STIFFNESS CORRIDORS OF THE EUROPEAN FLEET FOR PEDESTRIAN SIMULATIONS.

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Paper Number 07-0267

ABSTRACT

Multibody simulations of pedestrian impact scenarios as well as pedestrian accident reconstructions have been used and improved through the years to enhance the pedestrian protection (Lestrelin 1980, Wismans 1982 to Van Hoof 2003, Yao 2005).

In these years, pedestrian multibody models have been developed and validated extensively but there has not been a uniform approach to the pedestrian-vehicle contact interactions. In general, the reference values used for the stiffnesses of the impacted cars were individually obtained for each car through testing (Mizuno 2000) or through FEM simulations (Van Rooij 2003).

This paper aims to define and supply to the research community appropriate and wide test based estimates on the stiffnesses of the European vehicles front parts for pedestrian simulations through the development of a set of stiffness corridors based on the pedestrian subsystem tests from EuroNCAP.

Based on the 425 tests that EuroNCAP has made available for APROSYS SP3 sub-project, this paper defines procedures to derive the vehicle stiffness out of these pedestrian tests. Moreover, these methodologies are applied extensively to these 425 tests to build a set of stiffness corridors for the different vehicle front parts areas.

Finally, some guidelines are included in the paper to use appropriately the obtained corridors to simulate properly the different current European vehicles.

INTRODUCTION AND APPROACH.

As pedestrian subsystem tests have been performed since 1998, EuroNCAP owns a huge database with over 3,000 pedestrian tests. This dataset includes tests on at least 18 pedestrian potential impacting areas in each car, with four different impactors: adult and child headform, legform and upper legform (EuroNCAP 2004).

Considering the raw data channels of these tests, it is feasible to define procedures to process these data and derive information regarding the behaviour of the vehicle structure in those tests, that can be used as contact characteristics into pedestrian simulation models.

In a first phase, the kinematics of the different test configurations has been analysed. These analyses have led to identify a set of assumptions to define a unique methodology to obtain the force-deflection characteristics for the different impactors (headform tests, legform tests and upper legform tests).

Secondly, these methodologies have been applied extensively to the whole set of tests (425), differentiating the adult headform tests impacting on the bonnet from the ones impacting on the windscreen base.

The responses have been grouped for each test configuration (legform tests, upper legform tests, child headform tests, adult headform tests on the bonnet and adult headform tests on the windscreen base) in five vehicle groups (super mini cars SMCs, small family cars SFCs, large family cars LFCs, multi purpose vehicles MPVs and sport utility vehicles SUVs), getting 25 groups.

An analysis on these 25 groups showed the existence of different stiffness trends in the same test configurations not linked to the vehicle groups; therefore, an EuroNCAP rating variable (red, yellow, green) was included to explain these differences. Consequently, each test was rated individually, following EuroNCAP rating protocols, and a re-grouping was performed to the whole set of tests into red, yellow and green groups in each test configuration.

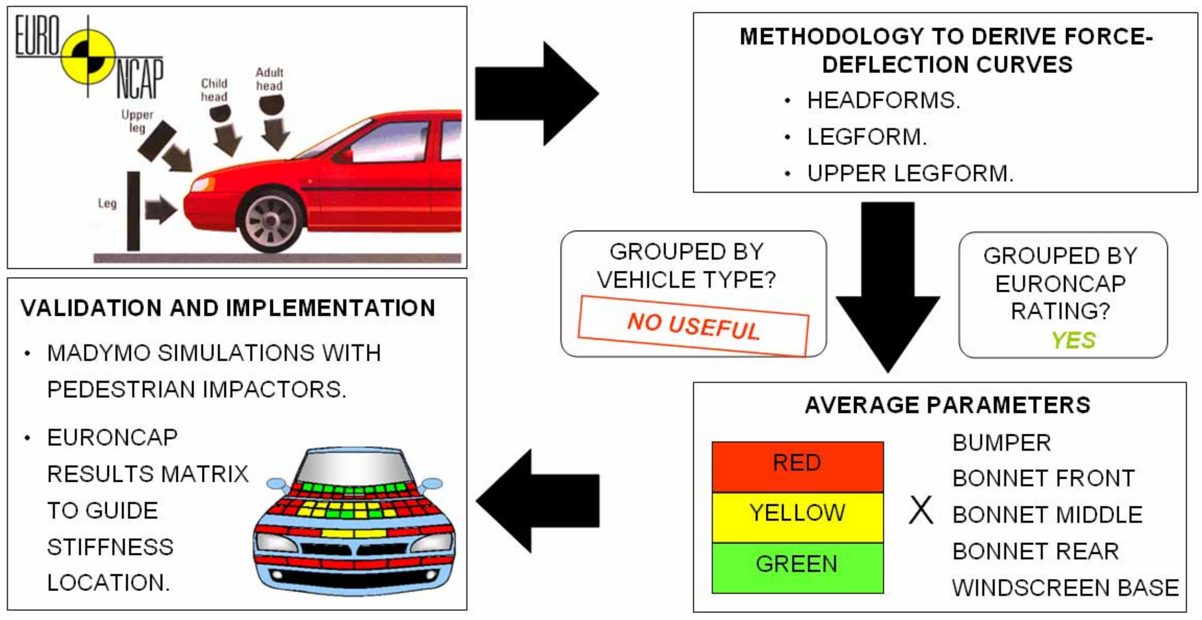

Figure 1: Approach to the development of stiffness corridors for the European fleet.

As a next step, average parameters (average curves, standard deviation and average unloading slopes) have been calculated for each of the 15 groups (red, yellow and green groups in each of the 5 test configurations defined) leading to a set of corridors, which have been simplified into straight lines to ease handling and dissemination.

The validity of these corridors have been checked with MADYMO. It has been analysed that impacts with the different pedestrian impactors, according EuroNCAP configurations, into detailed vehicle models implemented with the average contact characteristics curves obtained for the different groups do result in EuroNCAP ratings according the groups they represent.

Finally, to couple the obtained 15 corridors with the current European fleet, guidelines are given on how to implement them into simulation models based on the matrix used by EuroNCAP for defining the impact points and rating the pedestrian tests.

METHODOLOGIES TO OBTAIN CONTACT CHARACTERISTICS FROM SUB-SYSTEM PEDESTRIAN TESTS.

Objective and limitations.

Considering the kinematics of the different impactors along with the instrumentation used in each of the test configurations, it is intended to define the most suitable methods to obtain force-deflection characteristics for each of the three pedestrian impactors (headform, legform and upper legform) in the most realistic and univocally possible way.

As in most cases no trigger signal has been available for the analysis, a t_0 has needed to be set. This t_0 has been defined as the time when the corresponding acceleration or force in the impactor exceeded a certain limit, as described in Table 1.

In order to quantify the effect of the non-zero value of the acceleration or force in t_0 in the force-deflection curve calculation, an error analysis has been performed for the three different impactors and test configurations.

The average time delay for the different channels to exceed their limits with respect its zero value has been calculated and summarized in Table 1.

Table 1: t_0 definition for the different test configurations and time delay to reach it.

Test configuration	t_0 definition	Average time delay
Headforms	Time where Fore-aft acceleration > 2g	0.3 ms
Legform	Time where Tibia acceleration > 2g	0.4 ms
Upper legform	Time where Sum of forces > 100 N	0.5 ms

Supposing a linear behaviour of the acceleration within this delay, an error in the change of velocity and in terms of deflection caused by this delay can be calculated as shown in the Table 2.

In the case of headform and legform tests, the velocity is fixed to 11.1m/s in the protocol. However, in the case of the upper legform tests, the parameters are dependent on the geometry of the vehicle.

