INF GR/PS/101

Technical Feasibility Study on EEVC/WG17 Pedestrian Subsystem Test

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Japan Automobile Research Institute

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Part 1. Technical Feasibility Study on EEVC/WG17 Pedestrian Headform to Bonnet Top Test

ABSTRACT

1) A technical feasibility study was conducted on the EEVC/WG17 child headform to bonnet top test proposed as part of the EU Pedestrian Protection Directive Phase 2. The results indicated that bonnet hinges complying with the child head protection test requirement can be developed only under an unrealistic condition of removing the fenders and that bonnet hinges cannot satisfy various performances besides pedestrian protection performance.

2) Although some advance technologies such a pop-up bonnet and hood airbags has a chance to satisfy the EEVC/WG17 headform test requirement satisfying with the other bonnet hinge requirements, deep examination will be necessary into the possibility of these advanced technologies to deteriorate the vehicle's performances other than pedestrian protection. Many years, not 5 years or so, will be required to install such advanced technologies to all car models by getting user acceptance including price, like air bag experience.

3) The present study focused on a technical feasibility for a bonnet hinge, however, other car parts also have a same problem (confliction between the pedestrian safety and the other car requirements, especially for durability)). Thus, we believe that to complying with the EEVC/WG17 headform to bonnet top test requirement is not feasible especially for durability required parts.

1. Background

Discussion is underway in Europe on the EU Pedestrian Protection Directive Phase 2 applicable to vehicles on sale from 2010 onward. The current basis of this Directive is the EEVC/WG17 Pedestrian Protection Test proposed by the European Enhanced Vehicle-safety Committee or EEVC. However, doubts have been raised on the validity and technical feasibility of the EEVC/WG17 Test. While this Test consists of wide-ranging tests for adult/child head protection test (hereafter "adult/child headform test"), leg protection test (hereafter "legform test"), and hip-thigh protection test (hereafter "upper legform test"), the present study was focused on the technical feasibility of the EEVC/WG17 child headform test.

2. Test Results on the EEVC/WG17 Adult/Child Headform Test

The EEVC/WG17 adult/child headform test was conducted under the New Car Assessment Program in Europe (Euro-NCAP), and the results obtained are reported in Figures 2.1. While the EEVC/WG17 adult/child headform tests require the Head Performance Criterion or HPC calculated from the impact acceleration of a headform to be no more than 1,000, vehicle manufacturers will probably aim at a considerably lower value in view of deviations in product finish and test conditions. The present study assumed the target of vehicle manufacturers to be an HPC 800 which is shown by a broken line in the figures.

The results indicated that the derived HPC exceeded the target of 800 at all the tested points in and around the bonnet area of a car. This was however not attributed to the vehicle manufacturer's failure to utilize adequate pedestrian protection technologies, but was ascribed to a difficulty in satisfying both pedestrian protection performance and other performances, especially the durability performance of body parts.

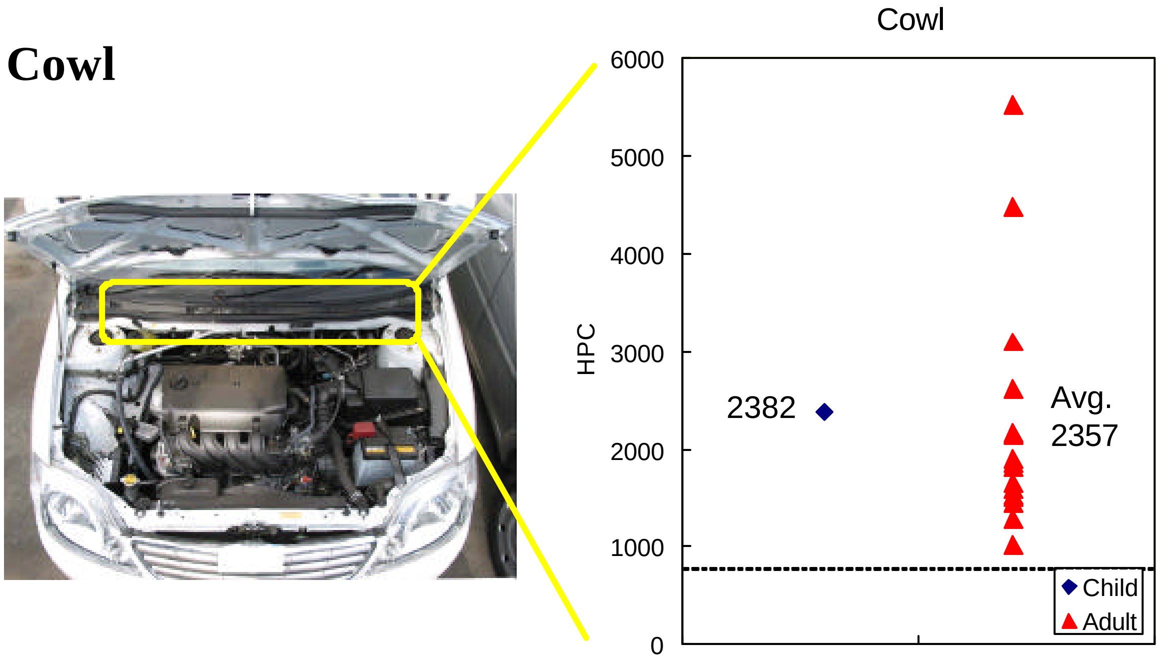


Figure 2.1(a) EEVC/WG17 headform impact test results (Cowl)

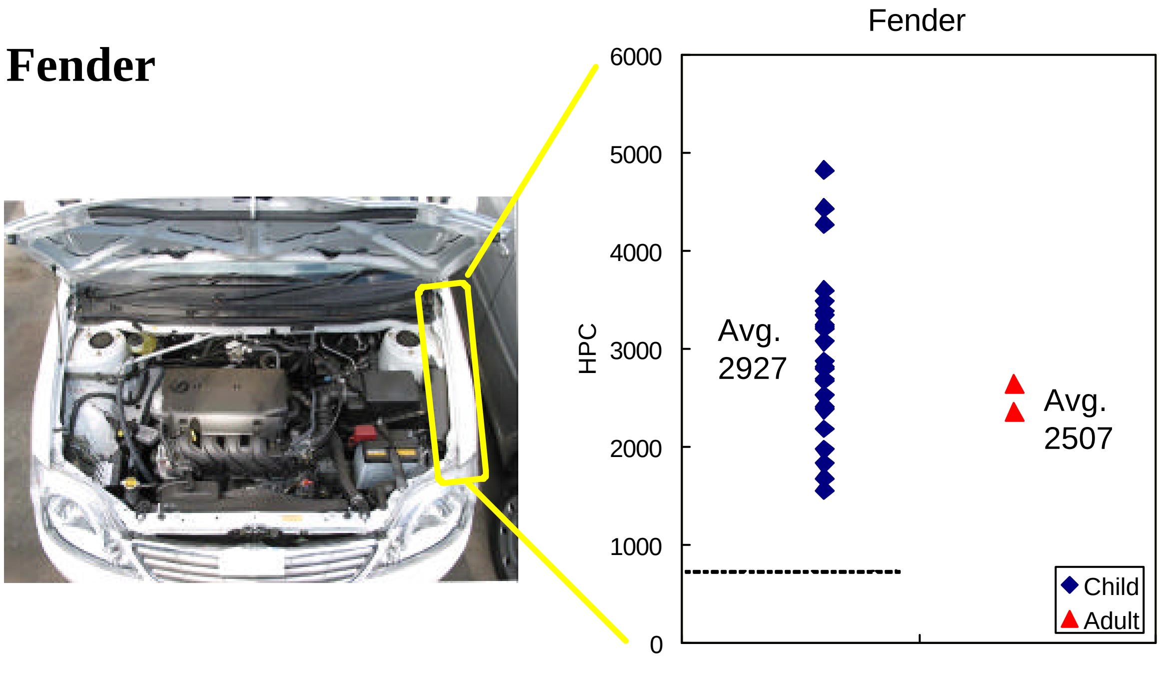


Figure 2.1(b) EEVC/WG17 headform impact test results (Fender)

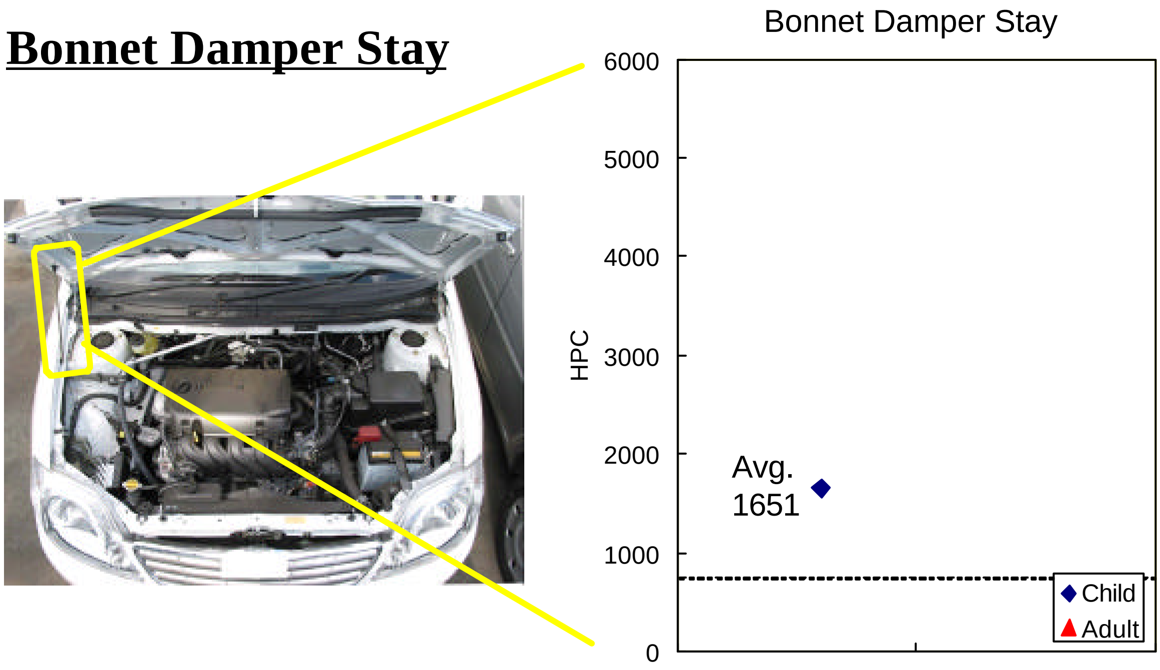


Figure 2.1(c) EEVC/WG17 headform impact test results (Bonnet damper stay)

Head Light

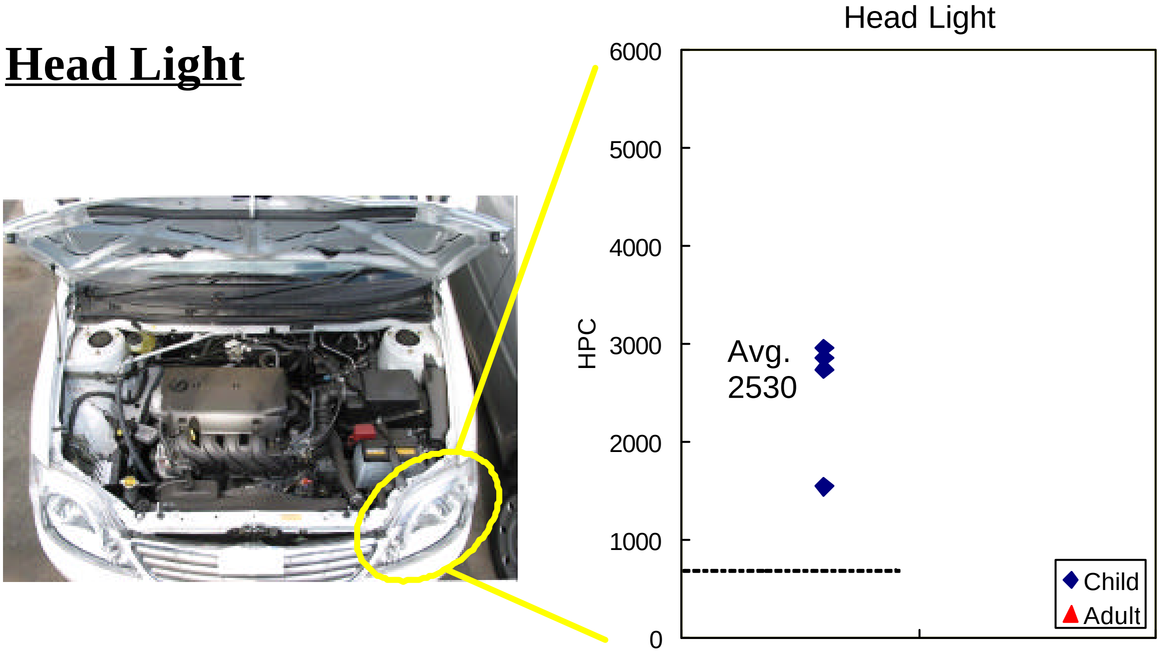


Figure 2.1(d) EEVC/WG17 headform impact test results (Head light)

Bonnet Hinge

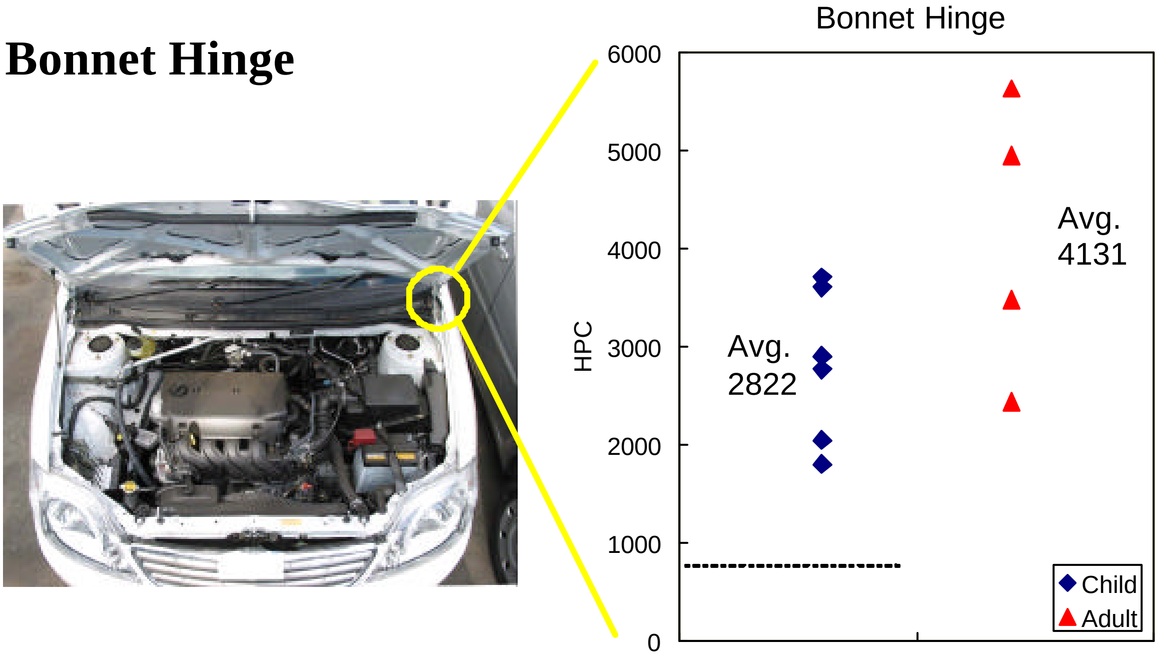


Figure 2.1(e) EEVC/WG17 headform impact test results (Bonnet hinge)

Bonnet Lock

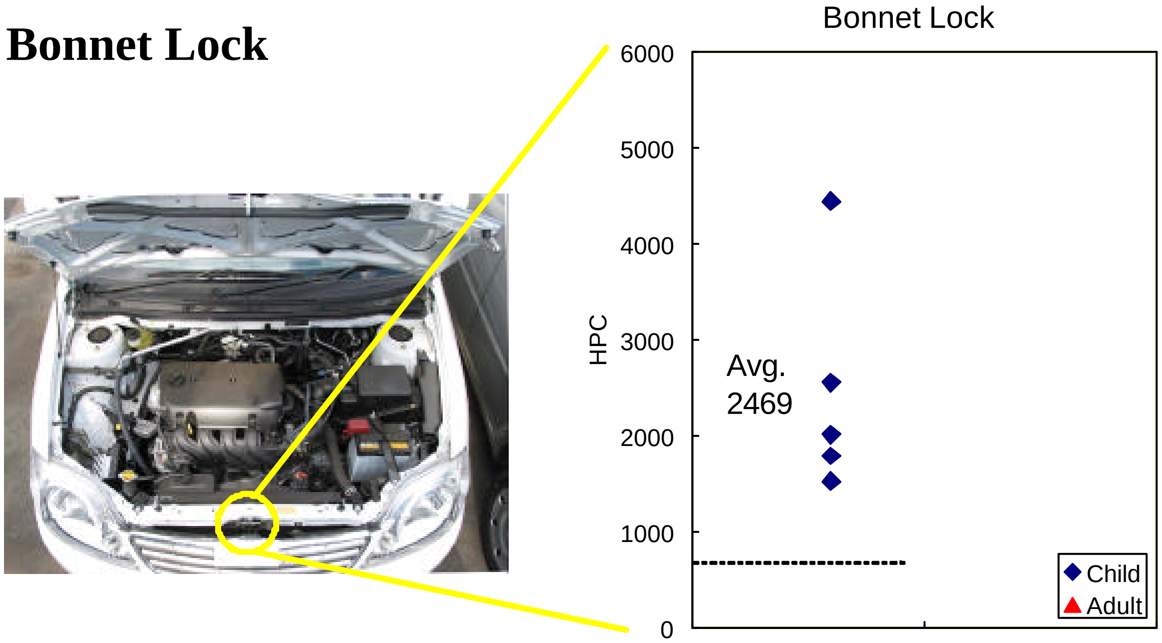


Figure 2.1(f) EEVC/WG17 headform impact test results (Bonnet lock)

