A PROPOSAL FOR AN IMPROVED METHOD OF EVALUATING VEHICLE COMPATIBILITY IN FULL-FRONTAL RIGID BARRIER TESTS

Akira Yamaguchi
Atsushi Hitotsumatsu
Tomosaburo Okabe
NISSAN MOTOR CO., LTD.
Japan
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ABSTRACT

In frontal collisions, injury risk can be reduced if the front body structure is able to absorb a greater amount of energy. In general, however, in front-to-front collisions between different-size vehicles, the smaller, lighter vehicle sustains greater damage than the larger, heavier one. To help improve vehicle compatibility in front-to-front collisions between such vehicles, what is required is better matching of the geometry and stiffness of the front structures of the colliding vehicles.

Several methods of measuring the geometry and stiffness of front structures have previously been reported. Among these are the AHOF400 and Kw400 metrics, which are measured in full-frontal rigid barrier tests using high-resolution barrier load cells. This paper proposes an improved method for evaluating compatibility in full-frontal rigid barrier tests based on a review of the purposes of and issues with the AHOF400 and Kw400 metrics.

The methods proposed in this paper are intended to help provide an improved compatibility assessment compared with the AHOF400 and Kw400 metrics by evaluating the forces on load cells in an area defined as the structural interaction zone. Like AHOF400 and Kw400, the aim of this research is to improve structural engagement and energy sharing in the event of a front-to-front collision.

INTRODUCTION

In front-to-front collisions involving vehicles of different sizes, the smaller vehicle tends to sustain greater damage because of the differences in mass and stiffness between the two vehicles. To help improve this situation, the front-end structures of both vehicles should deform appropriately to absorb more crash energy. In order to promote deformation of the front-end structures, they must be positioned so that they engage during collision and should be of similar stiffness. These aspects of compatibility are already widely known. Various organizations have reported methods for evaluating the height and stiffness of front-end structures for assessing compatibility.

One proposed approach to evaluating the height and stiffness of front-end structures is to use the AHOF400 and Kw400 metrics computed on the basis of barrier force data measured under the current US NCAP test conditions [1]-[2].

The AHOF400 metric is designed to evaluate the height (geometry) of front-end structures. To obtain force data for the calculation, load cells are positioned on the barrier so as to cover the entire front-end of the test vehicle. The Average Height of Force (AHOF) is calculated using the force measured with each load cell and the height of each load cell from the ground. The resultant AHOF value is a hypothetical average height of applied force and frequently does not indicate the actual height of the front-end structures.

The Kw400 metric, on the other hand, is designed to evaluate the stiffness of front-end structures. It indicates the force level calculated from the forces measured with all the load cells positioned so as to cover the entire front-end of the test vehicle, the same as for AHOF. The Kw400 value also includes forces other than those of the engaging front-end structures of the two vehicles involved in a car-to-car (CTC) frontal impact.

A limitation common to both AHOF400 and Kw400 is that one evaluation parameter is calculated from the force data of all the load cells. Consequently, the engaging structures of the two vehicles in a CTC frontal impact cannot be identified by the AHOF400 metric and the stiffness of the engaging structural components cannot be evaluated directly by the Kw400 metric.

We have researched an evaluation method that attempts to resolves these limitations. Our proposed

method defines a structural interaction zone in which the front body structures serve to manage the crash energy in a CTC frontal impact. Rather than calculating an evaluation parameter from the forces measured with all the load cells, our method evaluates the force loads within and outside the interaction zone separately. This approach makes it possible to estimate and compare the approximate force level that would be generated by each vehicle in a CTC frontal impact.

As for the test conditions for evaluating compatibility, this study focused on the current US NCAP test conditions that are used in calculating AHOF400 and Kw400. These conditions specify a full-frontal test using a rigid barrier instrumented with 125 mm x 125 mm load cells. The issues inherent in the method of evaluating AHOF400 and Kw400 under these test conditions were identified. An improved method for resolving these issues was then researched.

