

# Research on vehicle aggressiveness evaluation based on full frontal crash test

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**Abstract.** In the frontal accident, vehicles with strong aggressiveness are an important factor in causing death or injury to vulnerable vehicles. To effectively evaluate the aggressiveness of vehicle frontal crash, the dynamic load values and distribution of vehicle frontal structures are collected using the load-cell wall. On this basis, evaluation intervals in the horizontal and vertical directions are established, and the standard deviation and negative deviation of collision loads were analyzed. Normalization is carried out to establish evaluation indices for horizontal and vertical load effects. The effectiveness of the evaluation indexes is verified through analysis of frontal collision tests on several vehicle models. The results showed that the vertical and horizontal collision energy transfer at the front end of the vehicle still needs to be strengthened.

**Keywords:** Full frontal crash test; Vehicle aggressiveness; Evaluation Method.

## 1. Preface

With the advancement of automobile safety technology, most vehicles can achieve high scores in the NCAP frontal collision test, but traffic accident statistics show that car-to-car collisions are still one of the leading causes of occupant casualties, accounting for roughly half of all car accident deaths [1]. Because of the differences in mass, stiffness, and geometric shape between the two sides, the weak side does not adequately protect its occupants in this type of collision accident. The root of the problem is the current lack of technical constraints on vehicle collision compatibility, which causes automobile manufacturers to prioritize their own occupant protection over other occupant protection during the design process [2].

Despite the fact that such collision accidents occur frequently and have a high death and injury rate, the collision compatibility test is not included in collision regulations or the new car safety assessment system. With the increasing variety of automobile products, particularly large vehicles such as SUVs, the associated problems have become increasingly prominent in recent years. As a result, collision compatibility will be a research focus in the field of automobile safety in the coming years.

How to accurately evaluate vehicle crash compatibility has long been a hot research topic internationally, but no unified evaluation method exists [3].

This paper examines the current state of vehicle collision compatibility research and proposes a vehicle aggression evaluation method based on the TRL index. The evaluation method's consistency and repeatability are confirmed. The results of 20 full frontal crash force wall tests are analyzed to determine the compatibility status of the tested vehicles. It serves as a foundation for the future development of relevant standards and regulations in China.

## 2. Background

Collision compatibility research can be traced back to the 1970 ESV conference in the United States. Chillon of Renault Company introduced the concept of vehicle aggression at the meeting. To ensure that light trucks and trucks have a common structural interaction area, the American automobile industry made an important voluntary commitment in 2003: the height of the energy-absorbing structure at the front end of all SUVs or light trucks sold in the United States must meet the requirements of the 581(406mm-508mm) area (Fig. 1): the height of the vehicle's first energy-absorbing structural member (PEAS) should cover 50% of the vehicle's total height. At the

same time, more than 50% of the PEAS height overlaps with area 581; if the height of the vehicle's first energy-absorbing structure cannot meet the overlap rate of the aforementioned area 581, the vehicle must have a second energy-absorbing structure (SEAS) covering the area 581 [4]. European organizations such as EEVC-WG 15 and FIMCAR have also conducted related research and achieved some successes in collision form and evaluation index, but they have not developed an effective evaluation standard system. The MPDB test scheme is published in the EURO-NCAP 2020-2025 road map, and it is planned to include vehicle compatibility as a sub-item in the evaluation scoring system [5-6]; Japan also actively participates in vehicle collision compatibility research, and has conducted extensive technical exchanges with Europe and America: it is suggested that the combination test of full frontal crash test and second energy-absorbing structure (SEAS) be used for evaluation. When the load on SEAS reaches 100KN, the displacement of SEAS must be controlled within 400mm [7]. At the moment, China's collision regulations and C-NCAP test methods are primarily aimed at protecting vehicle occupants, but no research on its own aggression has been conducted.