This test configuration is performed at energy levels between 200 J and 700 J with a practical lower limit in the impactor mass behind the load cell (M_{LC}) of 6.95 kg, which limits the maximum speed in this configuration to 12.13 m/s. In this configuration, the worst case is considered to calculate the error.

Table 2: Summary of error parameters calculated.

Test	Delta V error
Headform	0.5·(2g)·(0.0003s) = 0.00294m/s
Legform	0.5·(2g)·(0.0004s) = 0.00392m/s
Upper legform	0.5·(100/M_{LC} min)·(0.0005s) = 0.00359m/s
Test	**Deflection error**
Headform	11.10m/s · 0.0003s = 0.00333m
Legform	11.10m/s · 0.0004s = 0.00444m
Upper legform	12.13m/s · 0.0005s = 0.00605m

These change of velocity errors are rather below the impact velocity tolerance of the test (± 0.2 m/s). Furthermore, these errors are within the range the accuracy for the speed measurement devices and no extra error is added in these calculations.

Regarding deflection, the error obtained in the calculation process is of 3, 4 and 6 mm for the headforms, legform and upper legform respectively, which represent 3-4% with respect to the maximum deflection values found in the different test configurations.

It can be concluded that the velocity error is negligible while the deflection errors due to the t_0 definition is acceptably low for the scope of this methodologies .

Methodology applied for headform tests.

The pedestrian headform tests consist of a set of free flight impacts at 11.1 m/s (± 0.2) of a headform into the bonnet and windscreen area of the vehicle between WAD (Wrap Around Distance) 1000 and 2100 mm. (child and adult areas)

The pedestrian adult headform is a 4.8kg ± 0.1 rigid sphere of 165mm ± 1 diameter fitted with a vinyl skin. It impacts on the vehicle area determined by WADs between 1500 and 2100 mm, with an impact angle of 65º (± 2º) to the ground.

The pedestrian child headform is a smaller rigid sphere, 2.5 kg ± 0.05 kg and 130 mm ± 0.1 diameter also fitted with a vinyl skin. It impacts on a vehicle area determined by WADs between 1000 and 1500 mm, with an impact angle of 50º (± 2º) to the ground.

These two headforms are equipped with a tri-axial accelerometer in the centre of the sphere and the HIC is used as the rating criterion.

Further details on the headforms and the procedure are given in EEVC WG17 1998, EuroNCAP 2001, 2004.

The next table summarizes the test parameters measured in the test and calculated in the post-process to derive the force deflection functions from the headform tests.

Table 3: Tests parameters for headform tests.

Parameters	Value
Headform mass (M_H)	A (4.8 kg); C (2.5 kg)
Impact angle (α_I)	Measured.
Impact speed (V_0)	Measured.
Fore/aft acceleration (A_{FH})	Channel output.
Vertical acceleration (A_{VH})	Channel output.
Lateral acceleration (A_{LH})	Channel output.
Normal angle at the impact point in headform coordinate system (α_H)	*Calculated*
Normal angle at the impact point with respect the impact angle (α_N)	*Calculated.*
Normal angle at the impact point with respect the ground level (α_{NG})	*Calculated.*
Normal Force at the impact (F_N)	*Calculated*
Normal velocity at the impact (V_N)	*Calculated*
Normal deflection (D_N)	*Calculated*

Considering that the characteristic functions for a contact in multibody or facet surfaces need to be defined in terms of normal force vs. normal penetration (TNO, 2003), the normal at the impact point is a key parameter to get the stiffness. Moreover, its importance is higher as the headform angles of impact with the car are not always perpendicular.

The headform protocol requires that the free flight headform direction prior to impact is to be contained in a vertical plane parallel to the midline of the car. However, in the rebound phase of the tests, the headform may be ejected from this plane due to many factors, for example the structure deformation or the surface curvature.

Moreover, as the impact is not performed perpendicular to the car surface, the high friction coefficients between the headform and the bonnet causes tangent forces that may induce rotation in the headform. The less perpendicular the impact is, the more important these effects become.

These two effects are not considered to be significant in the relevant window analysed in the tests (on average, the time to max acceleration is 10-15 ms) and, therefore rotations around both axis are neglected.

In the first moment of impact, the acceleration channels signs and values are such that the resultant acceleration coincides with the normal direction of impact. In this moment, the three angles of the acceleration components with respect to the headform reference coordinate system define the orientation of the normal at the impact point in the headform reference coordinate system.

If rotations are neglected during the relevant time window of the tests, it can be assumed that:

- These three angles will be constant during the relevant test window.
- As the headform c.o.g is contained in a vertical plane parallel to the midline of the car, the lateral acceleration contribution to the normal will be always equal to zero.
- The normal resultant acceleration A_{RN} will be the result of projecting, with their signs, the fore/aft and the vertical components of the acceleration.

Orientation of the normal direction at the impact point.

With the given assumptions, the normal direction at the impact point coincides with the direction of the normal resultant acceleration A_{RN}.

α_H is the angle of this normal resultant acceleration (A_{RN}) with respect the positive direction of A_{VH}, and therefore, of the normal direction at impact with respect to the headform coordinate system. This angle is obtained by calculating the inverse tangent of A_{VH} and A_{FH}, transformed to degrees. and it is defined as the normal angle at the impact point with respect the headform reference coordinate system (α_H).

To compare this angle with the one measured in the real car, a conversion to the laboratory coordinate system needs to be performed. To ease this conversion, α_H is expressed with respect to the impact angle direction by a 90º rotation, resulting in the α_N angle, that added to the impact angle (α_I) results in the normal direction angle at the impact point with respect to the ground level (α_{NG}).

This methodology has been verified geometrically measuring in the lab the normal to the impact point in several adult and child headform test locations and comparing it with the data obtained analytically.

Two cases are shown in Figure 2 and Figure 3 as examples: An adult headform test impacting on the windscreen and a child headform test impacting on the bonnet.

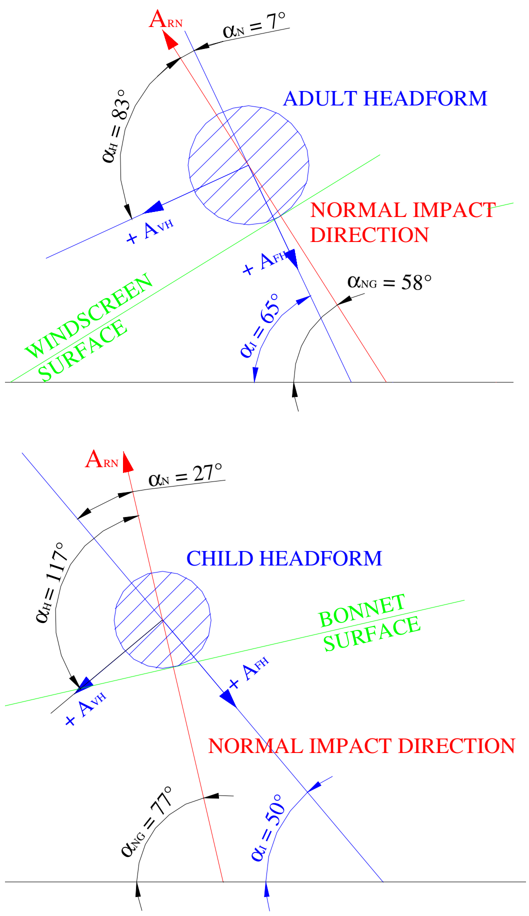

Figure 2: Summary of angles calculated for the example tests.