GEOMETRY EVALUATION: ISSUES WITH AHOF400

The AHOF400 metric for evaluating the height of front body structures is a parameter of the average height of force that is calculated using the individual force values measured with all of the load cells and the height of each load cell from the ground. The load cells are positioned on the barrier so as to cover the entire front-end of the test vehicle as shown in Fig. 1. One concern with this metric is that it is not known whether the front-end structures are actually at the height indicated by AHOF400. For example, light trucks or vans (LTVs) have a relatively high hood, so good engagement of the hood with the front-end structures of a passenger car cannot be expected. However the hood height influences the AHOF400 value. Moreover, although higher structures tend to have a lower probability of engagement with the other vehicle, as the height of the structure increases its proportional influence on AHOF400 also increases due to the calculation method.

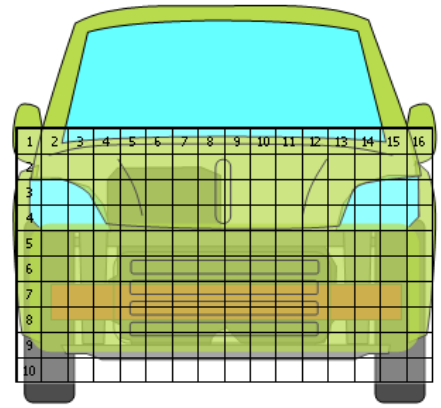

Fig. 1 Vehicle front-end and multi-load cell barrier

$$\mathbf{HOF}\,(x) = \sum_{i=1}^{n} f_i(x) \cdot H_i(x) \Big/ \sum_{i=1}^{n} f_i(x) \qquad (1)$$

where fi(x) is the force measured with a load cell and Hi is the height of each load cell.

$$\mathbf{AHOF400} = \sum_{x=25mm}^{400m} HOF(x) \cdot F(x) \Big/ \sum_{x=25m}^{400m} F(x) \qquad (2)$$

where F(x) is the vehicle force computed from the forces measured with all the load cells.

$$F(x) = \sum_{i=1}^{n} f_i(x)$$

Figure 2 shows the positional relationship between the main frame of the LTV used in the finite element analysis (FEA) conducted in this study and the barrier load cells, when the bottom of the barrier was at a height of 80 mm from the ground. The AHOF400 values are given in Table 1. The main frame of this LTV was positioned approximately in the center of the Part 581 zone, and the AHOF value calculated from the forces on all the load cells was 526 mm. That value was higher than the top of the Part 581 zone. An AHOF400 value of 503 mm was calculated for a hypothetical condition that excluded the forces on the top two rows of load cells corresponding to the hood height of this LTV. The latter AHOF value was located in the Part 518 zone. In other words, in order to position the AHOF400 value in the center of the Part 581 zone on this LTV, the height of the main frame would have to be lower than the center of the zone because of the influence of the hood height on

increasing the AHOF400 value. This same result has been reported in the literature [3].

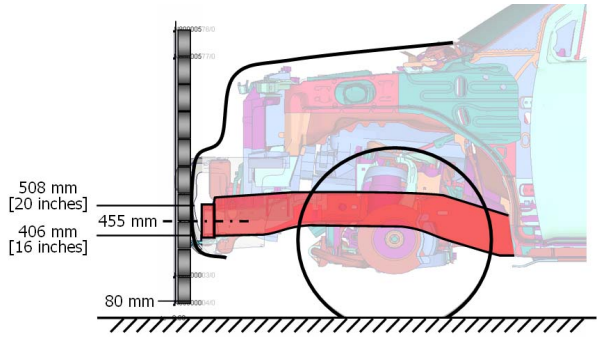

Fig. 2 Frame height on LTV used in FEA

Table 1 Calculated AHOF400 results

	AHOF
Forces on all load cells	526 mm
Forces on load cells excluding top 2 rows	503 mm

STIFFNESS EVALUATION: ISSUES WITH KW400

One issue with the Kw400 metric for evaluating the stiffness of front-end structures is that it is not as accurate as we could want in evaluating the actual stiffness levels of the engaging structures of the two vehicles in a CTC frontal impact. For example, the stiffness of the hood of the above-mentioned LTV would be included in the Kw400 value even though it would not likely be engaged with the front-end structures of a passenger car in an actual CTC frontal impact.

The equation for calculating Kw400 can be rewritten as shown below, which indicates that it is equivalent to evaluating the average force (Favr) in an evaluation range of 25 mm to 400 mm of vehicle displacement.