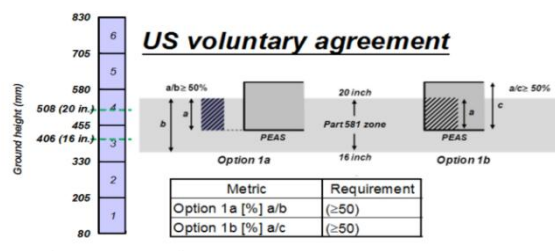


Fig.1 North American Autonomous Control Protocol

Through years of development, the evaluation index is represented by the front-end collision force, the height of force HOF, the front equivalent stiffness Kw, and the balance index. The most direct evaluation index is the front impact force, but the impact force limit and evaluation process are still being debated; HOF is used to investigate the height of the force exerted on the barrier by the collision structure at the front end of the vehicle (Fig. 2). The smaller the difference between the HOF values of the two vehicles when they collide head-on, the better the collision compatibility. However, some scholars have found that the measurement accuracy of HOF index increases with the increase of the number of measurement units and the decrease of unit area. When the number of load force measuring units is 8×16 and the force measuring wall barrier with the unit of 62.5mm×62.5mm is used, the measurement accuracy can be well solved [8]; The NHTSA proposes an evaluation index Kw (Fig. 3) for calculating the structural stiffness of the vehicle's front end in order to assess the vehicle's aggressiveness. Kw400 is based on the curve of vehicle collision force and displacement, and integrates vehicle front deformation in the range of 25mm-400mm [9]; both the HOF index and the Kw400 index should consider the overall load distribution interval, and a single index cannot effectively consider vehicle compatibility.

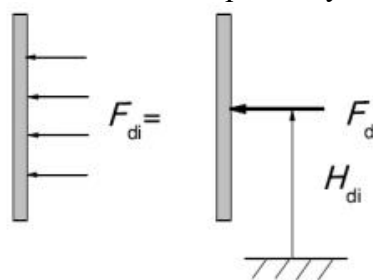


Fig. 2 schematic diagram of HOF definition

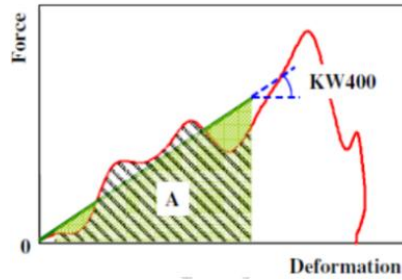


Fig.3 Schematic diagram of KW400 definition

### 3. Evaluation methods

Vehicle frontal collision compatibility is related to the load distribution characteristics of the vehicle's front end: first, the collision structure's height and stiffness, and second, the energy transfer between structures.

TRL proposes a vehicle balance evaluation method for determining whether the force distribution in the vehicle's front structure is balanced. That is, it is expressed as the relative change rate between the load element's peak force  $f_{ij}$  and the target load element's peak force  $l$  [10]. This index can accurately assess the energy transfer of structural components. The disadvantage is that the height and stiffness of vehicle collision structure distribution cannot be evaluated, and there is no objective derivation method corresponding to vehicle size when determining the evaluation area.

As a result, the TRL evaluation method has been improved. The structural interaction index (SI) concept is proposed, and vehicle compatibility is quantified by the size and uniformity of the vehicle front collision load in the corresponding evaluation area. The lower the SI value, the better the vehicle's collision compatibility. Vertical structural interaction index (VSI) and horizontal structural interaction index (HSI) are components of the SI index.

#### 3.1 VSI index

The VSI index corresponds to the vehicle's vertical structure (Fig. 4), and the load cell's response characteristics are examined in the corresponding height area. The VSI value is evaluated in two steps: the first is performed within the height corresponding to lines 3-4 of the force measuring wall (the size of the force measuring unit is 125mm125mm, and the clearance between the lower end and the ground is 80mm), and the peak load is required (VSIstep1); the second step is to analyze the peak load and its distribution in the area corresponding to lines 2-5 (VSIstep2).

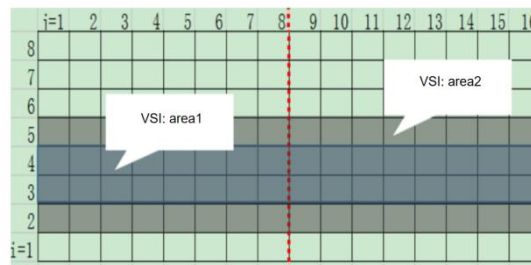


Fig. 4 schematic diagram of VSI calculation area

Where,

$$VSI_{STEP1} = \sum_{Row(i)=3}^4 (F_i \leq F_{target} \Rightarrow F_{target} - F_i) \tag{1}$$

$$F_{target} = 100 + \left[ \frac{\sum_{i=1}^8 \sum_{j=1}^{16} x_{ij}}{5} \leq 100 \Rightarrow \frac{\sum_{i=1}^8 \sum_{j=1}^{16} x_{ij}}{5} - 100 \right] \quad (2)$$

