AN ANALYTICAL ASSESSMENT OF PEDESTRIAN HEAD IMPACT PROTECTION

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ABSTRACT

In car-to-pedestrian collisions the lower limbs are usually struck first and the pedestrian's head arcs downward to strike the bonnet (hood) surface. Approximately 60% of pedestrian head strikes to vehicle front structures are to the bonnet, often supported by underlying reinforcement and engine bay structures. Pedestrian-friendly engine bay packaging and bonnet design has the potential to reduce the severity of the resulting head injuries. In order to achieve this aim, the important criteria for good pedestrian protection must be identified by understanding the physics of the impact and through impact testing. Much can still be learned from the protection levels offered by current vehicles especially in the bonnet regions where low Head Injury Criteria (HIC) are recorded during a headform impact.

In this paper the results of 70 headform impacts to the bonnets of seven European vehicles are examined. The vehicles represent the current European population and the tests were part of a series commissioned by ACEA (European Automotive Manufacturers Association). The effect of reinforcement and hard contact are described and the general principles of good structural design are given.

INTRODUCTION

In Europe pedestrian fatalities have been decreasing steadily in recent years but there are still approximately 7000 annually. Mackay recently estimated the proportion of pedestrian fatalities relative to all road user fatalities as being in the range 16-36% for motorised countries in Europe and the USA with the UK being at the high end of the range. In the UK 28% of the 3,598 road accident deaths reported by the Department of Transport in 1996 were pedestrians although the actual number of pedestrian fatalities had fallen by 43% with respect to the 1991 total. The reduction in pedestrian fatalities seen in the UK could be due in part to the increased use of traffic-calming measures in urban areas, city-centre pedestrian schemes and advertising campaigns and greater car use for short journeys. However, pedestrians still represent a substantial proportion of all road fatalities and, as such, their protection is being addressed by proposed vehicle safety legislation. The proposed sub-system test procedure was developed in an attempt to model a chaotic event (pedestrian/car impact) in a repeatable and meaningful manner and is still under development. It is therefore worth briefly considering the pedestrian kinematics before concentrating on the head/bonnet impact.

Pedestrian Accident Kinematics

The first point of contact is between the bumper and the lower extremities which are accelerated away breaking the frictional resistance between the pedestrian and the ground. A turning moment about the centre of gravity of the pedestrian is created by this first impact and causes the upper body to arc downwards. The next point of contact may be between the upper leg and the bonnet leading edge depending on the shape of the car, speed of impact and degree of braking. The third point of contact with the vehicle is usually between the bonnet top surface and the head although other parts of the body may also make contact. During this phase the bonnet usually deforms and may allow contact with underlying structures. In high speed impacts the head and upper body may contact the windscreen or header rail instead of the bonnet.

While the above impacts are occurring, the pedestrian is accelerated to the vehicle speed and as the vehicle stops, continues forwards and onto the ground where further injuries may be received.

Head injuries are among the most life threatening form of injury for pedestrians and are predominantly caused by a direct blow to the head or the face. The blows may cause fractures and/or give rise to accelerations causing relative motion of the brain and the skull. A common method of measuring the potential to cause head injury is the Head Injury Criterion (HIC). This was derived from the Wayne State tolerance curve that related the resultant head acceleration to the duration of exposure. Put simply, due to the response time of the brain, it is possible to sustain high levels of acceleration (of the order of 200-300g) for short periods of time (1-

2ms). The greater the length of time that the head is exposed to acceleration, the lower the tolerable magnitude of the acceleration. In this study the peak resultant acceleration is used to give an indication of peak forces experienced by the headform and HIC is also used as an indicator of head injury risk in line with the proposed legislation.

Proposed European Legislation

In October 1998 an EC proposal for regulation concerning the protection of pedestrians from vehicle fronts is expected. It will be based on the draft published earlier by the EC with additional modifications as recommended by the European Experimental Vehicles Committee (EEVC) working groups 17. The test procedure consists of a series of sub-system impactor tests that represent impacts between the pedestrian's leg, thigh/hip and head with the bumper, bonnet leading edge and bonnet top surface respectively. This paper considers only the headform impactor tests that represent child and adult head impacts. Details of the headform designs and test procedure are given in the references. The child and adult headforms are fired at impact angles of 50° and 65° to the horizontal respectively and both are fired at 40kph ($11.11 ms^{-1}$). The nominal masses of the impactors are 2.5kg and 4.8kg for child and adult respectively.

Experience gained to date suggests that cost-effective, vehicle-based pedestrian protection should be designed in at the earliest concept stage to minimise risks to the appearance of the vehicle and costs associated with any modifications applied later in the design and development phase. In order to benchmark current vehicles and to assess the test proposals ACEA (European Automotive Manufacturers Association) commissioned a series of impact tests from which these headform impacts were drawn.

The vehicles selected were the Citroen XM, Fiat Punto, Range Rover, Renault Twingo, Renault Espace, Volvo 940, and VW Golf. A maximum of twelve impact points were chosen on each vehicle. Six of these points were judged to be "good" points in terms of estimated HIC values based on an inspection of the bonnet structure and under-bonnet layout. The other impact points were chosen as prescribed in the draft proposal at "positions judged to be the most likely to cause injury". These were labelled "bad" points. Two of the smaller vehicles did not have an adult impact test zone so only child headform impacts were conducted for these. For a further vehicle, only four adult impact points could be tested instead of six.

The impacts were filmed at 1000 frames per second and the trajectory of the headform was traced as it deformed the bonnet. The data acquisition rate from the instrumented headforms was 10,000 samples per second. It was therefore necessary to reduce the resultant headform acceleration data in order to achieve the same time interval as displacement data from the high speed film analysis. This was done by selecting 1 in every 10 samples and the procedure gave a good estimate of the crush into the engine bay at different times during the impact. However, the peak accelerations obtained using this method may be less accurate than those given in the tables which were obtained using the higher sampling rate. All figures for dynamic displacement given in this report were measured normal to the bonnet surface.

THEORY

Head Injury Tolerance

Hodgeson and Thomas conducted drop tests using adult cadaver heads onto rigid flat plates reported recently by Viano and King. Their results showed that a peak uniaxial force of 4.82kN and a peak acceleration of 201g can be sustained without skull fracture. Skull fractures were found to occur at peak forces of 5.8 kN and peak accelerations of 188g so an overlap existed at least for accelerations. For more localised impacts the force limits for skull fracture is more likely to be in the region of 2kN (for example see Aldman). Bearing in mind that it is possible to receive serious brain injury without skull fracture, particularly for children, a mean load of 4kN can be used to establish an approximate distance in which a head can be safely brought to rest when striking a large surface such as a car bonnet.

$$\text{Adult} \qquad \frac{296\ \text{J}}{4.0\ \text{kN}} = 74\ \text{mm} \qquad (1.)$$

$$\text{Child} \qquad \frac{154\ \text{J}}{4.0\ \text{kN}} = 38.5\ \text{mm} \qquad (2.)$$

The headform impactors used for the proposed impact tests are fired into the bonnet at 65° and 50° to the horizontal for adult and child headforms respectively to account for the different whole body trajectory observed in dummy tests. The impact angles can be used to estimate the vertical components of the displacements in the equations above as 67 mm and 30 mm respectively. These would be the amounts that the bonnets would have to displace. Greater bonnet displacement will give the scope for lowering forces and therefore accelerations. This method of estimating the required displacement does not take into account any dynamic effects which are automatically included in an acceleration-based estimate. Such an estimate can be derived from the HIC calculation shown in below.

$$HIC=\left[\frac{1}{t_2-t_1}\int_{t_1}^{t_2} a\,dt\right]^{2.5}(t_2-t_1) \tag{3.}$$

Setting t_1=0 and HIC=1000, an expression can be written for the ideal acceleration-time curve:

$$a = 9.51t^{-0.4} \tag{4.}$$

This curve was used to find that the theoretical minimum stopping distance for the headforms given an impact speed of 11.11 ms^{-1} was 51.1 mm. Accounting for the impact angles of the two headforms, the vertical displacements would be 46 mm and 39 mm for adult and child respectively (Figure 1).

