 index of 546mm, a sedan AHOF400 index of 459mm. FMVSS Part 581 range is of 406mm to 508mm. So, the sedan AHOF400 index meets the requirements, while the SUV AHOF400 index does not. This indicates that the AHOF400 index can identify the average collision force height of different vehicle models and has good discrimination.

4.1.2 Homogeneity index RH

The homogeneity index RH reflects the distribution of vehicle collision force. The relative homogeneity index values of the SUV and sedan according to equations (3) and (4) are calculated. However, this index does not specify the evaluation area of each vehicle model. Different vehicle models may not necessarily have the same evaluation area due to different vehicle widths. The following three evaluation areas are selected for comparative analysis, as shown in Figure 11. The relative homogeneity indexes obtained are shown in Table 2. From the data of relative homogeneity indexes, it can be concluded that the results obtained from different evaluation regions differ greatly. It indicates that the RH values have certain uncertainty in calculation and poor comparability with each other.

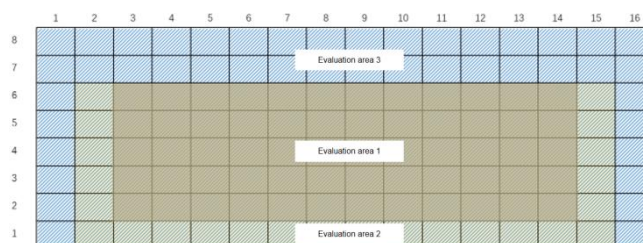


Figure 11. Schematic diagram of different evaluation areas

Table 2. Corresponding RH Values for Different Evaluation Regions

Vehicle	Evaluation area 1 RH	Evaluation area 2 RH	Evaluation area 3 RH
SUV	0.438	0.598	1.01
Sedan	0.483	0.607	1.12

4.1.3 Structural interaction index SI

(1) VSI evaluation index (vertical structure interaction index)

Calculate VSI_1 according to equation (5). The VSI_1 values of the SUV and sedan are both 0, indicating that the collision force of the third and fourth rows meets the requirements.

Calculate VSI_2 according to equation (6). The calculation results are shown in Figure 12. The VSI_2 value of the sedan is 0.655, with a weighted normalized homogeneity index (Load balance) of 0.245 and a weighted normalized minimum support index (Minimum support) of 0.41. The VSI_2 value of the SUV is 0.495, with a weighted normalized homogeneity index (Load balance) of 0.321 and a weighted normalized Minimum Support index of 0.174. It indicates that the vertical collision load distribution of the SUV is better than that of the sedan, but the homogeneity is worse than that of the sedan.

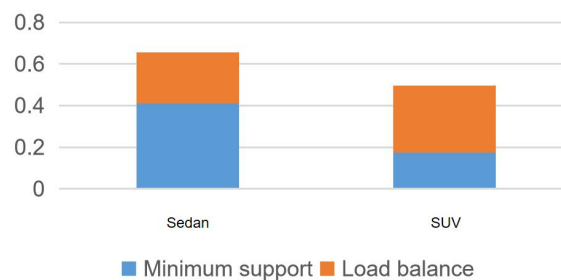


Figure 12. SUV and sedan VSI_2 indexes

TRL test data are collected and the statistical analysis is conducted. The recommended limit for VSI_2 is set to 1.0, and the VSI_2 value of the sedan and SUV both meet the limit requirements and collision compatibility requirements in the vertical direction.