Where  $F_i$  is the peak value of the row unit (the sum of the peak load forces before 40ms). 100KN,  $F_{target}$  is the target line load, if it is less than 100kn, it is 1/5 of the sum of the peak loads of all load cells, otherwise it is 100kn;  $X_{ij}$  the peak value of the load cell in row  $i$  and column  $j$  before 40ms.

$$VSI_2 = \alpha * CV_n + \beta * NDev_n \quad (3)$$

$$CV_n = \frac{\sigma_{row(2to5)}}{\bar{F}_{row(2to5)} * CV_{range}} \quad (4)$$

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

$VSI_2$  It consists of weighted normalized coefficient of variation  $CV_n$  and negative deviation  $NDev_n$  of collision load.  $\alpha$  and  $\beta$  are weight coefficients, and the values in this paper are both 1.  $\sigma_{row(2to5)}$  represents the standard deviation of the peak collision force from the second to the fifth lines;  $\bar{F}_{row(2to5)}$  represents the average of the peak collision force from the second to the fifth lines.  $CV_{range}$  represents the range of  $CV$  values from the second to the fifth line and is assigned 1;  $NDev_{range}$  represents the range of  $NDev$  values from the second to the fifth line and is assigned 100KN.

### 3.2 HSI index

The horizontal structure of the vehicle is represented by the HSI index. The load force of the collision load is analyzed in the horizontal direction, in the evaluation area corresponding to the vehicle width size. The horizontal area within the vehicle width is divided into three parts during the data division process: the middle area, the outer left area, and the outer right area. The middle area includes four load cell columns; the areas on both sides of the periphery correspond to 80% of the vehicle width; and the envelope areas are excluded from the middle six columns (Fig. 5-6).

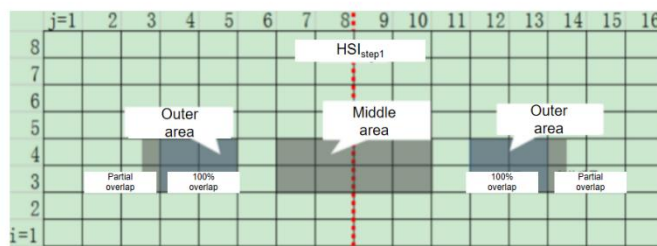


Fig. 5 is a schematic diagram of HSI calculation area

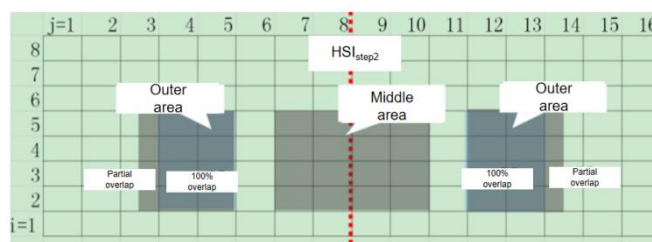


Fig. 6 Schematic diagram of HSI calculation area 2

Similar to the VSI method, the calculation of VSI index is divided into two steps: the first step is carried out in the area corresponding to lines 3-4 of the force wall (HSIstep1); The second step is carried out in the area corresponding to lines 2-5 (HSIstep2).

Where,

$$NDev_{centre} = \sum_{Row(i)} \sum_{Column(j)} TC_i \geq x_{ij} \Rightarrow TC_i - x_{ij} \tag{6}$$

For both sides of the area,

$$NDev_{outer} = \sum_{Row(i)} \left[ \sum_{Column(j)} (TC_i \geq x_{ij} \Rightarrow TC_i - x_{ij}) + \sum_{Column(k)} (TC_i * n \geq x_{ik} \Rightarrow TC_i * n - x_{ik}) \right] \tag{7}$$

Where, the collision force of each line of TCi target is calculated as follows

$$TC_i = 20 + \left[ \sum_{j=1}^{16} x_{ij} * \frac{125}{W} \leq 20 \Rightarrow \sum_{j=1}^{16} x_{ij} * \frac{125}{W} - 20 \right] \tag{8}$$

