AN EVALUATION OF PDB TEST RESULTS FOR PARTNER PROTECTION AND SELF PROTECTION

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ABSTRACT

The introduction of various vehicle safety standards and new car assessment programs in addition to automobile manufacturers' efforts to improve vehicle safety performance have led to significant improvements in vehicle safety performance over the past several years. Improving frontal impact compatibility is recognized as one approach to further enhancing vehicle safety performance. Various methods of improving frontal impact compatibility have been proposed and discussed.

In 1996, European Enhanced Vehicle-safety Committee Working Group 15 on Vehicle Compatibility was established to explore methods for assessing vehicle compatibility and to develop procedures for testing it. In their 2007 Final Report, EEVC WG15 proposed a Progressive Deformable Barrier (PDB) test as one candidate for testing vehicle compatibility. The PDB test was developed with the aim of assessing and improving partner protection while taking self protection into account as well.

This paper focuses on the PDB test. To assess its performance, several different category vehicles (small car, large car, midsize SUV, large SUV) were selected for study and PDB test results for them were compared with those obtained with the current ECE R94 offset deformable barrier (ODB) test and the vehicle-to-vehicle impact test. This study was simply an attempt to make an evaluation of the PDB test in comparison with other test procedures.

INTRODUCTION

Improving vehicle crash compatibility by reconciling self protection with partner protection has attracted greater attention in recent years as still another approach to further enhancing vehicle occupant safety. While various studies have been done on vehicle compatibility to date, more research is needed and this is still a much discussed subject [1]-[4]. In Europe, Working Group 15 (Car Crash Compatibility and Frontal Impact) was formed under the European Enhanced Vehicle-safety Committee (EEVC) in 1996 for the purpose of developing a test procedure and evaluation methods aimed at further improving vehicle compatibility in frontal impacts. In the final report of WG15's activities that was presented at the ESV Conference in 2007, the following three sets of combinations were proposed as possible candidates for a compatibility evaluation test procedure [5].

Set 1
- Full Width Deformable Barrier (FWDB) test
- Offset Deformable Barrier (ODB) test using an EEVC barrier

Set 2
- Full Width Rigid Barrier (FWRB) test
- Progressive Deformable Barrier (PDB) test

Set 3
- Combination of FWDB and PDB tests

The report also cited the following points as being essential aspects of any test procedure for evaluating compatibility:

1. It must be capable of evaluating structural interaction.
2. It must be capable of evaluating the frontal force level.
3. It must be capable of evaluating the passenger compartment stiffness.
4. There must not be any decline in the current level of self protection capability.

The PDB test was proposed by EEVC WG15 as one of the candidate evaluation procedures capable of assessing the four items above, though further discussion is deemed necessary concerning the evaluation criteria and parameters to be used with this test procedure.

Focusing on the PDB test, this study examined the issues currently under consideration and the suitability of the proposed evaluation parameters for assessing self protection and partner protection. That was done by comparing PDB test results with vehicle-to-vehicle impact test results and the results obtained with the current ODB test procedure.

EVALUATION FOR PARTNER PROTECTION PARAMETERS OF PDB TEST

The Average Height of Deformation (AHOD) and the Average Depth of Deformation (ADOD) are the principal parameters of partner protection in the PDB test procedure. These parameters were examined using the test results obtained for five types of vehicles.

PDB Test Conditions

The PDB test conditions used in this study are shown in Table 1. The points that differed from the current ODB test conditions were the barrier construction, impact speed and overlap ratio.

Table 1. PDB impact conditions

Barrier	PDB+
Impact speed	60 km/h
Overlap ratio	50%
Dummies	DR: Hybrid-Ⅲ AM50
	PS: Hybrid-Ⅲ AM50

PDB Barrier Characteristics

The characteristics of the PDB barrier used in the tests are shown in Fig. 1. The barrier consisted of four blocks. The block at the front of the barrier had a constant level of reaction force. The next block to the rear consisted of upper and lower levels, with a gradually increasing reaction force characteristic. The reaction force of the lower level block was greater than that of the upper level one. The rearward-most block had a constant level of reaction force and was provided to prevent the bottoming out of the barrier with large vehicles [6].

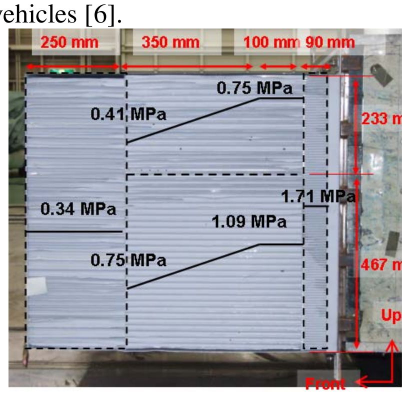

Figure 1. PDB+ Barrier Characteristics.

Calculation Method

The evaluation parameters used in the PDB test are calculated with a dedicated software program based on three-dimensional measurements of barrier deformation following the impact [7]. In this study, PDB Soft ver. 1.0 was used to calculate the parameters of AHOD, ADOD and barrier-absorbed energy. However, this software is for use with a barrier having a depth of 700 mm and is not compatible with the latest PDB+ barrier that is 790 mm deep. For that reason, the parameters were calculated by adding data for the extra 90 mm of depth. The equations used to calculate AHOD and ADOD are shown below as equations (1)-(4).

Average Height of Deformation (AHOD)

For a given rectangular investigation region, the "depth profile" is computed as a function of height.

$$\rho(z) = K \int_{y\,min}^{y\,max} X(y,z)dy \qquad (1)$$

Where K is a normalization constant ensuring that

$$\int \rho(z)dz = 1 \qquad (2)$$

The AHOD is then obtained as a mean value

$$AHOD = \int z\rho(z)dz \qquad (3)$$

The AHOD value indicates the average height of deformation over the barrier in the investigation area based on the deformed condition of the barrier. The aim of this parameter is to evaluate the position of the front-end structures of a vehicle.