In the case of the adult headform test, the obtained normal angle at the impact point (α_N) with respect the impact direction, following the above calculations, has resulted to be -7º, which means that the normal angle at the impact point with respect the ground level (α_{NG}), considering an impact angle of 65º, turns out to be 58º.

In the child case, as the impact occurs in the bonnet, the calculated normal angle at the impact point (α_N) with respect the fore-aft directions is 27º, which lead to a α_{NG} of 77º with an impact angle for the child headform of 50º.

On the other hand, the measures obtained in the laboratory for the car the same impact locations has led to normal angle at the impact point of 57º for the adult case and 79º for the child case (Table 4).

These results show that the method proposed to calculate the normal at the impact point (α_N) has an error within the tolerance interval that EuroNCAP permits for the impact angles in these tests protocols, therefore it is considered to be valid for the purpose of this methodology.

Table 4: Summary of angles calculated and measured compared to the tolerances in the EuroNCAP headform protocols.

	α_{NG} calc.	α_{NG} lab	Diff	Impact angle tolerance
Adult case	58º	57º	1º	± 2º
Child case	77º	79º	2º	± 2º

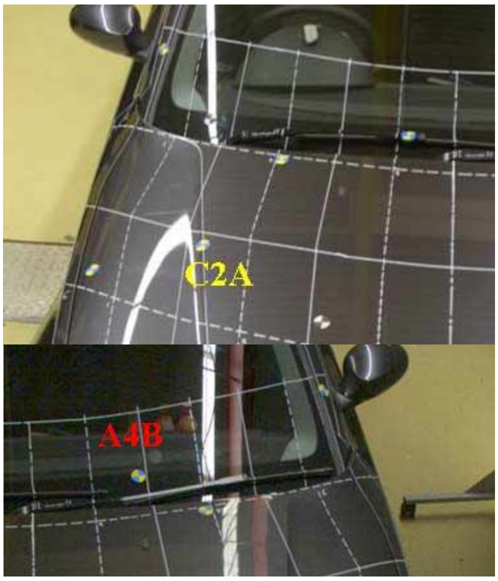

Figure 3: Impact point location of the adult headform and child headform tests example

<u>Headform tests stiffness calculation.</u>

With the assumption given regarding the lack of rotation, the next steps are followed to derive the stiffness.

- The test t_0 is determined when the fore-aft acceleration (A_{FH}) exceeds 2g.
- In the (t_0, $t_0 + 1$ ms) interval, the normal angle at the impact point with respect the fore-aft direction (α_N) is obtained as it has been described earlier.
- The vertical and the fore-aft acceleration signals are projected with respect the normal of impact obtaining the resultant normal acceleration (A_{RN}) as the addition of both projections.
- Multiply the A_{RN} with the impactor mass, M_H to obtain the normal force in the impact F_N.
- Project the impact velocity (V_0) to the normal of impact to get the initial normal velocity (V_{0N}) at t_0.
- Double integrate the A_{RN} to get deflection D_N using the V_{0N} as the initial velocity, making the zero of the displacement at t_0.

Methodology applied in legform tests.

The pedestrian legform tests involve a set of, at least three tests, of a legform impacting horizontally in free flight with the bumper area of the car. The bottom of the legform impactor shall be at Ground Reference Level at the time of first contact with the bumper (tolerance ± 10 mm) and the impact velocity of the legform at this instant shall be 11.1 ± 0.2 m/s.

This test is only performed to cars when the lower bumper reference line is less than 500 mm above the ground reference level.

The legform impactor consists of two foam covered rigid segments, representing femur (upper leg) and tibia (lower leg), joined by a deformable, simulated knee joint. The overall length of the legform impactor shall be 926 ± 5 mm, having a required test mass of 13.4 ± 0.2 kg. A full description of the legform along with the EuroNCAP procedure is given in EEVC WG17 1998 and EuroNCAP 2001, 2004.

This legform is equipped with a uni-axial accelerometer in the non impacted part of the tibia and two potentiometers, one in the tibia and one in femur to account for shear and bending.

The parameters involved in the legform tests and the stiffness derivation are:

Table 5:Tests parameters for legform tests.

Parameters	Value
Legform mass (M)	13.4 kg (6.8 in femur and 4.8 kg in tibia)
Test Speed (V_0)	Measured.
Shear displacement (sh)	Channel output.
Bending angle (Bd)	Channel output.
Tibia acceleration (A_T)	Channel output.
Force in the impact (F_L)	*Calculated*

Velocity (V_L)	*Calculated*
Deflection (D_L)	*Calculated*

Legform tests stiffness calculation.

Considering the channels measured and the real kinematics of the bending, some channels are missing to undertake a fully realistic stiffness derivation.

In order to get some approximate values a simplification is done considering the whole legform as rigid, which is not true, but it may approximate well in cases where knee bending is low. With this assumption, the calculated force is likely to be a overestimate in most cases.

With the assumption of a rigid legform impactor, the following steps have been followed to derive the stiffness.

- Define the t_0 of the test.
- Multiply the tibia acceleration A_T with the impactor mass, M to obtain the force in the impact F_L.
- Double integrate the A_T to get displacement using the V_0 as the initial velocity and making the zero of the displacement in the t_0. This displacement includes the car structure displacement together with the crush of the impactor (likely to be around 20 mm).

Methodology applied for upper legform tests.

The upper legform impactor is rigid, foam covered at the impact side and 350 ± 5 mm long.

Two load transducers are fitted to measure individually the forces applied at each end of the upper legform impactor, plus strain gauges measuring bending moments at the centre of the upper legform impactor and at positions 50 mm either side of the centre line.

The total mass of the front member and other components in front of the load transducer assemblies, together with those parts of the load transducer assemblies in front of the active elements, including the foam and skin, shall be 2.55 ± 0.15 kg.

The total mass of the upper impactor, as well as the impact angle and the impact velocity is dependent on the general shape of the front of the car. Further details on the impactor, the procedure and geometry dependencies are given in EEVC WG17 1998 and EuroNCAP 2001, 2004.

The upper legform tests parameters needed are the followings:

Table 6: Tests parameters for upper legform tests.

Parameters	Value
Upper Legform mass (M_{UL})	Geometry dependent
Impact angle (α_I)	Geometry dependent
Test Speed (V_0)	Geometry dependent
Force Top	Channel output.
Force Bottom	Channel output.
Sum of Forces (F_S)	Channel output.
Femur upper bending moment	Channel output.
Femur centre bending moment	Channel output.
Femur lower bending moment	Channel output.
Upper Legform mass behind the LC (M_{LC})	*M-2.55 kg*
Acceleration of the upper legform (A_{UL})	*Calculated*
Total Force (F_T)	*Calculated*
Velocity (V_{UL})	*Calculated*
Deflection (D_{UL})	*Calculated*

Upper legform tests stiffness calculation.

As the upper legform is a linear guided impact device measuring force, the following steps are needed to obtain the stiffness in these tests.

- Define t_0 of the test.
- Divide the sum of forces (F_S) with the upper legform mass behind the load transducer (M_{LC}) obtaining the acceleration of the whole device (A_{UL}).
- Multiply the calculated acceleration with the upper legform total mass (M_{UL}) to get total Force (F_T).
- Double integrate the A_{UL} to get displacement using the V_0 as the initial velocity and making the zero of the displacement in the very first moment of impact D_{UL}. Again, the displacement obtained through this procedure includes the displacement of the car structure together with the crush in the impactor (typically 40 mm).

PEDESTRIAN TESTS ANALYSIS.

Sample analysis.

EuroNCAP has made available for this analysis a total of 425 pedestrian sub-system tests, for a total of 26 vehicles, including super mini cars (SMC), small family cars (SFC), large family cars (LFC), multipurpose vehicles (MPV) and sport utility vehicles (SUV).