Wiper Arm

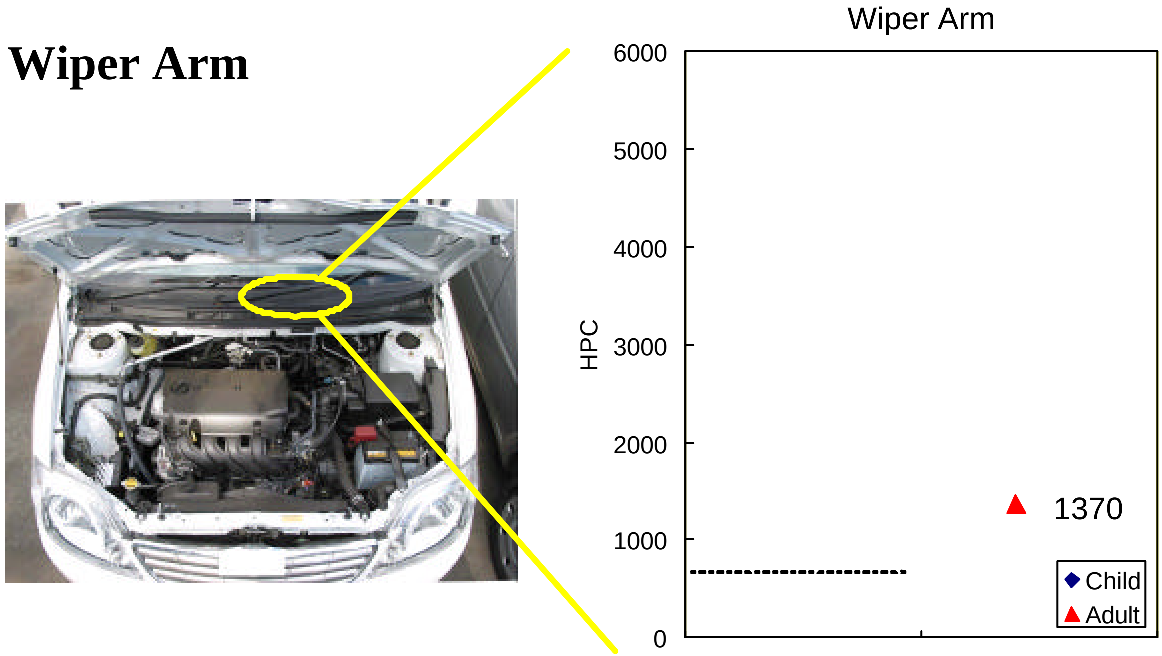


Figure 2.1(g) EEVC/WG17 headform impact test results (Wiper arm)

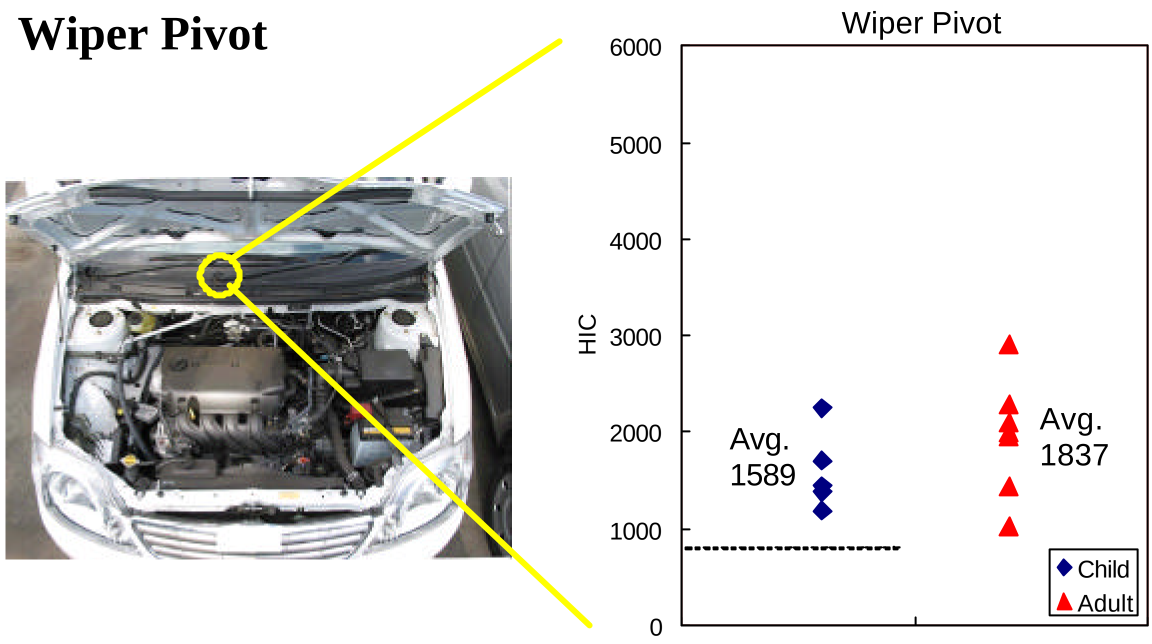


Figure 2.1(h) EEVC/WG17 headform impact test results (Wiper pivot)

Some of the required performances other than pedestrian protection are listed in Table 2.1 in relation to body parts involved. These performances demand a certain level of rigidity in body parts, while pedestrian protection demands a reduction in rigidity. Accordingly, pedestrian protection is just the opposite of other vehicle performances in technical requirement.

Table 2.1 Reasons for difficulty achieving EEVC/WG17 headform impact test requirements

Body Parts	Reasons
Cowl	Required strength for occupant crash safety. Difficulty obtaining clearance due to the wiper motor, pivot and links contained.
Fender	Required strength to prevent vibration under normal and rough running condition.
Bonnet damper stay	Required strength to support heavy hood.
Head light	Required strength and rigidity to prevent the light from vibrating when running.
Bonnet hinge	Required strength to prevent vibration and to keep hood in a frontal crash.
Bonnet lock	Required strength to prevent vibration and to keep hood in a frontal crash.
Wiper Arm	Required strength to prevent the wiper arm from breaking.
Wiper pivot	Required strength and rigidity to support the wiper and wiping performance.

For example, vibration energy on the fender was measured when the fender's supporting rigidity was reduced from HPC 1,855 to HPC 1,194 in the other study [Figure 2.2]. This rigidity reduction resulted in an increase in vibration energy by about 10dB, meaning the fender's durability against fatigue is diminished to less than one-234th according to analysis by a vehicle manufacturer. Clearly, pedestrian protection weakens the fatigue resistance of the fender.

In discussing the feasibility of the EEVC/WG17 headfrom test, therefore, it is important to accurately determine the effects of pedestrian protection measures on the other performances of the vehicle. The present study was focused on the bonnet hinge which is required to have a certain level of rigidity to support the hood. The purpose of the present study was to analyze the feasibility of compliance with the EEVC/WG17 child headform test and to evaluate the effects of such compliance on other performances.

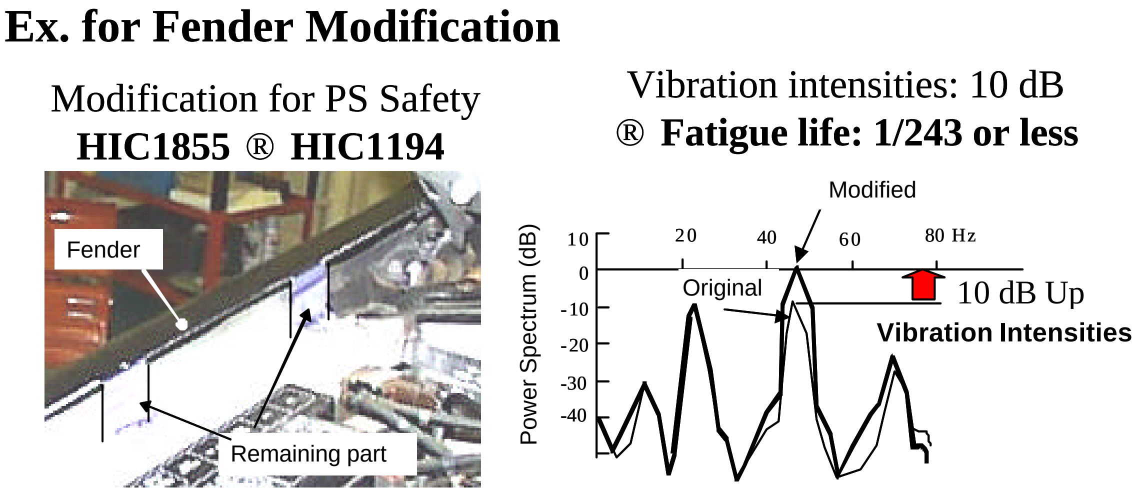


Figure 2.2 Influence of fender modification

3. Feasibility of Developing a Complying Bonnet Hinge

3.1. Finite Element Model

The finite element models of a car and a child headform employed in the present study are introduced in Figures 3.1 and 3.2. Using these computer simulation models, attempts were made to develop a bonnet hinge that would comply with the EEVC/WG17 child headform test.

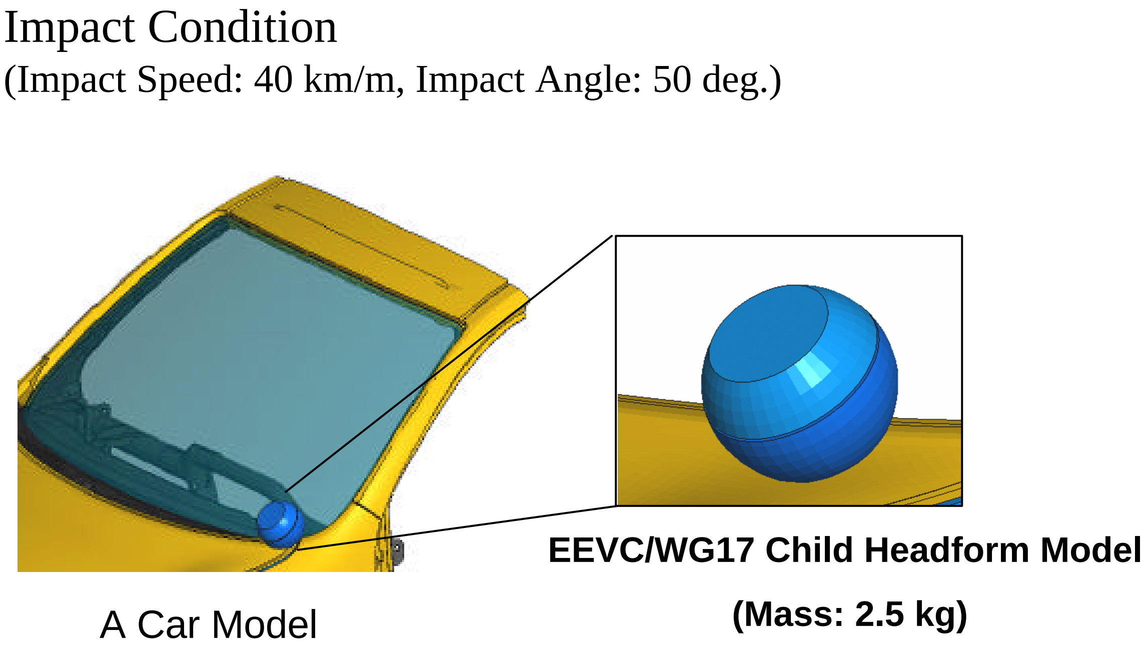


Figure 3.1 Computer simulation model
(A car model and EEVC/WG17 child headform model)

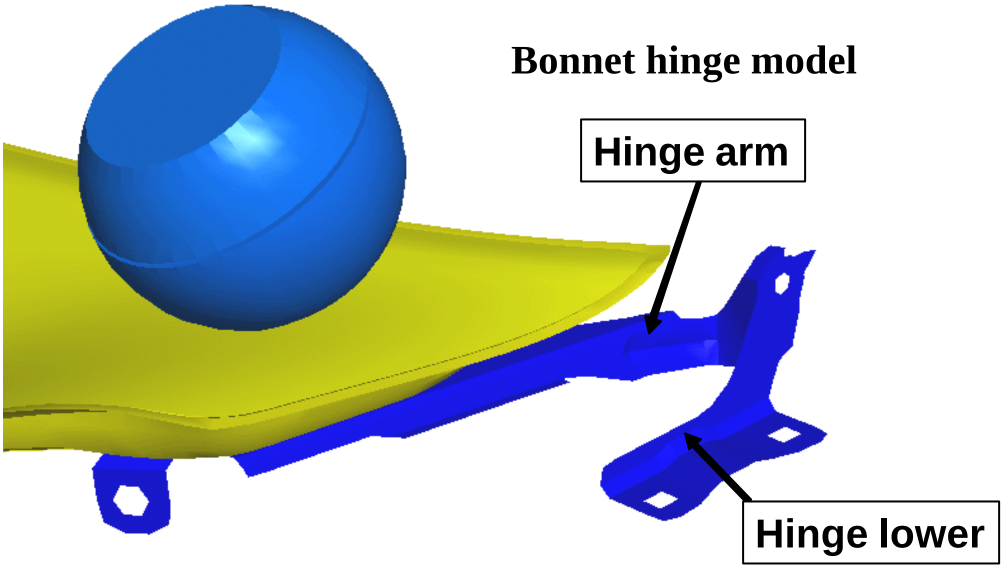
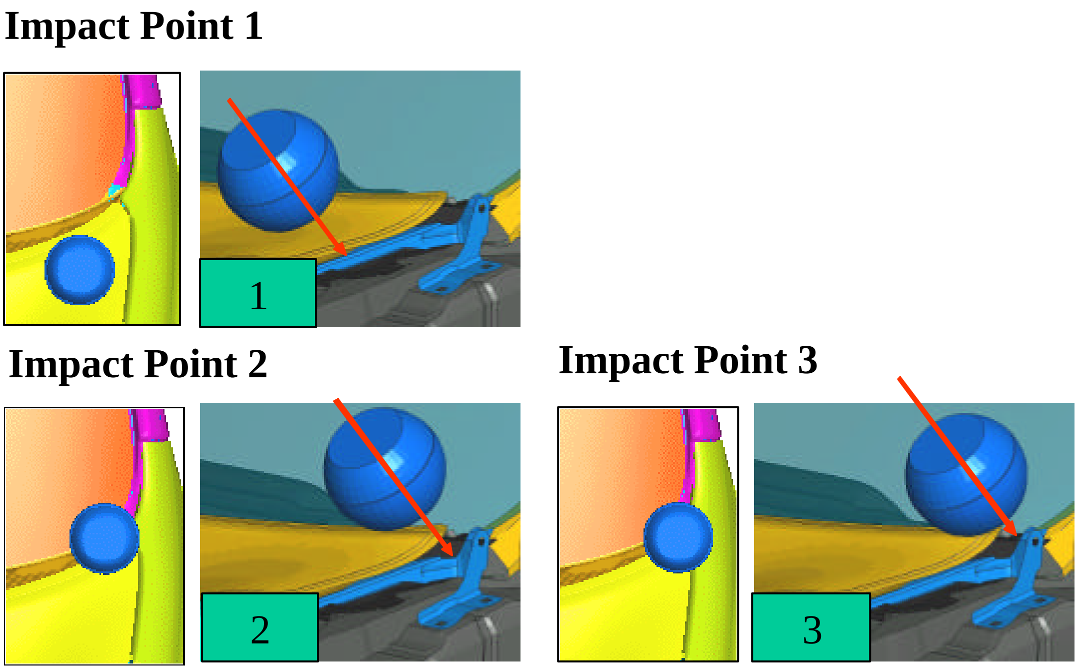


Figure 3.2 Computer simulation model (Bonnet hinge model)

3.2. Selection of Analysis Points

The three impact points shown in Figure 3.3 were tentatively selected for the analysis of bonnet hinges. HPC values at these points were measured [Figure 3.4], and Impact Point 3 recorded the highest HPC value, and the influence of the bonnet hinge is most significant comparing to the other impact points. Consequently Point 3 was selected as the analysis point for the development of a complying bonnet hinge.


