A SIMPLIFIED MODEL OF PEDESTRIAN UPPER LEGFORM IMPACT FOR ESTIMATE OF ENERGY-ABSORPTION SPACE UNDERNEATH BONNET LEAD

Bingbing Nie, Yong Xia, Jun Huang, Qing Zhou
State Key Laboratory of Automotive Safety and Energy
Tsinghua University
China
Paper Number 11-0014

ABSTRACT

Pedestrian upper leg impact protection is a challenging requirement in the Euro NCAP assessment. This study is aimed to develop a simplified model to provide a more reasonable estimate of the minimum energy absorption (EA) space underneath bonnet lead for upper leg impact protection. Typical shapes of upper legform impact response (the impact force vs. legform intrusion) are summarized. Then a simplified finite element model is built to represent the stiffness characteristics of vehicle front-end, especially for the local area around the bonnet leading area. Energy flow under different initial energy levels is analyzed using the simplified model. A feasible estimation on the EA space requirement for achieving specified Euro NCAP rating is established for upper legform tests.

INTRODUCTION

In the current pedestrian impact safety assessment test methods, the upper legform impactor is used to represent the human femur and pelvis in vehicle impacts. For vehicles with high front ends, e.g. SUVs, the bonnet and its leading edge are most frequent sources of injury [1]. However, compared to the pedestrian head impact protection and lower leg impact protection, there have been much fewer vehicle models that have received good scores in the Euro NCAP assessment test of the upper legform to bonnet leading edge [2]. Pedestrian upper leg impact protection is a quite challenging requirement.

The upper legform impactor consists of rigid front and rear members, with foam covered on the impact side [3]. The impactor is launched with a specified velocity and its motion is constrained by a guiding system. When contacting with the target vehicle, the upper legform moves only in the guided straight direction, representing the human femur and pelvis kinematics in real vehicle-to-pedestrian impacts [4][5].

The initial kinetic energy, velocity, and impact angle of the upper legform are specified on a look-up diagram in the test protocol based on the bonnet leading edge height (BLEH) and the bumper lead (BL) of the target vehicle. Proper spatial arrangement and structure design of the parts underneath the bonnet lead will benefit the upper legform impact response [6]. Vehicle’s styling and main styling related dimension parameters are usually determined at the very early stage in the vehicle development process, which then determine the initial kinetic energy level of the upper legform impact test. The pedestrian impact protection design is usually started in a later stage after the styling and components packaging designs are finalized or almost finalized. If the styling causes a high initial energy input for the upper legform impact, and/or the packaging does not leave sufficient EA space underneath the bonnet lead, the pedestrian protection design would be very difficult. Therefore, it is required to have a simple tool in the early vehicle development stage to estimate the required EA space for upper legform impact. The early development stage usually includes the styling and packaging designs, while most other detailed structural information may not be available.

In upper legform impacts, the sum of the impact forces and the peak bending moment measured in the main legform member are the injury indexes. The Euro NCAP test prescribes threshold values to the injury indexes for their assessment rating. In general, given the sum force below the threshold, the peak bending moment would always meet the requirement. For this reason, in this study, the impact forces are taken as the study object while the peak bending moment is only monitored. A substantial portion of the initial legform kinetic energy will be absorbed by the deformation of the vehicle body components around the impact area. The maximum displacement of the vehicle front-end structure in the impact direction is referred to as energy-absorption (EA) space.

To obtain a deep understanding to this problem, the impact response, characterized by the impact force vs. legform impactor intrusion and measured on the upper legform, should be analyzed. An ideal situation for achieving the minimum EA space underneath the bonnet lead is that the impact response is close to a square wave and the plateau force is close to the injury threshold.

Denote the initial kinetic energy of the upper legform as E_{ini}, and the intrusion of the upper legform as D. In the Euro NCAP upper legform test rating, to get a full score, the sum of the impact forces should not be greater than 5 kN. As aforementioned, the initial kinetic energy level is determined by the geometrical parameters of vehicle front-end. Taking the highest initial energy input, 700 J, for an example, in accordance with the force requirement ($F \leq 5$ kN), the minimum EA space calculated from ideal square wave should be:

$$D_{\min} = \frac{E_{ini,upper}}{F_{threshold}} = \frac{700\ J}{5\ kN} = 140\ mm$$

(Foam compression neglected) (1).