Kw400 is given as:

$$\mathbf{Kw400} = 2\int_{25mm}^{400mm} F(x)\,dx \Big/ [(400)^2-(25)^2] \qquad (3)$$

Favr is given as:

$$\mathbf{Favr} = \int_{25mm}^{400mm} F(x)\,dx \Big/ (400-25) \qquad (4)$$

Hence, Kw400 is proportional to Favr.

$$\mathbf{Kw400} = \frac{2 \cdot \mathbf{Favr}}{(400+25)} \propto \mathbf{Favr} \qquad (5)$$

Accordingly, the following issues can be envisioned.

(1) For example, depending on the size of the energy-absorbing bumper components within evaluation range installed for pedestrian protection, the Kw400 value will vary even at the same levels of vehicle stiffness as shown in Fig.3.

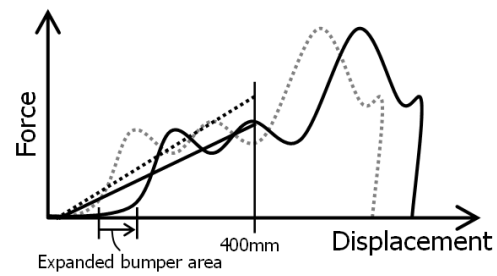

Fig. 3 Influence of bumper on Kw400

(2) The engine inertial force will be included in the Kw400 value in the case of small vehicles with a short front body, but it will not be included for large vehicles having a long front body. Accordingly, Kw400 values will not reflect the relationship of the actual vehicle body stiffness for those vehicles.

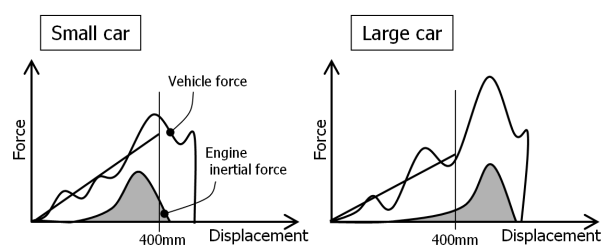

Fig. 4 Influence of engine inertial force on Kw400

Let us reconfirm here once again the issue of stiffness in vehicle compatibility. The rational requirements for compatibility can be summed up as follows. The front body of large cars having relatively high levels of stiffness must deform sufficiently, and small cars having relatively low levels of stiffness must have sufficient cabin stiffness to be able to deform the front body structures of large cars. In other words, an evaluation based on the peak force produced by the

engaging front-end structures of the two colliding vehicles is assumed to provide a better assessment of whether one vehicle body is crushed by the other vehicle than an evaluation of the average force of the vehicles in a certain given evaluation range, for example that of the Kw400 metric.

An evaluation range up to 400 mm of vehicle displacement may be suitable for evaluating the front body structures of large vehicles for which the high levels of force produced are generally the concern. However, for small vehicles for which the low levels of stiffness are the concern, evaluations should be made in a range up to the largest displacement under the NCAP conditions including consideration of the cabin stiffness. The new evaluation method proposed here is outlined in Fig. 5. The upper force limit is regarded as the peak force that occurs in an evaluation range up to 400 mm of vehicle displacement; the lower force limit is regarded as the peak force that occurs in an evaluation range up to the largest amount of vehicle displacement. The use of these rational force limits resolves the two concerns mentioned above.

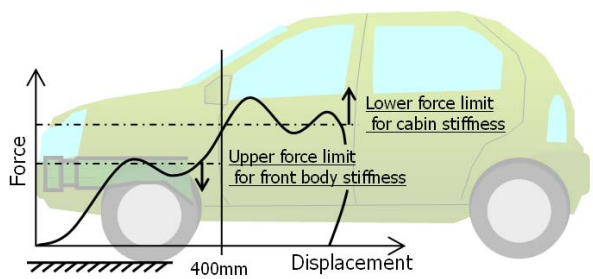

Fig. 5 Overview of new evaluation method

Let us also consider the issue of front end stiffness and self protection in the case of large vehicles. For good compatibility, the front body structures should be designed so that they deform easily while suppressing the peak force of each structure. On the other hand, to obtain the desired self protection performance, the front body structures must be capable of absorbing a certain level of impact energy. In other words, the vehicle force-displacement characteristic of large vehicles should have a rectangular curve exhibiting a low level of peak force and a high level of energy absorption. However, as shown in Fig. 6, the value of Kw400 increases as the force-displacement characteristic approaches a rectangular curve, even though the peak force generated is the same. That is because Kw400 is proportional to the average force and it causes misunderstanding as if it resulted in higher aggressivity.