This sample represents hardly 10% of the whole set of vehicles tested by EuroNCAP but it is considered to be large enough for the scope of this work.

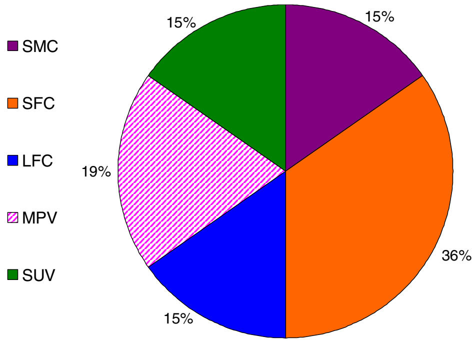

Figure 4: Vehicle type of the sample.

As defined in EuroNCAP pedestrian tests protocol (EuroNCAP 2004), a test is performed in the most dangerous point for a pedestrian to hit in each of the 18 areas in which a matrix divides each car front part. This matrix, defined individually for each car, consists of:

- Three zones for legform impact in the bumper and three zones for the upper legform impact in the bonnet leading edge.
- Twelve zones for the headform impact, six for the child headform at WAD between 1000 and 1500, and six for the adult headform at WAD between 1500 and 2100.

Table 7: Summary of tests considered in the study

Segment	Legform	Upper legform	Child head	Adult head	Total
SMC	14	15	25	15	**69**
SFC	24	32	63	34	**153**
LFC	9	12	22	13	**56**
MPV	14	16	39	11	**80**
SUV	8	9	26	24	**67**
TOTAL	**69**	**84**	**175**	**97**	**425**

The total number of tests analysed in this study is 425. The breakdown according test configurations and vehicle groups is found in Table 7.

Force-deflection curves derivation.

Following the methodologies defined the post-process of the EuroNCAP tests have been performed to get force-deflection curves for all the tests. Different trends were observed in each of the vehicle segment within the same configurations, not dependent on the vehicle groups.

Therefore a new variable needs to be incorporated capable to discriminate these tendencies. The EuroNCAP rating variable has been introduced in the analysis with such purpose.

As EuroNCAP rates each test individually to give a final rating to the car, the rating procedure followed by EuroNCAP (EuroNCAP 2004) has been applied in this point, with some remarks (* and **, see Table 8) to the whole set of tests.

Table 8: Rating procedure followed in the tests.

Test config	Red score	Green score	Yellow score
Headforms	HIC>1350	HIC<1000	Between red and green values
Upper legform*	Max bending >380Nm **Total forces >6.0 kN**	Max bending <300Nm **Total forces <5.0kN**	Between red and green values
**: As the total force is the parameter considered in the process to get to force-deflection, the rating procedure has only been based on results regarding total force criteria.*			
Legform**	Max shear>7mm Max bending>20º **Max tibia accel>200g**	Max shear <6mm Max bending <15º **Max tibia accel. <150g**	Between red and green values
*** As the impactor has been considered rigid in the process to get to force-deflection, the rating procedure has only been based on results regarding the maximum tibia acceleration criteria.*			

The next figure summarizes the distribution of the tests according this rating procedure per each test configuration.

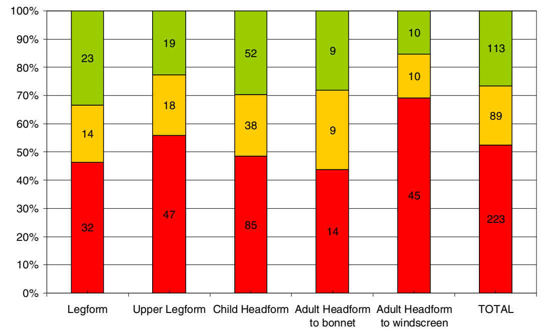

Figure 5: Distribution of test ratings along test configurations.

It can be seen that red curves represent in total over the 50% of all the tests, while green curves are near the 30%. Per test configuration, it seems that adult impacting on the windscreen area is the test configuration where red reaches its top value (almost the 70% of all the cases), while if it impacts in the bonnet area it reaches its minimum value (only the 45% of the cases).

Regarding the green curves, legform seems to be the test configuration where it reaches its maximum (33%) and the adult impacting on the windscreen where it reaches its minimum (15%).

Figure 6 to Figure 10 show the whole dataset once rated according the criteria from Table 8.

Two trends in the legform tests are clearly highlighted and linked to the red or the green curves group. Figure 6 suggests, for all the segments, the existence of a high stiffness trend characterized by steep slopes that reaches high peak forces, (over 40 kN) in short deflections (0.04 to 0.06 m) and a low stiffness trend were the slopes are rather progressive, the peak forces are keep below 20 kN and deflection stands over 0.08 m or more.

It similarly happens in the upper legform tests. Figure 7 shows how the narrow bunch of curves in the start (below 0.03-0.04 m) starts to open up to red curves with peak force over 12 kN at 0.08 m of deflection and green curves with peak forces below 6 kN at 0.12 m of deflection.

Moreover, in these two configurations the yellow group fits in between the red and the green one, which is rather coherent with the process.

With respect to the bonnet middle area, it is seen that most curves reach its peak force near 0.02 m of deflection to start decreasing from then. Green curves slopes are rather soft to reach a maximum deflection over 0.06 m, while a trend for red curves exists where deflection is kept below 0.06 m in all cases and steeper unloading slopes are registered.

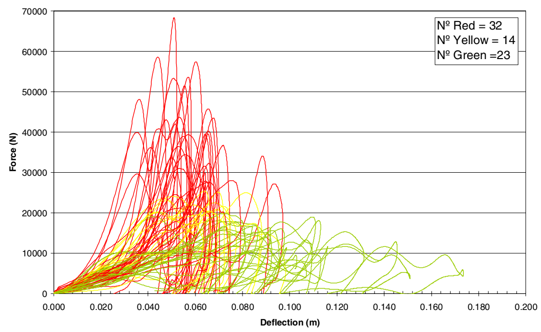

Figure 6: Force-deflection data for the bumper area.

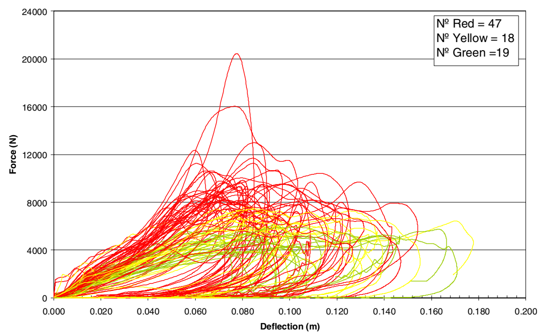

Figure 7: Force-deflection data for the bonnet front area.

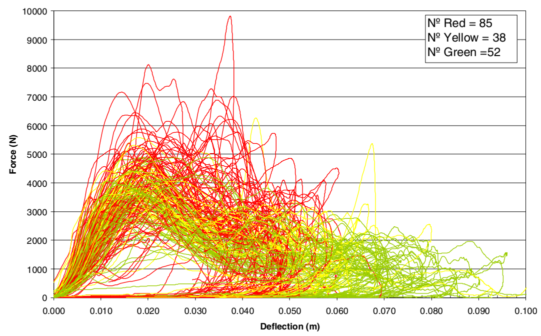

Figure 8: Force-deflection data for the bonnet middle area.

In the bonnet rear area, it can be seen red curves with soft loading slopes in the beginning and sudden steep slopes to get to the maximum and green curves where a plateau close to the maximum level is maintained throughout the deflection range. In terms of unloading slope, great difference appears according the former ways of loading.