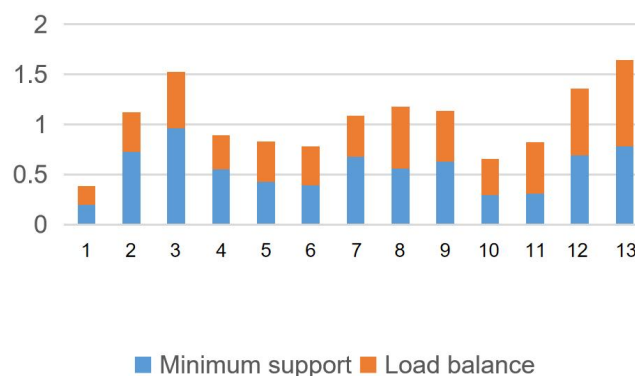


Figure 13. VSI_2 index Statistics

(2) HSI evaluation index (horizontal structure interaction index)

According to equation (16), calculate the lateral load distribution of sedan and SUV models, and obtain the evaluation area of the middle structure and both sides of the vehicle based on the width of the two vehicles, as shown in Figure 14. The HSI_1 of the sedan in lines 3 to 4 is 7.86, the negative deviation index of the middle structure is 7.19, and the negative deviation index of the two side structures is 0.67. The HSI_1 of the SUV in lines 3 to 4 is 8.36, the negative deviation index of the middle structure is 6.69, and the negative deviation index of the two side structures is 1.67, as shown in Figure 15. This indicates that the load distribution performance of the sedan and SUV in the middle structure is worse than that of the two side structures. TRL test data are collected and the statistical analysis is conducted. The recommended limit for HSI_1 is 6.0, and neither the sedan nor SUV HSI_1 meets the recommended limit requirements. Improvements need to be made to the lateral structure.

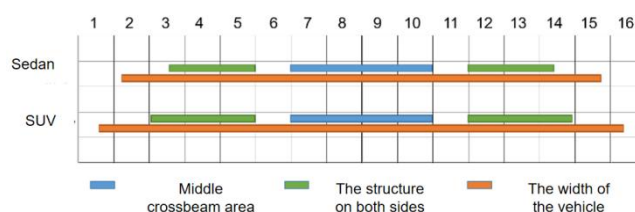


Figure 14. Vehicle lateral evaluation area

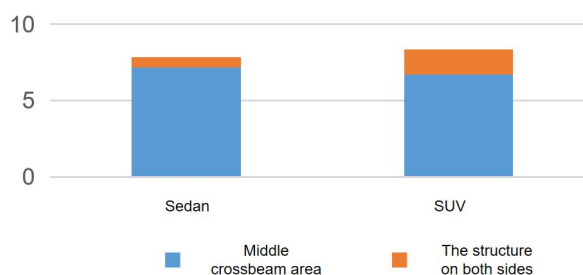


Figure 15. SUV and sedan HSI1 indexes

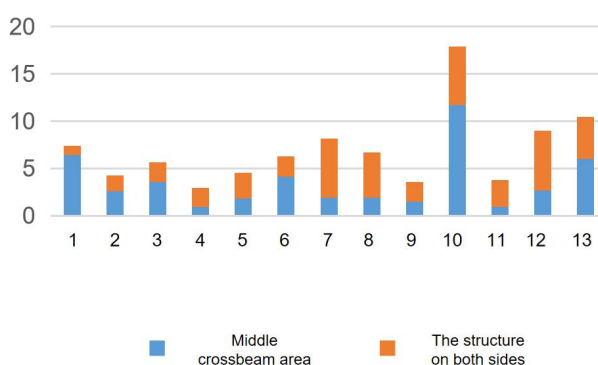


Figure 16. HSI1 index Statistics

The HSI2 of the sedan in lines 2 to 5 is 13.77, the negative deviation index of the middle structure is 9.71, and the negative deviation index of the two side structures is 4.06. The HSI2 of the SUV in lines 2 to 5 is 11.03, with a negative deviation index of 8.02 for the middle structure and 3.01 for the two side structures, as shown in Figure 17. TRL test data was collected and statistically analyzed. The recommended limit for HSI2 is 10.0, and neither the sedan nor SUV HSI2 meets the recommended limit requirements. Therefore, it is necessary to improve the distribution of collision loads horizontally.