$x_{ij}$  refers to the collision force on the force measuring unit, and  $W$  refers to the width of the vehicle.  $n$  is the adjustment factor when the load cells partially overlap:

$$n = \frac{W * 0.8}{250} - \text{INTEGER}\left(\frac{W * 0.8}{250}\right) \tag{9}$$

The HSI index is calculated according to (10)

$$HSI_{step1\&2} = \alpha * NDev_{centre(n)} + \beta * NDev_{outer(n)} \tag{10}$$

In the equation (10),

$$NDev_{centre(n)} = \frac{NDev_{centre}}{4}, NDev_{outer(n)} = \frac{NDev_{outer}}{(W * 0.8 / 125) - 6} \tag{11}$$

#### 4. Vehicle evaluation results

The measuring wall was used to collect the front collision load of 20 models in the frontal 100% frontal collision. The measuring wall (LCW) is made up of 128 125mm×125mm load sensors. The lower end has an 80mm clearance from the ground, and the data filtering frequency is CFC60. To reduce the impact of the engine and other components on the structural force during the collision, the SI index is calculated using load data from 40ms before the collision.

Three small cars, 12 regular passenger cars, and five SUVs are among the 20 models. The inter-regional schematic diagram of vehicle width and HSI level evaluation area of test vehicles is shown in Fig. 7.

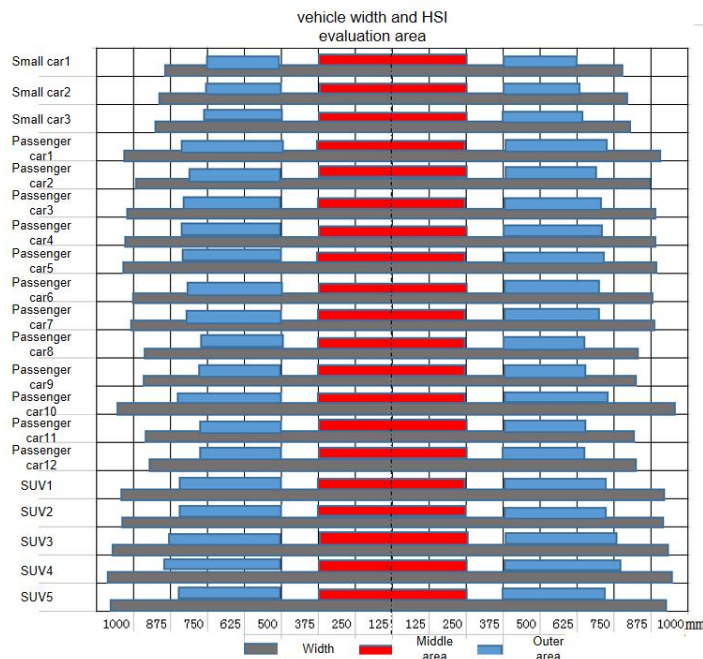


Fig. 7 Vehicle width and HSI level evaluation area of test vehicle.

4.1 VSI index

VSIstep1 is tested at a height of 333mm-458mm above the ground. As with the SEAS test in the United States, the sum of vehicle collision peaks on the third and fourth lines must be greater than  $F_{target}$ , so the expected value of VSIstep is 0. The evaluation results of 20 vehicles show (Fig. 8) that only four ordinary passenger cars, accounting for 20% of the total number of evaluated vehicles, do not meet the requirement of zero value.