However, both the deformations of the upper legform and the vehicle body components would contribute to the impact energy absorption. Considering that the foam compression in the early impact stage could only reach a much lower force level than the deformation of the vehicle body components in the later impact stage, in reality, it is impossible to achieve a square wave for the entire impact process. Therefore, a more reasonable approach is needed to calculate a more feasible minimum EA space requirement, and this is the objective of this study.

This paper documents the description of a simplified FE model to represent the structure stiffness characteristics of vehicle front-end and analysis of the energy flow during the impact process. Based on these analyses, it is aimed that the approach and model developed in this study can provide a more reasonable estimate of the minimum EA space underneath bonnet lead for given vehicle's front-end geometry to guide further vehicle structure design for pedestrian upper legform impact protection.

TYPICAL FORCE RESPONSE OF UPPER LEGFORM IMPACT TESTS

Figure 1 shows typical simulation results of upper legform impact on a sedan model in the middle position. In this simulation, the mass of the legform is 14.00 kg and the initial impact velocity is 9.77 m/s. The upper legform impact force response usually exhibits multi-peak characteristics. The three obvious peaks are in accordance with the first contact of the upper legform on the bonnet lead, the second and third impacts with the hard points underneath the bonnet lead. The sedan model used for generating the upper legform impact response is not designed for meeting the Euro NCAP requirement. The front-end structure is too stiff, resulting in the first force peak over the injury threshold. Besides, the space underneath the bonnet lead is not enough, resulting in the second and third force peaks over the threshold as well. It indicates that the remaining kinetic energy of the legform is still high when it impacts with the hard points underneath the bonnet lead. To generate a more optimized impact force response, there must be sufficient EA space as well as adequate EA structure design.

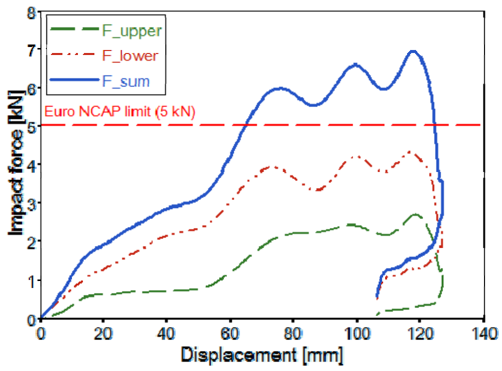


Figure 1. Typical upper legform impact response (14.00 kg, 9.77 m/s).

Although the under-bonnet structures around the upper legform impact area are very different from vehicle to vehicle, the upper legform impact responses share common characteristics. Based on test and simulation results of different vehicle models, the upper legform impact responses can be characterized by a piecewise linear approximation as shown in Figure 2. The corresponding mathematical expression is as below:

$$F(x) = \begin{cases} k_1(x - D_0) + F_0 & D_0 < x < D_1 \\ F_1 & D_1 < x < D_2 \\ k_2(x - D_2) + F_1 & D_2 < x < D_3 \\ F_2 & D_3 < x < D_4 \\ k_3(x - D_4) + F_2 & D_4 < x < D_5 \end{cases} \quad (2).$$

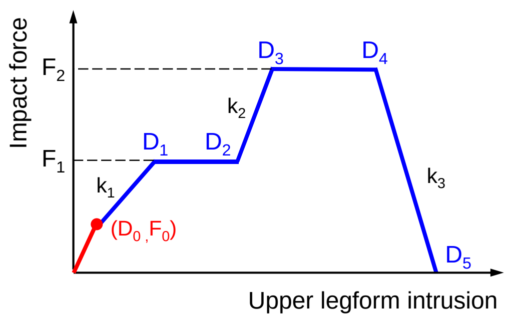
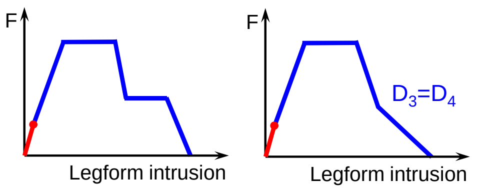