Average Depth of Deformation (ADOD)

For a given investigation region with an area S

$$ADOD = \frac{1}{S} \int X(y,z)dydz \qquad (4)$$

The ADOD value indicates the average depth of deformation over the barrier in the investigation area based on the deformed condition of the barrier. The aim of this parameter is to evaluate the stiffness of a vehicle.

Investigation area

The investigation area used in this study in calculating these parameters is shown in Fig. 2. The dimensions of the investigation area were fixed in the vertical direction. For horizontal direction, the dimension from the centerline of a vehicle was fixed. However, the width of the investigation area was determined separately for each test vehicle taking the vehicle width into account.

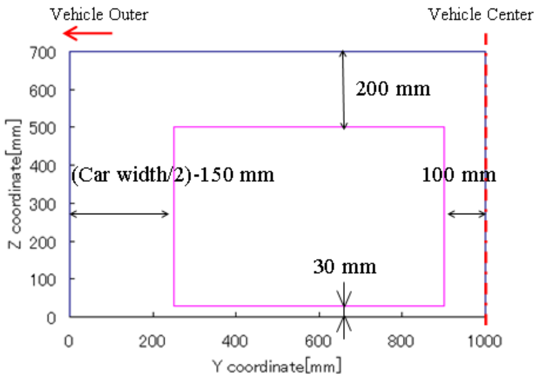

Figure 2. Investigation area.

Test Vehicles

Five types of test vehicles were used in this study and are denoted here as small car A, large car B, midsize SUV C, midsize SUV D and large SUV E. The midsize SUV D was the previous generation model of the midsize SUV C. The bumper beam on the latter vehicle was positioned higher than on the midsize SUV C. All of the test vehicles had a left-hand steering wheel. The specifications of each test vehicle and a simplified diagram of its front-end structure are shown in Figures 3-7, respectively.

Vehicle	Small Car A
Test Weight	1250 kg
Width	1660 mm
Drive	Front
Load Path	Single
Body	Unibody

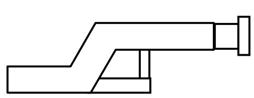

Figure 3. Small car A specifications.

Vehicle	Large Car B
Test Weight	1996 kg
Width	1800 mm
Drive	Rear
Load Path	Double
Body	Unibody

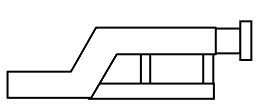

Figure 4. Large car B specifications.

Vehicle	Midsize SUV C
Test Weight	2063 kg
Width	1880 mm
Drive	AWD
Load Path	Double
Body	Unibody

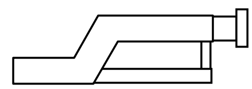

Figure 5. Midsize SUV C specifications.

Vehicle	Midsize SUV D
Test Weight	2087 kg
Width	1880 mm
Drive	AWD
Load Path	Double
Body	Unibody

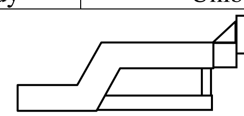

Figure 6. Midsize SUV D specifications.

Vehicle	Large SUV E
Test Weight	2754 kg
Width	2000 mm
Drive	AWD
Load Path	Single
Body	Body on frame

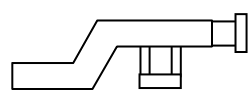

Figure 7. Large SUV E specifications.

PDB Test Results

The test results obtained for each vehicle in terms of the AHOD, ADOD and maximum barrier force are given in Table 2.

Table 2. PDB test results

Vehicle	S/Car A	L/Car B	M/SUV C	M/SUV D	L/SUV E
AHOD	414 mm	408 mm	436 mm	423 mm	453 mm
ADOD	236 mm	324 mm	366 mm	308 mm	397 mm
Fmax	347 kN	484 kN	461 kN	448 kN	597 kN

AHOD

Figure 8 shows the positional relationship between the AHOD and the top and bottom of the longitudinal members. The results indicate that the AHOD values were nearly the same for all five test vehicles, regardless of the position of their longitudinal members.

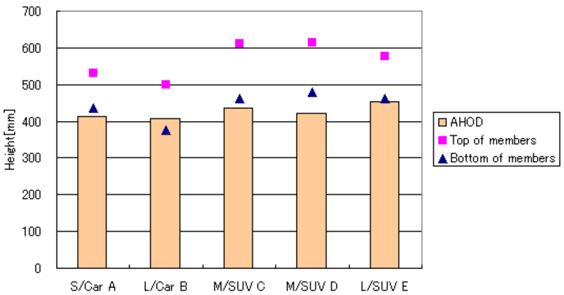

Figure 8. AHOD and the height of longitudinal members.

The relationship between the amount of barrier deformation caused by each test vehicle and the positions of the transmission, engine, tires and principal structural components are shown in Figures 9-13, respectively.

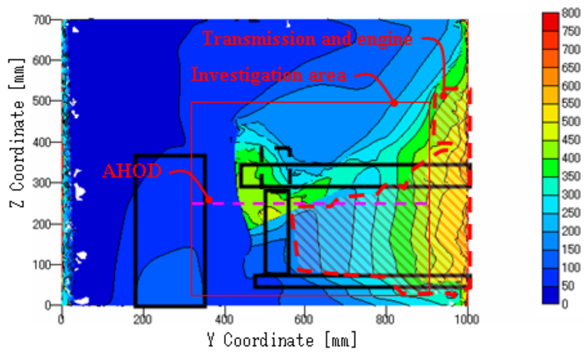

Figure 9. PDB barrier deformation with small car A.

