# Pedestrian Protection:
# Use of LS-DYNA to Influence Styling and Engineering

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*Abbreviations:*
HIC - Head Injury Criterion
HPC - Head Performance Criterion
NCAP - European New Car Assessment Program
WG17 - European Working Group 17

*Keywords:*
Pedestrian, LS-DYNA, Styling, Leg form, Head form

## ABSTRACT

This paper describes the use of LS-DYNA for pedestrian protection analysis. A testing procedure has been documented, that may form the basis of proposed future legislation in Europe. Testing is already carried out regularly as part of the European New Car Assessment Program. Large-scale changes in current styling and engineering practices are needed to pass the tests; often, such changes can be accommodated only if identified at concept or pre-concept stage.

This paper includes validation of the impacter device models and illustration of their use in establishing design concept guidelines at a non-product-specific level. The limitations imposed on styling are potentially onerous, and are discussed in the paper.


## INTRODUCTION

*Background*
Safety improvements in vehicle and highway design, and widespread use of restraint systems such as seat belts and airbags, have led to a falling trend in deaths and serious injuries from road accidents. However, in Europe around one quarter of the fatalities are to pedestrians and the number of deaths in this category have not been reducing. It is likely that new legislation will be introduced in Europe to address this, involving impact tests on the fronts of vehicles. Draft procedures have been published (WG17 1998) and the European New Car Assessment Program (Euro-NCAP) already tests cars to a version of these procedures (Williams, 1999, and Hobbs, 1999).

At the time of writing, the pedestrian impact tests have been carried out by Euro-NCAP on 41 vehicles. The best vehicle achieved seven passes out of eighteen impact locations and achieved two stars out of a possible four.

*Objectives*
It seems likely that passing the pedestrian impacter tests will involve compromise in many areas of vehicle design. Possibly, some other aspects of safety may be adversely affected. This paper sets out to demonstrate how LS-DYNA can be used to explore the styling and engineering issues raised by the introduction of pedestrian-friendly vehicle design.

*Outline of testing procedures*
Four test devices are used: leg, upper leg, child headform and adult headform. Full details can be found in the references but in summary:

- The leg impacter simulates the upper leg, lower leg and knee of a pedestrian struck from the side by the vehicle. Three impact locations are tested with the leg vertical. The first point of contact for most cars is with the bumper, just below the knee.

- The upper leg impacter simulates a secondary impact of the upper leg with the bonnet leading edge, after the pedestrian has rotated due to the first impact at bumper height. Three impact points are selected. For this test, the impact energy depends on the geometry of the vehicle: the higher the bonnet leading edge, the higher the impact energy.

- The child headform impact simulates the head of a child impacting the bonnet. Six impact sites are chosen, at wrap-around distances between 1.0 and 1.5m from the ground. The bonnet is divided laterally into three zones, each of which has two impact points. The acceptance criterion is Head Performance Criterion (HPC), calculated in the same way as HIC except that the maximum time interval considered is 15ms.

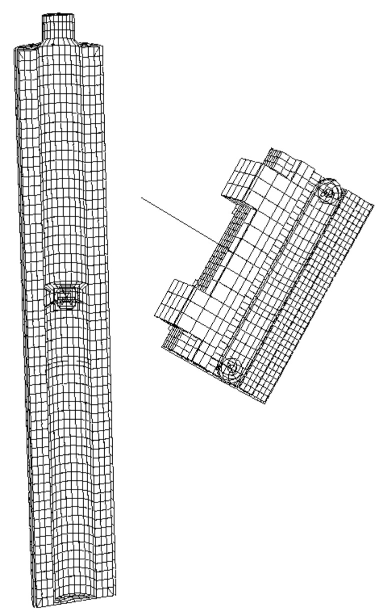
- The adult headform also has six impact points, at wrap-around distances between 1.5 and 2.1m. Again, three zones are used with two impact points per zone.

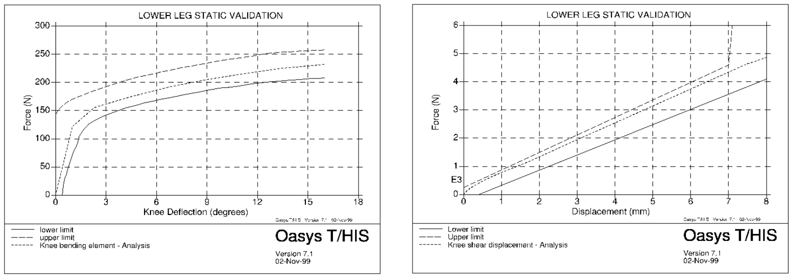
There are some differences in the procedures followed by NCAP and the most recent recommendations of the European Working Group 17, that can be studied by comparing the respective documents. One important difference is that in the WG17 procedure, if the impact energy for the upper leg test (calculated from vehicle geometry) is less than 200J, the upper leg test is not performed.