The HIC calculation is very sensitive to slight changes in impact location and speed so in order to make sure that a design meets the HIC≤1000 specification an in-house specification should perhaps be somewhat lower.

Figure 2 shows a typical acceleration trace for HIC≤1000. An approximate response is also shown.

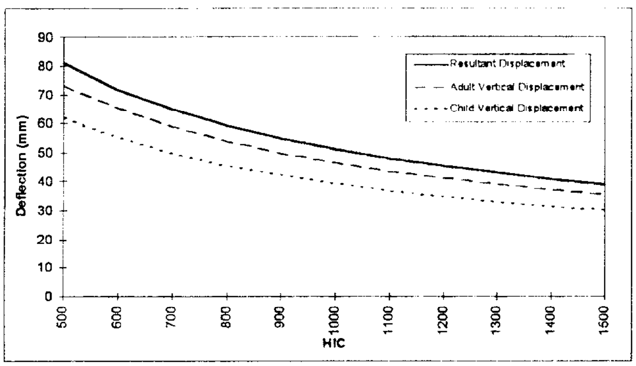

Figure 1. Minimum theoretical displacements for various HIC

Here the calculation is focused around the first peak because the rest of the response is at a relatively low level. The second peak in acceleration is due to the increased resistance caused by secondary contacts remote from the impact site. If this secondary peak is of sufficient magnitude it will be included in the HIC calculation.

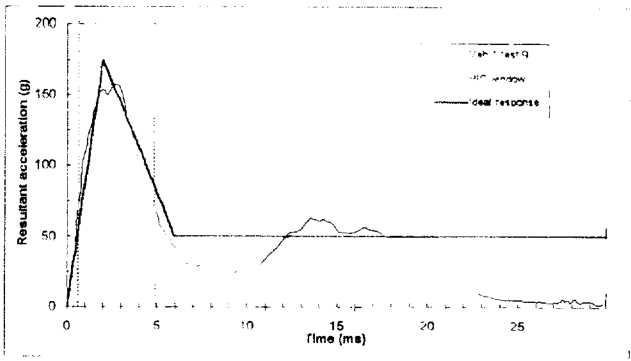

Figure 2. Typical adult acceleration result

This type of response is compared to other hypothetical responses in Figure 3 which can be used to determine a strategy for achieving low HIC values. Over a period of 10ms, various hypothetical acceleration traces have their HIC results compared.

Two strategies are suggested by the graph:-

- Strategy 1. Evolve the steel bonnet controlling the initial peak. In this case the post-peak response must be maintained at or below 60g.
- Strategy 2. Develop a structure to give a square pulse with a maximum of 100g. This may be possible with a low-density material that will not give an inertial spike.

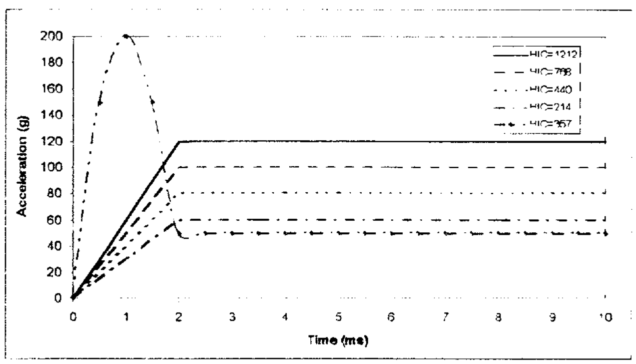

Figure 3. Hypothetical acceleration traces and resulting HIC

TEST RESULTS

An overview of the 70 impact test results is given in Figure 4. Approximately 23% of the targets resulted in HIC < 1000, 22% of the child headform impacts and 35% of the adult headform impacts. In Figure 5 individual results are compared to the theoretical minimum dynamic displacement as described above.

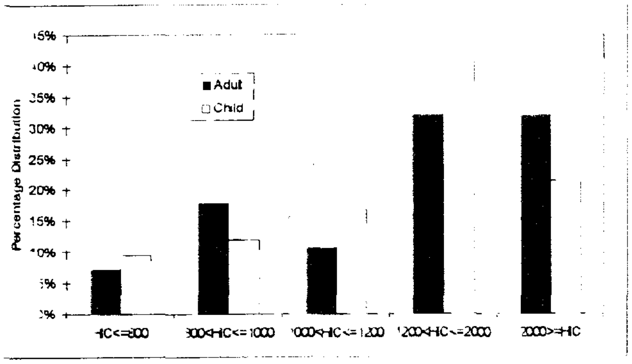

Figure 4. Summary of Test Results

Inspection of the bonnet and engine bay post test and analysis of the high speed films revealed that the main reason for HIC values much greater than 1000 was insufficient displacement of the headform. This applied when the headform contacted rigid structures such as windscreen wiper spindles, scuttle panels at the base of the windscreen and the bonnet surface close to the outboard edges. It is therefore more constructive to investigate the outcomes when sufficient displacement was possible. The remainder of this paper therefore concentrates on the impacts that resulted in HIC ≤ 1000 as these will indicate practices that can be carried over into new designs.

A brief description of the type of structure at the 16 impact sites resulting in HIC ≤ 1000 is given in Table 1. All the points were either in the middle third of the bonnet or close to the border between the mid- and outer thirds. None of the points were close to the fender tops or the front edge of the bonnet and all bonnets except for one vehicle were fabricated in steel with reinforcements under an outer skin . Vehicle 7 had a Fibre Reinforced Plastic (FRP) bonnet.

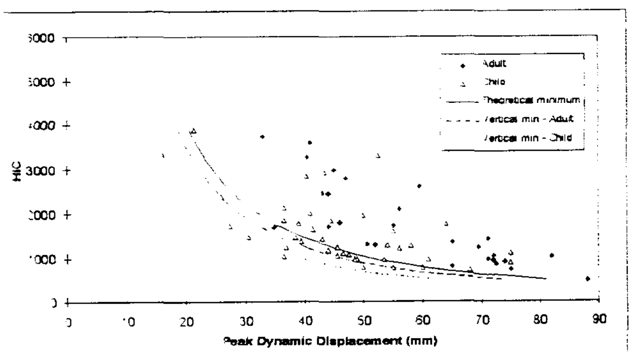

Figure 5. Comparison of Test Results with Theory

Tables 2 and 3 show the HIC, peak acceleration and maximum dynamic displacement for these impact tests. In these tables (G) and (B) represent "good" and "bad" points as previously defined.