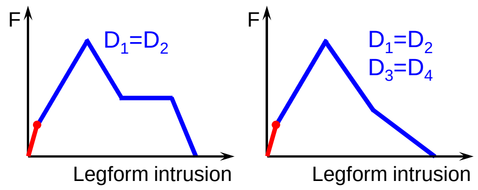
Figure 2. Piecewise linearity approximation of the upper legform impact response.

The initial soft contact stage (0 ~ D_0) is dominated by the foam characteristics. Since the legform foam is much softer than the vehicle bonnet lead, we assume that all the foam compression occurs before the vehicle structure deforms. Thus the foam compression characteristics due to the upper legform impact with bonnet lead can be considered as independent of vehicle structure's characteristics. This deformation response phenomenon and the associated assumption have been confirmed by FE simulations of upper legform impact with various bonnet leads under various initial energy levels. Therefore, the value of D_0 and F_0 can be taken as constants regardless vehicle body characteristics.

The other parameters (F_1, F_2, k_1, k_2, k_3, D_1, D_2, D_3, D_4, D_5) are determined by vehicle front-end geometry and structural stiffness. Note that only 7 of them are independent parameters. All different combinations of the parameters can be divided into two groups: front multi-peak and front single-peak, as shown in Figure 3. Taking $F_1 > F_2$ for example, it indicates that the upper legform encounters a front peak during the impact.



(a) Front Multi-peak



(b) Front Single-peak

Figure 3. Possible shapes for characterizing upper legform impact responses (F_1> F_2).

As aforementioned, the ideal square impact response is not realistic because of the initial soft contact. After that the force on the upper legform should reach a plateau as quickly as possible and maintain the plateau level till the legform rebounds. This is referred to as "semi-ideal" impact response, as shown by the solid line in Figure 4, and considered as the vehicle design target of upper legform impact response. In other words, the semi-ideal response represents the possible "best" structure in reality for upper legform impact. The semi-ideal response can be used to estimate a more realistic minimum EA space for achieving a good Euro NCAP rating score. Such generated EA space estimate should be taken as a lower limit for further vehicle model design.

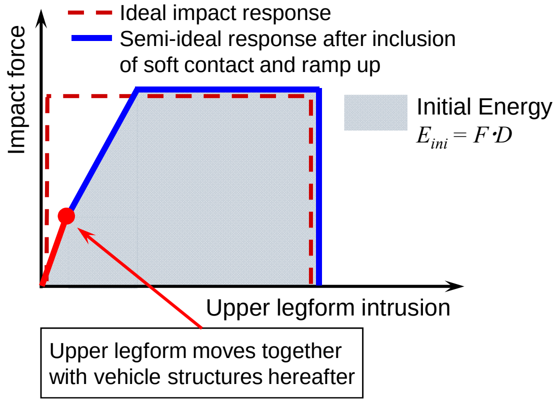


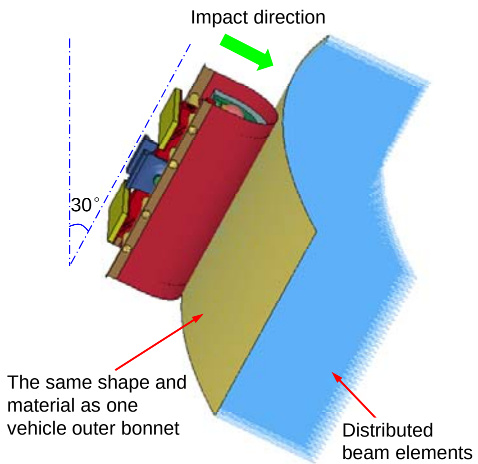
Figure 4. Vehicle design target of upper legform impact response (semi-ideal impact response).