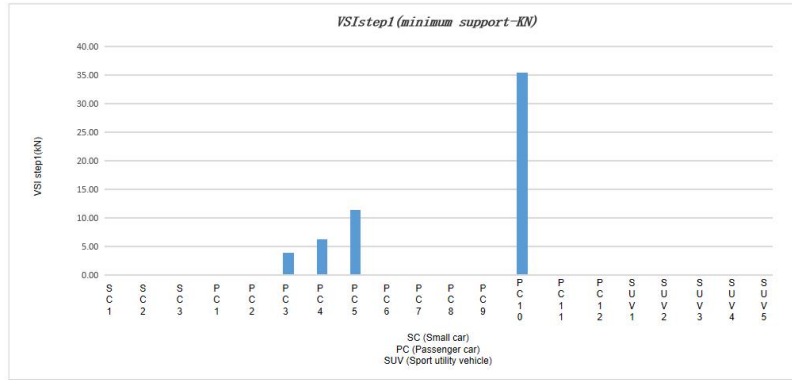


Fig. 8 VSIstep1 value of test vehicle

The VSIstep2 value is evaluated in the height area of 208mm-583mm above the ground. Fig. 9 shows the evaluation results of the above 20 models. It can be seen that the coefficient of variation contributes more to the value of VSIstep2 among the two indicators that constitute the value of VSIstep2. The peak load CV value of the test vehicle at the height of line 2-5 is shown in Fig. 10. The CV value deviation between SUVs is greater when compared to small cars and ordinary passenger cars, indicating that different SUVs have greater differences in the balance index. Fig. 11 depicts the test vehicle's negative load deviation on lines 2-5. The NDev value appears primarily in the second and fifth lines, with small cars having a higher NDev value in the fifth line and ordinary passenger cars and SUVs having a higher NDev value in the second.

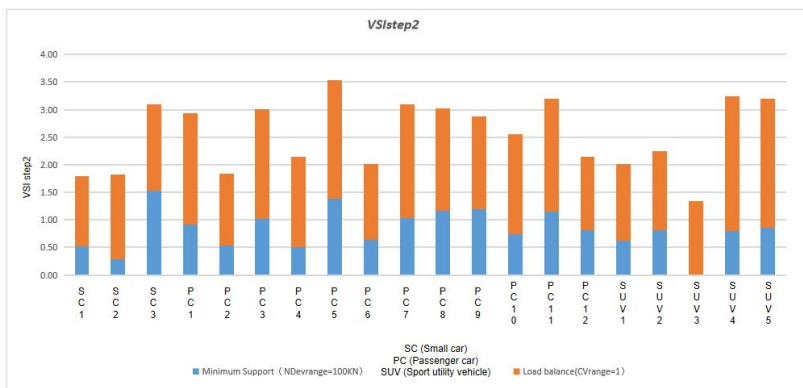


Fig. 9 VSIstep2 value of test vehicle type

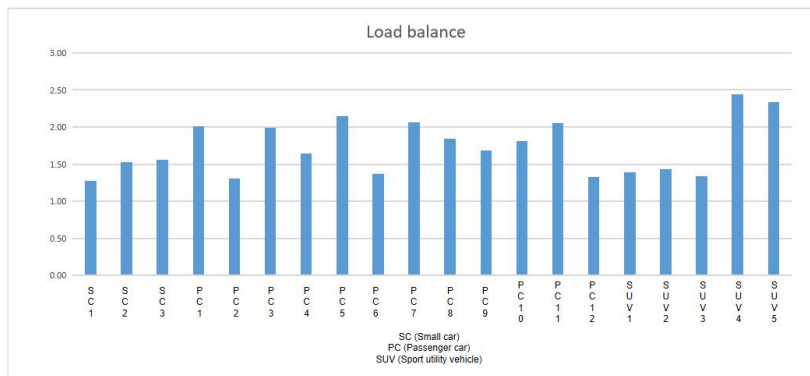


Fig. 10 CV value of peak load in line 2-5 of test vehicle.

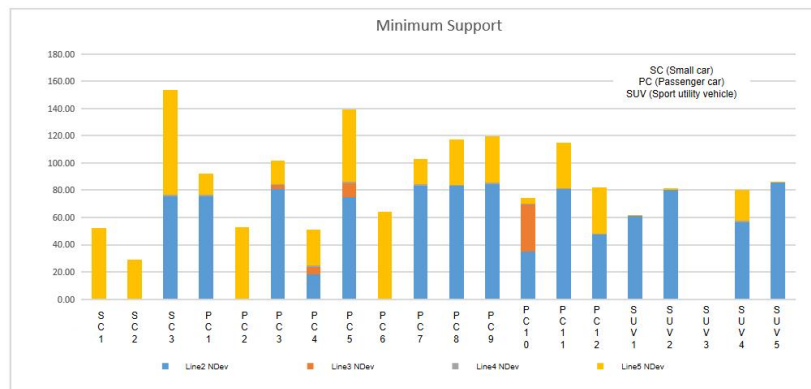


Fig. 11 Peak NDev value of line 2-5 load of test vehicle type

The VSI value indicates that 80% of the vehicles in the evaluation area can meet the crash strength requirements in the first step. The NDev value on the fifth line of the small car is too large in the second step evaluation area, so the energy transfer and absorption on the upper path should be strengthened. The NDev value in the second row of the SUV is too high, indicating that the energy transfer and absorption in the lower path need to be strengthened. At the same time, the balance of load distribution of the SUV is the greatest difference among all models, indicating that the overall energy transfer performance of its front-end components needs to be improved.