In all tests except for test 7:5 above there was evidence of some under-bonnet contact either on the sound-proofing felt or on the bonnet reinforcement structure. The contact was not always directly below the impact point and its severity could be judged by the severity of any secondary peaks in the acceleration response.

The acceleration-time, acceleration-displacement, and speed-displacement curves for five of the above tests are given in the Appendix to demonstrate the main findings. The time window used to calculate the maximum HIC is indicated with vertical dashed lines (for the acceleration-displacement curves the window has been read across to displacement values for the given times). The speed indicated is an approximation from the resultant acceleration using the initial impact speed for the integration. Side by side comparison of the graphs permits the translation of acceleration peaks and troughs into physical events occurring in the vehicle structure.

DISCUSSION OF RESULTS

The peak acceleration recorded by the headform in the 16 tests with HIC≤1000 was in the range 110-201 g. The lowest HIC was recorded by the child headform into a non-metallic bonnet. Apart from that special case however it was generally observed that the child headform tended to experience higher peak accelerations. The initial peak occurs as the bonnet as a whole is accelerated and yields locally to the impact point. Although both headforms are fired at the same speed, the child headform has approximately half the momentum of the adult and so experiences a greater initial impulse arising from momentum transfer when impacting similar points. The amount of permanent deformation caused by the child impactor was also observed to be much less than that caused by the adult. This was especially true for impacts directly over reinforcements. Where the adult impactor would cause plastic deformation in the bonnet skin and reinforcements, the child impactor would tend to bounce off leaving only a small indentation in the skin.

The technique used to measure the dynamic displacement was accurate to within ±5 mm so worst-case figures can be calculated from the tables given. Adult and child headforms should be allowed a minimum of

70mm and 54 mm displacement if current bonnet technology is used.

The following refers to the responses shown in the Appendix:-

Vehicle 1 test 9 Adult: This response is close to the ideal. The HIC calculation was focused around the first peak and subsequent energy absorption took place at moderate accelerations.

Vehicle 2 test 2 Adult: Here the HIC calculation was spread over most of the trace because of the relatively low levels of acceleration. The result was the lowest of the test series in terms of HIC and the traces show no sign of a secondary hard contact. This impact point was on a bonnet reinforcement member.

Vehicle 2 test 7 Child: The good response of this test point derives from the low initial peak and subsequent acceleration history. Of the six child headform impact tests resulting in more than 50 mm dynamic displacement, four of them were on vehicle 2. This would seem to indicate that the child headform was able to cause large deformations in this steel bonnet. However, analysis of the test film revealed that the bonnet hinges permitted 20-30 mm of downward translation of the bonnet from the initial position. This would have occurred at lower forces than those required to cause plastic deformations.

Vehicle 2 test 8 Adult: The relatively low initial peak indicates that the headform was able to overcome the bonnet inertia and cause plastic collapse relatively easily. An under-bonnet contact was made at approximately 60 mm displacement however. This contact was sufficiently hard to cause a secondary peak large enough to be included in the calculation of the maximum HIC. It must be pointed out that, at the point of secondary contact the headform was travelling at approximately half the initial speed. The impact point was directly over a reinforcement which was observed to have been partially crushed after the impact.

Vehicle 7 test 5 Child: Of the 16 impacts reported in detail here, this test alone did not leave any evidence of secondary under-bonnet contacts either at or remote from the impact site. The secondary peak seen clearly in the acceleration-time graph was a result of the headform being accelerated back out of the FRP bonnet which bonnet was nearly perpendicular to the impact direction for this vehicle. Up to approximately 8 ms (55 mm) the response was close to the ideal for strategy 2 described above and would have continued well had the bonnet been designed to release the impact energy at a slower rate.

CONCLUSIONS

Seven European vehicles have been tested using the proposed legislative procedure for headform impact. Although 50% of the impact points chosen were expected to meet the pass criteria, only 23% actually did. For these results the following ranges were observed:-

- For adult headforms the maximum dynamic displacement ranged from 65mm (HIC=813) to 88mm (HIC=477).
- For child headforms the maximum dynamic displacement ranged from 49mm (HIC=955) to 68mm (HIC=728) for steel bonnets.
- For the successful child headform against a FRP bonnet the maximum dynamic displacement was 75mm but the HIC (886) was higher than the minimum for the steel bonnet due to a combination of the bonnet angle and the elasticity of the bonnet.

The theoretical minimum stopping distance normal to the bonnet surface to achieve a HIC of 1000 or less was calculated as 46 mm and 39 mm for adult and child headforms respectively so there is some scope for more efficient use of the under-bonnet package space where that space is available.

The tests confirm that (allowing 5mm for film analysis accuracy) the minimum under-bonnet package space required using current construction is 70 mm.

To minimise peak accelerations for the child headform impacts a combination of bonnet material specification and bonnet installation design may prove the most fruitful way forward. This way the response is not solely determined by the local stiffness of the bonnet structure. The elastic storage of impact energy is only advisable if the subsequent release of that energy is damped to prevent a second interaction between the bonnet and the headform.

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Table 1.
Description of the Structure at Analysed Impact Locations

Veh.:Test	Description of Structure
1:2	Single skin thickness, approx. 40 mm from reinforcement
1:6	Double skin thickness on reinforcement edge
1:7	Large area of single skin thickness, approx. 90 mm from reinforcement
1:9	On a joint of reinforcements
1:10	Small area of single skin thickness, approx. 50 mm from reinforcement
2:2	Directly over reinforcement
2:3	Double skin thickness, on edge of reinforcement near a joint of reinforcements
2:5	In the middle of a large area of single skin thickness
2:6	Double skin thickness, on reinforcement edge
2:7	In middle of a large area of single skin thickness
2:8	Directly over reinforcement
3:7	Approx. 10 mm from edge of reinforcement
5:3	Approx. 30 mm from reinforcement near a joint of reinforcements
5:9	Single skin thickness, approx. 40 mm from reinforcement
5:11	In the middle of a small area of single skin thickness, approx. 50 mm from reinforcement
7:5	FRP bonnet no under-bonnet contact was recorded