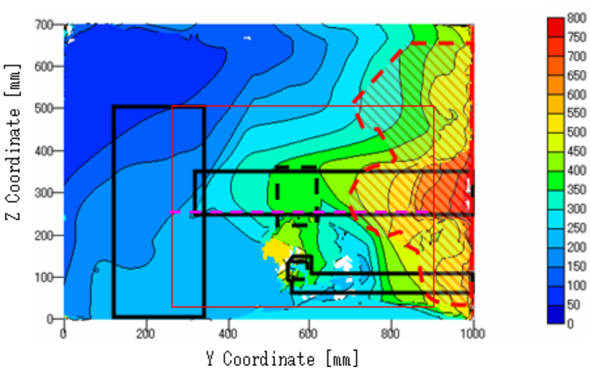

Figure 10. PDB barrier deformation with large car B.

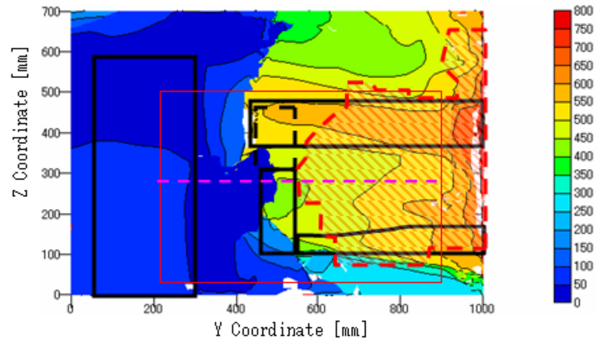

Figure 11. PDB barrier deformation with midsize SUV C.

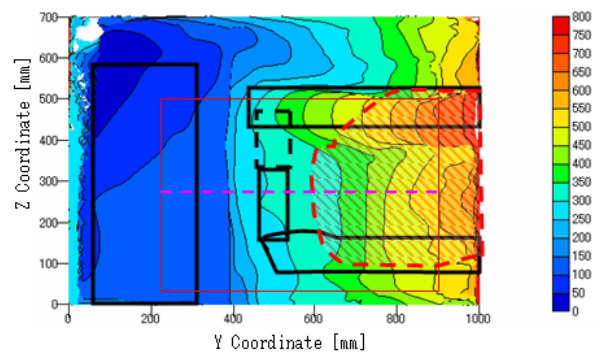

Figure12. PDB barrier deformation with midsize SUV D.

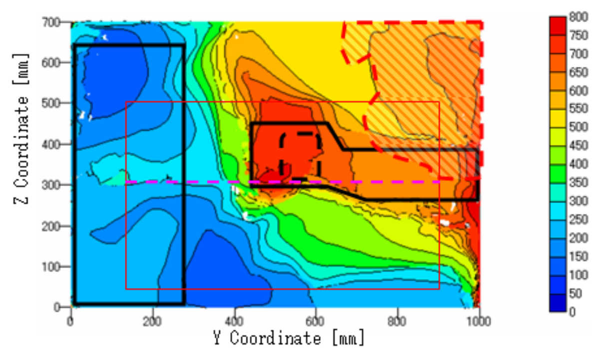

Figure13. PDB barrier deformation with large SUV E.

It is seen from the results in these figures that the transmission and the engine accounted for the greater part of the barrier deformation for many of the test vehicles. Because the AHOD parameter calculates the height of the average deformation in the investigation area, it is substantially influenced by the positions of the transmission and the engine. That is why all five test vehicles show similar AHOD values, regardless of the positions of their principal structural components. The presence of a lower load path is regarded as an important factor with respect to compatibility. However, no significant difference is seen in the

AHOD values between the vehicles with a lower load path (large car B, midsize SUV C and midsize SUV D) and those without one (small car A and large SUV E). These results indicate that it is difficult to detect the presence of a lower load path on the basis of the AHOD alone.

ADOD

The relationship between the ADOD and the test vehicle weight is shown in Fig. 14, and the relationship between the ADOD and the maximum PDB barrier force is shown in Fig. 15. The results indicate that the ADOD tended to increase with a heavier vehicle weight and a higher PDB barrier reaction force.

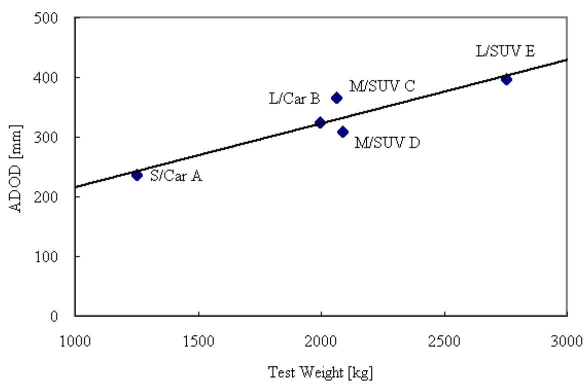

Figure 14. ADOD vs. test weight.

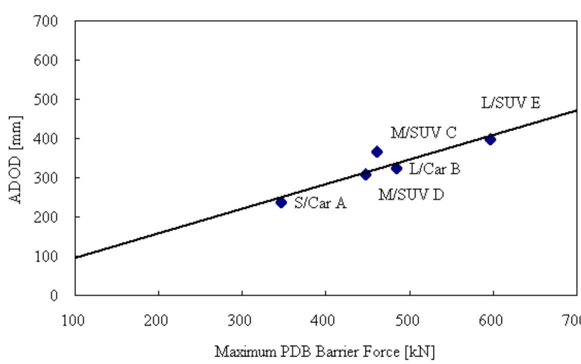

Figure 15. ADOD and maximum PDB barrier force.

An investigation was made of the general effect of changes in the vehicle weight and vehicle reaction force on the ADOD. The effect was considered in relation to the following patterns assumed for the characteristics of the PDB barrier reaction force and the vehicle reaction force.

Case 1: The ADOD increases to the extent of the increase in the vehicle reaction force.