In the windscreen base impacts, it is generally observed an initial peak to describe the breaking of the glass during the impact (independent of the colour) and then, a softer slope to get a second maximum peak force, with the slope variation in this second loading, linked to the different ratings.

In general, in headform tests, the yellow curves fit below the red ones but they overlap significantly with the green curves.

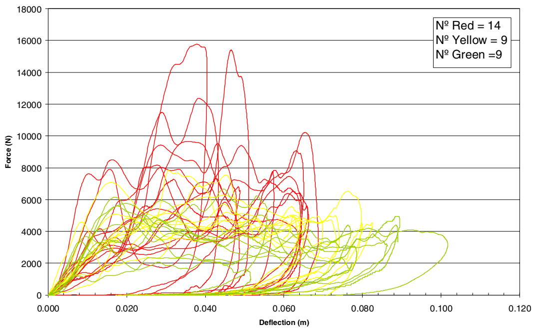

Figure 9: Force-deflection data for the bonnet rear area.

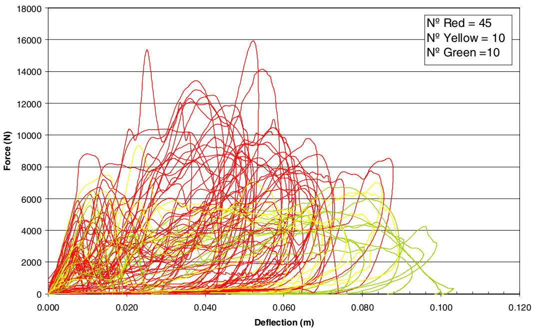

Figure 10: Force-deflection data for the windscreen base area.

PROPOSED STIFFNESS CORRIDORS.

The average parameters have been calculated for each of the 15 groups (red, yellow and red groups in each of the 5 test configurations defined) taken into account that:

- As the force deflection curves come from a cross plot between force-time and deflection-time, they result in curves with different sample rates in deflection in the same group.
- There are force deflection curves in the same group that reaches different maximum deflection levels.

To tackle the former, a re-sampling in deflection has been applied to all curves.

To address the latter, and not to penalty the average curves, only the curves with force level different from 0 in each deflection step are considered in the calculation of the averages instead of using the whole set of curves. Even with this approach, it can be observed in the averages the discontinuities caused by the end of the different curves. If the mean values were used instead, not only were these discontinuities higher but also, at high deflection levels, the mean curves will be considerably under-estimating the actual curves.

Considering the great variation in force and deflection level of the peak value, the average force ±1 standard deviation at each point in deflection is the method preferred (Hynd 2005) to derive the contact characteristics corridors as it describes better the local behaviour of the curves.

However, due to that great variation, an overlapping between rating groups in some of test configuration appear, especially for the cases of the headform impactor.

This variation may induce some problems in the corridor interpretation if corridors are expected to univocally define red, green or yellow areas. However, considering how the corridors have been constructed, they aimed to represent the mean value of the sample with an indication of its variability through the standard deviation.

With these premises the average curves and corridors have been generated and are shown in Figure 12 to Figure 16. As seen in these figures, the calculated average curves, along with the upper and lower boundaries of the corridors, are reduced to a number of points that represents their real shape details in order to ease their handling as simulation inputs and dissemination possibilities. The tabular form of these curves is included in Appendix I.

The similarity of the simplified curves with the real curves has been ensured by restraining the difference in area below each curve to less than 1‰ difference in all cases, as shown in Figure 11.

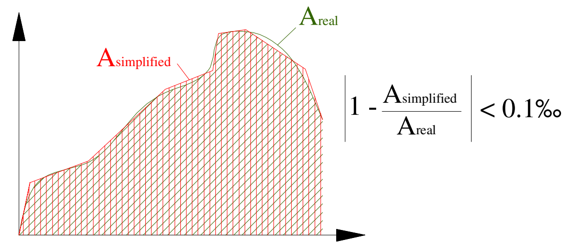

Figure 11: Area coverage between the simplified curve and the real curve.

It is relevant to observe that the rating does reflect three significantly different average trends for the legform and the upper legform tests, while this is not so clear in the case of headform tests, where trend differences are not so highlighted.

In Figure 12, legform red average curve reaches peak values over 25kN at deformations of 0.06m, while green average curve gets to peak values near 10kN at deformation of 0.08m and a plateau until deformations of 0.15m. In this case, the average yellow curve lies in between, with peak values below 20 kN and maximum deformations in 0.09m.

It can be seen in this figure that the corridor for the red group is broader than the green and yellow ones, especially in the areas of maximum forces, and considerably shorter in deflection. The higher deflection needed in green curves (over 0.1m, which may mean 0.08m in the vehicle) can give a hint on the deformation space needed in the bumper to achieve a “green score.

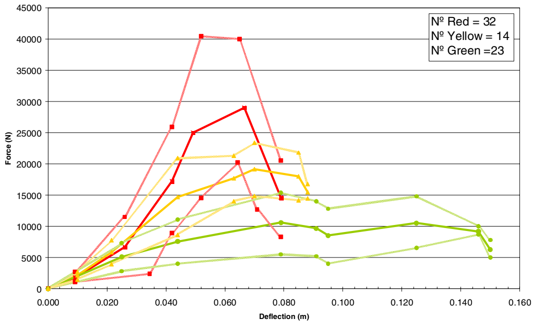

Figure 12: Simplified average force deflection curves and ±1 standard deviation corridors for the bumper.

Regarding the upper legform, red average curves reach a peak value of 8.5kN at 0.08m of deformation, while green stands below 5.0kN with the same deformation levels. Again, the yellow average curves lie in between, with peak values of 6.0kN, although the first slope (deformation <0.06m) is the same as the green curve.

In the case of corridors, the red corridor width is again higher than for the yellow and green corridors, but the deflection ranges are rather similar. In any case, the overlap between the three corridors is clear, especially for the yellow and the green one, as it can be seen in the Figure 13.

It is interesting in this case that green curves maintains the force value close to 5 kN over 0.06m of deflection (which may mean 0.02-0.03 m deflection in the vehicle). This force value at these deflection ranges can be a valuable target for "green scores" in the bonnet front.

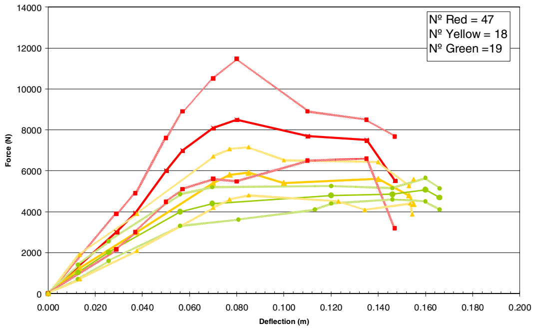

Figure 13: Simplified average force deflection curves and ±1 standard deviation corridors for the bonnet front.

Regarding the child headform tests, the average red curve reach a peak of 4.0kN at 0.022m of deflection while the green one gets to 3.4kN at lower deflection (0.02m). Moreover, it can be seen in the Figure 14 that the average red curve maximum deflection is 0.06m, while for the green one, it goes up to 0.10m. The yellow curve stands in between red and green (peak value of 3.6kN and maximum deflection of 0.08m).

It is remarkable in this case that the initial slope (deformation <0.015m) is the same for the three average curves, however, when they reach the maximum, they decrease significantly when similar curves to the ones for the adult case may be expected. It seems that the high non-perpendicular impact angle of child tests causes this sudden decrease due to the slip of the impactor on the bonnet.