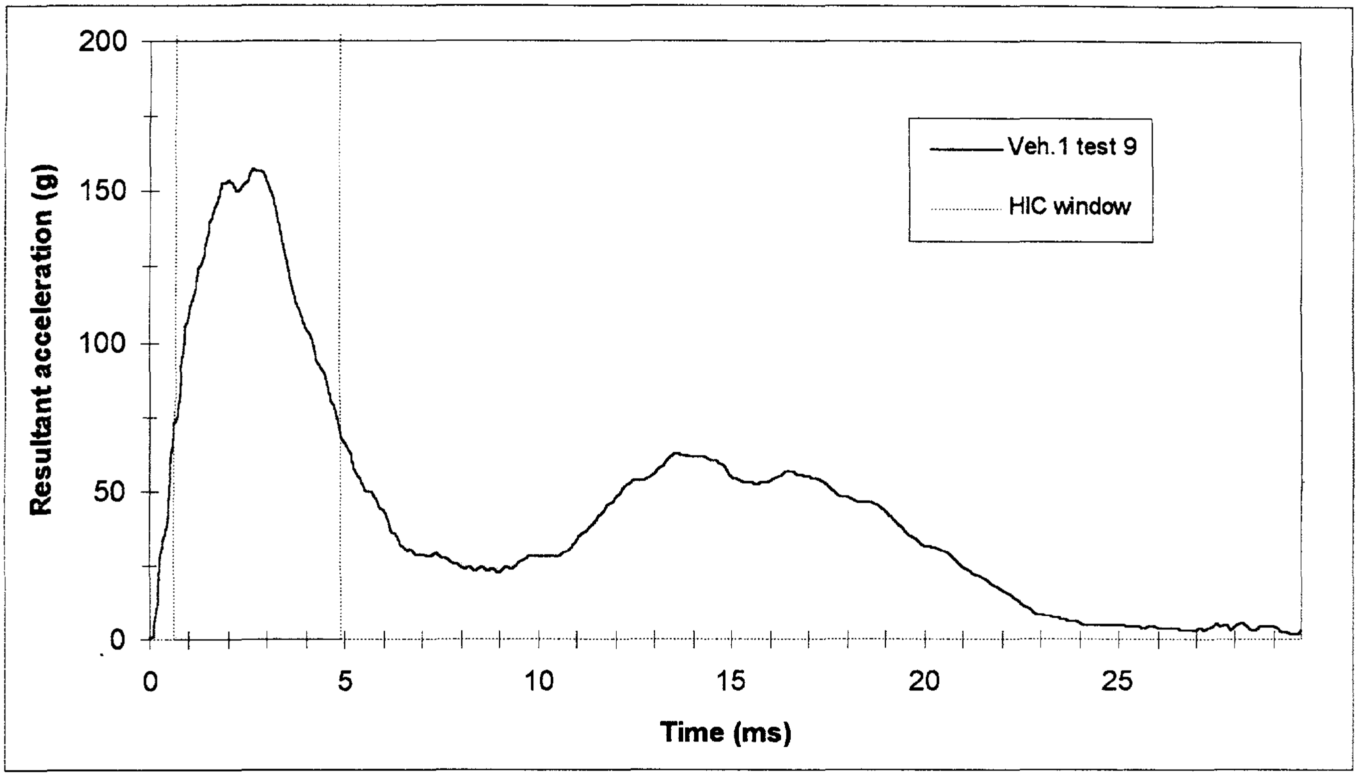
Table 2.
Results for HIC≤1000 – Adult Headform

Veh.: Test	Target	Bonnet Angle (°)	Impact Speed (ms^{-1})	HIC	Peak Acc. (g)	Max. Displ. (mm)
1:2	Between fan cowling and engine (G)	7.2	11.56	888	170	74
1:9	Over air intake transfer pipe (G)	5.9	10.86	734	158	75
1:10	Over area between fuse box and air/fuel intake system (G)	4.8	11.18	813	191	65
2:2	Between engine and brake fluid reservoir (G)	6.5	10.92	477	127	88
2:8	Over injector mechanism (G)	7.4	11.32	844	130	73
3:7	Between rear of engine and vehicle bulkhead (G)	9.8	11.37	929	164	72
5:3	Over rear corner of engine (G)	10.2	11.44	960	146	71

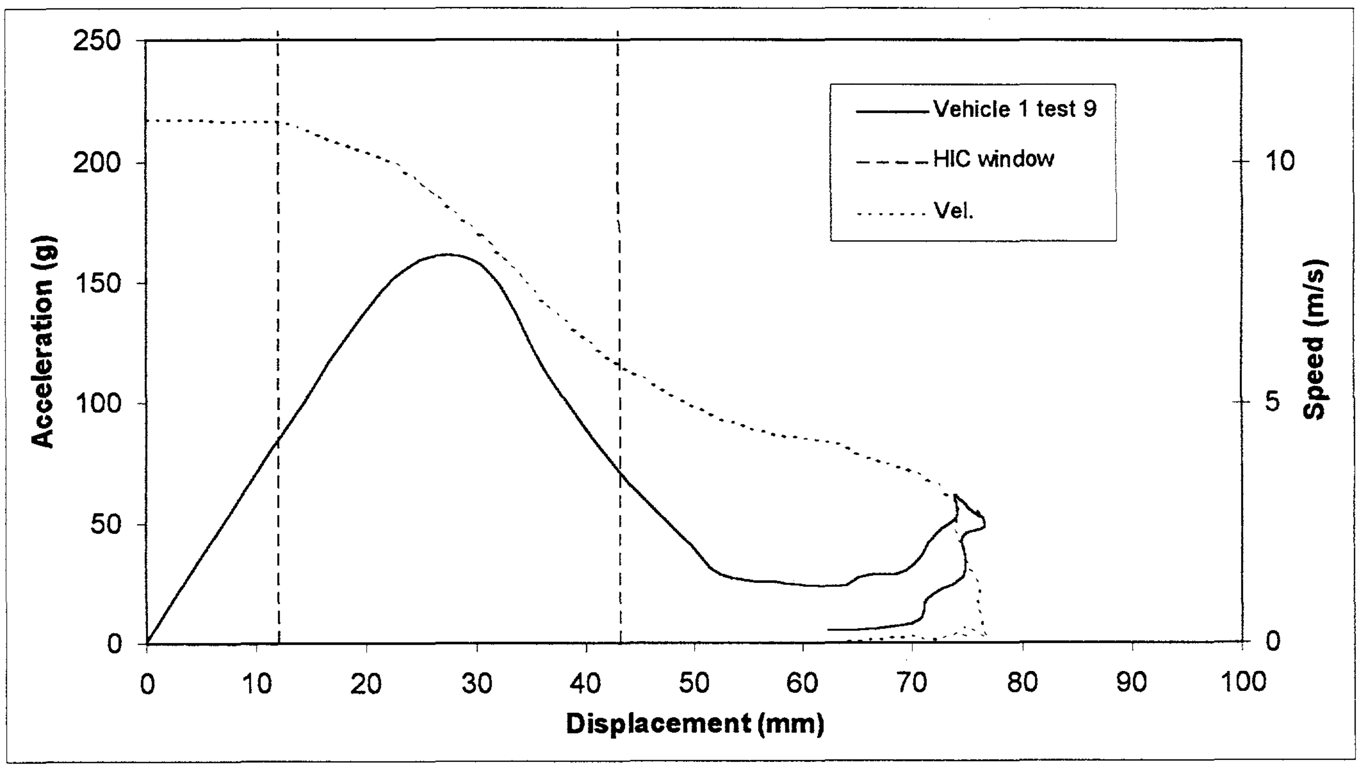
Table 3.
Results for HIC≤1000 – Child Headform

Veh.:Test	Target	Bonnet Angle (°)	Impact Speed (ms^{-1})	HIC	Peak Acc. (g)	Max. Displ. (mm)
1:6	Over transmission fluid reservoir (G)	9.2	11.05	959	191	54
1:7	Over fan cowling (G)	7.8	10.86	793	160	50
2:3	Over oil cap (B)	8.3	10.98	960	201	61
2:5	Between engine and ABS unit (G)	9.8	10.96	773	156	55
2:6	Over cooling hose (G)	11.1	11.00	728	182	68
2:7	Over air hose (G)	9.1	11.10	764	159	60
5:9	Over engine (B)	10.6	11.17	956	183	49
5:11	Over valve cover (G)	14.5	11.34	957	189	49
7:5	Over engine (G)	36.4	11.16	886	110	75