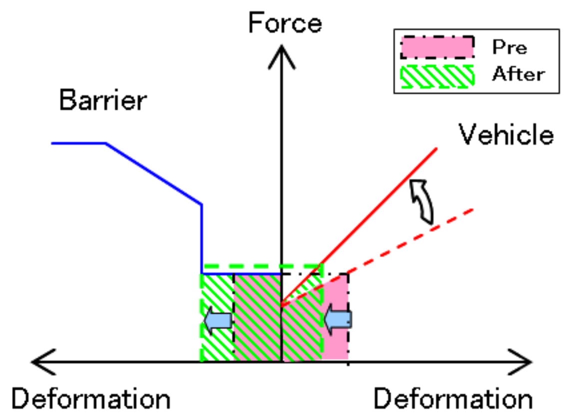

Figure 16. Deformation prediction for case 1.

Figure 16 illustrates the increase in the amount of barrier deformation (ADOD) corresponding to the increase in the vehicle reaction force. Since there is a proportional relationship between the vehicle reaction force and the ADOD, the latter value can be used in this case as a substitute for the former value.

Case 2: The ADOD increases only due to the influence of the increase in vehicle weight.

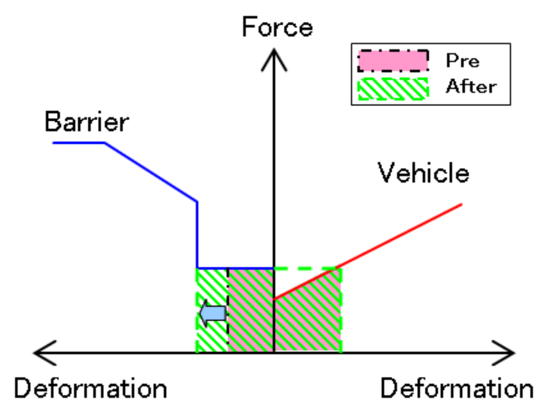

Figure 17. Deformation prediction for case 2.

Figure 17 shows a prediction of the barrier deformation in case 2 where the vehicle weight increases without any increase of the reaction force. In this case, the deformation of the barrier absorbs the increase in the kinetic energy due to the increased vehicle weight. In actuality, the vehicle also usually absorbs some of this kinetic energy, but this figure considers only the energy absorbed by the barrier to make the prediction easier to understand. The results for this case show that the ADOD increases when the vehicle mass is simply increased without any change in the reaction force characteristic of the vehicle.

The factors defined for cases 1 and 2 are presumed to be the main reasons for the increase seen in the ADOD. In actuality, from the standpoint of self protection, the vehicle reaction force tends to increase with an increase of the vehicle mass. Accordingly, when these two factors occur simultaneously, the ADOD increases.

Case 3: There is little change in the ADOD despite an increase of the vehicle reaction force.

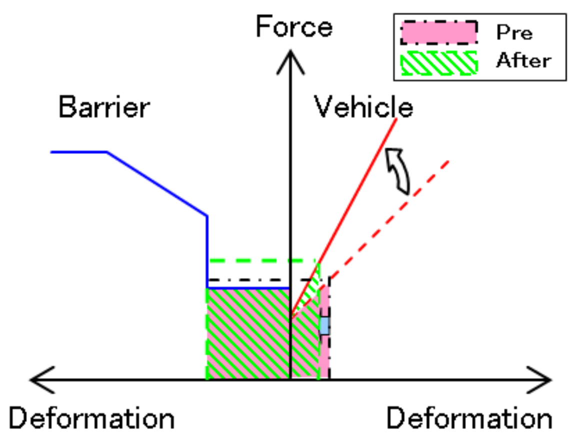

Figure 18. Deformation prediction for case 3.

Figure 18 shows the barrier deformation condition for case 3 in which the vehicle reaction force is increased further beyond the level in case 1. Even though the vehicle reaction force is increased in this case, the amount of barrier deformation does not increase appreciably and the ADOD shows little change in the range where the barrier strength increases rapidly.

In cases 2 and 3, the reaction force is not expressed correctly by the ADOD parameter. Similarly, the vehicle reaction force differs for the same ADOD between the case where the upper level of the second block is deformed and the case where the lower level is deformed. The reason for that is attributed to the difference in PDB characteristics between the upper and lower levels of the second block (Fig. 1). These factors presumably account for the cases where the ADOD values don't indicate the vehicle body stiffness accurately. Therefore, as a substitute for the vehicle reaction force, it is better to measure the barrier reaction force directly. Moreover, in order to take the kinetic energy into account, the vehicle weight should also be considered.

One point that is common to both the AHOD and ADOD parameters is that the necessary information cannot be obtained accurately on account of the averaging performed on the measured barrier deformation. The direct use of the maximum height of deformation or the maximum barrier force would provide more accurate information. In addition, the use of direct measurements would reduce the error due to the three-dimensional measurements of barrier deformation that are currently used in calculating these parameters.

EVALUATION OF PARTNER PROTECTION PARAMETERS USING VEHICLE-TO-VEHICLE TEST RESULTS

The parameters of partner protection were examined using the results of vehicle-to-vehicle frontal impact tests.

Vehicle-to-vehicle impact test conditions

The impact conditions used in the vehicle-to-vehicle tests are given in Table 2. Test 1 involved a frontal impact between the small car A and the large car B, and test 2 was between the small car A and the midsize SUV C. The overlap ratio was set at 50% of the small car A.

Table 3. Vehicle-to-vehicle impact conditions

Test	1		2	
Vehicle	Car A	Car B	Car A	SUV C
Test Weight	1203 kg	1996 kg	1202 kg	2058 kg
Impact Speed	50 km/h for each vehicle			
Overlap Ratio	50% of S/Car A			
Dummies	DR: Hybrid-Ⅲ AM50			
	PS: Hybrid-Ⅲ AM50			

Test Results

<u>**Structure deformation mode**</u>

The engine compartment deformation modes of the small car A and the large car B in the PDB test and the vehicle-to-vehicle impact test are shown in Figures 19 and 20, respectively.

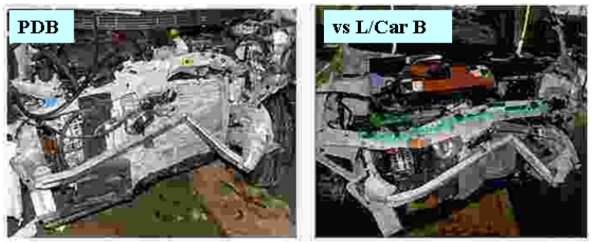

Figure 19. Small car A front deformation.