Impact Point 1

Impact Point 2

Impact Point 3

Figure 3.3 Selection of analysis points

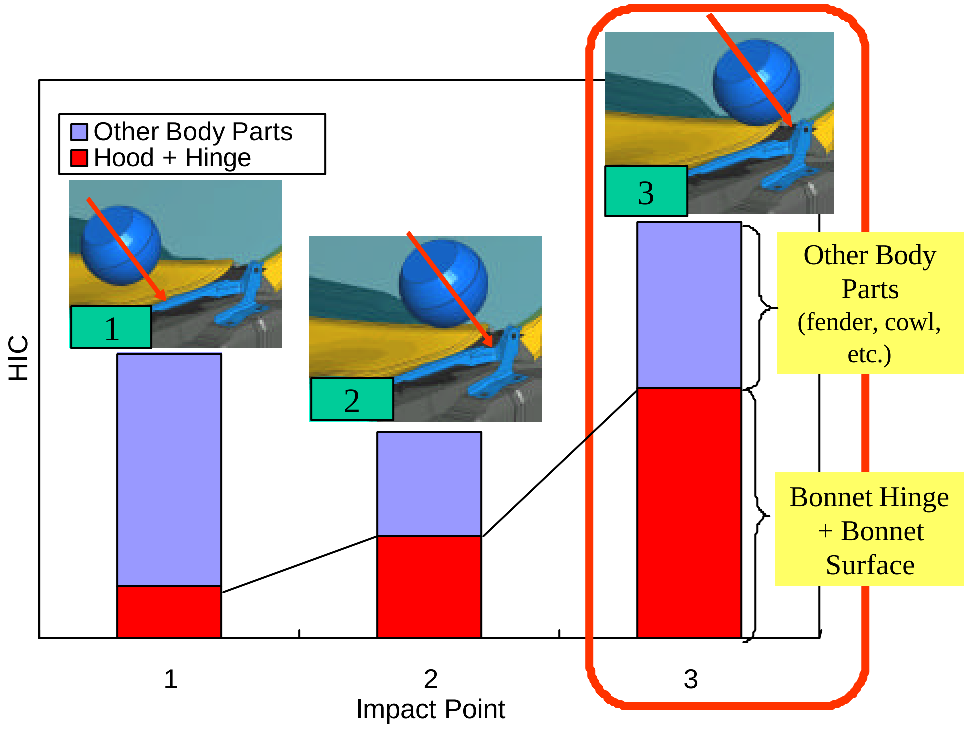


Figure 3.4 Influence of bonnet hinge

3.3. Development

3.3.1. Step 1: Reduction of Bonnet Hinge Thickness

HPC was measured for three hinge thicknesses – 2.6mm (original thickness), 1.8mm, and 1.0mm as shown in Figure 3.5. The impacting behavior of the child headform model was compared between the three thicknesses [Figure 3.6]. As apparent from the figure, the headform behavior did not change according to hinge thickness. The fender was therefore made invisible to observe any deformation in the bonnet hinge due to impact from the headform [Figure 3.7]. No or little deformation difference was found according to hinge thickness.

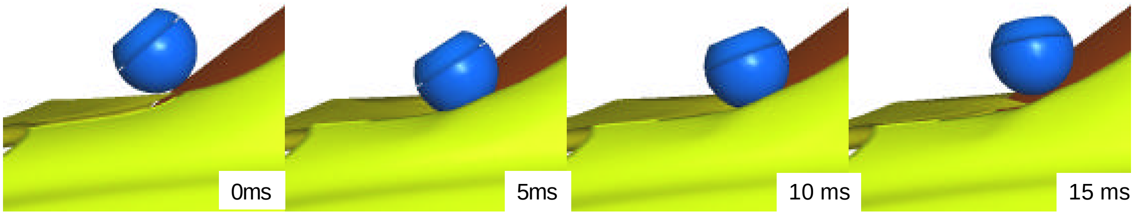
Thickness reduction
- Original (2.6 mm*), 1.8 mm, 1.0 mm

* Measured value

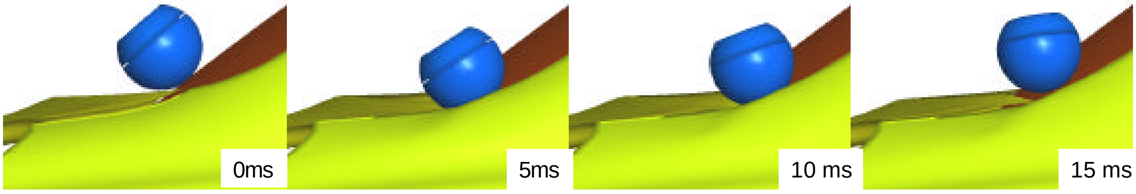
Fender is invisible.

Figure 3.5 Parameter study (Thickness reduction)

Original hinge, t=2.6 mm



Original hinge shape, t= 1.8 mm



Original hinge shape, t= 1.0 mm

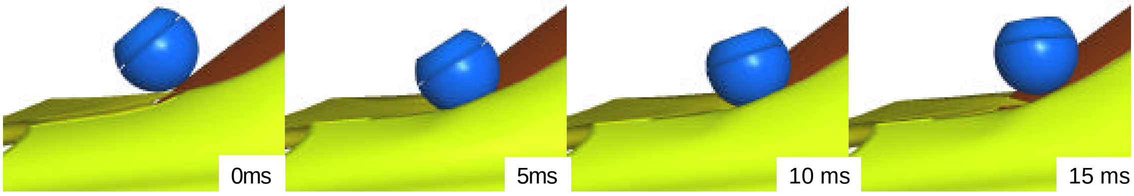
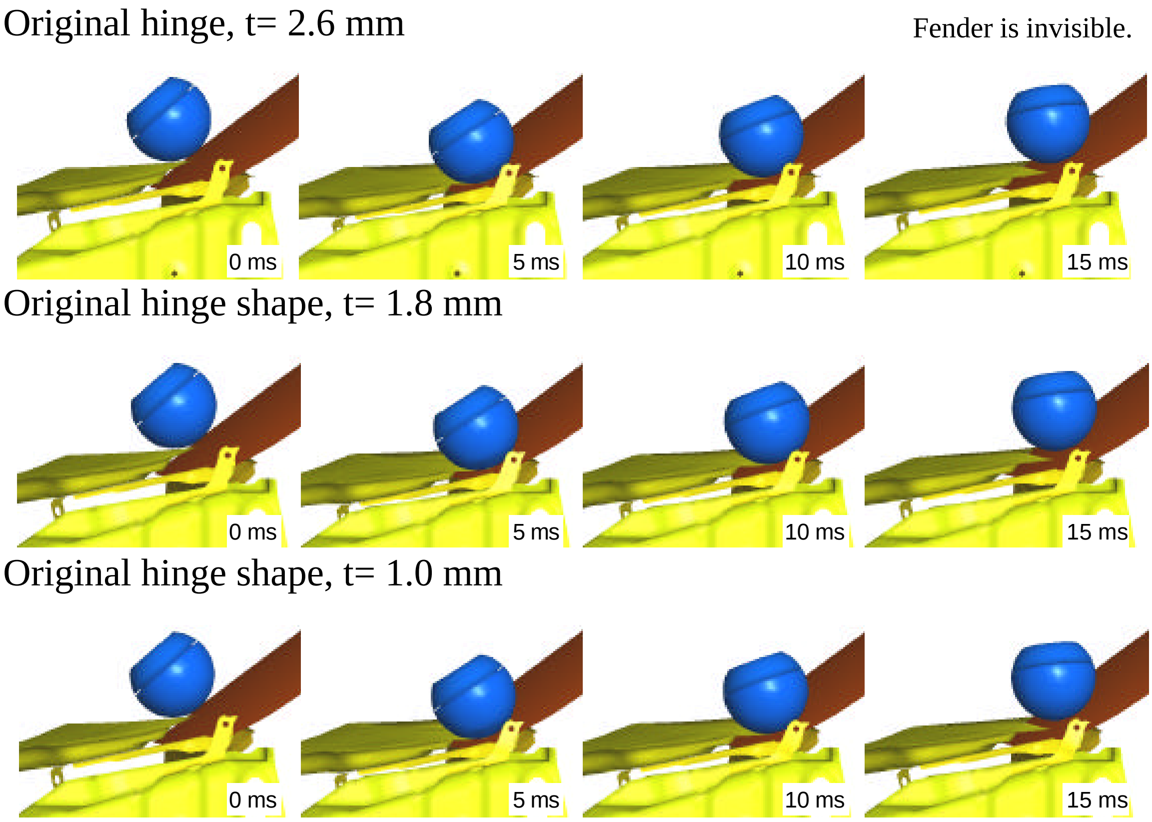


Figure 3.6 Simulation results (Kinematics)


Original hinge, t= 2.6 mm

Fender is invisible.

Original hinge shape, t= 1.8 mm

Original hinge shape, t= 1.0 mm

Figure 3.7 Simulation results (Kinematics; fender is invisible.)

The acceleration waveform and HPC of the headform were measured in relation to hinge thickness [Figures 3.8 and 3.9]. Although both acceleration and HPC exhibited some decline with the decrease of hinge thickness, the decline was not significant. This was attributed to two factors: One, because the short length of the bonnet hinge made it difficult to generate a buckling deformation, the reduction of thickness was not sufficient to absorb the impact energy of the headform. Two, inversely the impacts from other body parts such as the fender and cowl intensified so that the combined impact against the headform was intense.

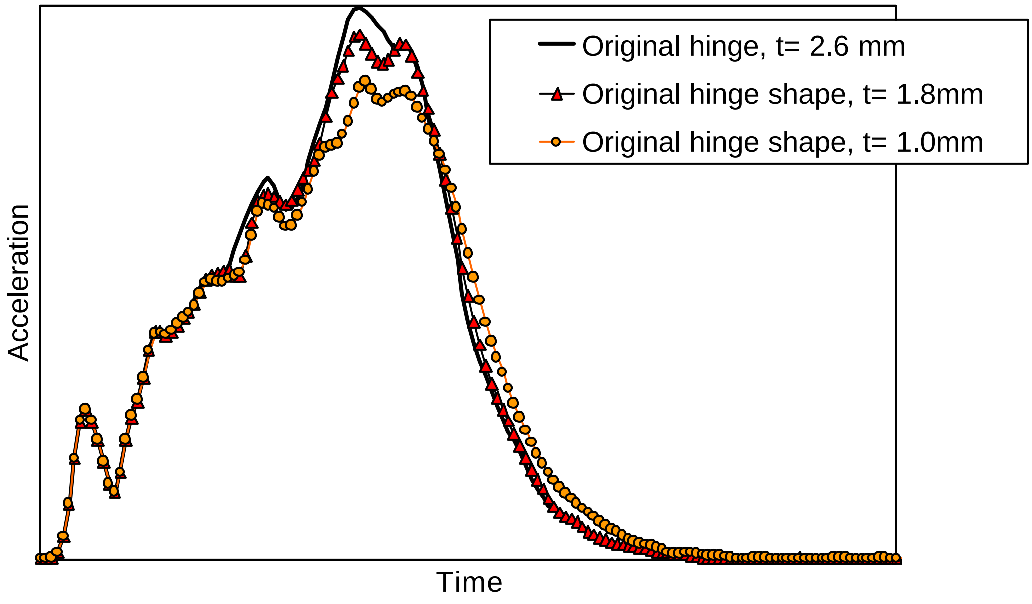


Figure 3.8 Simulation results (Acceleration)

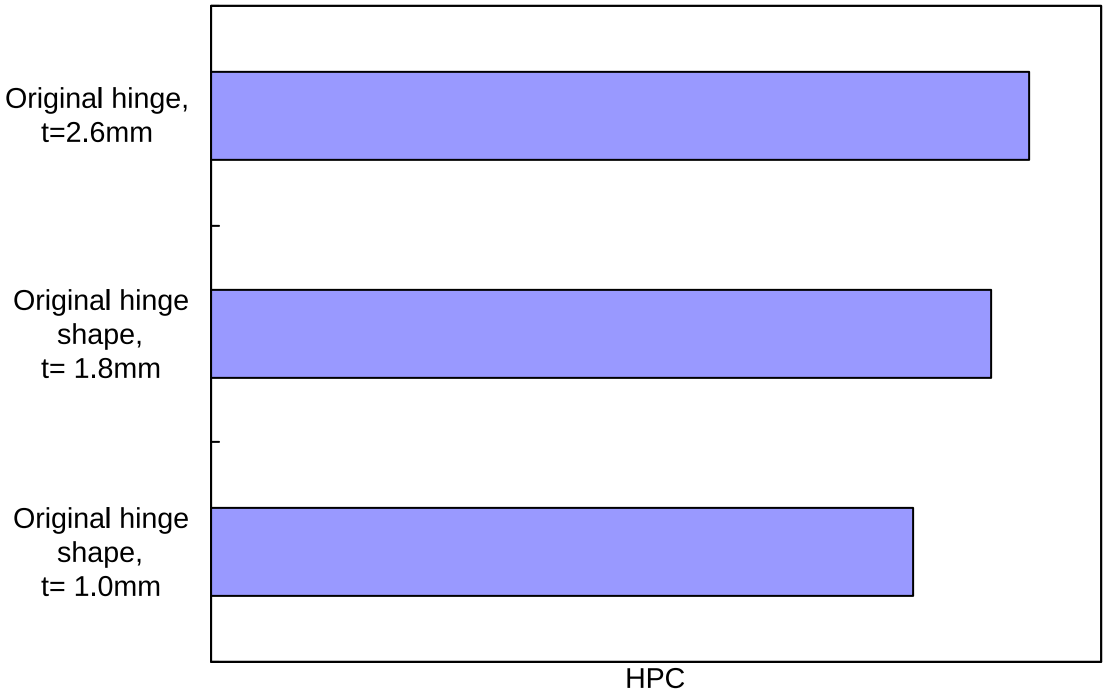


Figure 3.9 Simulation results (HPC)

3.3.2. Step 2: Thinning and Lengthening of the Bonnet Hinge and Removal of the Fender

In addition to thinning the bonnet hinge, its length was increased and the fender was removed to examine effects on the impact of the child headform [Figure 3.10]. The behavior of the headform model and the deformation of the bonnet hinge are shown in Figure 3.11. It was found that a bending deformation could be generated in the hinge's center area by increasing its length. As a result, more impact energy could be absorbed by a longer hinge.

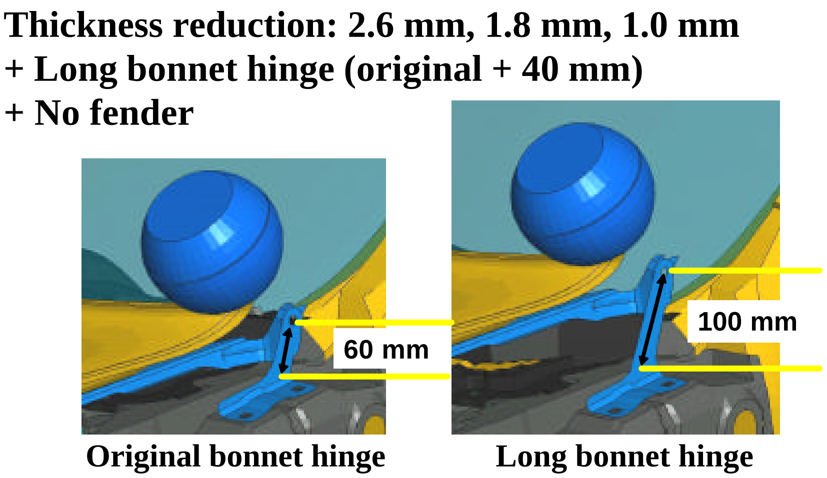
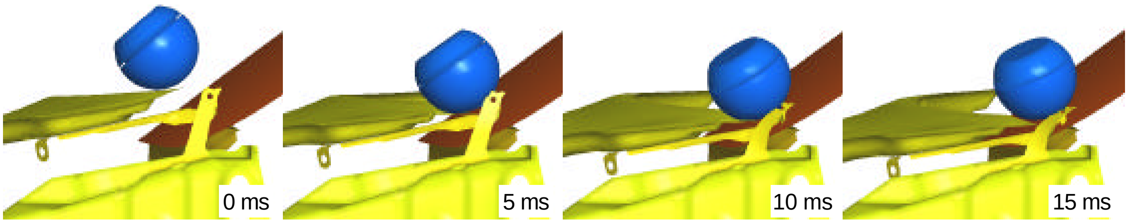
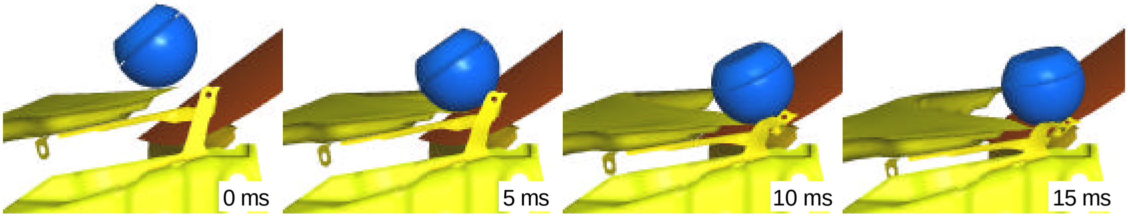


Figure 3.10 Parameter study
(Thickness reduction, long bonnet hinge, and no fender)

Long bonnet hinge, t= 2.6 mm



Long bonnet hinge, t= 1.8 mm



Long bonnet hinge, t= 1.0 mm

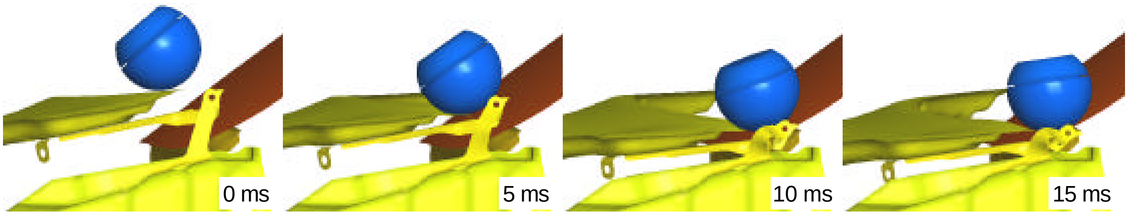


Figure 3.11 Simulation results (Kinematics)

The acceleration waveform of the child headform is shown in Figure 3.12. As evident from the case of a long hinge 2.6mm thick and with no fender, the headform's acceleration was markedly reduced by using a longer hinge and by removing the fender. Moreover, the peak acceleration value was further lowered by reducing the hinge thickness from 2.6mm to 1.8mm. When the thickness was further reduced to 1.0mm, however, the bonnet hinge bent more deeply and landed on the vehicle body so that the headform's acceleration peaked in the latter part of the impact period.