## APPROACH

*Leg Model*
The test device consists of two 70mm diameter tubes, joined by a deformable knee element. A mechanism inside the upper tube allows up to 8mm of shear displacement at the knee joint, while bending rotation occurs within the knee element itself. A damping mechanism reduces oscillation of the shear response. The whole leg skeleton is enclosed by a 25mm thick Confor foam tube, with a 6mm neoprene skin. The LS-DYNA model contains 7457 elements (Figure 1).

Validation was performed against the calibration tests (WG17, 1998). Figure 2 shows results for the static shear and bending test simulations.





The dynamic calibration test simulation results are set out in the Table 1 below.

Table 1: Leg model dynamic calibration test results

| | Model | Calibration range |
|---|---|---|
| Acceleration | 218g | 195-235g |
| Bending angle | 10.3 deg | 9.7-11.7 deg |
| Shear displacement | 5.9mm | 5.5-6.5mm |

*Upper leg model*

A tubular beam instrumented to measure shear force and bending moment is supported at its ends within a rigid structure. The beam is enclosed within a 50mm thick Confor foam tube and neoprene skin. The model, also shown in Figure 1, consists of 13410 elements and is calibrated against the tests (WG17, 1998). Results are shown in Table 2 below.

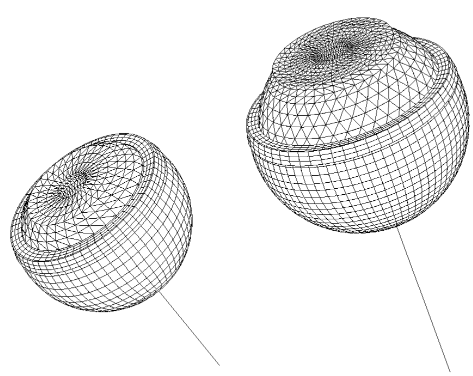
Table 2: Upper leg model dynamic calibration test results

| | Model | Calibration range |
|---|---|---|
| Upper femur force | 1.48kN | 1.20-1.55kN |
| Top bending moment | 170Nm | 160-220Nm |
| Centre bending moment | 212Nm | 190-250Nm |
| Bottom bending moment | 170Nm | 160-220Nm |

*Head models*

The head models are shown in Figure 3. The adult head form consists of a phenolic resin sphere on a steel skeleton with 8mm thick rubber skin. The head model contains 33706 elements: the large number is primarily due to the use of tetrahedron elements (type 10) for the central sphere. Hexahedral elements were used for the skin. It has been validated against the calibration test (Hobbs, 1999). The peak acceleration of the model was 252g, compared with a calibration acceptance range of 225 to 275g. The child headform is of similar construction and contains 16492 elements.

A new construction for the headforms was recommended by WG17 together with new calibration tests. At the time of writing, the new headforms are still being developed and were not modeled in this study.



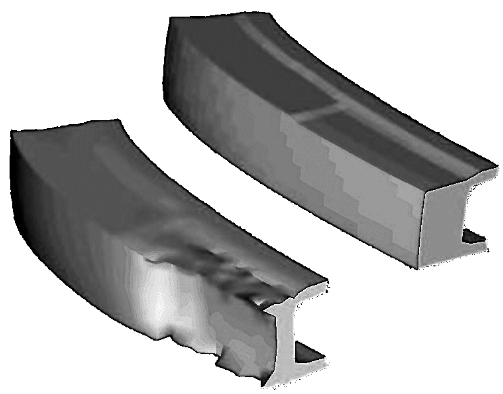
## DISCUSSION OF RESULTS

*Leg Impacts*

To pass the leg impact tests, the first requirement is that the acceleration should be less than 150g. This is governed by the crush strength and depth of the bumper foam. Optimization studies with a 140mm tall bumper showed that a 30g/liter expanded polypropylene foam at least 80mm deep will be sufficient, compared to 40-60mm of foam typical on today's vehicles. For more typical 100mm high bumpers more typical of cars, it is expected that 45g/liter foam of the same depth would offer similar performance in preventing excedance of the acceleration criterion.

Bending rotation and shear displacement at the "knee" must be below 15 degrees and 6.0mm respectively to pass the test. Studies with the LS-DYNA model showed that the leg must be supported above or below the bumper during the impact. A high, vertical front surface achieves this objective but is contrary to the requirements of the upper leg test. A foam-covered beam beneath the main bumper offers a potential solution.