APPENDIX



Veh.1 test 9
HIC window
Resultant acceleration (g)
200
150
100
50
0
0
5
10
15
20
25
Time (ms)



Vehicle 1 test 9
HIC window
Vel.
Acceleration (g)
250
200
150
100
50
0
Speed (m/s)
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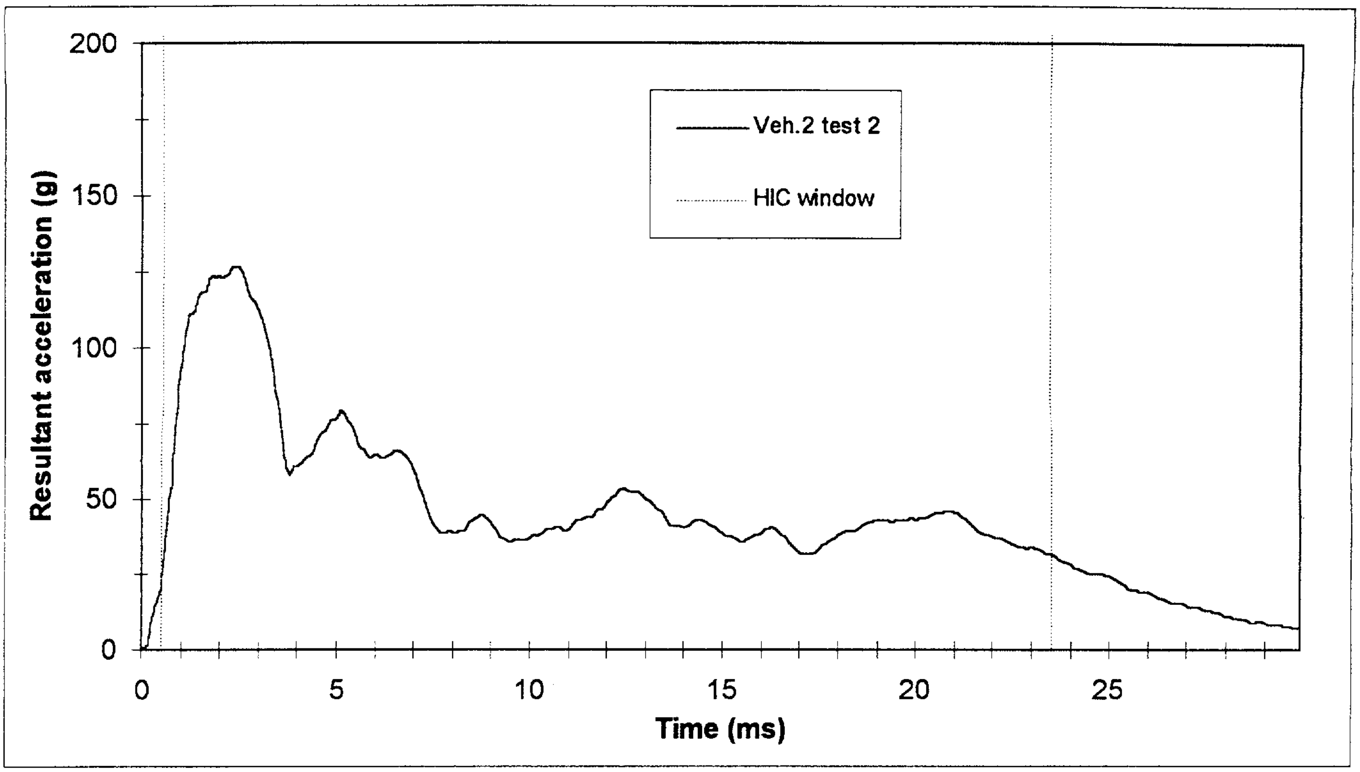
0
10
20
30
40
50
60
70
80
90
100
Displacement (mm)


Veh.2 test 2
HIC window
Resultant acceleration (g)
Time (ms)
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150
100
50
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0
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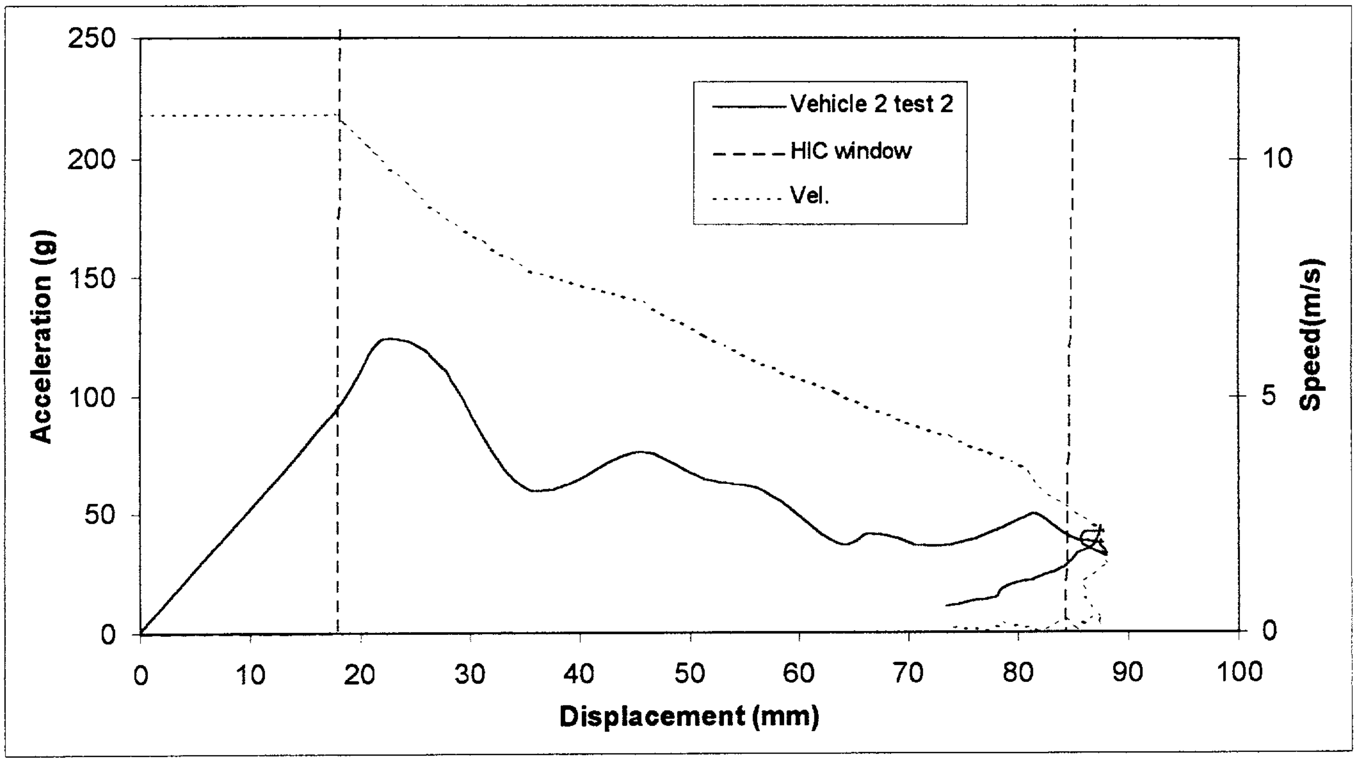
10
15
20
25