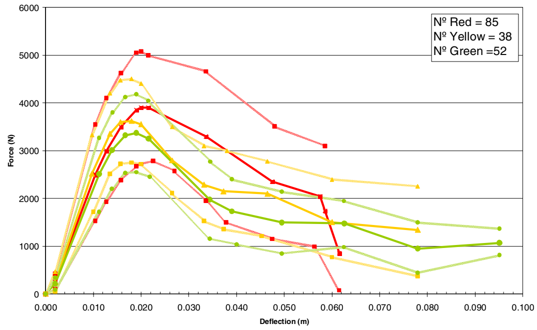

Figure 14: Simplified average force deflection curves and ±1 standard deviation corridors for the bonnet middle.

In the case of the adult headform tests on the bonnet (Figure 15), red trend seems to deviate from the green-yellow one after 0.01m of deflection. Only then, the red curve continues increasing until values of 7.0kN, the green curve loads up to 4.3kN at deflection 0.018m and start decreasing from then and the yellow curve reaches its maximum also in 4.3kN but with an increasing slope until 0.05m of deflection.

In this case, green and yellow curves maintains the force value close to 4kN over 0.02 m of deflection. Again, these values can be good estimates for getting a "green" bonnet rear.

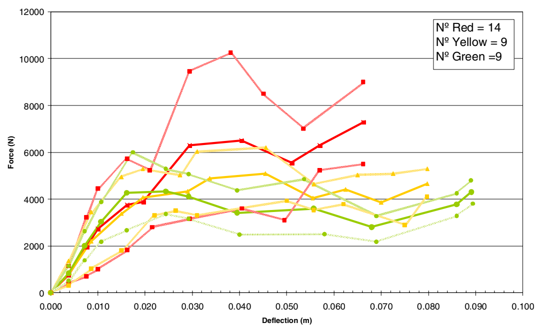

Figure 15: Simplified average force deflection curves and ±1 standard deviation corridors for the bonnet rear.

At last, the adult headform tests on the windscreen in Figure 16 show the effect of glass breaking. The red average curve reflects it with a short plateau at deformation values of 0.01m and 2.5kN and then it continues increasing to 7.0kN at 0.06m.

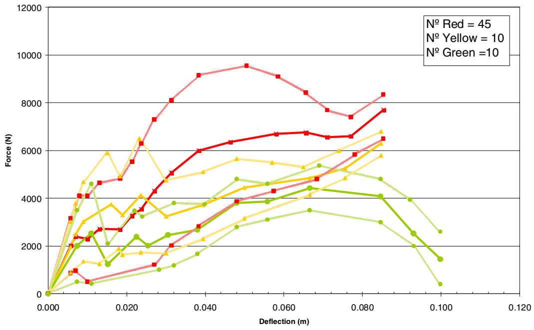

Figure 16: Simplified average force deflection curves and ±1 standard deviation corridors for (in order) the windscreen base.

The green curve shows it with a first peak of 2.5kN at 0.01m and then, following an unloading phase, a moderate increasing phase until 4.5kN at 0.08m. Finally, the yellow curve, again mostly between the red and green curve, increase to values of 4.0kN at 0.02m, maintains similar values up to 0.03m, and then continues increasing up to 6.0kN at 0.08m.

In the case of headforms, the corridors overlap considerably, especially the green and yellow ones. Moreover, for the three configurations, the lower half red corridor is partially contained in the yellow or green corridors while the upper half red corridor stands differentiated.

For the case of unloading slopes, it is analysed as a range of variation (maximum-minimum) and is presented in Table 9.

In general, the slope ranges within each colour are rather wide (max/min is about 100 times), which indicates that the variability is very high for all configurations.

Table 9: Maximum, average and minimum unloading slopes for the different groups and impacted vehicles area.

Units: N/m	Bumper	Bonnet front	Bonnet middle	Bonnet rear	Wind screen base
Max	7.07 E8	1.70 E7	2.63 E7	1.38 E8	1.84 E7
Avge	9.61 E7	1.46 E6	2.05 E6	1.32 E7	2.85 E6
Min	1.58 E6	1.45 E5	4.031 E4	6.63 E4	1.60 E5
Max	1.35 E8	1.04 E7	8.82 E7	1.85 E6	6.00 E6
Avge	1.53 E7	1.66 E6	7.50 E6	8.47 E5	1.05 E6
Min	9.73 E5	9.00 E4	5.85 E4	1.40 E5	7.71 E4
Max	2.17 E7	2.08 E6	4.68 E6	1.51 E6	4.00 E6
Avge	3.29 E6	6.30 E5	4.92 E5	4.81 E5	8.79 E5
Min	2.51 E5	1.39 E5	2.85 E4	7.96 E4	2.01 E5

STIFFNESS CORRIDORS VALIDATION WITH MADYMO MODELS.

The main output of this work consists of a set of stiffness corridors for the different parts of the vehicle front to be used as input for simulation with pedestrian and vehicle interactions. To check that the corridors proposed behave accurately in simulation and they represent what it is expected, a validation has been performed in MADYMO.

To evaluate the force-deflection calculated corridors, different models have been constructed to reproduce the EuroNCAP pedestrian test configurations.

As in the case of upper legform and legform tests the vehicle geometry plays an important role, these cases have been kept out of this preliminary validation and only headform tests have been reproduced.

Two MADYMO models have been constructed to reproduce the adult and the child headform EuroNCAP pedestrian tests configurations on a real vehicle.

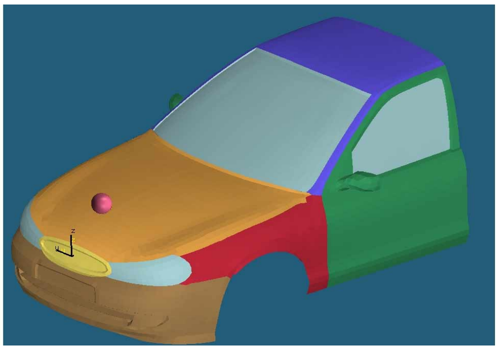

Figure 17: MADYMO models for the three EuroNCAP pedestrian configurations.

In both cases, the model consists of two systems:

- The MADYMO ellipsoid headform impactor, with the mass and geometry properties as well as the initial speed and direction from the EuroNCAP corresponding protocol.
- A real vehicle, with the contact characteristics given by the force-deflection simplified average curve calculated for the red, green or yellow cases in the bonnet middle, bonnet rear and windscreen area, with fixed friction coefficient (0.25 for the bonnet and 0.15 for the windscreen)

Comparison of results

In order to compare the simulation results with the experimental tests, the mean HIC value is obtained for the red, yellow and green test groups in each of the three configurations (adult-bonnet, adult-windscreen and child-bonnet). The average and the standard deviation is including along with the results from the simulation in Table 10.

Table 10: Comparison of the HIC values.

		Child headform bonnet	Adult headform bonnet	Adult headform windscreen
Red	Expected	2324 (±1014)	2440 (±1306)	2388 (±961)
	Obtained	2356	2444	2430
Yellow	Expected	1180 (±108)	1169 (±106)	1182 (±140)
	Obtained	1273	1287	1255
Green	Expected	801 (±114)	809 (±109)	831 (±115)
	Obtained	909	920	913

It can be seen that HIC output from the models in all cases is rather similar to the mean HIC value obtained from the tests.

It is remarkable that red behaviours are very close with their targets and very well distinguished from the other two rankings.

Regarding the yellow and green best fit, they are also considerably close to the target.

However, the output of these two models has been found to be dependant on the value in the hysteresis slope showing cases where green and yellow behaviour are exchanged, especially in the bonnet impacts. This behaviour is not surprising as the average curves in these two configurations show a significant overlap.