A SIMPLIFIED MODEL FOR ENERGY-ABSORPTION SPACE ESTIMATE

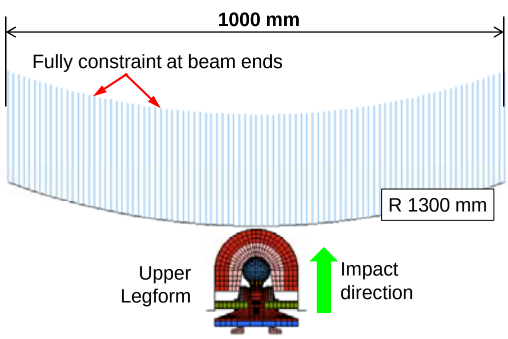
Setup of a simplified model

To fulfill the Euro NCAP rating requirement of the upper legform impact, only a small EA space underneath bonnet lead is needed if the vehicle front-end structure is well-designed. Although it is difficult to achieve such an ideal structure in practice, it can be considered as a design target. To estimate the minimum EA space requirement, a simplified model is built to represent equivalent structural stiffness of the vehicle front-end structure, a pretty ideal structure. The simplified model consists of beam elements and outer shell elements as a deformable panel, as shown in Figure 5. LS-DYNA finite element analysis software is used for the simplified model, the upper legform model, and the simulations. The upper legform model is developed and validated by Livermore Software Technology Corporation (LSTC) based on the pedestrian upper legform description in regulation EC No 631/2009. The outer shell elements represent the bonnet lead panel, primarily providing membrane force resistance to the upper legform impact. The beam elements represent the lump-sum, ideal and equivalent stiffness of the components underneath the bonnet lead and its deformation length represents the EA space provided by the vehicle structure.

The material and thickness properties of the shell elements in the model are adopted from the bonnet of a real vehicle model. Even though the bonnet structure properties are different from vehicle to vehicle, we feel it is appropriate to choose a typical one in the simplified model as the function of the shell elements is not as significant as that of the beam elements in terms of estimating the EA space. In the height direction, the shell panel has the same length as the upper legform to provide a full support to the upper legform impact. The actual upper legform contact with the bonnet lead is around the middle section of the legform in tests, instead of a full contact. The full contact is a simplification and can also avoid some numerical difficulties caused by large deformation of soft solid elements in FE simulations. In the width direction, the shell panel is an arc with 1300 mm radius and 1000 mm width based on geometric characteristics of a real vehicle bonnet. The shell element size is 10 mm. The beam elements are particular to the shell elements' surface. Each of the shell element nodes is connected to a beam element. One end of the beams share nodes with the shells, and the other ends are constrained with *BOUNDARY_SPC option. The initial length of the beam elements is 200 mm, and the material model is *MAT_024 (elasto-plastic material) in LS-DYNA. The material properties (Young's modulus E and Yield stress σ_y) and geometrical parameters (beam diameter d) are design variables in further optimization to generate the most effective impact responses for EA space estimate with respect to different input energy levels.



(a) Axonometric view



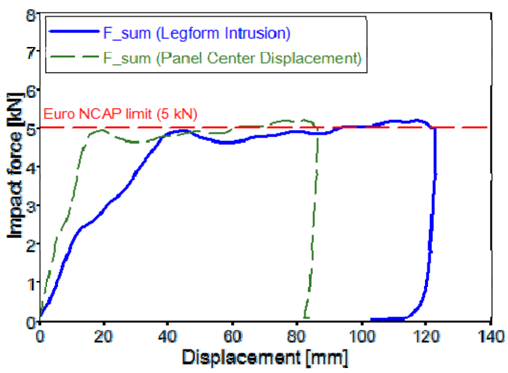
(b) Top view

Figure 5. The simplified model representing equivalent stiffness of vehicle front-end structure.