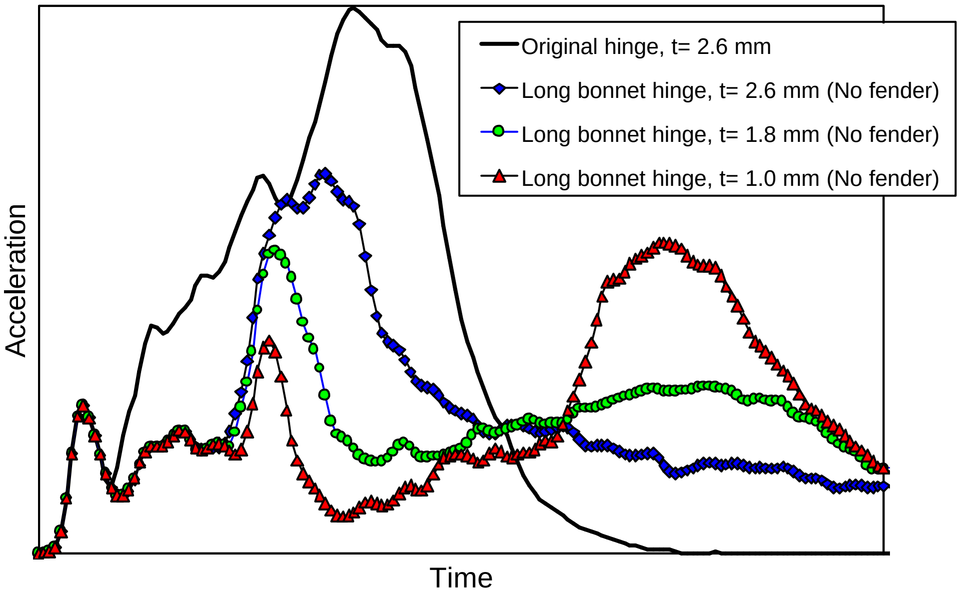


Figure 3.12 Simulation results (Acceleration)

HPC values were compared under various analytical conditions [Figure 3.13]. HPC was notably lowered simply by increasing the hinge length and removing the fender, as shown by the case of a long hinge 2.6mm thick and with no fender. When the thickness of the long hinge was reduced to 1.8mm with no fender, HPC was further lowered to a level complying with the EEVC/WG17 child headform test. Nevertheless a further thinning of the bonnet hinge to 1.0mm pushed up HPC, because the bent hinge landed on the vehicle body.

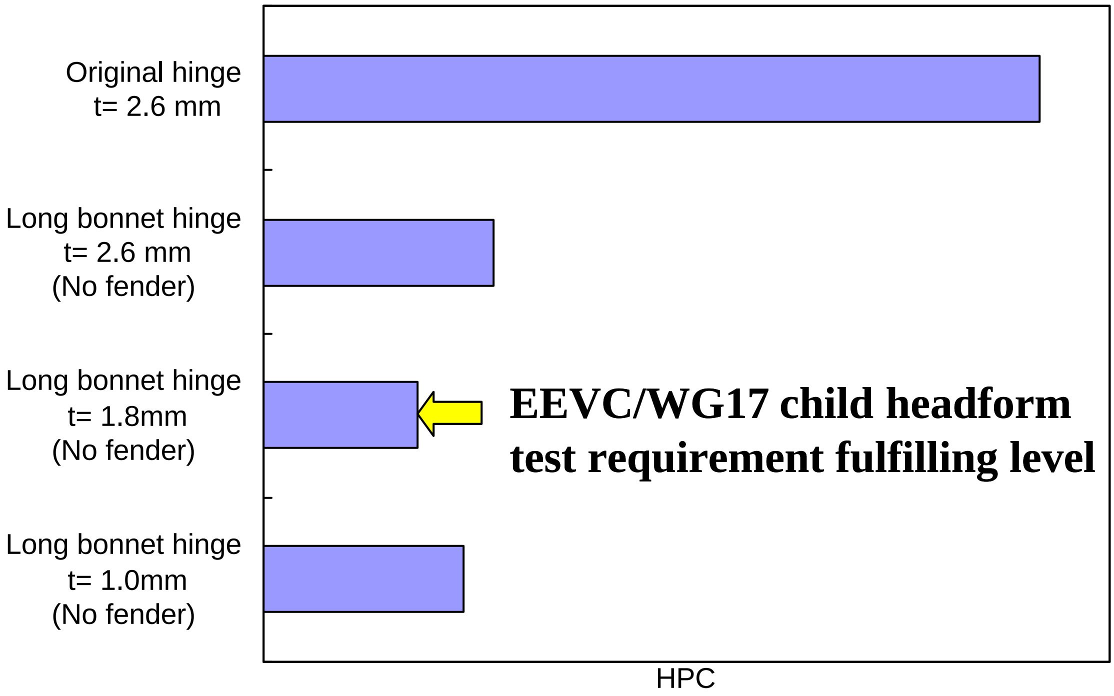


Figure 3.13 Simulation results (HPC)

3.3.3. Step 3: Confirmation by a Vehicle Test

A vehicle test was conducted to verify the simulation results reported in the above section 3.3.2. As shown in Figure 3.14., a modified bonnet hinge (long hinge, t = 1.8mm, hereafter "modified hinge") was mounted on a vehicle white body. The modified hinge was 40mm longer than the original one [Figure 3.15].

Figure 3.14 Confirmation test situation

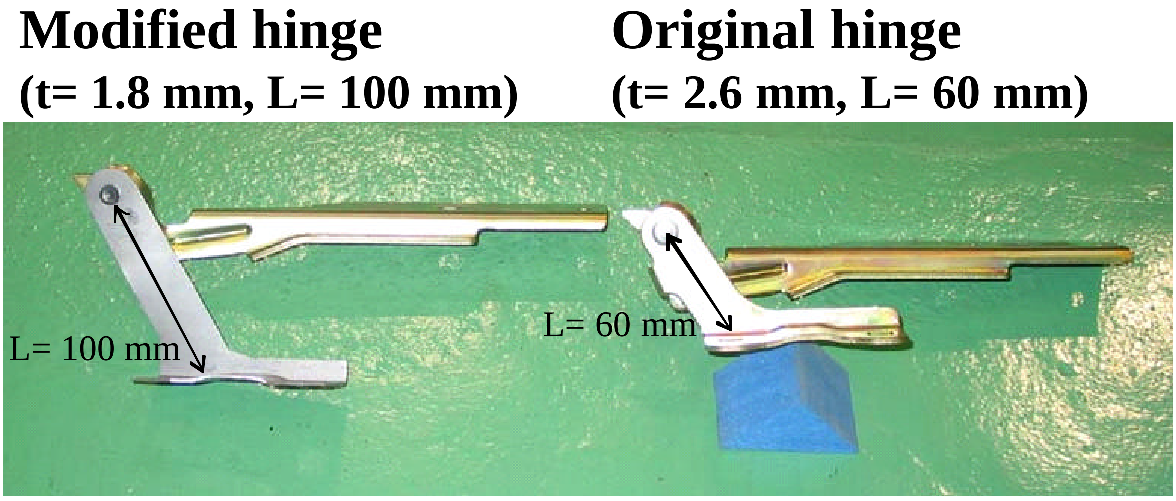
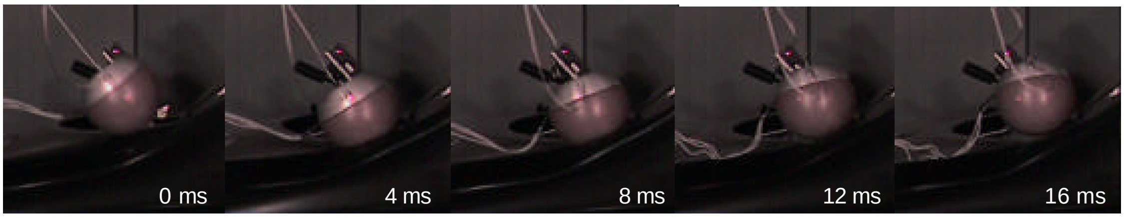


Figure 3.15 Modified hinge and original hinge

The observed behavior of a child headform in the vehicle test was compared with that in the simulation test with regard to the original and modified hinges in Figures 3.16(a) and 3.16(b). With the original hinge in the vehicle test, the headform exhibited a large rebound. With the modified hinge, however, it bent down in its central area so that the headform's impact was moderated. The results proved equivalent between vehicle test and simulation test, and a good impact absorbing performance of the modified hinge was confirmed by the vehicle test.

Original hinge

TEST



Simulation

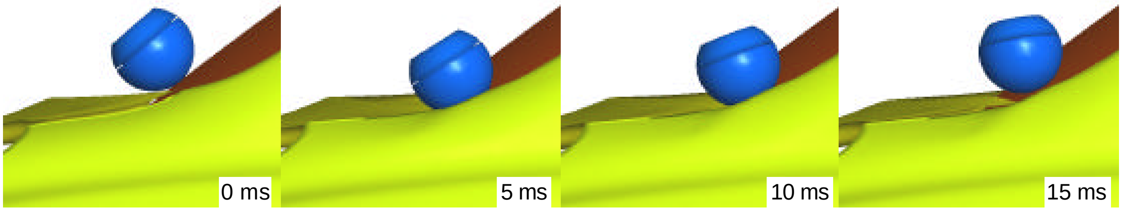
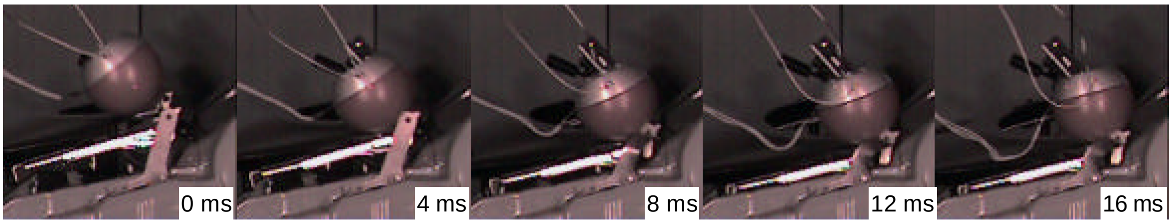


Figure 3.16 (a) Test and simulation kinematics for original hinge

Modified hinge (No fender)

TEST



Simulation

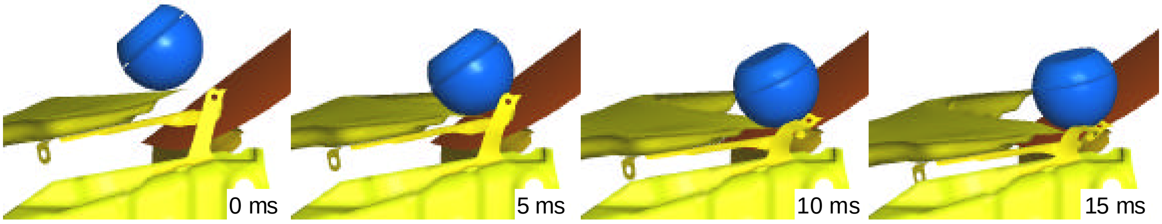


Figure 3.16 (b) Test and simulation kinematics for modified hinge

Similarly, the measured acceleration waveform of a child headform in the vehicle test was compared with that in the simulation test [Figure 3.17]. With the modified hinge, the headform's acceleration was markedly reduced in agreement with the simulation test results. HPC values were also compared between original and modified hinges and between vehicle test and simulation test [Figure 3.18]. Compared to the original hinge, the modified hinge exhibited a notably lower HPC in both tests so that its HPC lowering capability was confirmed by the vehicle test.

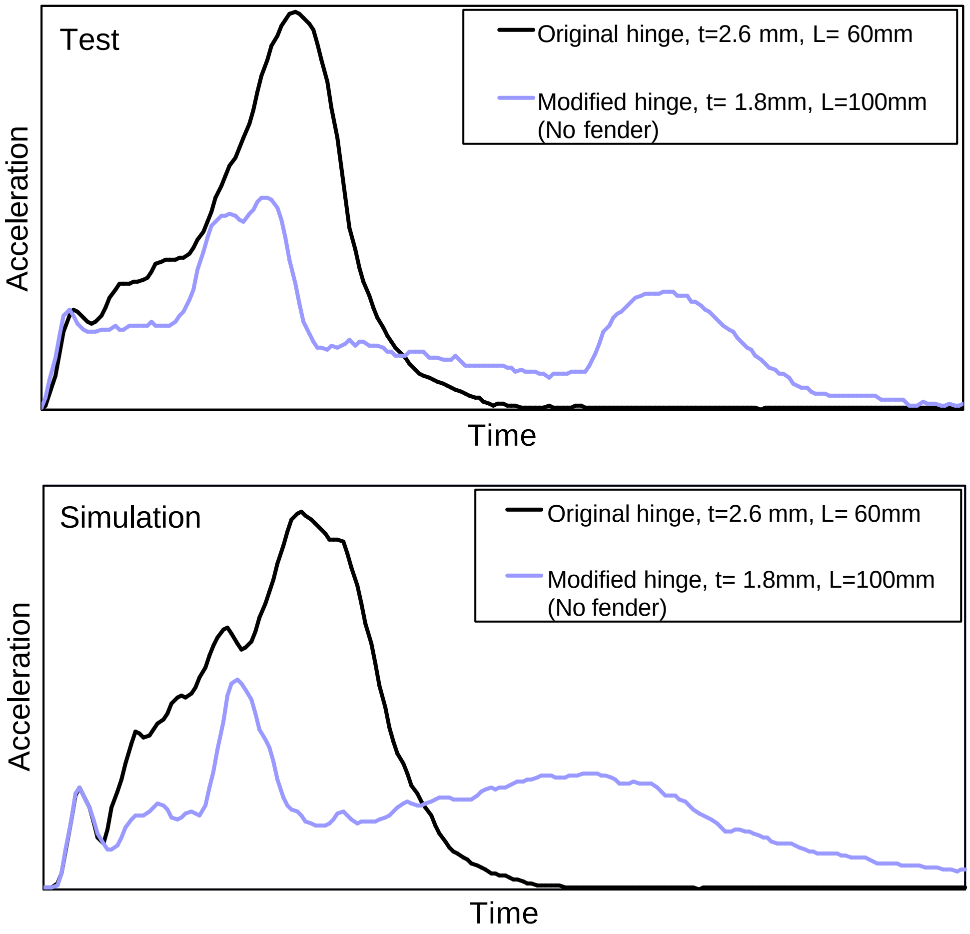


Figure 3.17 Test and simulation results (Acceleration)

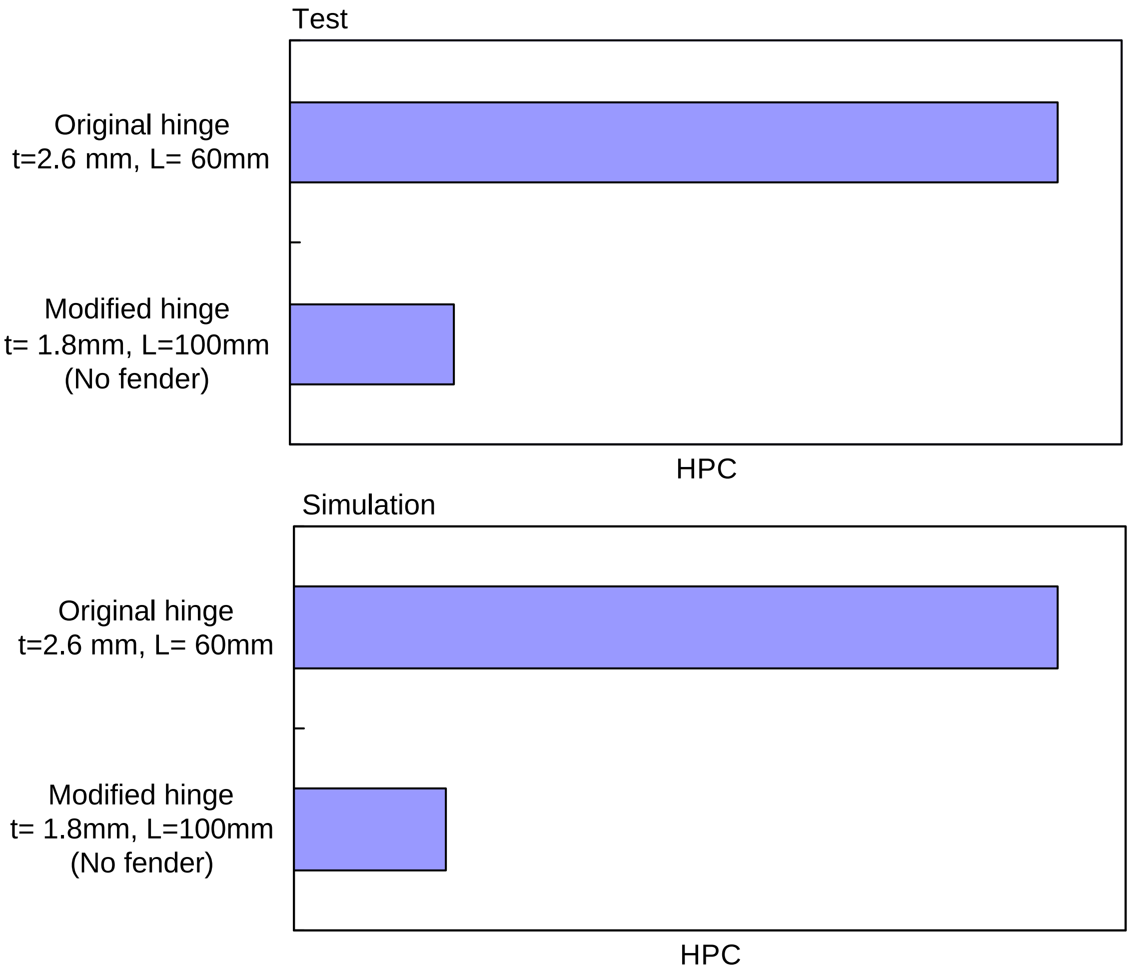


Figure 3.18 Test and simulation results (HPC)

3.4. Discussion

The simulation analysis in the present study pointed to the possibility of developing a vehicle that complies with the EEVC/WG17 child headform test by, for example, thinning and lengthening the bonnet hinge and by removing the fender. However, it is impractical to sell vehicles without fenders.