Vehicle 2 test 2
HIC window
Vel.
Acceleration (g)
Speed(m/s)
Displacement (mm)
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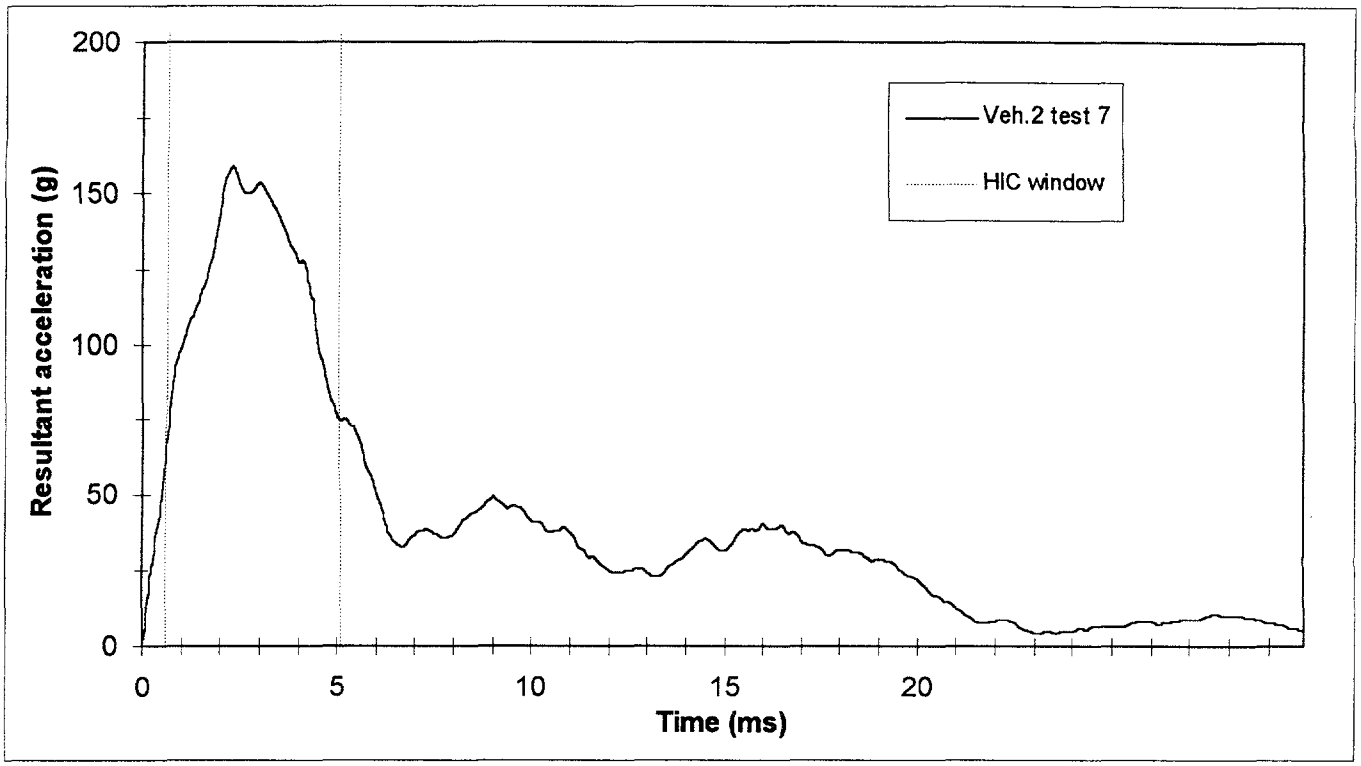
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Resultant acceleration (g)
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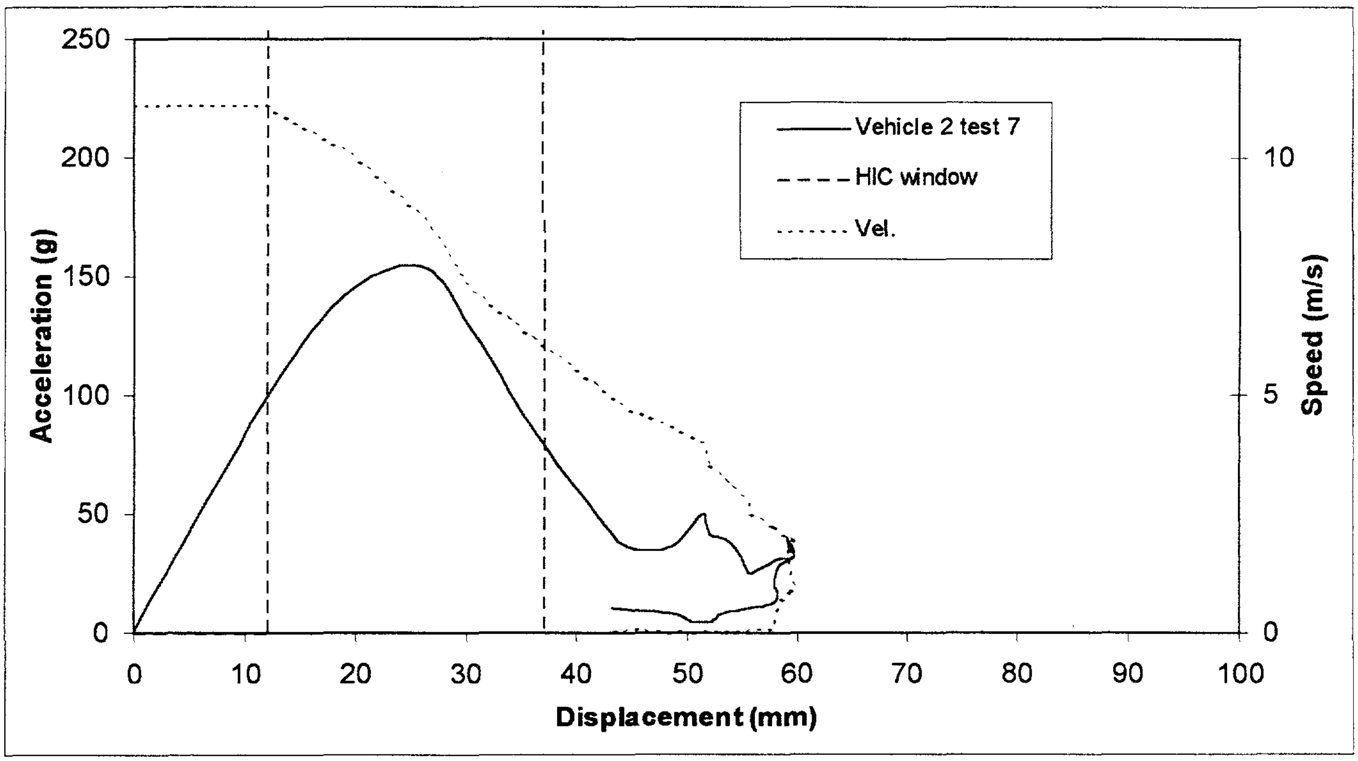
Time (ms)
Veh.2 test 7
HIC window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Acceleration (g)
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Displacement (mm)
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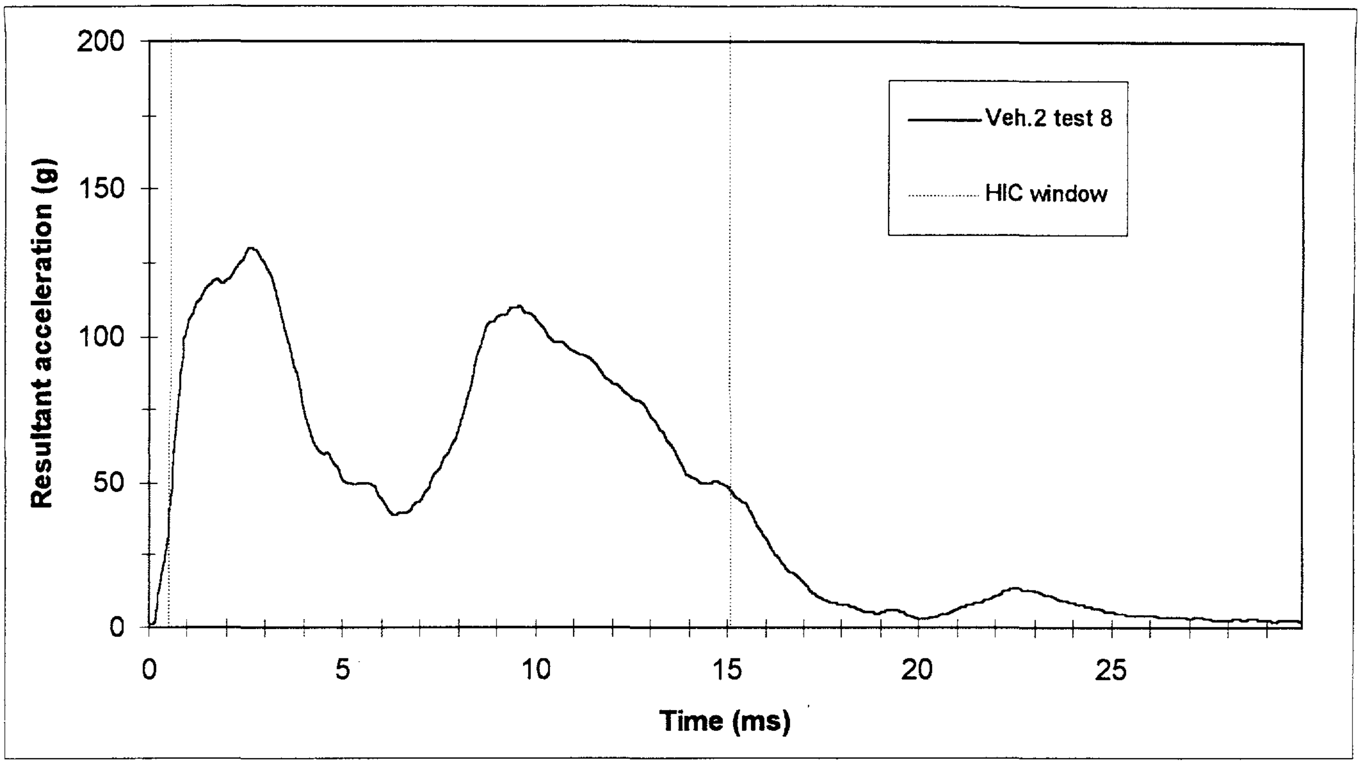
Speed (m/s)
Vehicle 2 test 7
HIC window
Vel.