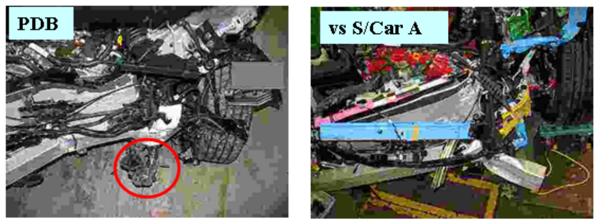

Figure 20. Large car B front deformation.

The results in Fig. 19 for the small car A show similar deformation modes for the longitudinal members in both tests in terms of their crush behavior.

On the other hand, the results in Fig. 20 for the large car B show that the lower members that served as the lower load path were partially crushed in the PDB test and fully crushed in the vehicle-to-vehicle test.

The engine compartment deformation modes of the small car A and the midsize SUV C in the PDB test and the vehicle-to-vehicle impact test are shown in Figures 21 and 22, respectively.

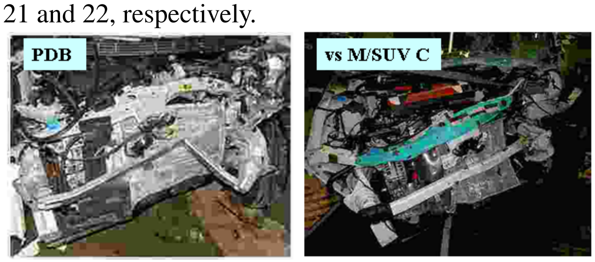

Figure 21. Small car A front deformation.

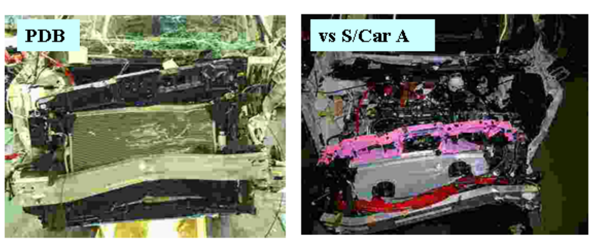

Figure 22. Midsize SUV C front deformation.

The results in Fig. 21 for the small car A indicate that the longitudinal members were more crushed in the vehicle-to-vehicle test, with the deformation mode differing from that of the PDB test. The reason for that is attributed to the good engagement of the structural components of the two vehicles during the impact in test 2 (small car A to midsize SUV C). The results in Fig. 22 for the midsize SUV C indicate that the deformation modes in the vehicle-to-vehicle and PDB tests were similar, which is attributed in part to the small amount of deformation that occurred in both tests. It is inferred from the overall results that the longitudinal members are more apt to display less deformation in a PDB test than in a vehicle-to-vehicle impact test.

Although the difference in the AHOD values of the vehicles was smaller in test 1 than in test 2, the structural members passed each other on the outside in the former test, while good structural engagement occurred in the latter test. Therefore, an assessment of structural engagement must take into account not only the vertical direction but also the horizontal direction.

Vehicle deformation

Figure 23 shows the relationship between the ADOD parameter, which indicates the vehicle stiffness, and the amount of deformation of the small car A in the vehicle-to-vehicle impact test.

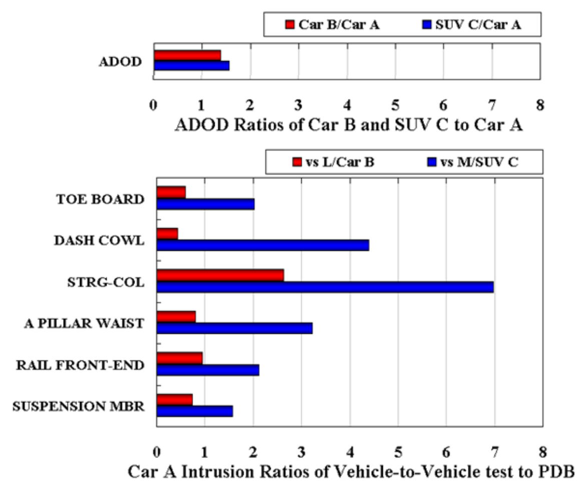

Figure 23. ADOD ratios and small car A intrusion ratios.

The upper graph in the figure shows the ratios of the ADOD values of the large car B and the midsize SUV C to that of the small car A. The lower graph shows the ratio of the body deformation of the small car A in the vehicle-to-vehicle impact test to that in the PDB test. The results in these graphs make it possible to compare the effect of the difference in the ADOD values on the amount of vehicle deformation in the vehicle-to-vehicle impact test. The comparison shows that as the ADOD ratio relative to the small car A increased, the amount of deformation sustained by the small car A in the vehicle-to-vehicle impact test increased. However, the deformation ratios differed greatly. The reasons for that can be attributed to the differences in the following two points due to the variation in the engagement conditions during the impact:

(1) the reaction force generated in the vehicle and

(2) the crush stroke of the engine compartment in the impact.

As discussed here, because the amount of body deformation differs markedly depending on the engagement conditions, it is first necessary to make an assessment of the stable structural engagement between two colliding vehicles. In this case as well, the assessment should also take into account engagement in the horizontal direction.

EVALUATION OF PARAMETERS OF SELF PROTECTION

Comparison between The PDB Test and Current 64km/h Offset Barrier Test

The 60 km/h PDB test (60PDB) and the 64 km/h offset deformable barrier test (64ODB) currently conducted in many countries are compared here in terms of dummy injury measures, vehicle intrusion and energy absorbed by the barrier and the vehicle.