*Effect on low speed impact damage*
The softer, deeper foam recommended for leg protection will adversely affect the vehicle's ability to survive low speed collisions without damage. The European pendulum impact test (ECE R42) was simulated on such a bumper (Figure 4). The pendulum impacter has the same mass as the vehicle and an initial velocity of 1.11m/s (2.5mph). Figure 4 shows the bumper before the test and at the point of maximum deformation. Results showed that, although only the bumper was contacted and hence the legal requirements of no loss of function of any of the vehicle systems are met, the bumper suffers 70mm of crush and may not recover fully. This would be deemed unacceptable by most manufacturers, because after a real life accident of similar severity to the pendulum test, the bumper would need to be replaced. Cost of ownership would rise. Additionally, if the vehicle were not repaired after a low speed accident, pedestrian protection would be lost.



*Upper leg impacts*

Evidence from the NCAP tests indicates that the upper leg test is the most difficult to pass – none of the 41 vehicles tested to date has passed at any upper leg impact location. The LS-DYNA model was used to investigate the challenges of designing to protect the upper leg.

*Effect of vehicle type and impact velocity*. The impact velocity in the test is calculated from the height of the bonnet leading edge (defined by contact with a plane 50 degrees to the vertical) and by the bumper lead (horizontal distance between the bumper front surface and the bonnet leading edge). The full relationship is shown in Figure 3 of Annex 2 of the WG17 report (WG17, 1998) , but in summary, to test at the lowest velocity (20km/h) in Euro NCAP, the bonnet leading edge should be no more than 650 to 675mm from the ground.  In the more recent WG17 proposals, cars with these bonnet leading edge heights would not be tested at all for upper leg impact.

Table 3: Upper leg impact test conditions

| Vehicle type | Typical bonnet leading edge height | Upper leg test impact velocity & energy | Test required by WG17 |
|---|---|---|---|
| Sedan or sports | 600-675mm | 20km/h < 200J | No |
| Sport Utility | 850-1000mm | 40km/h 700J | Yes |

The effect of impact velocity on results was studied using the LS-DYNA upper leg form impacting onto a vehicle model. The vehicle is the same in each case, only the impact energy was changed.

Table 4: Effect of upper leg impact velocity on results

| Impact velocity, Energy | Force kN | Moment Nm | WG17 Pass/fail | NCAP points |
|---|---|---|---|---|
| 20km/h, 175J | 4.5 | 320 | (Fail but no test reqd) | 0.9 |
| 40km/h, 700J | 8.7 | 510 | Fail | 0 |

Results show that even at the lower impact speed used for typical cars, further changes are needed to achieve high NCAP scores. For typical Sport Utility vehicles, 700J of energy must be absorbed with a maximum force of 5kN to satisfy the requirements of WG17, implying crush space of at least 140mm. To achieve this in practice will require substantial changes in engineering design and packaging, possibly leading to increased size and weight of vehicles to accommodate the extra space.

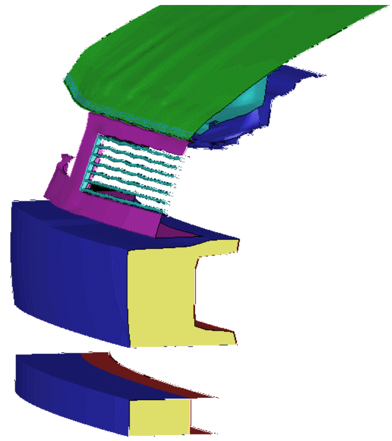
*Effect of curvature of leading edge*. The shape of the bonnet leading edge has a large effect on the bending moment recorded by the upper leg form. Large radii of curvature offer best results: this is compatible with today's softer styling in which the front surface sweeps smoothly onto the bonnet. A study was performed in which rigid circular section surfaces were struck by the upper leg form. In each case, the rigid surface was supported by a single crushable element representing the bonnet leading edge compliance. Impact velocity was 20km/h (175J impact). Results were as follows:

Table 5: Effect of radius of leading edge on upper leg results

| Radius mm | Force kN | Moment Nm | WG17 Pass/Fail | NCAP points |
|---|---|---|---|---|
| 25 | 5.4 | 430 | Fail | 0 |
| 100 | 4.9 | 350 | Fail | 0.6 |
| 500 | 4.4 | 250 | Pass | 1.7 |

Even the most favorable conditions studied above did not achieve maximum NCAP points at the lowest allowable impact velocity. These models showed crush in the supporting element of 30-40mm. It is not possible to score maximum points in NCAP if the vehicle behaves rigidly at the impact location.