#### 4.2 HSI index

In the HSI value evaluation area, the front end structure of the vehicle is on a 125mm×125mm unit, and the peak value of the collision force is taken as the target value, with the central area corresponding to the position of the cross beam and the two side areas corresponding to the position of the longitudinal beam.

Fig. 12-13 depicts the HSIstep1 and HSIstep2 values of 20 vehicles. In the HSI assessment area, 70% of the vehicles (14 models) have a greater negative load deviation in the central area than in the peripheral sides, indicating that the collision bearing capacity at the central beam position is weak. As a result, in order to improve the clarity of the force transmission path between the cross beam and the longitudinal beam and achieve a structure with uniform mass distribution, the stiffness of the cross beam and related components should be increased to ensure the coordination of stiffness and guiding performance of the vehicle's front-end anti-collision structure.

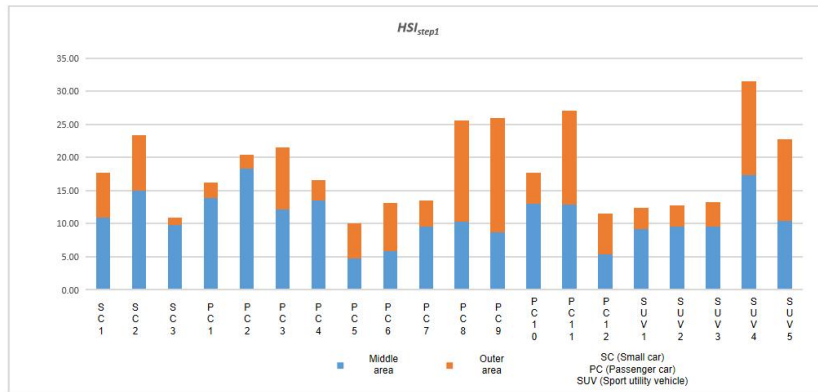


Fig. 12 HSIstep1 value of test vehicle

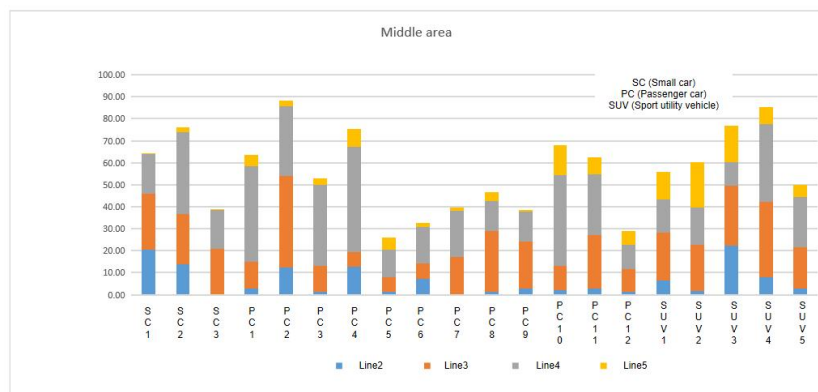


Fig. 13 HSIstep2value of test vehicle

Fig. 14-15 depicts the distribution of negative deviation values of load associated with HSIstep2. The vehicle's overall NDev value on the third and fourth lines is too high, indicating that the lateral stiffness of the vehicle, including the longitudinal beam structure, should be properly strengthened while the vehicle's lateral stiffness is strengthened.