Dummy Injury Measures

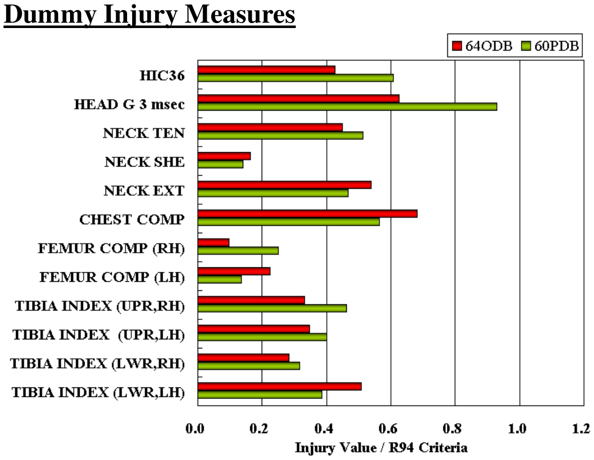

Figure 24. Small car A dummy injury measures.

The dummy injury measures shown in Fig. 24 for the small car A indicate that head injury values are higher in the 60PDB test than in the 64ODB test, but that the other values are nearly the same.

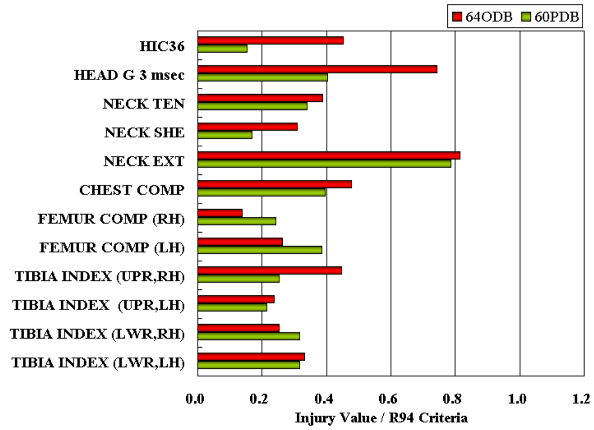

Figure 25. Large car B dummy injury measures.

For the large car B, head injury values are lower in the 60PDB test, while the other values are almost identical, as seen in Fig. 25. However, because the sitting position in the large car B in the 64ODB test differs somewhat from that in the 60PDB test, the injury values for the large car B are treated only as reference data.

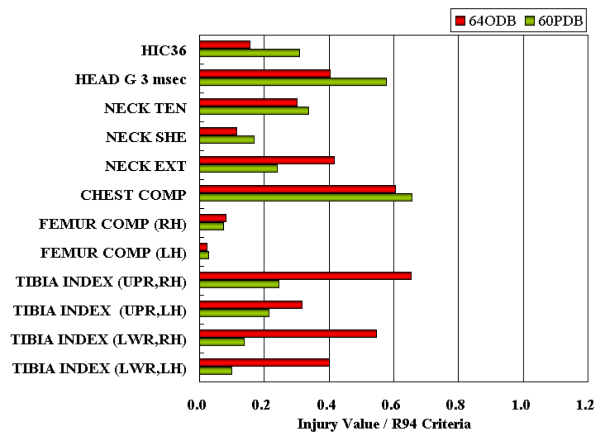

Figure 26. Midsize SUV C dummy injury measures.

The results in Fig. 26 for the midsize SUV C show that head injury values are slightly higher in the 60PDB test, but that all leg injury values are lower than in the 64ODB test.

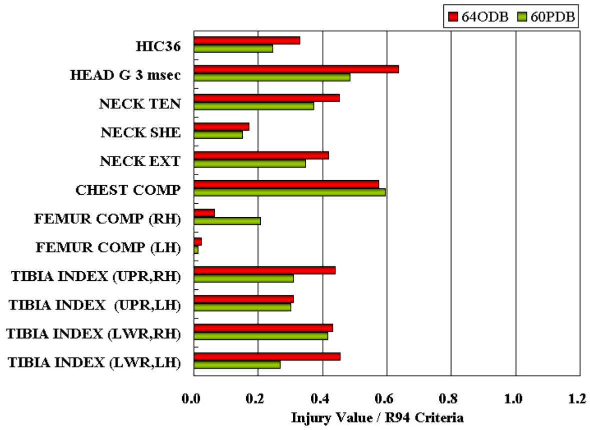

Figure 27. Midsize SUV D dummy injury measures.

As shown in Fig. 27 for the midsize SUV D, injury values tend to be lower overall in the 60PDB test, albeit only slightly.

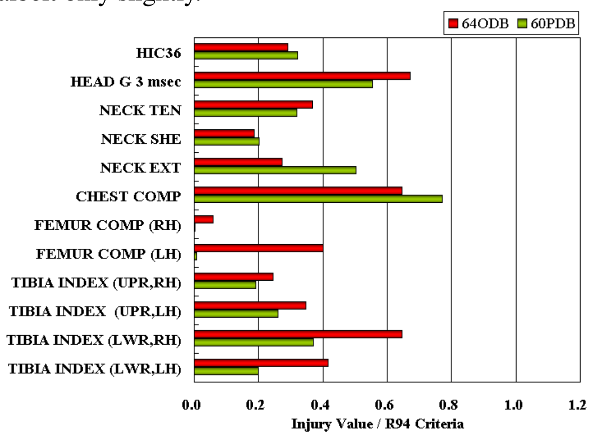

Figure 28. Large SUV E dummy injury measures.

The results for the large SUV E in Fig. 28 show that neck and chest injury values are somewhat higher in the 60PDB test, but that the injury values for the femur and tibia are generally lower than in the 64ODB test.

Because of the large variation in injury values, it is difficult to discern fine tendencies, but it is thought that the following observations can be made based on the results in these figures. For the small cars, both the 60PDB test and the 64ODB test tend to show almost the same injury values overall. As the vehicle size becomes larger, injury values mainly lower leg tend to be lower in the 60PDB test than in the 64ODB test.