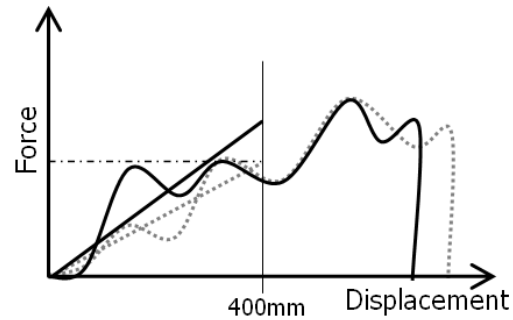

Fig. 6 Relationship between peak force in evaluation range and Kw400

BASIC CONCEPTS OF PROPOSED METHOD

The improved evaluation method researched in this study consists of the following three concepts.

(1) An interaction zone is defined in which energy management is performed by the front body structures that would be engaged in an actual CTC frontal impact.

(2) An evaluation is made of the combined force of the individual rows of barrier load cells corresponding to the interaction zone. This force is referred henceforth as the interaction force.

(3) An optional test is conducted to evaluate the interaction force in cases where it cannot be accurately detected in a full-frontal rigid barrier test. This optional test uses load cell rows 3 and 4 that are defined as the interaction zone extending from a rigid wall.

With regard to the third concept here, there is the concern that the load cells on a fully flat rigid barrier cannot accurately detect the stiffness of front body structures that are set more rearward among the many structural parts composing the front end of a vehicle. Consequently, the force in the interaction zone might not be detected accurately in cases where high levels of force are generated in areas outside the zone. This problem has been resolved by introducing the concept of the override barrier test proposed by the U.S. National Highway Traffic Safety Administration (NHTSA) [1]. The interaction force is then re-evaluated in a test conducted with the height of the contoured barrier set to match the interaction zone.

The three concepts of the proposed evaluation method are explained in detail in the following sections.

DIFINITION OF THE INTERACTION ZONE

Figure 7 shows the positional relationships of the 125 mm x 125 mm load cells, the Part 581 zone and the geometry requirements specified in the "Enhancing Vehicle-to-Vehicle Crash Compatibility" voluntary industry agreement in the U.S, when the bottom of the rigid barrier is set at 80 mm from the ground. Based on these two requirements that have already been introduced, the interaction zone can be appropriately defined as rows 3 and 4 of the load cells.

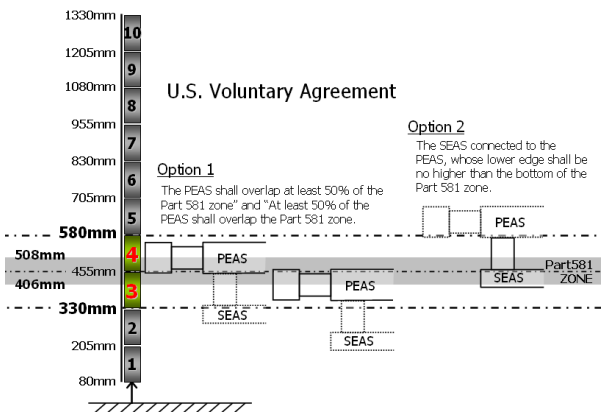

Fig. 7 Relationship between load cells, Part 581 zone and geometry requirements of U.S. voluntary agreement

EVALUATION OF INTERACTION FORCE

In order to determine a criterion for evaluating the interaction force, it is necessary to conduct accident analyses to examine the actual benefits under real-world conditions. An investigation was made of a force criterion that was deemed suitable with respect to the predicted real-world benefits reported in reference [2] concerning NHTSA's Kw400 metric.

In reference [2], Kw400 values above 1318 N/mm are defined as the High zone, values between 1004 and 1318 N/mm as the Medium zone and values below 1004 N/mm as the Low zone. A study was made of the effect on the injury rates sustained in large and small vehicles in CTC frontal impacts when categorized in terms of these zones. When the zones are divided on the basis of these criteria, it has been reported that injury rates are lower if the Kw400 values of the colliding vehicles are in the same zone than if their Kw400 values are in different zones.