*Analysis of pedestrian-friendly vehicle design for leg protection*. The design features offering best protection to the leg and upper leg were combined into one vehicle model, shown in Figure 5. The important features are:



- Bonnet leading edge 650mm above the ground, bumper lead is such that upper leg impact velocity for NCAP is 20km/h and impact energy is 175J. In the procedure proposed by WG17 no test would be required.

- Large radius of bonnet leading edge

- Bumper is 140mm tall, with top surface 500mm above ground, and has 80mm depth of 30g/liter expanded polypropylene foam. Similar protection might be achieved with a 100mm high bumper and 45g/liter foam, but this combination has not been analyzed.

- Bumper has extra foam-covered beam centred at 267mm above ground.

- Crushable plastic radiator grille, extends forward of bumper armature to support the lower leg, leaving it vulnerable to damage in low speed impacts.

Only the center of the vehicle was tested, there was no attempt to model impact on headlamps. Results are shown in Figure 6 and in Table 6.

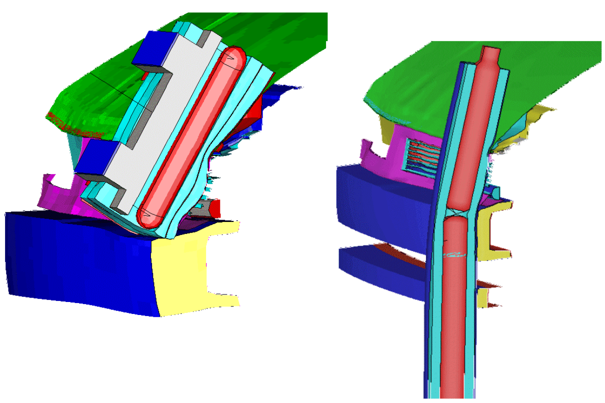


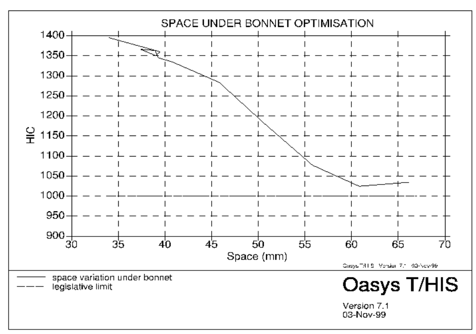
Table 6: Upper leg and leg impact on pedestrian-friendly vehicle model: results

| | Result | NCAP lower limit | NCAP points | WG17 Pass/Fail |
|---|---|---|---|---|
| **Upper leg impact** | | | 2.0 | Pass (but test not reqd) |
| Upper leg force | 3.65kN | 4.0kN | | |
| Upper leg moment | 215Nm | 220Nm | | |
| **Lower leg impact** | | | 2.0 | Pass |
| Lower leg acceleration | 145g | 150g | | |
| Lower leg rotation | 14.3deg | 15deg | | |
| Lower leg shear displ | 4.2mm | 6.0mm | | |

These results show a marginal pass and do not offer an adequate safety margin to accommodate test-to-test variation. The results for this center-line impact position could be improved by further design changes, but the most difficult issues such as headlamps and bonnet latch have not been addressed.

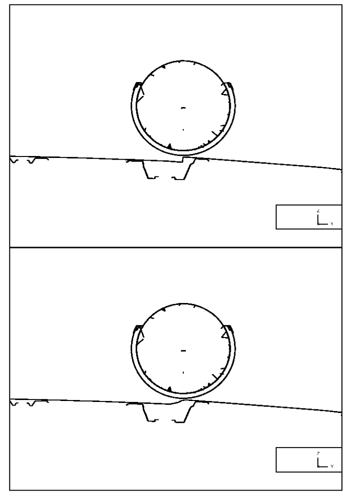
*Head Impacts*
A detailed model of the front of a vehicle was used to examine some of the issues involved in head impacts. The model consists of over 120000 elements, representing bonnet inner and outer, in addition to supporting structure and under-bonnet items. For confidentiality reasons, pictures of the model cannot be shown in this paper.

*Effect of clearance*. It is widely known that, to avoid contact with hard structures under the bonnet, about 75mm clearance is needed. However, providing the clearance may not be sufficient. The LS-DYNA model of the adult head was impacted onto the bonnet directly above a rigidly modelled fluid reservoir. A sequence of models was run, with the clearance between the bonnet inner panel and the reservoir varying from 35mm to 70mm. The models were automatically created and run using Altair Hyperopt. Results are shown in Figure 7. Although the predicted HPC reaches a minimum at 60mm clearance, all results were above 1000.