GUIDELINES TO APPLY THE STIFFNESS CORRIDORS TO THE CURRENT FLEET OF EUROPEAN VEHICLES.

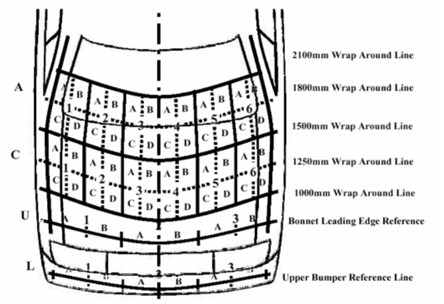

Figure 18: EuroNCAP test matrix definition.

Considering that EuroNCAP test selection is performed on an individual vehicle-based matrix (Figure 18), and this matrix is also the basis for the ratings (Figure 19), it is coherent to use it as a template to apply the proposed characteristics.

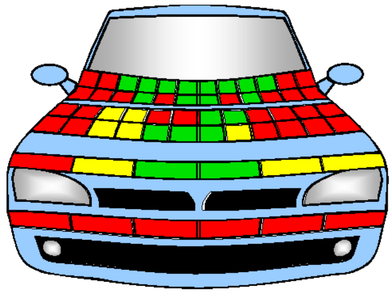

Figure 19: EuroNCAP typical pedestrian rating.

Moreover, as the result matrix for each car tested in EuroNCAP since September 2005 are available on the website, it can be used to apply the red, green and yellow curves obtained in this paper in the red, green and yellow rated areas on the car.

Four consideration are to be taken into account when applying these stiffnesses to the vehicle models:

- The force deflection curves derived do not separate the deflection of the vehicle and the one from the impactor. Therefore when the contact characteristic is defined in the model, this issue should be considered to define the stiffness correctly.
- The force deflection curves derived only cover deflections up to those seen in the EuroNCAP tests from which they were derived, so they may not be suitable for modelling higher severity impacts.
- The matrix areas on the A pillars are not tested in EuroNCAP and are given a red score directly. Red curves obtained in this study may underestimate the real stiffness of this part.
- The matrix areas on the middle of the windscreen are not tested in EuroNCAP and are given directly a green score. Green curves obtained in this study may not represent the real behaviour of this part and more dedicated studies on glazing impact should be used.

CONCLUSIONS.

The following conclusions can be drawn from the work herein presented.

1. Three methodologies have been developed and extensively applied to obtain force-deflection curves from the EuroNCAP pedestrian tests. These methodologies have proved to be accurate enough to obtain the contact characteristics from these tests.
2. The five sets of three stiffness corridors that have been generated in this work is an

important source of data for pedestrian simulation purposes that represents widely the European fleet stiffnesses ranges in the front part of the vehicle.

3. From these corridors, target values to get a "green" score can be derived based on the forces and deflection achieved in the tests. Deflections over 0.08m in the bumper and force levels in 4-5kN in the bonnet over 0.02m of deflection are valuable targets to get "green scores" in the different tests.
4. Newly tested cars may change the average green, yellow and red curves of the fleet herein obtained, however, since the evaluation has been done gathering red, yellow and green curves, their validity as estimates will be maintained while the EuroNCAP rating of the tests is maintained.
5. The stiffness maps for each individual vehicle segment define the way to implement the stiffness corridors into the current European fleet. Since 2005, EuroNCAP website publish this map for each tested vehicle.
6. These two sets of data are valuable not only to identify the gaps in the current European fleet regarding pedestrian protection, but also, and together with the feasibility limitations (Lawrence 2004), to focus future research efforts to further improve the pedestrian protection in Europe.

ACKNOWLEDGEMENTS.

This work has been developed within the APROSYS project (TIP3-CT-2004-506503 VI Framework Programme UE) Sub-project 3: Pedestrian and cyclist accidents.

The authors would like to thanks EuroNCAP for making available for APROSYS SP3 the pedestrian tests required to develop this task.

The authors would also like to thanks the Spanish Ministry of Science and Education, that partially founded this activity under the Complementary Action with reference number TRA2005-25911-E and the Community of Madrid, that contributed to this work through the SEGVAUTO programme (S- 0505/ DPI-0329).

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APPENDIX I: STIFFNESS SIMPLIFIED CORRIDORS.

The next tables present the different stiffness force-deflection corridors (deflection in m and force in N), in its simplified version, for each of the vehicle front parts and each of the three rating groups.

Table-AI- 1: Simplified force deflection data for the bumper area (from the legform tests).

BUMPER																	
AVERAGE						TOP						LOW					
Red		Yellow		Green		Red		Yellow		Green		Red		Yellow		Green	
0.0000	0	0.000	0	0.000	0	0.000	0	0.000	0	0.000	0	0.000	0	0.000	0	0.000	0
0.0092	1794	0.010	2183	0.025	5100	0.009	2685	0.010	2670	0.025	7300	0.009	1080	0.010	1500	0.025	2800
0.0260	6699	0.022	5844	0.044	7560	0.026	11500	0.022	7765	0.044	11090	0.035	2399	0.022	3950	0.044	4000
0.0420	17195	0.044	14700	0.079	10595	0.042	25900	0.044	20900	0.079	15400	0.042	8900	0.044	8650	0.079	5495
0.0492	25000	0.063	17700	0.091	9650	0.052	40450	0.063	21300	0.091	14000	0.052	14520	0.063	14026	0.091	5200
0.0665	29000	0.070	19150	0.095	8500	0.065	40000	0.070	23400	0.095	12800	0.064	20200	0.070	14850	0.095	4000
0.0790	14595	0.085	17995	0.125	10500	0.079	20500	0.085	21800	0.125	14800	0.071	12700	0.085	14150	0.125	6550
		0.088	15485	0.146	9160			0.088	16800	0.146	10000	0.079	8289	0.088	14450	0.146	8690
				0.150	6250					0.150	7800					0.150	4985

Table-AI- 2: Simplified force deflection data for the bonnet front area (from the upper legform tests)

BONNET FRONT																	
AVERAGE						TOP						LOW					
Red		Yellow		Green		Red		Yellow		Green		Red		Yellow		Green	
0.0000	0	0.0000	0	0.0000	0	0.0000	0	0.0000	0	0.0000	0	0.0000	0	0.0000	0	0.0000	0
0.0290	3000	0.0134	1250	0.0127	1030	0.0290	3900	0.0134	1900	0.0127	1400	0.0290	2150	0.0134	695	0.0127	700
0.0370	3946	0.0377	3000	0.0257	2015	0.0370	4900	0.0377	3900	0.0257	2550	0.0370	3000	0.0377	2100	0.0257	1600
0.0500	6000	0.0700	5400	0.0560	4000	0.0500	7600	0.0700	6700	0.0560	4850	0.0500	4475	0.0700	4190	0.0560	3300
0.0570	7000	0.0770	5800	0.0696	4400	0.0570	8900	0.0770	7065	0.0696	5200	0.0570	5100	0.0770	4600	0.0807	3615
0.0700	8100	0.0850	5910	0.1200	4800	0.0700	10500	0.0850	7150	0.1200	5250	0.0700	5600	0.0850	4800	0.1132	4100
0.0800	8500	0.1000	5400	0.1460	4850	0.0800	11470	0.1000	6511	0.1460	5150	0.0800	5480	0.1231	4500	0.1200	4400
0.1100	7700	0.1400	5600	0.1600	5075	0.1100	8900	0.1400	6425	0.1600	5645	0.1100	6495	0.1342	4080	0.1460	4600
0.1350	7500	0.1530	4800	0.1660	4690	0.1350	8495	0.1530	5250	0.1660	5142	0.1350	6590	0.1535	4400	0.1600	4500
0.1470	5510	0.1550	4380			0.1470	7675	0.1550	5590			0.1470	3197	0.1545	3875	0.1660	4100

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Table-AI- 3: Simplified force deflection data for the bonnet middle area (from the child headform tests).