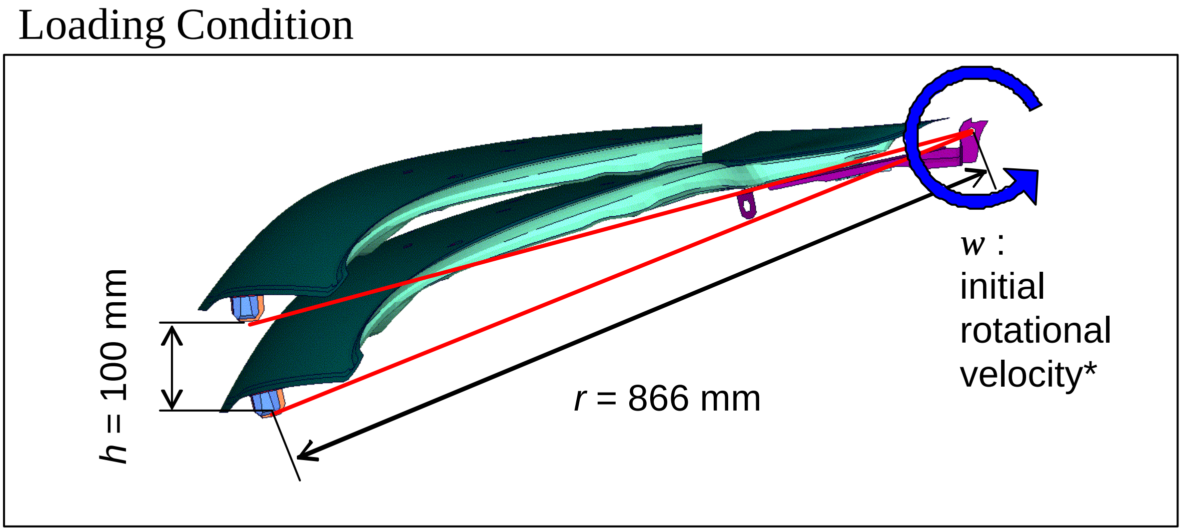
To keep the fenders, the modified hinge thickness should be less than 1.8mm. However, the 1.8mm modified hinge already has a high possibility to do not have enough performance for other vehicle requirements. For this reason, the developed 1.8mm modified hinge is evaluated its performance to the other vehicle requirements in the next section.

4. Deterioration of Hinge Performances Besides Pedestrian Protection

To analyze the effects of the modified hinge on vehicle performances other than pedestrian protection, two bonnet-related performances were selected: durability against the fatigue of opening and closing the bonnet (hereafter "durability") and the keeping of the bonnet in its position at the time of a frontal collision (hereafter "position keeping").

4.1. Durability against Fatigue of Bonnet Opening-Closing

Stress on the bonnet hinge at opening and closing the bonnet was analyzed to compare the durability of the modified and original hinges, employing the finite element model of a bonnet [Figure 4.1]. The height from which to close the bonnet was set at 100mm as measured from the bonnet's front edge. The bonnet model was given a parameter of rotational speed around the hinge to reproduce the load condition of bonnet closing from a 100mm drop height.



* Initial rotational velocity of the hood closing

$$w = \frac{\sqrt{2gh}}{r} = \frac{\sqrt{2\times 9800\times 100}}{866} = 1.62 \quad \mathrm{rad/s}$$

Figure 4.1 Bonnet closing simulation

As shown in Figure 4.2., the maximum stress was 1.8 times greater on the modified hinge than on the original hinge. This result was applied to the fatigue durability curve of bonnet hinge materials to compare the durability performance between modified and original hinges [Figure 4.3]. Since it was found that the stress on the original hinge was below the lower limit of the fatigue durability curve for hinge materials, it was evident that the original hinge would not fracture no matter how many times the bonnet was opened and closed.

On the other hand the stress on the modified hinge was above the lower limit so that it could possibly fracture at the repeated opening and closing of the bonnet. The load generated by closing the bonnet from a 100mm height was considered small, while in the actual vehicle use the bonnet is closed from a far greater height. Accordingly the rigidity of the modified hinge was considered extremely low in relation to the actual condition of bonnet opening and closing.

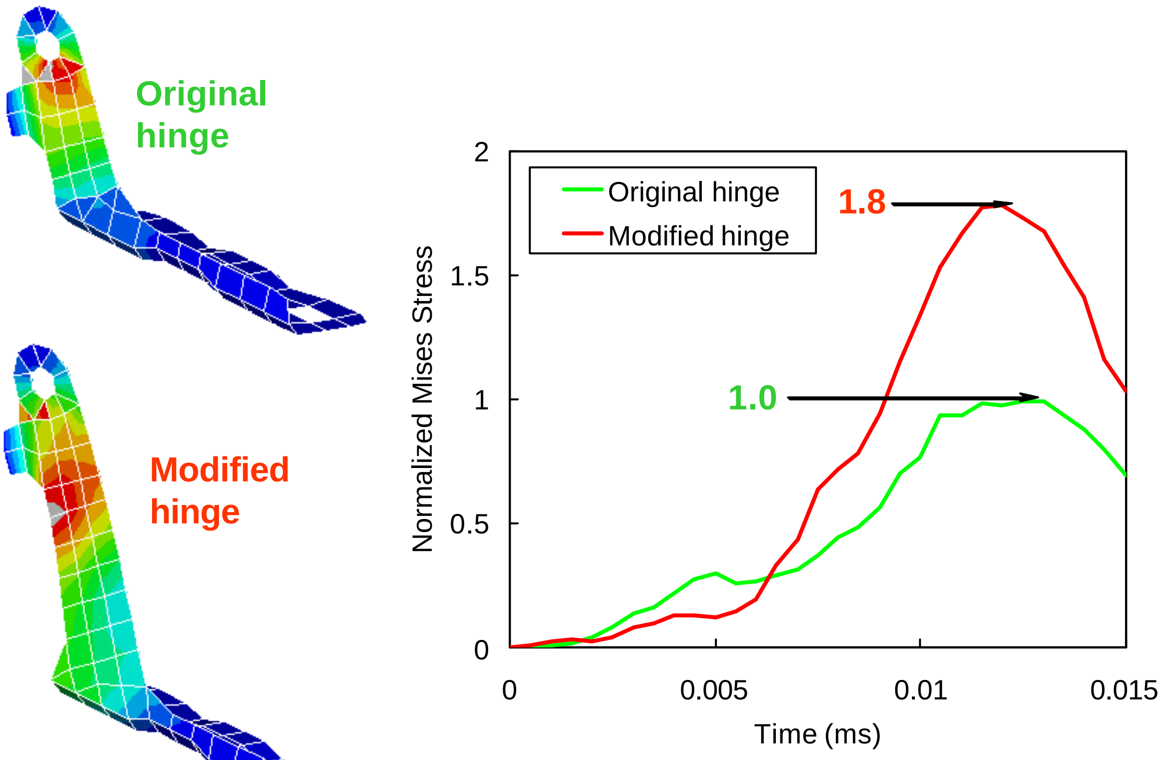


Figure 4.2 Stress on bonnet hinge

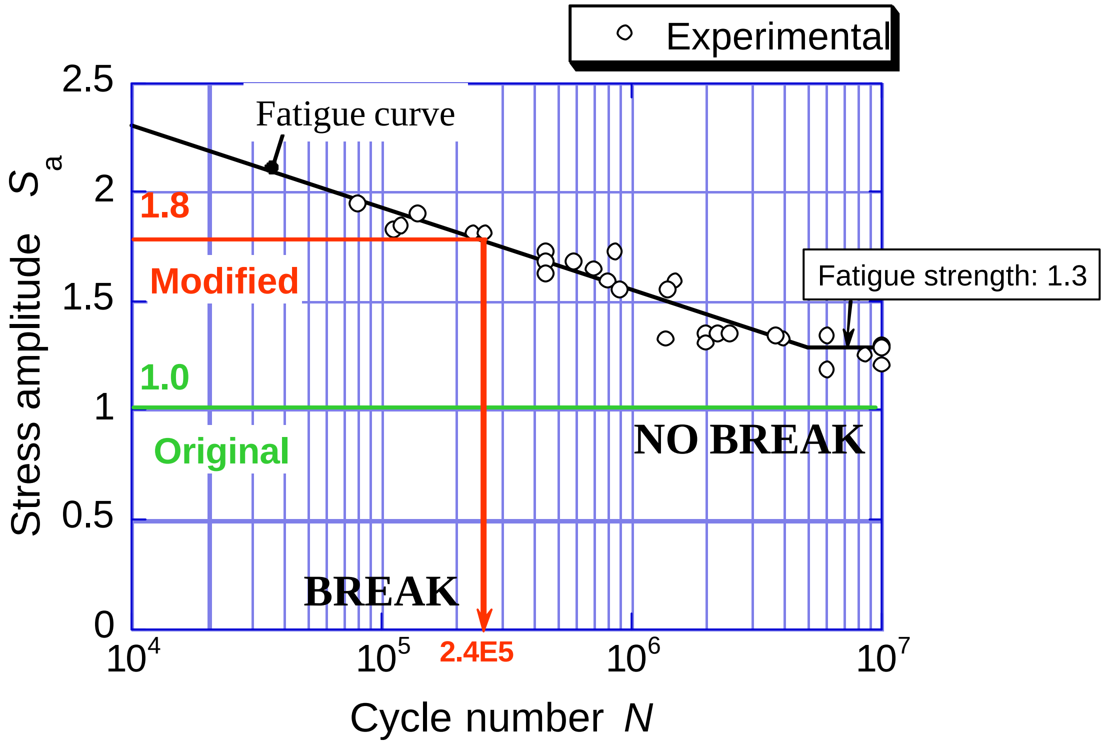
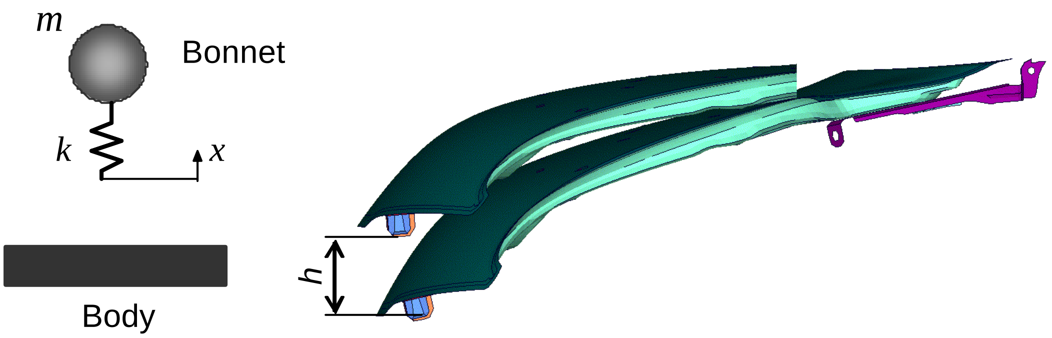


Figure 4.3 Fatigue level (closing height: 100 mm)

In the next step, therefore, a similar analysis was performed by increasing the bonnet closing height from 100mm to 300mm. Since stress on the bonnet hinge was found to be in proportion with the square root of drop height [Figure 4.4], the stress on the bonnet hinge at closing the bonnet from a 300mm height was assumed to be 1.7 times that from a 100mm height [Figure 4.5]. Accordingly it was predictable that, in the case of a 300mm drop height, the original hinge would endure tens of thousand times of closing-opening repetitions but that the modified hinge would fracture after only tens of times of repetitions. This clearly indicated a deficiency of rigidity in the modified hinge.



Impact speed: v $\quad v=\sqrt{2gh}$

Energy conservation $\quad \frac{1}{2}mv^2 = mgh = \frac{1}{2}kx^2$

m, g, k: const $\quad h \propto x^2$

F= kx $\quad F \propto \sqrt{h}$

S= F/A $\quad S \propto \sqrt{h}$

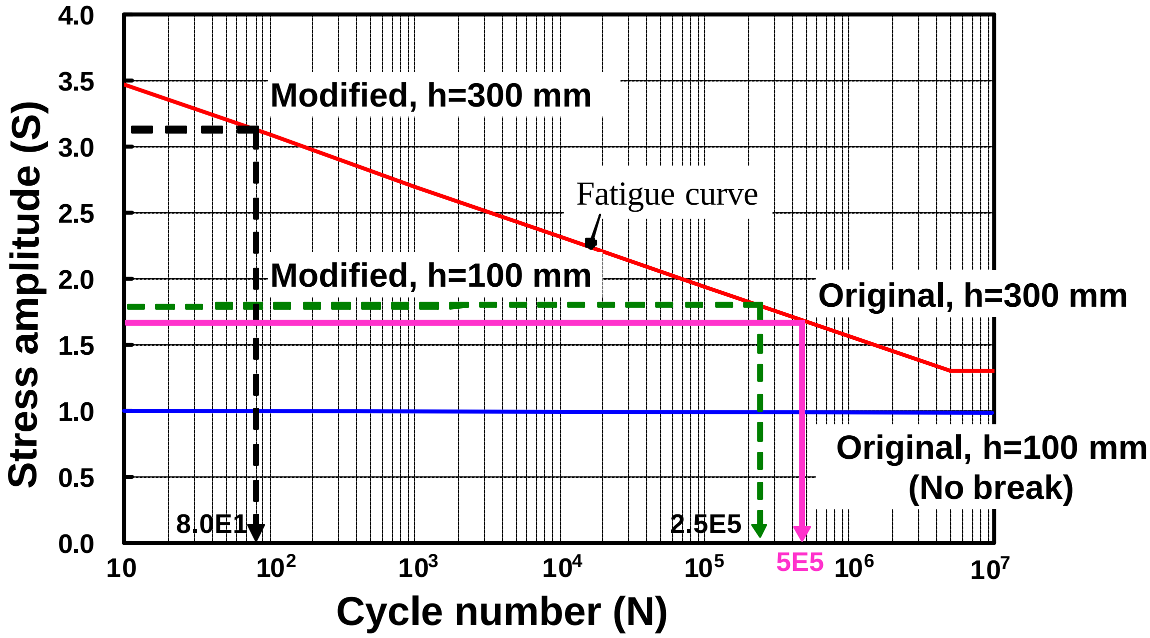


Figure 4.5 Fatigue level (closing height: 100 mm or 300 mm)

4.2. Bonnet Position Keeping Performance in Frontal Collision

Load on the bonnet hinge in a vehicle's frontal collision was analyzed to compare the bonnet position keeping performance of the modified and original hinges, employing the finite element model of a vehicle [Figure 4.6]. A rigid wall was installed immediately in front of the bonnet in the computer simulation, and the load condition of vehicle frontal collision was reproduced by introducing a parameter of vehicle displacement in a frontal collision with the rigid wall.