In reference to these results, the relationship between the combined force on rows 3 and 4 of the load cells, which were defined here as the interaction zone, and Kw400 was plotted in a graph. An investigation was then made of the improvement effect that might be expected with the evaluation method researched in this study.

Figure 8 shows Kw400 as a function of the peak combined force generated on rows 3 and 4 of the load cells in a range of 25 to 400 mm of vehicle displacement, which is the same evaluation range used for the Kw400 metric. This relationship is shown in the figure for a total of 29 tests, 18 of which were conducted in-house at Nissan and 11 of which were NHTSA's research tests.

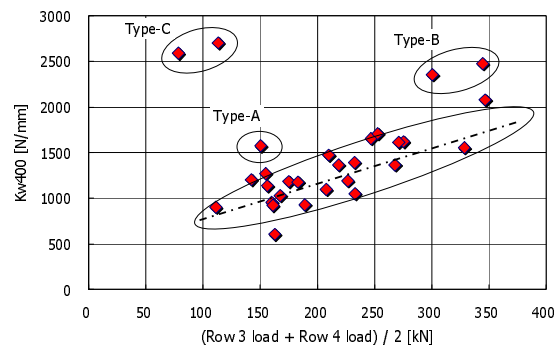

Fig. 8 Relationship between Kw400 and combined force on load cell rows 3 and 4

As noted above, Kw400 indicates the level of the average force in a vehicle displacement range of 25 to 400 mm. With the current vehicle body construction, the main frame usually generates the greater part of the vehicle force that occurs in the first half of an impact. When the main frame is located in the interaction zone, the vehicle force and the combined force on rows 3 and 4 show close values. Moreover, when the vehicle force and the combined force on rows 3 and 4 show linear curves, the value obtained by dividing the peak combined force by two is close to the average force. That is why a good correlation is seen in Fig. 8 between Kw400 and the value obtained by dividing the peak combined force on rows 3 and 4 by two.

It is known that the Type-A and Type-B vehicles that deviate from this correlation in Fig. 8 have the following characteristics:

Type-A: The vehicle's main frame is located outside the interaction zone.

Type-B: The vehicle's force characteristic is not a linear function that increases monotonically.

Type-C: A composite of Type-A and Type-B

The force-displacement curves of the vehicle group with a good correlation (normal type), Type-A vehicles and Type-B vehicles are shown in Figs. 9-11, respectively.