BONNET MIDDLE																	
AVERAGE						TOP						LOW					
Red		Yellow		Green		Red		Yellow		Green		Red		Yellow		Green	
0.0000	0	0.0000	0	0.0000	0	0.0000	0	0.0000	0	0.0000	0	0.0000	0	0.0000	0	0.0000	0
0.0020	250	0.0020	250	0.0020	215	0.0020	420	0.0020	465	0.0020	340	0.0020	99	0.0020	50	0.0020	90
0.0104	2500	0.0097	2520	0.0112	2510	0.0104	3550	0.0097	3325	0.0112	3270	0.0104	1530	0.0100	1715	0.0112	1720
0.0127	3000	0.0135	3350	0.0139	3010	0.0127	4100	0.0135	4199	0.0140	3800	0.0127	1930	0.0135	2515	0.0139	2200
0.0158	3500	0.0157	3600	0.0167	3323	0.0158	4625	0.0157	4475	0.0167	4120	0.0158	2380	0.0157	2725	0.0167	2535
0.0190	3850	0.0180	3620	0.0190	3370	0.0190	5050	0.0180	4500	0.0190	4180	0.0190	2675	0.0180	2750	0.0190	2550
0.0200	3900	0.0200	3550	0.0216	3250	0.0200	5075	0.0200	4400	0.0215	4045	0.0200	2720	0.0200	2720	0.0218	2450
0.0215	3900	0.0265	2795	0.0344	1975	0.0215	5000	0.0265	3500	0.0345	2770	0.0225	2785	0.0265	2110	0.0344	1155

0.0336	3300	0.0332	2285	0.0390	1730	0.0336	4660	0.0332	3100	0.0390	2400	0.0270	2575	0.0332	1525	0.0400	1034
0.0475	2355	0.0373	2150	0.0495	1495	0.0480	3505	0.0380	3000	0.0495	2140	0.0336	1950	0.0373	1355	0.0495	845
0.0575	2045	0.0465	2100	0.0626	1475	0.0585	3095	0.0465	2775	0.0625	1945	0.0378	1500	0.0453	1210	0.0625	980
0.0585	1740	0.0600	1500	0.0780	950			0.0600	2397	0.0780	1495	0.0475	1150	0.0600	770	0.0780	440
0.0615	853	0.0780	1341	0.0951	1068			0.0780	2250	0.0951	1364	0.0563	990	0.0780	369	0.0951	810
												0.0615	75				

Table-AI- 4: Simplified force deflection data for the bonnet rear area (from the adult headform tests).

BONNET REAR																	
AVERAGE						TOP						LOW					
Red		Yellow		Green		Red		Yellow		Green		Red		Yellow		Green	
0.0000	0	0.0000	0	0.0000	0	0.0000	0	0.0000	0	0.0000	0	0.0000	0	0.0000	0	0.0000	0
0.0038	765	0.0040	840	0.0038	825	0.0038	1140	0.0038	1350	0.0038	1140	0.0038	400	0.0038	310	0.0038	510
0.0076	1950	0.0086	2200	0.0072	2000	0.0076	3225	0.0086	3440	0.0072	2620	0.0076	700	0.0086	1020	0.0072	1380
0.0100	2723	0.0150	3375	0.0107	3030	0.0100	4450	0.0150	4950	0.0107	3880	0.0100	1000	0.0150	1800	0.0107	2180
0.0162	3750	0.0195	4070	0.0161	4265	0.0162	5725	0.0195	5290	0.0174	6000	0.0162	1820	0.0220	3300	0.0161	2665
0.0196	3875	0.0290	4334	0.0244	4330	0.0210	5235	0.0274	5020	0.0244	5285	0.0215	2800	0.0265	3500	0.0244	3365
0.0294	6300	0.0337	4880	0.0292	4110	0.0294	9450	0.0310	6020	0.0292	5060	0.0294	3150	0.0310	3300	0.0292	3155
0.0404	6500	0.0455	5080	0.0395	3410	0.0381	10250	0.0456	6200	0.0395	4370	0.0405	3600	0.0500	3925	0.0400	2485
0.0510	5550	0.0555	4050	0.0557	3600	0.0451	8500	0.0557	4630	0.0537	4850	0.0495	3100	0.0557	3530	0.0580	2500
0.0570	6300	0.0625	4400	0.0680	2800	0.0535	7005	0.0650	5030	0.0690	3271	0.0570	5225	0.0620	3780	0.0690	2180
0.0662	7283	0.0700	3865	0.0860	3774	0.0662	8999	0.0725	5080	0.0860	4250	0.0662	5500	0.0750	2890	0.0860	3280
		0.0798	4650	0.0891	4300			0.0798	5290	0.0890	4800			0.0797	4100	0.0894	3802

Table-AI- 5: Simplified force deflection data for the windscreen base area (from the adult headform tests)

WINDSCREEN BASE																	
AVERAGE						TOP						LOW					
Red		Yellow		Green		Red		Yellow		Green		Red		Yellow		Green	
0.0000	0	0.0000	0	0.0000	0	0.0000	0	0.0000	0	0.0000	0	0.0000	0	0.0000	0	0.0000	0
0.0057	2015	0.0057	1960	0.0074	2004	0.0057	3150	0.0057	3025	0.0074	3500	0.0057	870	0.0057	890	0.0074	500
0.0070	2388	0.0070	2485	0.0110	2525	0.0080	4100	0.0070	3785	0.0110	4600	0.0070	970	0.0090	1360	0.0110	425
0.0100	2295	0.0090	3027	0.0152	1235	0.0100	4100	0.0090	4685	0.0152	2100	0.0100	500	0.0131	1250	0.0282	1010
0.0131	2715	0.0160	3735	0.0225	2385	0.0131	4640	0.0151	5900	0.0220	3480	0.0270	1215	0.0180	1890	0.0320	1190
0.0183	2700	0.0190	3290	0.0254	2012	0.0183	4825	0.0183	4925	0.0240	3230	0.0314	2020	0.0190	1630	0.0380	1665
0.0214	3271	0.0236	4125	0.0305	2460	0.0214	5530	0.0232	6500	0.0320	3799	0.0383	2825	0.0236	1730	0.0480	2800
0.0237	3545	0.0300	3240	0.0380	2680	0.0237	6300	0.0300	4750	0.0398	3750	0.0480	3870	0.0300	1690	0.0558	3105
0.0270	4300	0.0395	3715	0.0480	3800	0.0270	7300	0.0395	5100	0.0480	4800	0.0574	4308	0.0395	2300	0.0665	3500
0.0314	5060	0.0500	4447	0.0558	3860	0.0314	8100	0.0480	5650	0.0558	4600	0.0684	4800	0.0500	3150	0.0846	2999
0.0383	5990	0.0666	4840	0.0666	4425	0.0383	9150	0.0570	5497	0.0690	5375	0.0780	5825	0.0666	4150	0.0930	2000
0.0464	6350	0.0756	5240	0.0846	4075	0.0505	9550	0.0650	5300	0.0846	4800	0.0853	6500	0.0756	4845	0.0998	399
0.0580	6700	0.0847	6300	0.0930	2520	0.0585	9100	0.0740	6000	0.0920	3941			0.0847	5800		
0.0656	6749			0.0998	1447	0.0656	8420	0.0847	6798	0.0998	2599						
0.0710	6550					0.0710	7690										
0.0770	6600					0.0770	7400										
0.0853	7699					0.0853	8351										