Vehicle Intrusions

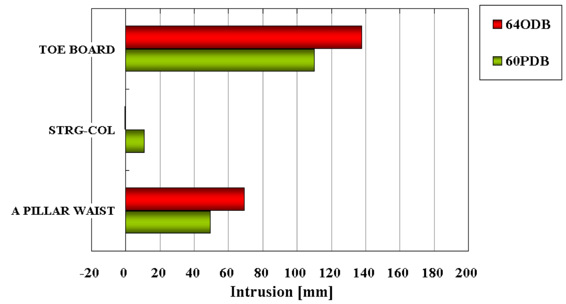

Figure 29. Small car A intrusions.

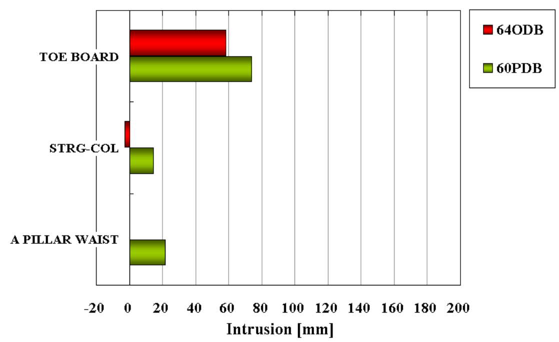

Figure 30. Large car B intrusions.

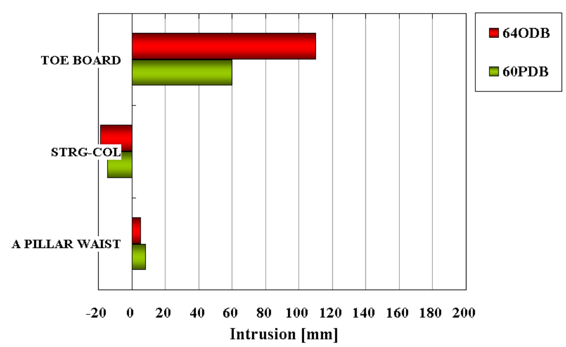

Figure 31. Midsize SUV C intrusions.

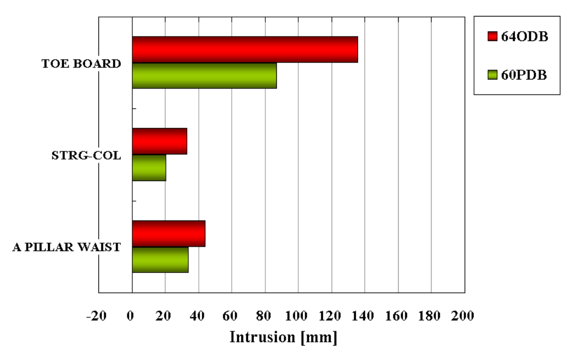

Figure 32. Midsize SUV D intrusions.

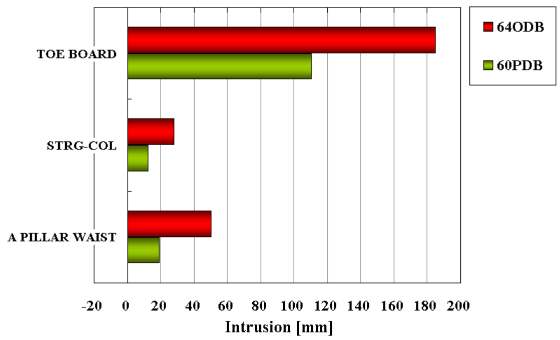

Figure 33. Large SUV E intrusions.

The intrusion data for each vehicle in the two tests are shown in Figures 29 to 33, respectively. No pronounced difference is seen in the intrusion data for the small car A and the large car B, but the intrusion values for the midsize SUV C, midsize SUV D and large SUV E are smaller in the 60PDB test than in the 64ODB test. The smaller amount of cabin intrusion that occurs with increasing vehicle size presumably accounts for the difference in injury values mentioned above, especially the difference in lower leg injury values.

Barrier Absorbed Energy

Figure 34 shows the amount of energy absorbed by the barrier in each test, as calculated from the amount of barrier deformation. A comparison of the values indicates that the barrier absorbed more energy in the 60PDB test than in the 64ODB test. This difference between the tests tended to increase as the size of the vehicle became larger. The reason why the amount of energy absorbed by the barrier did not increase with the larger vehicles in the 64ODB test is that the current barrier bottoms out with large vehicles. In contrast, because the barrier does not bottom out in the 60PDB test, the amount of energy absorbed by the barrier shows a pronounced increase for the larger vehicles.

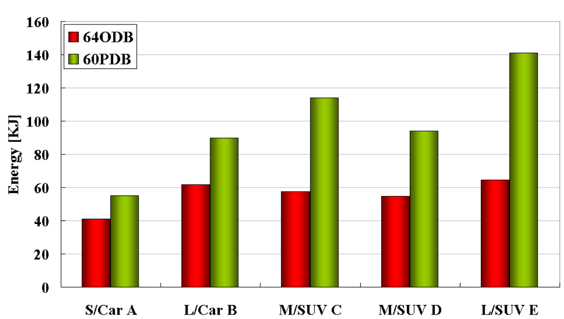

Figure 34. Barrier-absorbed energy.

Test Severity

Figure 35 shows the values of the Energy Equivalent Speed (EES) that were calculated based on the amount of energy absorbed by the vehicle in each test. The EES parameter expresses the amount of energy absorbed by a vehicle as the initial velocity at the time the vehicle crashes into a rigid barrier. It is given by Eq. (5) below.

$$EES(km/h) = 3.6 \times \sqrt{\frac{2 \times Eabs}{M}} \qquad (5)$$

Eabs = Energy absorbed by the vehicle [J]
= Kinetic energy – Energy in the barrier
M = mass of the vehicle [kg]

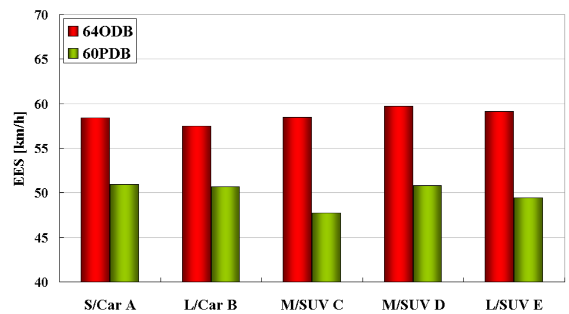

Figure 35. Energy Equivalent Speed.