Energy-absorption space requirement

To fine tune the simplified model, the loading parameters from the upper legform are set to be 14.00 kg, 10.00 m/s, respectively, which is the upper limit of kinetic energy level (700 J) set in the Euro NCAP test protocol. The beam elements should have a quite high Young's modulus to ensure that the impact response has a quick ramp-up in the initial stage. However, if the Young's modulus is too high, it may cause force oscillations, which is not desirable. The yield stress of the beam material corresponds to the plateau force of the upper legform. In tuning the simplified model, the injury threshold for the peak impact force, 5 kN, is set as the plateau force level. A quick force ramp-up in the initial stage and a plateau force level at the injury threshold should render a minimum EA space.

By manual optimization, the values of the design variables for generating a semi-ideal impact response with 5 kN force limit can be determined. The simulation results and the corresponding parameter values are shown in Figure 6. The maximum displacement at the panel center is 86 mm (measured from the panel contact point), which is taken as the minimum EA space requirement by this semi-ideal model. This is obviously smaller than the estimated value of 140 mm based on equation (1). The upper legform intrusion is 122 mm (measured by the displacement of the rigid rear member of the legform in the impact direction). The difference between the two is mainly due to the outer legform foam compression, of which the maximum value is about 36 mm in the middle part. Therefore, 86 mm is the possible minimum EA space requirement to fulfill the Euro NCAP full score rating requirement.



Beam diameter d	0.10 mm
Young's modulus E	40.95 GPa
Yield stress σ_y	1.02 GPa
Tangent modulus $ETAN$	0.00
Possion ration v	0.29

Figure 6. Upper legform impact response with semi-ideal simplified model.

Energy flow in upper legform impacts

During the impact process, the initial legform kinetic energy E_{ini} flows to the following sources:

- E_1: the energy absorbed by the deformation of the vehicle front-end structures
- E_2: the energy absorbed by the deformation of the legform itself (mainly due to the compression of the outer foam)
- E_{UL}: the remaining kinetic energy of the upper legform
- E_{veh}: the kinetic energy of the vehicle

At any time during the upper legform impact process, the energy balance equation is:

$$E_{ini} = E_1 + E_2 + E_{UL} + E_{veh} \qquad \# \ (3).$$

For easy description, hereafter the analysis on energy flow is at time t_R when the upper legform starts rebound from the vehicle, and thus $E_{UL} = 0$ and $E_{ini} = E_1 + E_2 + E_{veh}$. The energy flows calculated from the real sedan model simulation (Figure 1) and from the semi-ideal simplified model (Figure 5) simulation are shown in Table 1. Although the two models are not comparable in many aspects, the results in Table 1 show that the energy allocation by the simplified model is reasonable.

For the real sedan model, internal energy of the vehicle parts (E_1) due to part deformation accounts for most of the input energy of 450 J; while energy absorbed by legform foam compression (E_2) accounts for 160 J. Most of the vehicle parts get quite low velocity, which result in a low vehicle kinetic energy (E_{veh}) of about 35 J. As for the semi-ideal simplified model, energy absorbed by the outer foam (E_2) increases to 255 J due to the regular geometric shape of the panel. This indicated that evenly compressed legform foam has a higher energy absorption capability. This is exactly why the required EA space 86 mm (Figure 6) is much smaller than the 140 mm value in equation (1) from ideal square wave estimation without foam consideration.

MINIMUM ENERGY-ABSORPTION SPACE REQUIREMENT UNDER DIFFRERNT INITIAL ENERGY LEVELS

In the early stage of a vehicle development process, it is needed to estimate the minimum EA space required for upper legform impact protection. This may be done by using the simplified model developed in this study. The required EA space depends on the initial energy level of the upper legform. The parameters of the upper legform impact test, energy input, initial velocity, and impact angle, are determined by vehicle front-end geometric parameters: BLEH and BL. These styling related parameters are usually determined in the early stage as well. In the Euro NCAP look-up diagram, the BLEH and BL values are limited in the ranges of 550-1050 mm and 0-400 mm, respectively. Different combinations of the two parameters represent different front-end styling characteristics. Using 50 mm as an interval, in the ranges of BLEH and BL values, totally 99 cross combinations form the entire possible test parameter matrix. In the matrix, 70 pairs have non-zero initial energy input. These energy input levels are plotted in Figure 7 as the function of the impactor mass and initial velocity.