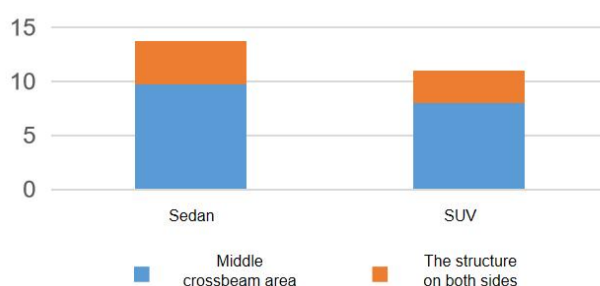


Figure 17. SUV and sedan HSI2 indexes

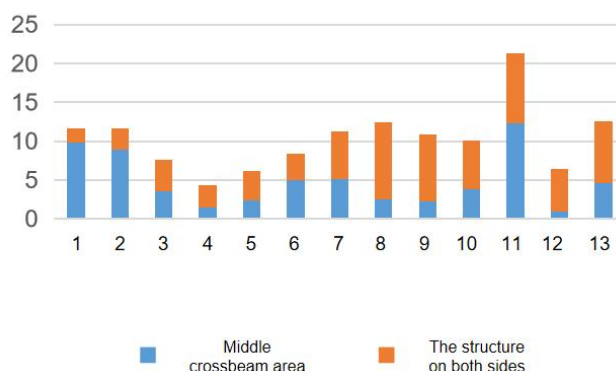


Figure 18. HSI2 index Statistics

By analyzing the VSI evaluation index (vertical structure interaction index) and HSI evaluation index (horizontal structure interaction index), it can be found that VSI and HSI can comprehensively evaluate the distribution of collision loads in the vertical and horizontal directions of vehicles. The indexes reflect the homogeneity and relative position of the vehicle's front-end structure, which show good differentiation and can guide the improvement of the vehicle's front-end structure.

4.1.4 FIMCAR evaluation indexes

According to equations (17) and (18), calculate the evaluation index proposed by FIMCAR. The data of collision force with the time of 40ms are extracted. Calculate the peak force of the load-cell wall data and the peak force of the combined force in the third and fourth rows. The data are obtained in Table 3 below.

Table 3. FIMCAR Evaluation Index Values (Unit: kN)

Vehicle	F3 max	F4 max	Min(100, 0.2*FT40)	Y/N
sedan	104.11	115.80	100	Y
SUV	112.61	160.85	100	Y

Both the sedan and SUV meet the load-cell requirements proposed by FIMCAR. However, the evaluation index of FIMCAR and the first step of VSI evaluation index are almost the same. Therefore, when selecting indexes, repeated evaluations should not be conducted.

Based on the analysis from 4.1.1 to 4.1.4, the AHOF400 index can effectively reflect the average height of the impact force on the front end of the vehicle. VSI and HSI can comprehensively evaluate the vertical and horizontal collision load distribution of vehicles. There is uncertainty when calculating the homogeneity index RH due to the lack of effective methods to determine the evaluation area. The evaluation index proposed by FIMCAR overlaps with the first step of VSI. Therefore, based on the above analysis, the AHOF400 index, VSI, and HSI indexes can be used as effective indexes for evaluating compatibility in full width deformable barrier test.

5. Conclusion

This article focuses on the collision compatibility in the full width deformable barrier test, summarizing and analyzing the collision compatibility indexes and evaluation methods in the tests. The performance of the indexes is verified through real vehicle collision test data, and a combination of indexes that can be used for collision compatibility evaluation in the full width deformable barrier test are proposed.

The AHOF400 index can effectively reflect the average height of the front end load-cell of a vehicle. VSI and HSI can comprehensively evaluate the vertical and horizontal collision load distribution of the vehicle. There is uncertainty when calculating the homogeneity index RH. The evaluation indexes proposed by FIMCAR repeat the first step of VSI. Therefore AHOF400 indexes, VSI, and HSI indexes are selected as effective indexes for evaluating the compatibility of the full width deformable barrier test.

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