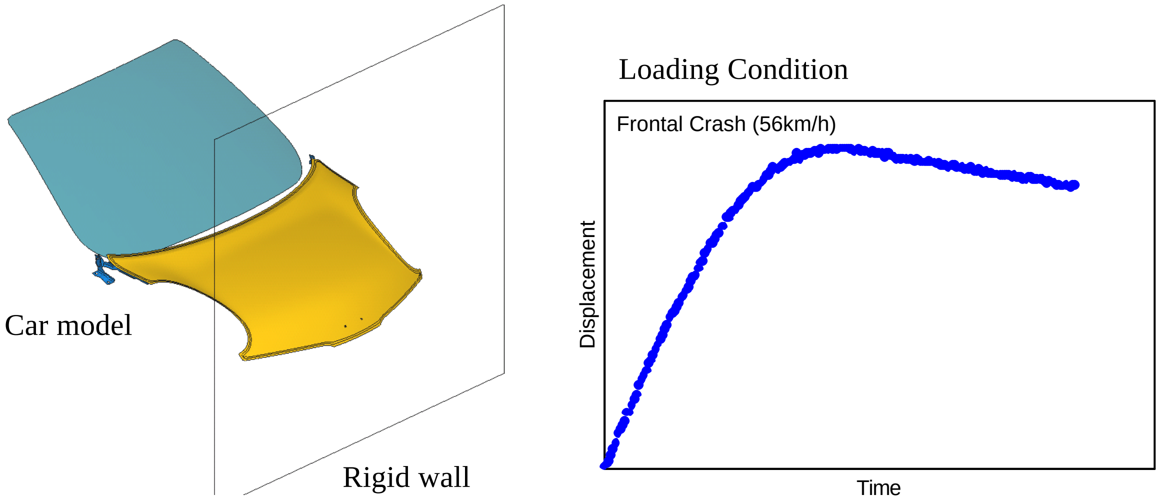


Figure 4.6 Frontal crash simulation

As shown in Figure 4.7, it was found that the modified hinge, but not the original hinge, fractured in the frontal collision. The fracture was attributed to a decline in rigidity accompanying the reduction of thickness and the increase of length in the modified hinge. If the bonnet hinges break in a frontal collision, the disengaged bonnet may intrude into the passenger compartment to injure the occupants. If it lands on the road, nearby pedestrians may be injured. The modified hinge proved to lack the strength required by each vehicle manufacturer in his in-house vehicle performance standard.

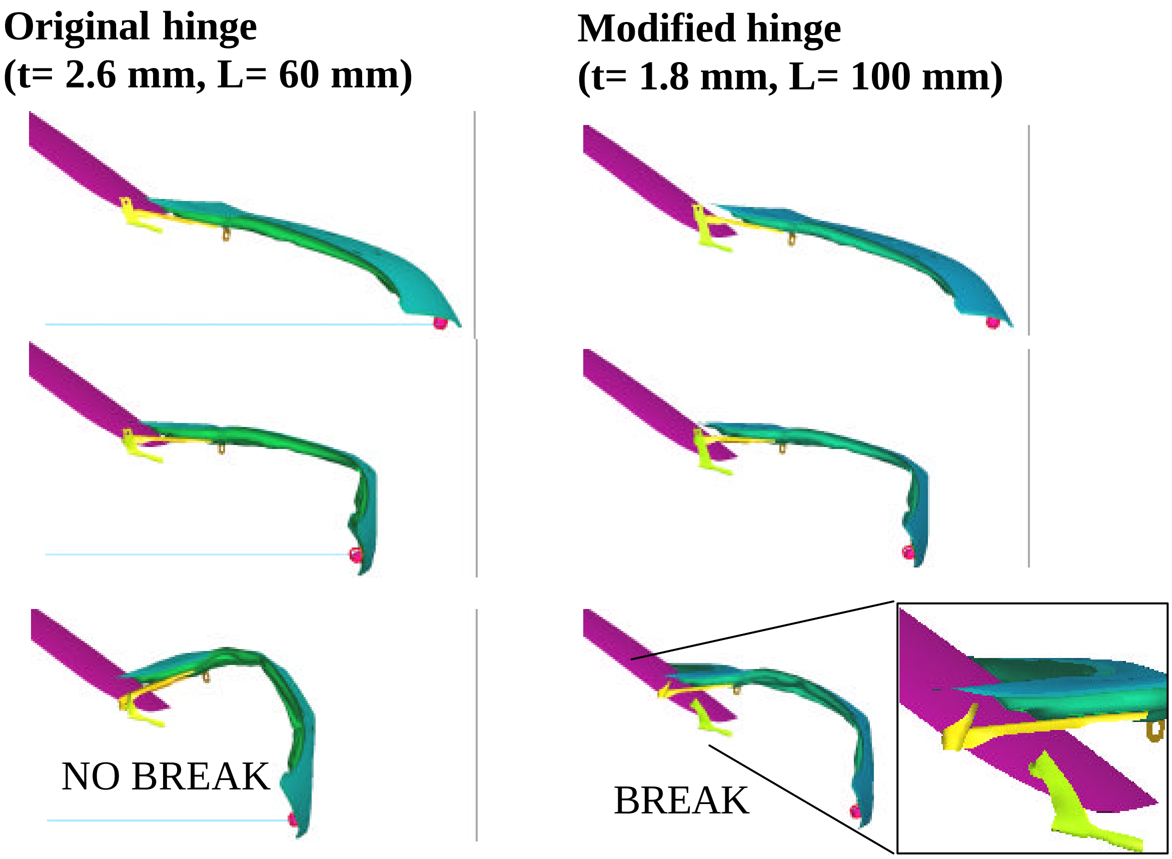


Figure 4.6 Simulation results

4.3. Discussion

In section 4.1 the modified hinge was found less durable than the original hinge against the repeated closing-opening of the bonnet and liable to fracture after tens of closing-opening repetitions from a 300mm drop height. Since no manufacturers design their vehicles to suffer the fracture of bonnet hinges during the vehicle's service life under normal using conditions, the modified hinge clearly failed to satisfy the in-house durability requirement of vehicle manufacturers.

In section 4.2 the modified hinge was found to fracture in a frontal collision of the vehicle, disengaging the bonnet from its fixed position. On the other hand the original hinge remained intact, keeping the bonnet in its position. Since vehicle manufacturers in their in-house standards require bonnet hinges to withstand the impact of frontal collisions for the safety of vehicle occupants and nearby passengers, the modified hinge failed to satisfy the manufacturers' bonnet position keeping requirement.

Besides, bonnet hinges are subjected to more other performance requirements such as durability against running vibrations and bonnet position keeping during high-speed running, and it was suspected that the modified hinge would fail to meet these requirements also.

Consequently, to develop a bonnet hinge which complies to the EEVC/WG17 child headfrom test requirement, beside to meet other bonnet hinge requirements is extremely difficult.

Some advance technologies such a pop-up bonnet and hood airbags has a chance to satisfy the EEVC/WG17 headform test requirement satisfying with the other bonnet hinge requirements, however, deep examination will be necessary into the possibility of these advanced technologies to deteriorate the vehicle's performances other than pedestrian protection. Many years, not 5 years or so, will be required to install such advanced technologies to all car models by getting user acceptance including price, like air bag experience.

The present study focused on a technical feasibility for a bonnet hinge, however, other car parts also have a same problem (confliction between the pedestrian safety and the other car requirements, especially for durability)). Thus, we believe that to complying with the EEVC/WG17 headform to bonnet top test requirement is not feasible especially for durability required parts.

5. Conclusion

1) The present study demonstrated that a bonnet hinge complying with the EEVC/WG17 child headform to bonnet top test requirement could be developed only under the unrealistic condition of removing the fender and that such a hinge could not satisfy various required performances apart from pedestrian protection performance.

2) Although some advance technologies such a pop-up bonnet and hood airbags has a chance to satisfy the EEVC/WG17 headform test requirement satisfying with the other bonnet hinge requirements, deep examination will be necessary into the possibility of these advanced technologies to deteriorate the vehicle's performances other than pedestrian protection. Many years, not 5 years or so, will be required to install such advanced technologies to all car models by getting user acceptance including price, like air bag experience.

3) The present study focused on a technical feasibility for a bonnet hinge, however, other car parts also have a same problem (confliction between the pedestrian safety and the other car requirements, especially for durability)). Thus, we believe that to complying with the EEVC/WG17 headform to bonnet top test requirement is not feasible especially for durability required parts.

ACKNOWLEDGEMENTS

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We would like to express special thanks to their contributions.

Part 2. Technical Feasibility Study on EEVC/WG17 Pedestrian Upper Legform to Bonnet Leading Edge Test

ABSTRACT

1) Given the fact that, in a passenger car vs pedestrian accident, there is a low rate of sustaining an AIS 2+ injury to the thigh or hip region, no existing passenger car can comply with the EEVC/WG17 upper legform to bonnet leading edge test. Thus, this test, which all cars failed, is apparently contradictory to the actual situation in a real-world car-pedestrian accident. If the passenger car could comply with the EEVC/WG17 upper legform to bonnet leading edge test, only a special car design can be employed: e.g., a car with an extremely low bonnet leading edge, a car with an extremely long bumper lead, or a car with an extremely high bonnet leading edge. However, this special design would come into conflict with the requirements for other vehicle performance characteristics such as aerodynamics or fuel consumption. Therefore, the EEVC/WG17 upper legform to bonnet leading edge test itself is unreasonable and inapplicable to say the least.

2) The test poses serious problems in terms of the impact energy, the test tool in relation to biofidelity, and the injury acceptance levels. The impact energy derived from the look-up graph of the EEVC/WG17 upper legform to bonnet leading edge tests is overestimated as compared to the case of a real-world car-pedestrian accident. The EEVC/WG17 upper legform impactor has low biofidelity. The more biofidelity built into the upper legform impactor, the lower the measured value becomes, and more vehicles will thus be able to meet the acceptance level. The acceptance level of a 0.2 probability of femur fracture is 7.40 kN in the light of EEVC/WG17 upper legform impactor construction when the impactor has biofidelity. Accordingly, all these three important parameters of the EEVC/WG17 upper legform to bonnet leading edge test (inappropriate energy look-up graph, low biofidelity impactor, inadequate injury acceptance level) do not reflect the current real-world car-pedestrian accident situation.

1. Review of Bonnet Leading Edge Safety Performance in Current Passenger Cars

The New Car Assessment Program (Euro-NCAP) is now in place in Europe. The EEVC/WG17 Upper Legform to Bonnet Leading Edge Test is considered a valid procedure to confirm the safety performance of a new car bonnet leading edge when colliding with a pedestrian's hip or thigh. The new Euro-NCAP Phase 12 Test, which took effect in 2003, was conducted at 3 different locations on the bonnet leading edge of 16 new cars. The injury criteria were the impact force and bending moment measured with an upper legform impactor. The injury acceptance levels used were the 5 kN and 300 Nm proposed by the EEVC/WG17.

Figure 1 shows the EEVC/WG17 injury acceptance levels along with the impact force and bending moment obtained from 48 tests on 3 locations in 16 cars. The NCAP results indicated that all tested passenger cars failed to meet the EEVC/WG17 injury acceptance levels. The present results suggest that current passenger cars present a very great danger to the pedestrian hip or thigh.

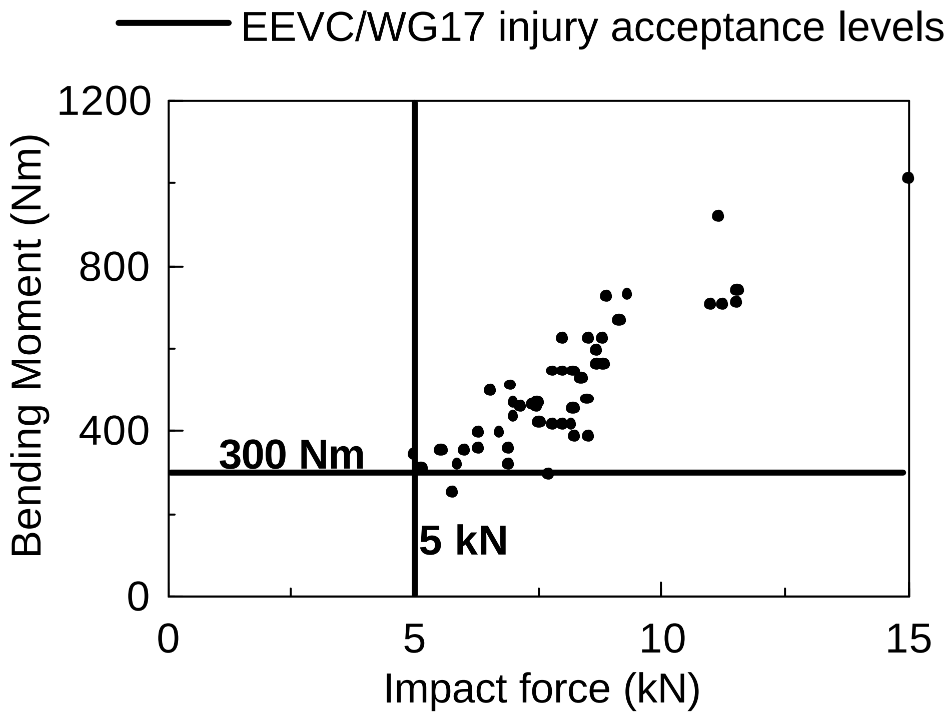


Figure 1 Euro-NCAP Phase 12 results shown by impact force and bending moment.

Next, we look at the proportion of AIS 2+ injuries to the femur or pelvis in an actual car accident involving a pedestrian. Table 1 shows the proportion of such injuries by body region. The data source is an IHRA 2001 report. Table 1 indicates the low proportion of AIS 2+ injuries to the pelvis or femur compared to head or lower leg injuries. Thus, the EEVC/WG17 upper legform to bonnet leading edge test, which all cars failed, is apparently contradictory to the actual situation in a real-world pedestrian accident. One may suppose that this test, therefore, poses serious problems in terms of the test conditions, test methods, and design of the upper legform impactor in relation to biofidelity, injury criteria and injury acceptance levels.

In the next section, we investigate the difficulties associated with measures to improve cars to meet the EEVC/WG17 Upper Legform to Bonnet Leading Edge Test requirement.

Table 1 Proportion of AIS 2+ injuries by body region

Body region	Proportion of AIS 2+ injuries	Test priority
Head	31.2%	1st
Face	4.6%	
Neck	1.4%	
Chest	11.8%	
Abdomen	6.0%	
Arm	8.1%	
Pelvis	7.5%	
Femur	3.5%	
Lower Leg	23.3%	2nd
Foot	2.5%	
Total	100%	

2. Consideration of Vehicle Complying with EEVC/WG17 Upper Legform to Bonnet Leading Edge Test

In this section, we consider vehicle measures to achieve the EEVC/WG17 Upper Legform to Bonnet Leading Edge Test requirement. In the Upper Legform test, the upper legform impactor is impacted against the bonnet leading edge with a certain energy. Figure 2 shows the impact energy determination graph proposed by EEVC/WG17. The impact energy is determined by two vehicle parameters; the bonnet leading edge height and the bumper lead. When the bonnet leading edge height is less than 650 mm, no test is required since the impact energy is less than 200 J. When the bonnet leading edge height is 700 mm, no test will be required if the bumper lead is put at over 350 mm. Thus, to eliminate the need for the upper legform impact test, the bonnet leading edge height should be extremely low (e.g., under 650 mm) on the vehicle (See Figure 3), or for a car that can be built with an extremely long bumper lead (See Fig. 4).

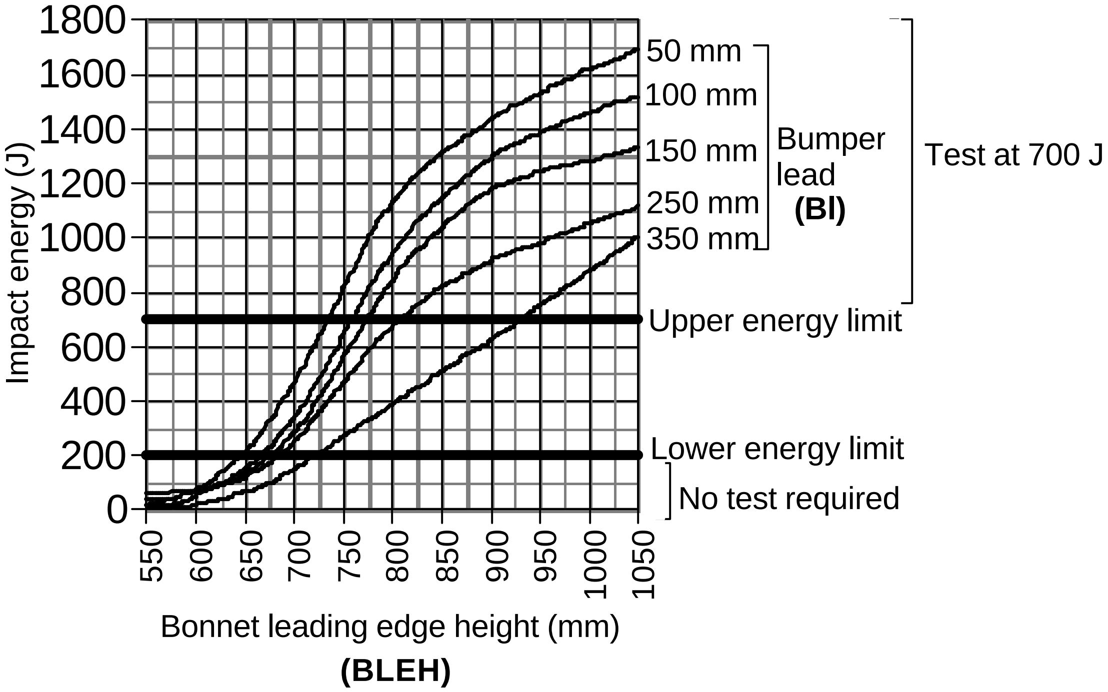


Figure 2 Impact energy determination graph proposed by EEVC/WG17.