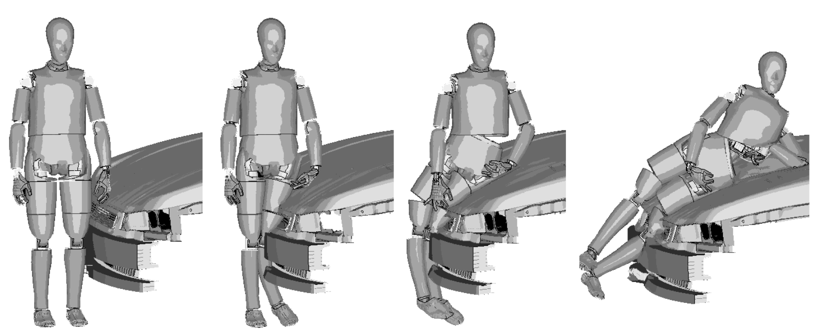

*Effect of styling features*. Styling features on bonnets might be expected to affect head impact performance. This was investigated for a 10mm high feature with two different profiles, as shown in Figure 8. In both cases, the feature was flattened easily by the impacter and the resulting HPC was little different: 748 for the 90 degree step, and 787 for the 30 degree ramp. It was concluded that typical small bonnet styling features have little effect on head impact performance.

*Effect of bonnet stiffness*. Even with no contact to the reservoir in the example above, the HPC was marginally above 1000 and would fail the proposed test. The impact location was near the edge of the bonnet. In the styling feature example the impact location was near the center of the bonnet and passed the test comfortably. In the experience of the authors, this is a common finding for steel bonnets: the edge restraints have very significant effect on HIC and may negate the supposed "pedestrian friendliness" of clamshell bonnets which are very stiff at the edges. Further measures are needed to reduce the local stiffness and strength of the bonnet under head impact conditions. However, such measures are likely to affect adversely the torsional and dynamic stiffness of the bonnet.



An example of the degree of change required was generated, using a single child head impact point on the example bonnet model. Under-bonnet clearance was sufficient to prevent contacts. The relative effects on head impact performance and torsional stiffness caused by reduction in gauge of the inner panel were studied. It was assumed that the gauge of the bonnet outer panel could not be reduced (for example, because of dentability concerns). Torsional stiffness was assessed using MSC NASTRAN. In this one instance, the HPC fell from 1152 to 939 when the gauge of the inner panel was reduced from 0.9mm to 0.7mm. This marginal pass was achieved at cost of 20% torsional stiffness.

*Model with standing Hybrid III Dummy*
LS-DYNA can be used to study real-life pedestrian impact events. Figure 9 shows a standing Hybrid III dummy model impacted by a vehicle front. The dummy model has frangible upper and lower legs, and these can be seen to break in the figure. However, it should be emphasized that the purpose of this simulation is to indicate the possibilities for future work, rather than to predict the nature of the injuries sustained. This type of simulation method might answer concerns about the relevance of impacter testing to reduction of injuries to pedestrians, by simulating the accident kinematics and loads on the different parts of the body, and could investigate how these are affected by different



vehicle designs. Some potential injury mechanisms can be assessed but it should be recognized that the Hybrid III dummy was not designed to show biofidelic response in side-on impacts. In future the model of the dummy, or parts of it such as the legs, could be replaced by a model of a human.

## CONCLUSIONS

LS-DYNA has been used to study the degree of design change needed to pass the pedestrian impacter tests. The studies were confined to locations where there was scope for beneficial change. Even in these locations, significant compromises had to be made and limitations placed on styling possibilities:

· The bumper will appear deeper, taller and more visually prominent than on many of today's vehicles. The required depth of foam is 80mm and the density will typically be 30-45g/liter.

· Cost of ownership will increase due to damage to the bumper in low speed impacts.

· Bonnet leading edge to have as large a radius as possible and to be no more than 650mm above ground (the exact figure depends on the bumper lead dimension). This will be compatible with current styling of many cars, but headlamp treatments may have to change. Sport Utility vehicles are unable to meet these guidelines.

· Clearance to under-bonnet items to be at least 75mm, and more in the regions close to both child and adult head impact zones. Unless the under-bonnet components can be relocated or made smaller, the height of vehicles will increase, with consequent penalties for fuel economy and emissions.

· Even when the clearance is achieved, many bonnets will need to have reduced stiffness to pass the tests; compromises may be needed in durability and tolerance of abuse loading.

The more challenging locations, such as wiper spindles, bonnet hinges and latches, and headlamps, present serious difficulties. It might be surmised that complete compliance with the tests would require some step changes in technology and extensive development. Partial compliance may be a more realistic goal, although even that requires some significant sacrifices.

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