Veh.2 test 8
HIC window
Resultant acceleration (g)
Time (ms)
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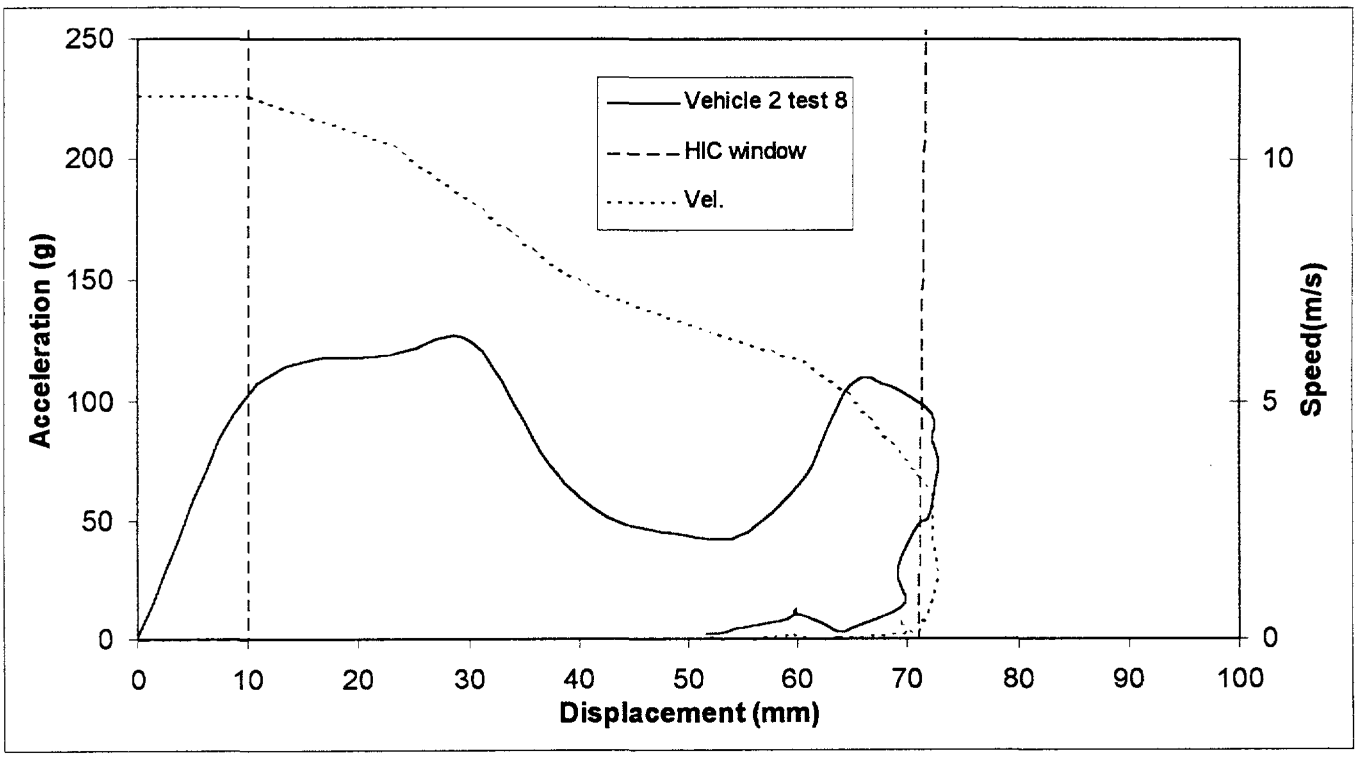
Vehicle 2 test 8
HIC window
Vel.
Acceleration (g)
Speed(m/s)
Displacement (mm)
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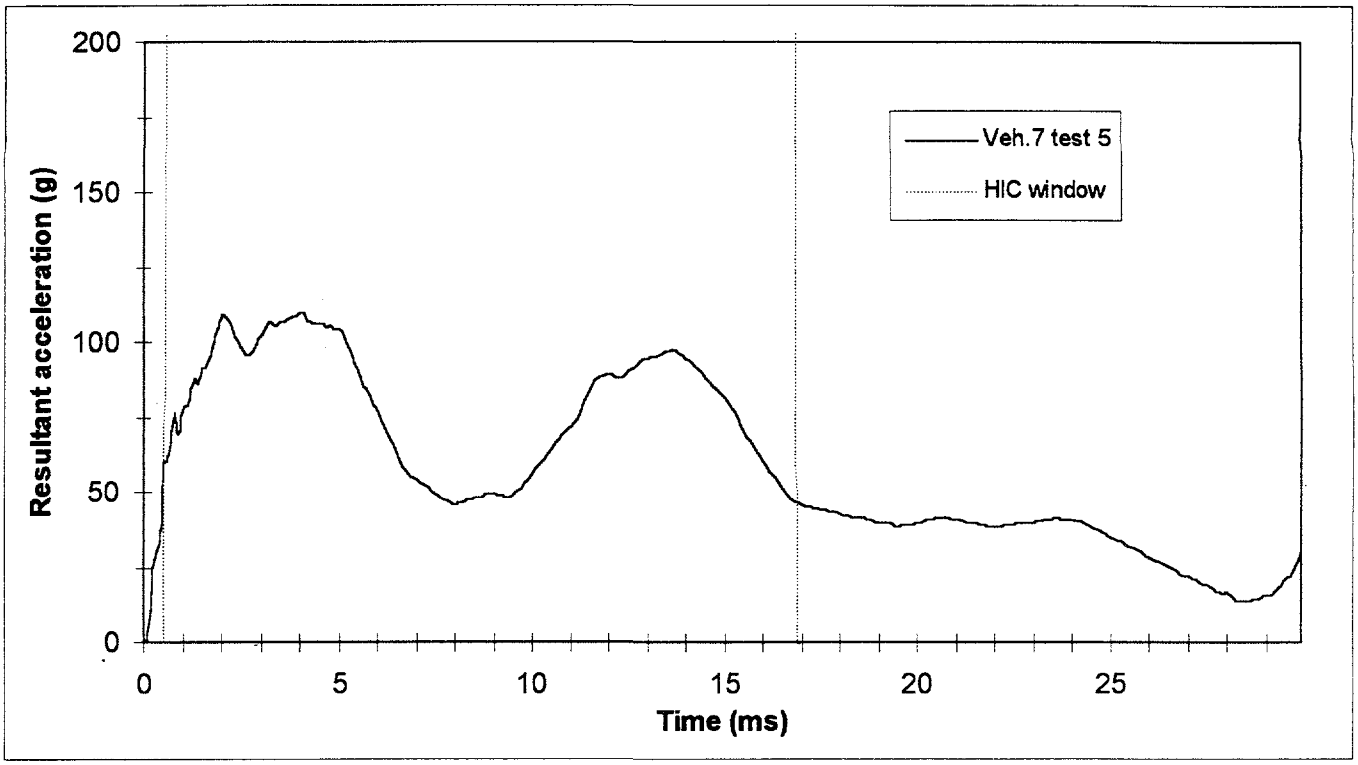