Figure 3 Example of vehicle with bonnet leading edge height less than 650 mm.

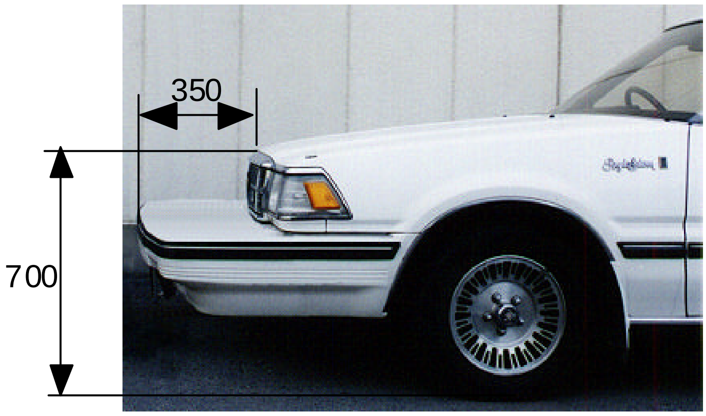


Figure 4 Vehicle front shape with bumper lead of 350 mm.

We look at the possibility of modification of the energy-absorbing structure in the bonnet leading edge. The deformation stroke of the bonnet leading edge (See Figure 5) for energy absorption was calculated, because the energy absorbing structure must be taken into account in the design of the bonnet leading edge. The deformation stroke of the bonnet leading edge was calculated based on the EEVC/WG17 acceptance level of 5 kN. An energy absorption efficiency of 60% was employed (See Figure 6). The deformation stroke (*Ds*) was determined using the following formula:

$$D_S = \frac{E}{F \times e} \qquad (1)$$

where E is the energy determined by EEVC/WG17, F is the impact force acceptance level of 5 kN proposed by EEVC/WG17, and e is the energy absorption efficiency of 60% (i.e., 0.6). The results of the calculation for the bonnet leading edge deformation stroke are shown in Figure 7. The figure indicates that when we need to develop a car which have to be applied an upper legform impact test (a car which has a bonnet leading edge height of 700 mm or more, and a bumper lead of 250 mm or less), one must keep at least 67 mm deformation stroke, and 233 mm deformation stroke in maximum. However, when we try to develop/modify a car, one must keep 233 mm deformation stroke at last.

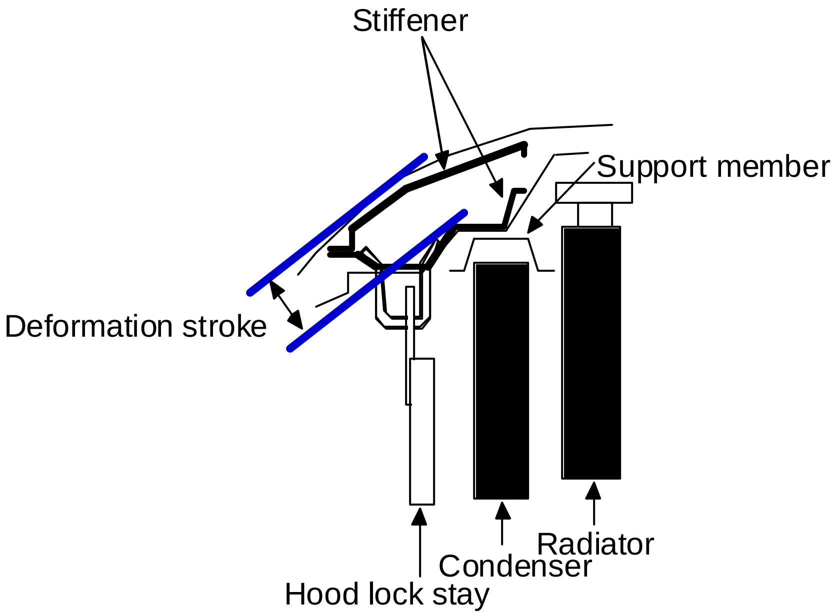


Figure 5 Bonnet leading edge structure.

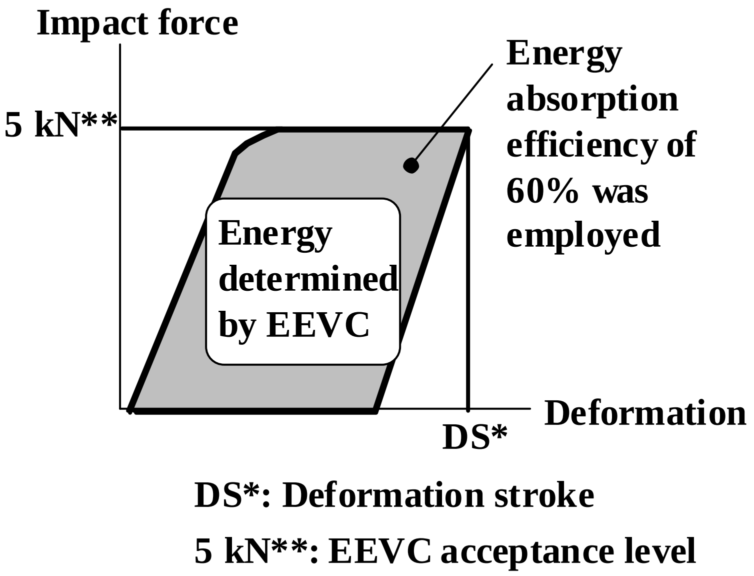


Figure 6 Calculation of bonnet leading edge deformation stroke based on EEVC/WG17 acceptance level (5 kN).

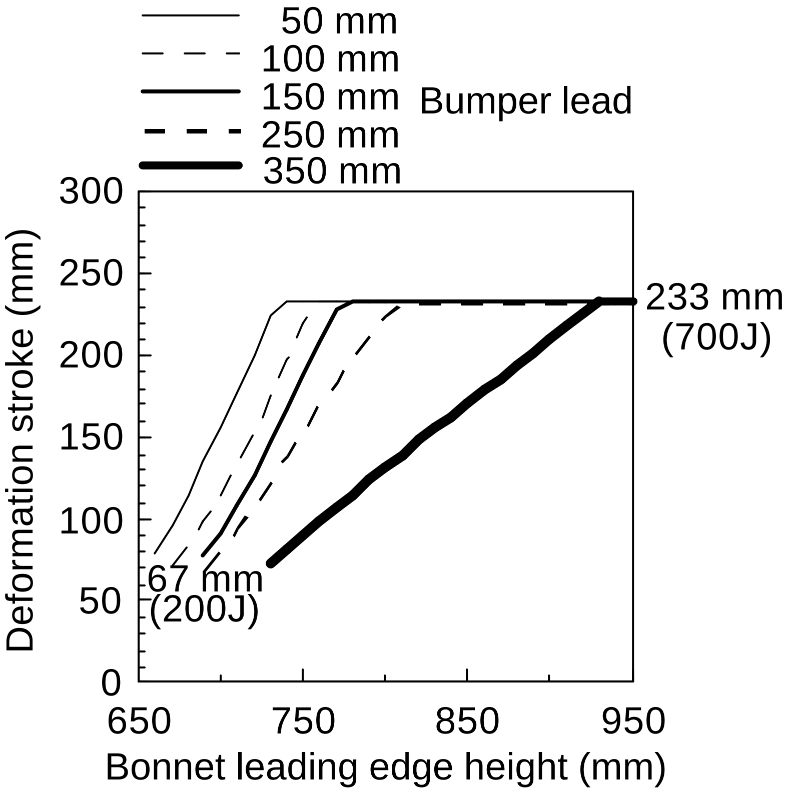


Figure 7 Calculated bonnet leading edge deformation stroke.

We demonstrate an example of a method to modify the vehicle front design keeping a bonnet leading edge height of 700 mm or more, and a bumper lead of 250 mm or less. Figure 8 shows the conceptualization of a way to modify the vehicle front design. To achieve the EEVC/WG17 requirement, the following five-step design procedures were taken into account:

(Bumper lead, bonnet leading edge height, required vehicle deformation stroke, and actual vehicle deformation stroke in each steps were summarized in Table 2. Vehicle front shapes of each design phase were shown in Figure 9.)

Step 1 (D1): In the initial car design, the bonnet leading edge height of 700 mm and the bumper lead of 50 mm required a bonnet leading edge deformation stroke of 156 mm.

Step 2 (D2): If we extend the bumper lead from 50 mm to 250 mm to reduce the impact energy (deformation stroke), the required deformation stroke becomes 81 mm. Since the original deformation stroke is 30 mm, we still have a 51-mm gap (See D2 in Table 2).

Step 3 (D3): To close the 51-mm gap, if we try to increase the bonnet leading edge from 700 mm to 750 mm (increase of deformation of 50 mm), the required deformation stroke becomes 155 mm. Since the actual deformation stroke in the present condition is 80 mm (original deformation stroke of 30 mm + increase of deformation of 50 mm in the present countermeasure), we still have a 75-mm gap between the required deformation stroke (155 mm) and the actual deformation stroke (80 mm) (See D3 in Table 2).

Step 4 (D4): To close the 75-mm gap, if we try to increase the bonnet leading edge from 750 mm to 825 mm (increase of deformation stroke by 75 mm), the required deformation stroke becomes 233 mm. Since the actual deformation stroke in the present condition is 155 mm (previous D3 deformation stroke of 80 mm + increase of deformation of 75 mm in the present countermeasure), we still have a 78-mm gap between the required deformation stroke (233 mm) and the actual deformation stroke (155 mm) (See D4 in Table 2).

Step 5 (D5): To close the 78-mm gap, if we try to increase the bonnet leading edge from 825 mm to 903 mm (increase of deformation of 78 mm), the required deformation stroke becomes 233 mm. Since the actual deformation stroke in the present condition is 233 mm (previous D4 deformation stroke of 155 mm + increase of deformation stroke by 78 mm in the present countermeasure), we can comply with the level of 5.0 kN proposed by EEVC/WG17 (See D5 in Table 2).

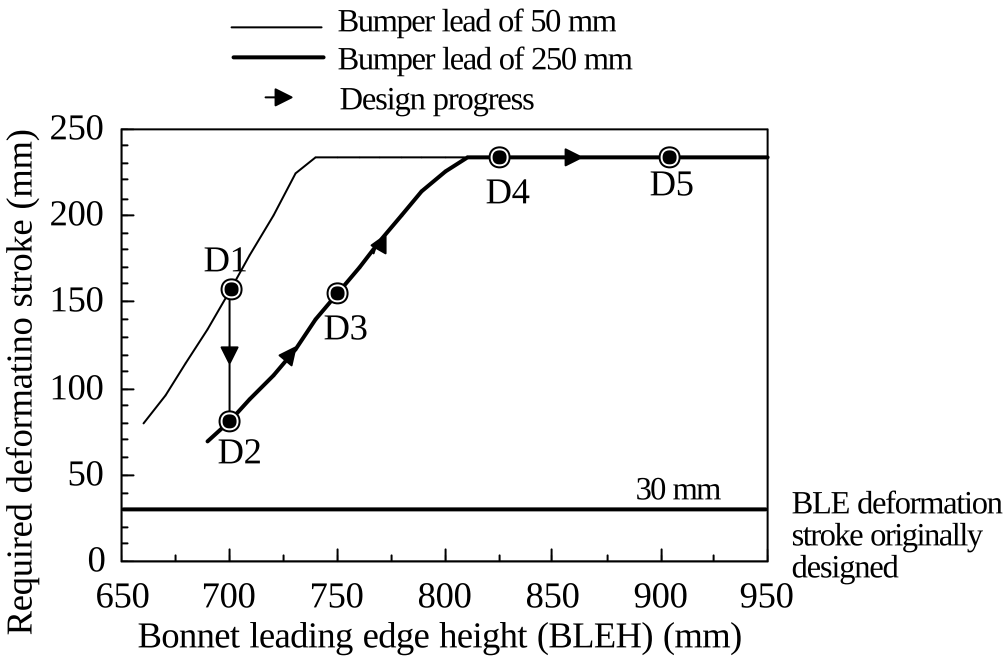


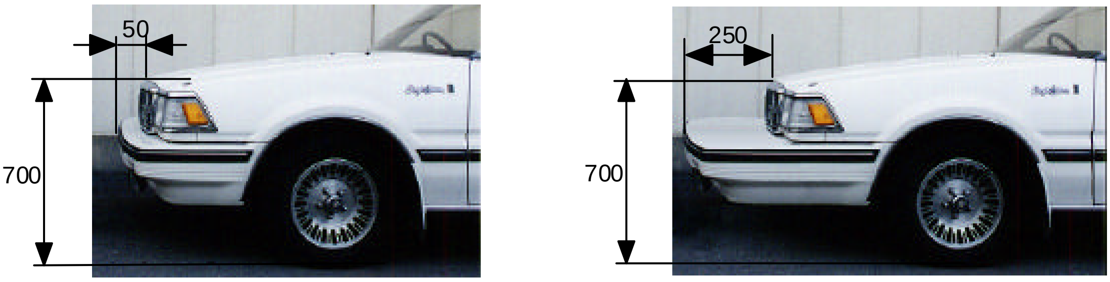
Figure 8 Conceptualization of a design taking into account both reduction of impact energy (bonnet leading edge deformation stroke) and maintaining the deformation stroke by increasing the bonnet leading edge height.

Table 2 Bumper lead, bonnet leading edge height, required vehicle deformation stroke, and actual vehicle deformation stroke

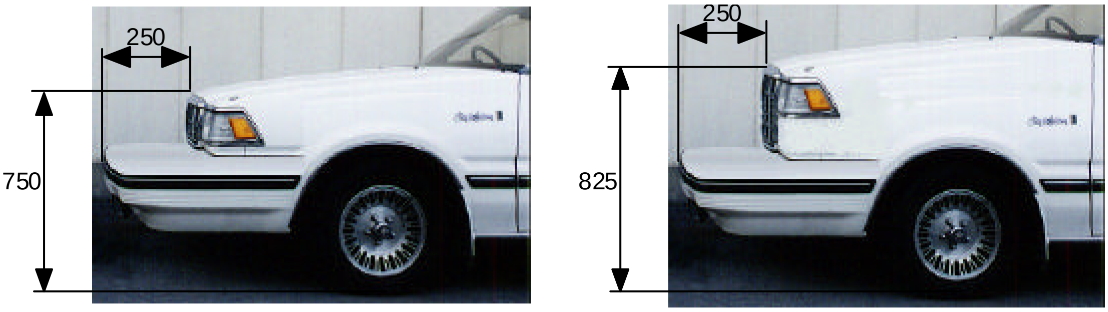
Design	Vehicle front shape (mm)		Deformation stroke (mm)			EEVC Test
	Bumper lead	Bonnet leading edge height	A: Required	B: Actual	Gap between A and B: A-B	
Design 1: D1	50	700	156	30	126	Possible Failure
Design 2: D2	***250****	700	81	30	51	Possible Failure
Design 3: D3	250	***750*(+50)***	155	80	75	Possible Failure
Design 4: D4	250	***825*(+75)***	233	155	78	Possible Failure
Design 5: D5	250	***903*(+78)***	233	233	0	Possible pass

*Modification locations are indicated by bold asterisks.

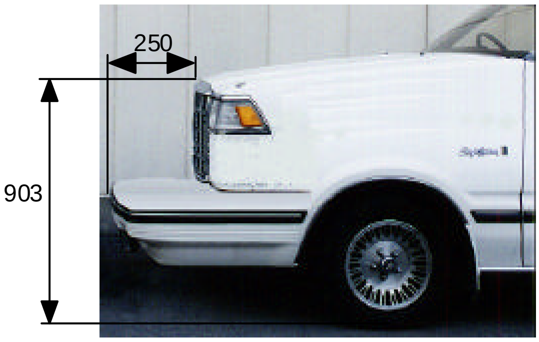
(+) Increase in bonnet leading edge height.



Design 1 (D1) Design 2 (D2)



Design 3 (D3) Design 4 (D4)



Design 5 (D5)

Figure 9 Vehicle front shapes in each design step.