The EES values for each vehicle were in a range of 57-60 km/h in the 64ODB test and 47-51 km/h in the 60PDB test. In order to examine the overall tendencies more closely, the number of vehicles (n) was increased by adding test data for other vehicle models. The relationship between the EES and test vehicle weight is shown in Fig. 36, which includes data obtained in 56 km/h offset deformable barrier (56ODB) tests using the current barrier.

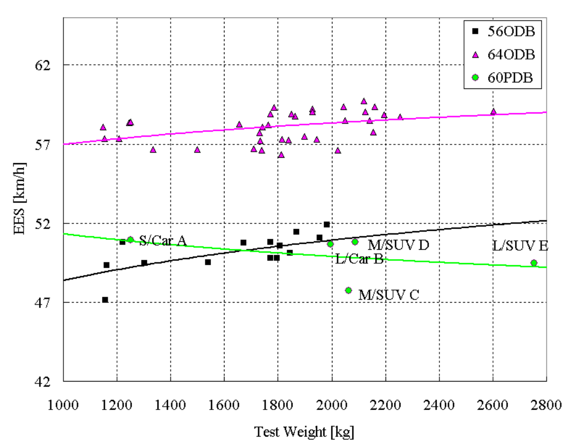

Figure 36. EES and test weight.

The data for the 64ODB test and 56ODB test show a gradual rise in the EES with increasing vehicle weight, whereas the 60PDB test data show a gradual decrease. As a result, the difference in the EES values between the 64ODB test and the 60PDB test becomes greater as the vehicle weight increases. This tendency explains the reason why the 64ODB and 60PDB tests showed a greater difference in the amount of vehicle deformation as the vehicle size increased. Between the 56ODB test that is the current regulatory test in Europe and the 60PDB test, the EES values become equal at around a test vehicle weight of 1,700 kg. For heavier vehicles above that level, the EES values are lower in the 60PDB test than in the 56ODB test. In connection with the introduction of the 60PDB test, it has been proposed this test replace the current regulatory 56ODB test at the initial stage. In that case, it is possible that the self protection performance of large vehicles would fall below the current assessment.

The United States, Japan and many other countries, excluding Europe, currently conduct Full Width Rigid Barrier (FWRB) tests and Offset Deformable Barrier (ODB) tests. In a FWRB test, because a wide area of the test vehicle's front end is crashed into the barrier, the amount of deformation is smaller and a higher deceleration pulse is generated in the vehicle. This test is designed to evaluate occupant protection performance, particularly that of the occupant restraint systems. In an ODB test, on the other hand, the input force is concentrated on one side of the test vehicle. This test is designed to evaluate occupant protection performance mainly in terms of the cabin strength.

The severity of the 60PDB test conditions was examined in relation to the FWRB and ODB test conditions. Figure 37 shows the forward displacement of the B-pillar as a function of the average G of the test vehicle in each test. The data used here for the FWRB test are for an impact velocity of 56 km/h (56FWRB) .

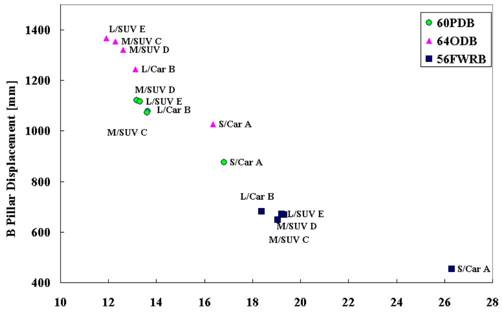

Figure 37. B pillar displacement and average G.

The data points for the PDB tests are generally located between the FWRB and ODB tests in Fig. 37. Conducting both the offset and full width barrier tests verifies the cabin strength and also confirms occupant protection performance based on the high deceleration pulse. Safety performance can thus be confirmed over a wider range of conditions compared with the verification of crashworthiness based on the PDB test alone.

CONCLUSIONS

Partner protection

•The Average Height of Deformation (AHOD) is strongly influenced by the engine and transmission and does not express the positions of the principal structural components such as the longitudinal members.
•The Average Depth of Deformation (ADOD) does not always indicate the vehicle body stiffness accurately.
•Because both the AHOD and ADOD parameters are found by averaging measured barrier deformation data, they do not accurately indicate the height or force of the structural components. Therefore, it is necessary to consider some other more direct methods of measurement such as directly measuring the barrier force.
•Evaluating the engagement of the structural components of two colliding vehicles is an important factor in assessing partner protection. Such engagement must be assessed in both the vertical and horizontal directions.

Self protection

•A comparison of the Energy Equivalent Speed (EES) values indicates that the current regulatory 56 km/h Offset Deformable Barrier (56ODB) test is more severe for heavier vehicles (a test vehicle weight of around 1,700 kg or more) than the Progressive Deformable Barrier (PDB) test. It is possible that the introduction of the PDB test to replace the current regulatory test might result in the self protection performance of heavier vehicles being evaluated at a lower level than at present.
•Conducting both the Full Width Rigid Barrier (FWRB) test and the ODB test makes it possible to verify the cabin strength and to confirm occupant protection performance based on the high deceleration pulse. This facilitates confirmation of crashworthiness over a wider range of conditions than what is possible on the basis of the PDB test alone.

Because the PDB test has many issues, it will be necessary to make further evaluations using a larger number of vehicles. Moreover, it will be necessary to examine what effect the introduction of the PDB test might have on safety performance in real-world accidents.

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