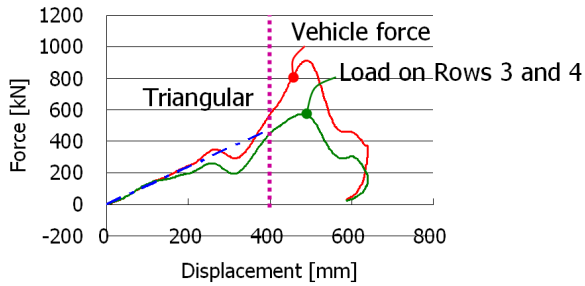

Fig. 9 Force-displacement curves for Normal-type vehicles

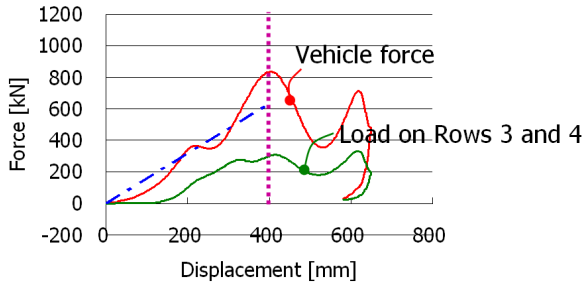

Fig. 10 Force-displacement curves for Type-A vehicles

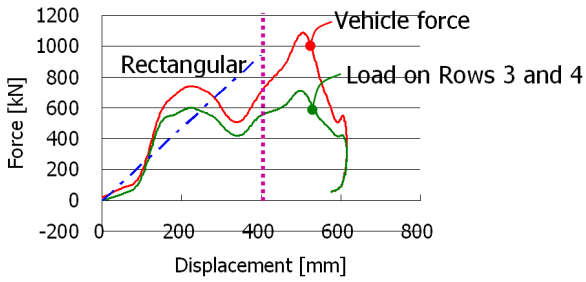

Fig. 11 Force-displacement curves for Type-B vehicles

For the vehicles classified as Type-A in Fig. 10, it is seen that a high level of force is generated outside the interaction zone. As a result, the combined force on rows 3 and 4 is smaller than the total force of all the load cells used in calculating Kw400. In this case, due to the poor engagement of the front-end structures, the force that occurs in an actual CTC frontal impact is assumed to be less than the total force of all the barrier load cells, i.e., the value of Kw400. It is possible that the combined force on rows 3 and 4 reflects the force actually produced in a CTC frontal impact better than Kw400. With the evaluation method researched in this study, the vehicles classified as Type-A would also be subjected to an override barrier test or some other optional evaluation to re-assess the combined force on rows 3 and 4 of the load cells.

As shown in Fig. 11, the vehicles classified as Type-B show a force characteristic curve that is almost rectangular, not linear. As was noted earlier, whether or not one vehicle unilaterally crushes the partner vehicle in a CTC frontal impact is presumably determined by the difference in stiffness between the two vehicles. Accordingly, it is probably determined by the peak force rather than by the average force such as that represented by Kw400.

As discussed here, there is a correlation between Kw400 and the peak combined force on rows 3 and 4 of the load cells. Even in cases which deviate from that correlation, it is possible that the combined force on rows 3 and 4 is a better representation of compatibility in an actual CTC frontal impact than the Kw400 value. Therefore, it can be estimated that the proposed evaluation method can probably obtain a real-world improvement effect equal to or greater than that reported in research studies concerning Kw400.

OPTIONAL TEST FOR DETECTION AND EVALUATION OF INTERACTION FORCE

As noted above, one concern with the proposed method is that the interaction force might not be detected accurately in a rigid barrier test. In order to resolve this concern, it is necessary to re-evaluate the force in the interaction zone by conducting an optional test such as the override barrier test proposed by the NHTSA. The necessity of conducting an optional evaluation is determined by whether forces outside the interaction zone are higher than the interaction force, regardless of whether the interaction force satisfies the specified force criterion or not.

Here we will consider a hypothetical case like that shown in the upper diagram in Fig. 12 where the position of the main frame corresponds only to row 4 of the load cells and does not overlap either row 3 or row 5. In this case, the combined force generated by the front-end structure on rows 3 and 4 divided by two is equal to the combined force on rows 4 and 5 divided by two. On the other hand, if the front-end structure overlaps row 5 even by a little (lower diagram in the figure), the combined force on rows 4 and 5 divided by two will be larger than the combined force on rows 3

and 4 divided by two. In other words, if the combined force on row n and row n+1 (n>4) divided by two is greater than that on rows 3 and 4 divided by two, the front-end structure is deemed to be positioned higher than row 4. In this case, the force in the interaction zone must be re-evaluated by conducting an override barrier test. This additional override barrier test results in a compound evaluation that includes not only a stiffness assessment but also a geometry assessment like that of the AHOF400 metric.

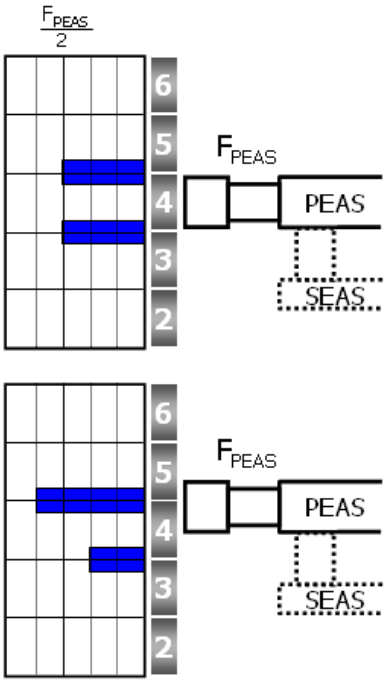

Fig. 12 Relationship between PEAS height and force generated on load cells

SUMMARY OF IMPROVED EVALUATION METHOD

The features of the improved evaluation method researched in this study are summarized below.