Therefore, if the prerequisite condition is a bonnet leading edge height of 700 mm or more, and a bumper lead of 250 mm or less, we should maintain the stroke of 233 mm. To keep the deformation stroke of 233 mm, we must consider a way to make the bonnet higher. Since this suggests that the roof of the vehicle would have to be higher, we must consider the effect of vehicle height on fuel consumption. We consider the relation between the aerodynamic drag and fuel consumption, where the vehicle height is increased 200 mm. The aerodynamic drag (*D*) was shown using the following formula:

$$D = C_D \times \left(\frac{rU^2A}{2} \right) \qquad (2)$$

where C_d is the drag coefficient, r is the air density, U is the air velocity, and A is the vehicle frontal area. Here we posit a passenger car with a full body width of 1.7 m, and an overall height of 1.5 m. If the car height is increased 200 mm, the vehicle frontal area will be about 13% larger. In this case, the aerodynamic drag (see formula 2) would have to be around 13% larger since the drag is to be in proportion to the vehicle frontal area. But if the aerodynamic drag were 10% larger, fuel consumption would be reportedly 3-5% worse (from city-driving to highway driving mode)1). This would bring about an increase in CO2, and presumably have a negative environmental impact.

From the foregoing results, the passenger car design that would comply with the EEVC/WG17 upper legform to bonnet leading edge test would be as follows.

1. A car with an extremely low bonnet leading edge of 650 mm or less.
2. A car with an extremely long bumper lead (e.g., with a 700-mm bonnet leading edge height, a car with a bumper lead of more than 350 mm would be necessary).
3. A car with a bonnet leading edge having an impact absorption stroke of more than 233 mm would be necessary. However, this type of design would have a negative environmental impact, thus posing a serious problem.

3. Discussion

The Euro-NCAP results indicated that all tested passenger cars failed to meet the EEVC/WG17 injury acceptance levels (5 kN, 300 Nm) (See Figure 1). The results suggest that current passenger cars present a very great danger to the pedestrian hip or thigh. However, recent accident statistics indicate the low proportion of AIS 2+ injuries to the pelvis or femur compared to head or lower leg injuries (See Table 1). Thus, the EEVC/WG17 upper legform to bonnet leading edge test, which all cars failed, is apparently contradictory to the actual situation in a real-world car-pedestrian accident. One may suppose that this test, therefore, poses serious problems in terms of the test conditions, the test tool in relation to biofidelity, and the injury acceptance levels.

The test condition (impact energy) in the EEVC/WG17 upper legform to bonnet leading edge test is decided by the vehicle front configuration. In the study by Matsui et al.,(2) impact tests using a full-scale dummy to simulate human dynamics and EEVC/WG17 upper legform to bonnet leading edge tests were conducted, and the residual deformation to the bonnet leading edge was compared in both tests. The results indicated that the EEVC/WG17 upper legform to bonnet leading edge test caused greater damage (See Figure 10). The impact energy derived from the look-up graph of the EEVC/WG17 upper legform to bonnet leading edge tests is overestimated as compared to the case of a real-world car-pedestrian accident. Hence, the impact energy, one of the EEVC/WG17 legform test conditions, would not reflect the real-world car-pedestrian situation.

1) After contact with upper legform impactor (700J)

2) After contact with full-scale dummy

Figure 10 Residual deformation on bonnet leading edge (Matsui et al.(2))

Next, we focus on the impactor biofidelity in the EEVC/WG17 upper legform to bonnet leading edge test. In this test, a steel (rigid type) front member simulating the femoral bone is equipped on the impactor (Figure 11). On the other hand, it has been reported(3,4), based on simulation analyses, that when the tibia and femur of an actual human lower limb are impacted, they show extensive deformation (Figure 12). Thus, the impactor used in the EEVC/WG17 upper legform to bonnet leading edge test may be presumed to have low biofidelity.

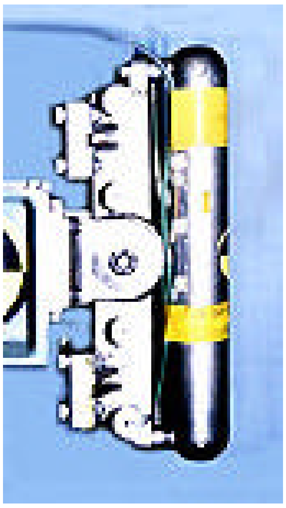


Figure 11 Upper legform impactor
; rigid construction

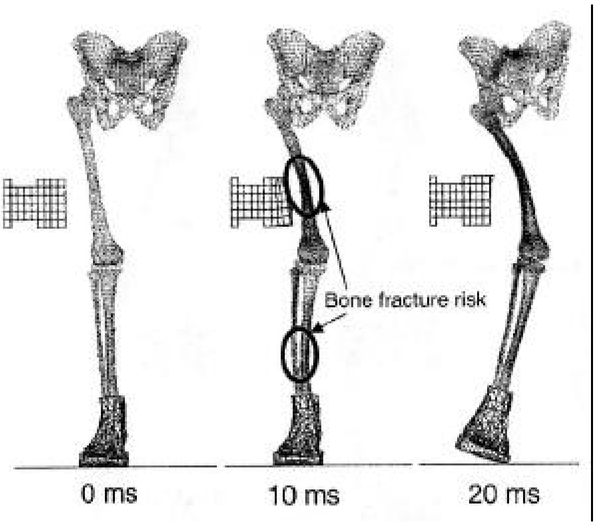


Figure 12 Dynamic sequence of human model (Nagasaka et al.(4)); flexible construction

Next, we discuss the measurement criteria for the present EEVC/WG17 upper legform impactor which is assumed to have biofidelity. In the study by Matsui et al.,(5) an impact test was conducted on the thigh using an completely intact cadaver, and the relationship was calculated between the force of the external impact to the thigh and the risk of femur fracture. An impact force of 8.84 kN was taken to correspond to a femur fracture probability of 0.2. In terms of the EEVC/WG17 upper legform impactor construction, this means that an impact force of 7.40 kN measured at the upper legform impactor would correspond to a femur fracture possibility of 0.2 if the upper legform impactor has human biofidelity (See Appendix for details). Thus, the acceptance level is 7.40 kN, supposing that the upper legform impactor has biofidelity. If the upper legform impactor (one with high biofidelity) has the same stiffness of a human femur, the measured impact force should be lower than the measured value obtained with the EEVC/WG17 upper legform impactor (Table 3). Therefore, the more biofidelity built into the upper legform impactor, the lower the measured value becomes, and more vehicles will thus meet the acceptance level (Figure 13).

Table 3 Comparison on stiffness and measurement criteria between EEVC/WG17 upper legform impactor and human thigh

	Stiffness	Measurement value
EEVC/WG17 upper legform impactor	Rigid	Higher
Human thigh	Soft (flexible)	Lower

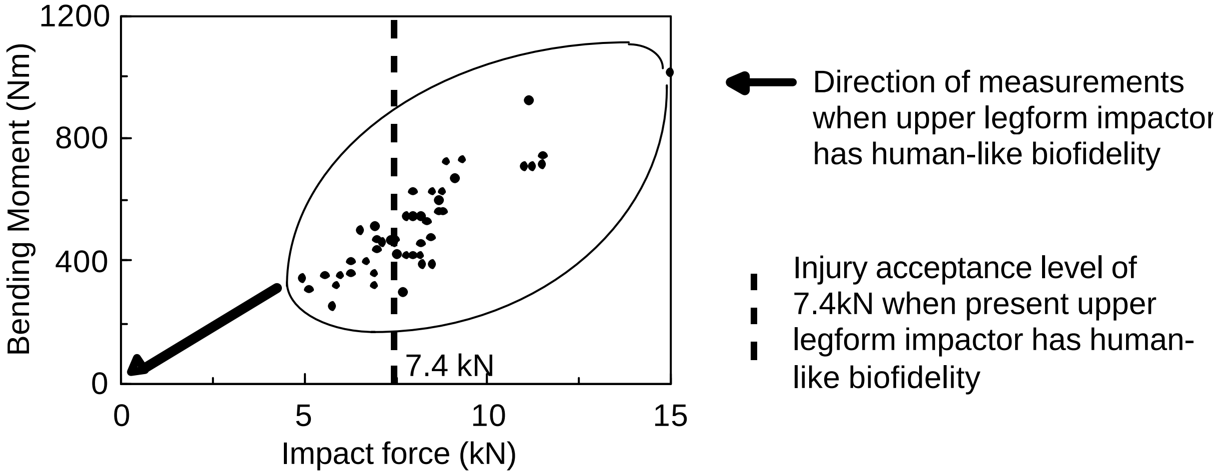


Figure 13 Euro-NCAP Phase 12 results when EEVC/WG17 upper legform impactor is given greater biofidelity

Based on the above findings, Table 4 provides an overall comparison between the EEVC/WG17 upper legform to bonnet leading edge test and the impact conditions of a real-world car-pedestrian accident. Since the existing impact energy condition does not reflect a real-world car-pedestrian accident, certain improvements are called for. The present upper legform impactor lacks biofidelity, and an upper legform impactor of high biofidelity must be developed. Moreover, the acceptance level adopted in regulations should take human tolerance into account.

Table 4 Comparison of EEVC/WG17 upper legform to bonnet leading edge test with impact situation of a real-world car-pedestrian accident

	EEVC/WG17 upper legform to bonnnet leading edge test	Impact situation of a real-world ca pedestrian accident
Impact energy	larger	smaller
Biofidelity	Low biofidelity: rigid steel front member	Biofidelic flexible long bone
Injury acceptance level at 20% ris to AIS2+ thigh injury	5 kN	7.4 kN*

*Measurement criterion when upper legform impactor has biofidelity. 7.4 kN is the value in the light o EEVC/WG17 upper legform impactor construction with 8.8kN (Matsui et al.(5)) as the tolerance level f human femur.

4. Conclusion

(1) Given the fact that, in a passenger car vs pedestrian accident, there is a low rate of sustaining an AIS 2+ injury to the thigh or hip region, no existing passenger car can comply with the EEVC/WG17 upper legform to bonnet leading edge test. Thus, this test, which all cars failed, is apparently contradictory to the actual situation in a real-world car-pedestrian accident. If the passenger car could comply with the EEVC/WG17 upper legform to bonnet leading edge test, only a special car design can be employed: e.g., a car with an extremely low bonnet leading edge, a car with an extremely long bumper lead, or a car with an extremely high bonnet leading edge. However, this special design would come into conflict with the requirements for other vehicle performance characteristics such as aerodynamics or fuel consumption. Therefore, the EEVC/WG17 upper legform to bonnet leading edge test itself is unreasonable and inapplicable to say the least.

(2) The test poses serious problems in terms of the impact energy, the test tool in relation to biofidelity, and the injury acceptance levels. The impact energy derived from the look-up graph of the EEVC/WG17 upper legform to bonnet leading edge tests is overestimated as compared to the case of a real-world car-pedestrian accident. The EEVC/WG17 upper legform impactor has low biofidelity. The more biofidelity built into the upper legform impactor, the lower the measured value becomes, and more vehicles will thus be able to meet the acceptance level. The acceptance level of a 0.2 probability of femur fracture is 7.40 kN in the light of EEVC/WG17 upper legform impactor construction when the impactor has biofidelity. Accordingly, all these three important parameters of the EEVC/WG17 upper legform to bonnet leading edge test (inappropriate energy look-up graph, low biofidelity impactor, inadequate injury acceptance level) do not reflect the current real-world car-pedestrian accident situation.

Reference

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(4) Nagasaka K., Mizuno K., Tanaka E., Yamamoto S., Iwamoto M., Miki K. and Kajzer J., ‘Finite Element Analysis of Knee Injury Risks in Car-to-Pedestrian Impacts’, Traffic Injury Prevention Vol. 4 Issue 4 2003, pp.345-354.

(5) Matsui Y., Schroeder G. and Bosch U., ‘Injury Pattern and Response of Human Thigh under Lateral Loading Simulating Car-pedestrian Impact’, SAE International Congress & Exposition, Society of Automobile Engineers, 2004.

(6) Matsui Y., Ishikawa H. and Sasaki A., ‘Validation of Pedestrian Upper Legform Test — Reconstruction of Pedestrian Accidents’, 16th Enhanced Vehicle Safety Conference, 1998.

Appendix

The measurement criteria were calculated by the following procedure on the assumption that the present EEVC/WG17 upper legform impactor has biofidelity. In the study by Matsui et al.,(5) under virtually the same conditions as in a real-world car-pedestrian accident, thigh impact tests were conducted with completely intact cadavers (Figure A1), and the relationship between the external impact force exerted on the thigh and the femur fracture risk was calculated. In the same study, 8.84 kN is reported to be the impact force corresponding to a 0.2 probability of femur fracture (Figure A2).

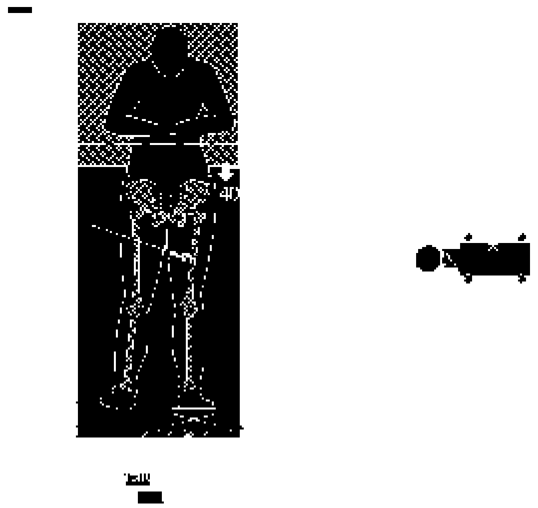

Figure A1 Test setup using PMHSs (Matsui et al.(5))

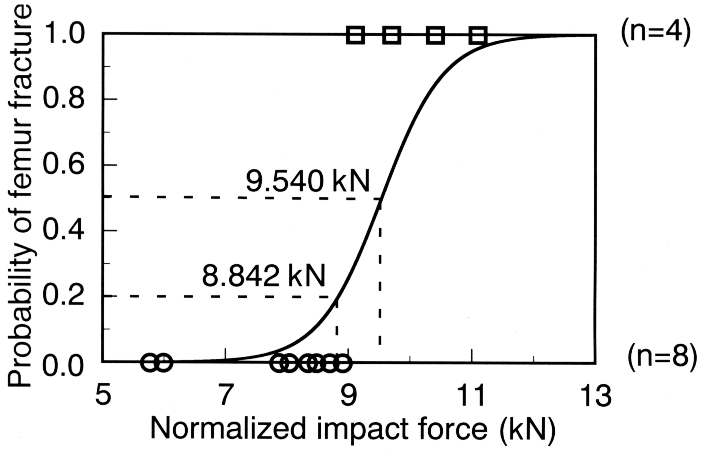

Figure A2 Femur fracture risk curve plotted from external impact force obtained from impact test using complete intact cadavers (Matsui et al.(5))

As shown in Figure A3, the present EEVC/WG17 upper legform impactor consists of 2 built-in loadcells (above and below in the center), one positioned in front at the front part, and one located in the rear at the rear part. The total mass at the front part comes to 2.505 kg, including the front member, confor foams, and half the skin. According to the EEVC/WG17 upper legform to bonnet leading edge test, however, since the energy from the bonnet leading edge changes, the mass of the impactor's rear part changes. For example, in the study by Matsui et al.,(6) an impact test is conducted with an upper legform impactor with an overall mean mass of approximately 15 kg. Here, if we suppose an overall upper legform impactor mass of 15 kg, the mass at the rear part is 0.83 in relation to the overall mass of the upper legform impactor. Matsui et al.(5) obtained the external impact force on the thigh of complete intact cadavers. Therefore, the external impact force shown in Figure A2 is multiplied by 0.83; and if one were to estimate the impact force measured by the EEVC/WG17 upper legform impactor, the upper legform impactor impact force of 7.339 (8.842 kN x 0.83), corresponding to the external impact force of 8.842 kN (result of thigh impact test with complete intact cadavers), would be a 0.2 probability of femur fracture. This is the impact force exerted on the loadcells by the mass of the rear part of the upper legform impactor.

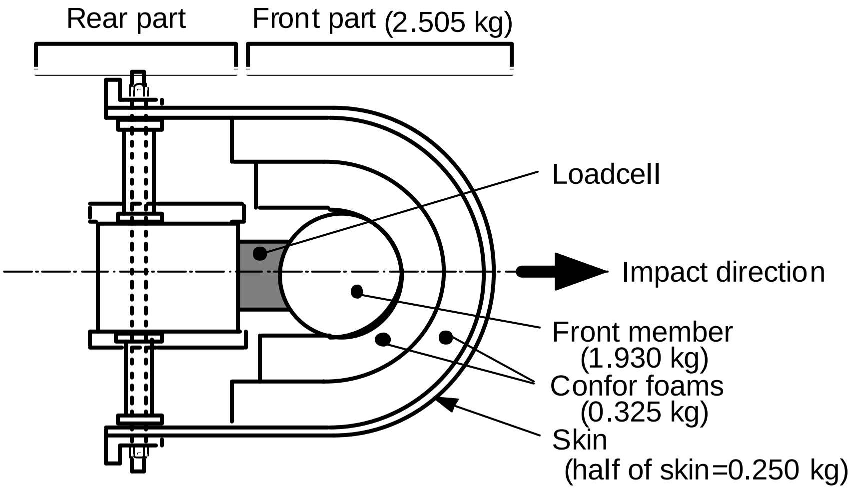

Figure A3 EEVC/WG17 Upper legform impactor (View from top)