Veh.7 test 5
HIC window
Resultant acceleration (g)
Time (ms)
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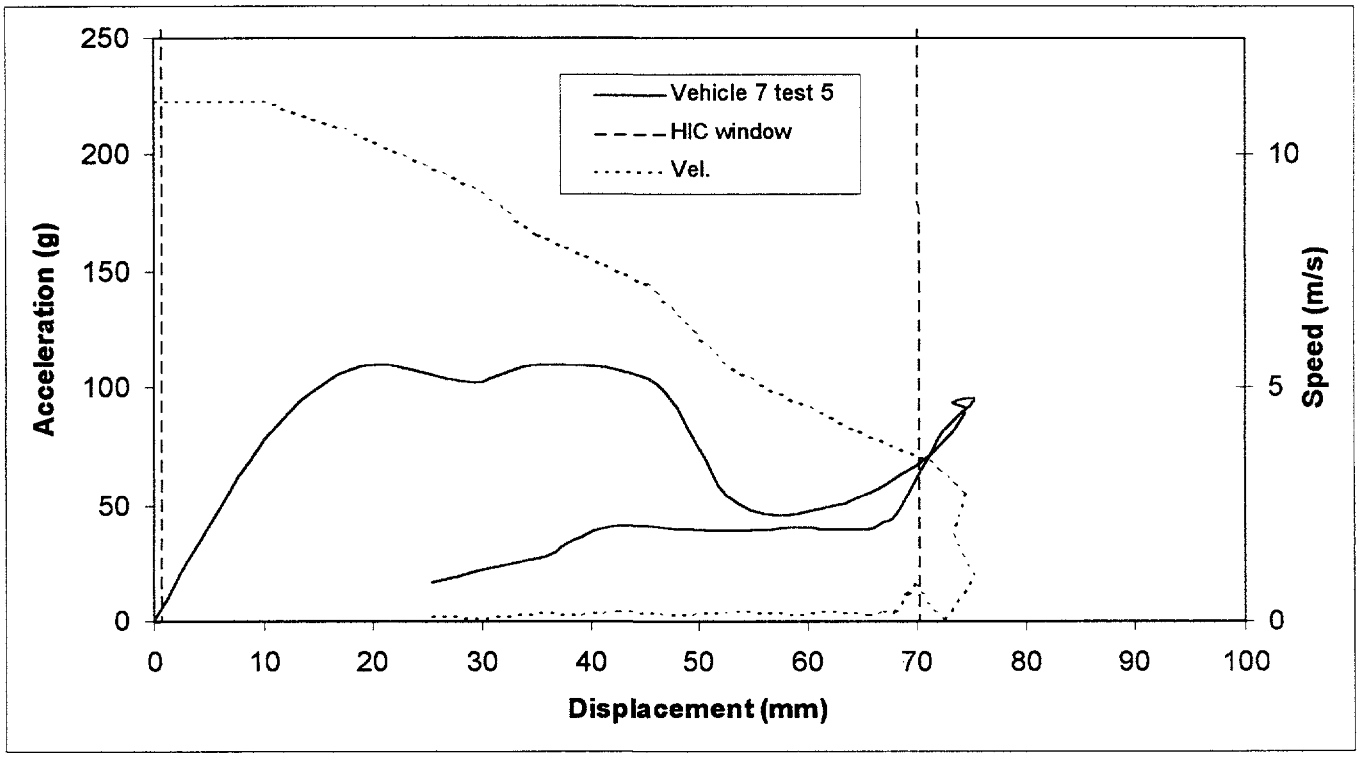

Vehicle 7 test 5
HIC window
Vel.
Acceleration (g)
Speed (m/s)
Displacement (mm)
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