(1) Compatibility is evaluated using the interaction force, which is the value obtained by dividing the peak combined force on rows 3 and 4 of the load cells by two.

(2) An upper force limit is defined for the front body structure as the stiffness requirement. Because the objective is to evaluate the front body structure, the evaluation range is defined as the first half of the impact for vehicle displacement up to 400 mm, which is the same, for example, as that used for AHOF400 and Kw400.

(3) If force exceeding the interaction force is generated outside the interaction zone, which is defined as rows 3 and 4 of the load cells, an override barrier test is conducted to re-evaluate the interaction force. This test is conducted using a barrier that extends above the height of the interaction zone.

Based on the relationship between Kw400 and the interaction force, the medium zone of Kw400 reported in the literature serves as a reference for setting the evaluation criterion for the interaction force. However, the lower force limit must be examined anew because of the difference in the evaluation range. Similarly, the force criterion used in the override barrier test must take into account the differences in the test conditions.

EVALUATION RESULTS FOR UPPER FORCE LIMIT ONLY

It was shown above that there is a correlation between Kw400 and the interaction force, which is defined here as the combined force on rows 3 and 4 of the load cells. Accordingly, it was explained that the use of the interaction force can also be estimated to achieve a real-world improvement equal to or better than that assumed to be achievable with Kw400. To validate this hypothesis, the stiffness of the front body structure was evaluated using 300 kN as the upper limit of the interaction force in a vehicle displacement range up to 400 mm. This upper limit was set in reference to the average force (280.075 kN) obtained with Eq. (5) from the upper limit reported for the medium zone (1004-1318 N/mm) of Kw400. The results obtained are explained below.

Figure 13 shows the evaluation results obtained in tests conducted in-house at Nissan and in NHTSA's research tests. The types of vehicles evaluated and their test weights are also shown. Vehicles labeled with the letter "A" were ones for which the interaction force exceeded 300 kN. Vehicles labeled with the letter "B" were ones for which a re-evaluation of the interaction force in an override barrier test was deemed necessary because force higher than the interaction force occurred outside the interaction zone.

The results indicate that a re-evaluation in an override barrier test was necessary for the LTVs, which generally have a higher frame height. In addition, the results also identify several large LTVs for which a reduction in vehicle body stiffness would be necessary

according to the above criteria.

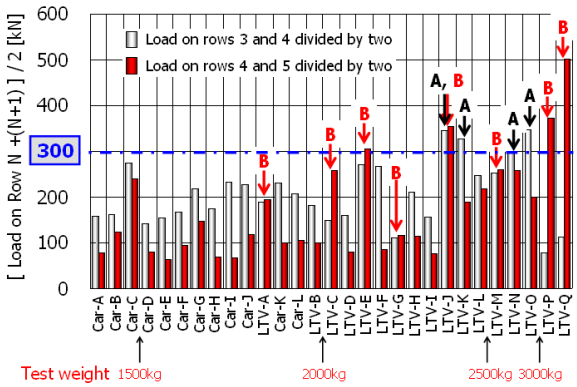

Fig. 13 Evaluation results of front body stiffness

CONCLUSION

This paper has described certain issues in evaluating vehicle compatibility with the AHOF400 and Kw400 metrics in full-frontal rigid barrier tests. A new compatibility evaluation method was presented that was researched in this study for the purpose of resolving these issues. The AHOF400 and Kw400 metrics represent separate parameters that are applied to evaluate geometry and stiffness, respectively. With the method proposed here, the impact forces inside and outside a defined structural interaction zone are evaluated separately. The proposed method was applied to evaluate a front body stiffness based on an upper force limit. The results showed that the proposed method can evaluate both geometry and stiffness simultaneously.

The real-world improvement effect that might be obtained with the proposed evaluation method was estimated only in an evaluation of the upper force limit of the front body structure in reference to research reports concerning Kw400. In future work, it will be necessary to conduct accident analyses that take into account the lower force limit in order to investigate a force criterion capable of yielding real-world benefits. In addition, it will be necessary to confirm whether the evaluation results are consistent with the compatibility shown in actual CTC frontal impacts by the vehicles sampled in this study. The accuracy of the proposed evaluation method must also be improved by increasing the number of vehicles considered.

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