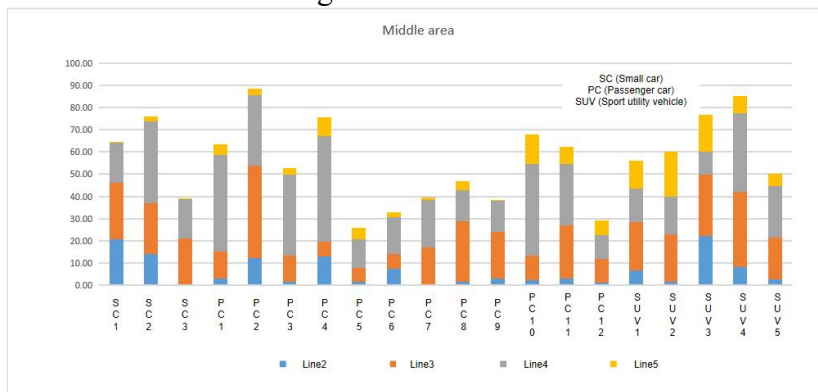


Fig. 14 NDev value of load corresponding to HSIstep2 in central area



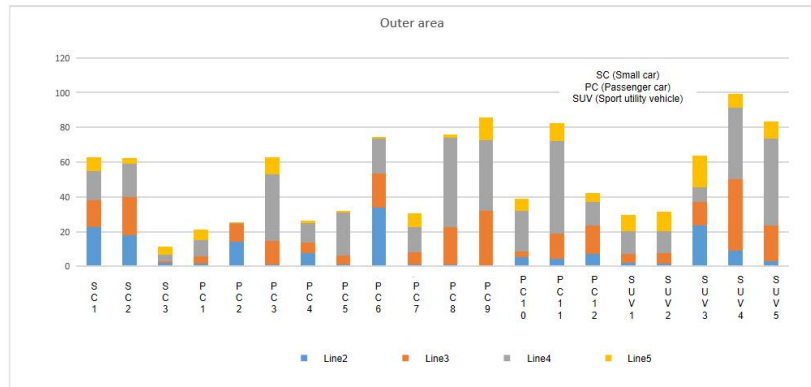


Fig. 15 NDev value of load corresponding to HSIstep2 on both sides

### 4.3 SI index

Fig. 16 depicts the distribution of SI indexes of evaluation vehicles. The VSI value of the vehicle front-end load distribution index in horizontal/vertical direction is small, indicating that the vehicle type has good vertical load distribution performance; in the two horizontal evaluation areas, the HSI values of different vehicles are quite different, and the lateral load distribution performance is quite different, especially for SUV. As a result, it is critical to optimize the collapse mode and stiffness between components while considering the entire force transmission path, including the beam.

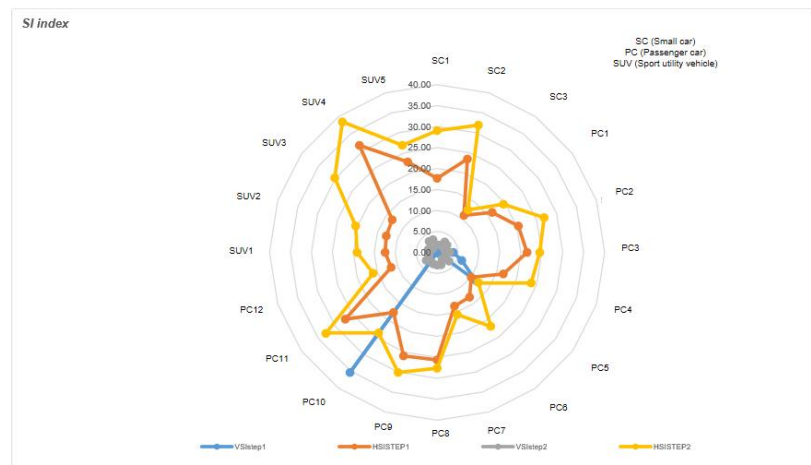


Fig. 16 SI value corresponding to the test vehicle type

## 5. Conclusion

(1) To quantify vehicle attack performance, a method based on the size/uniformity of vehicle front collision load is proposed after analyzing the advantages and disadvantages of existing evaluation indexes. This method can assess the horizontal and vertical transmission of vehicle collision loads, as well as the synergy between force transmission mode and vehicle front-end stiffness.

(2) The full frontal crash test of 20 models was performed through the loadcell wall. The test results show that 80% of the vehicles' front collision load distribution performance meets the requirements of the first step of VSI in the vertical direction, in the area of 333mm-458mm from the ground; in the horizontal direction, the lateral energy transfer performance of vehicles needs to be strengthened, particularly the synchronization between the front stiffness of SUV and the force transfer mode.

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