Table 1.
Energy flow comparison between a real sedan model and the simplified model

	Items	Sedan model	Simplified model
Simulation results	Initial energy E_{ini} [J]	668.17	700.00
	Impactor mass m [kg]	14.00	14.00
	Initial velocity v_{ini} [m/s]	9.77	10.00
	Rebound time t_R [ms]	25.0	22.5
	Legform intrusion D [mm]	144	128
Energy flow at t_R	Energy absorbed by vehicle structure E_1 [J]	450	430
	Energy absorbed by legform E_2 [J]	160	255
	Kinetic energy E_{veh} [J]	35	0.4
	Hourglass energy [J]	30	10
	Energy summation E_{sum} [J]	675	695
	Difference between E_{sum} and E_{ini}	1.02%	-0.71%

The distribution shown in Figure 7 includes 13 groups. Some are scattered points and some are clustered points. These 13 groups are chosen as typical test points for upper legform impacts. In the cases of the clustered points, the center points of the clusters are chosen to represent the clusters, respectively. The simplified model is used to analyze these 13 typical cases and the results are shown in Table 2. The "Base" run refers to the parameter group for determination of the semi-ideal simplified model (Figure 6).

As aforementioned, in the Euro NCAP test protocol, the vehicle styling parameters determine initial energy input. And the results in Table 2 clearly show the relationship between the initial energy levels and the required minimum EA space underneath the bonnet lead. In the semi-ideal simplified model (Figure 5), the legform foam is evenly compressed in the height direction, and the compression amount is definite. As verified in Table 2, the legform foam compression is equal to the legform intrusion (*D*) minus the EA space. For all the cases in Table 2, which are under different loadings, the legform foam compression amount is all approximately 40 mm. The relationship between the initial energy input and the EA space requirement is shown in Figure 8 (a). The solid line is the linear

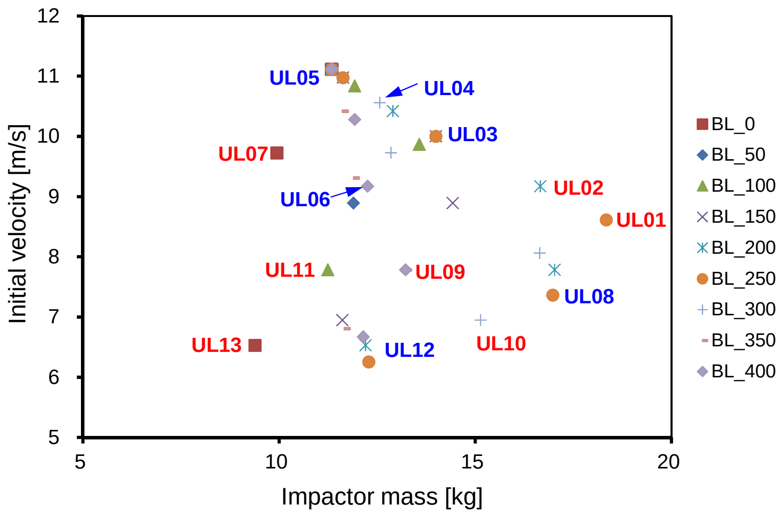
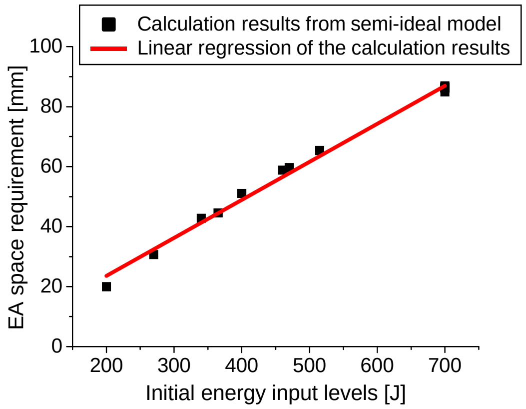


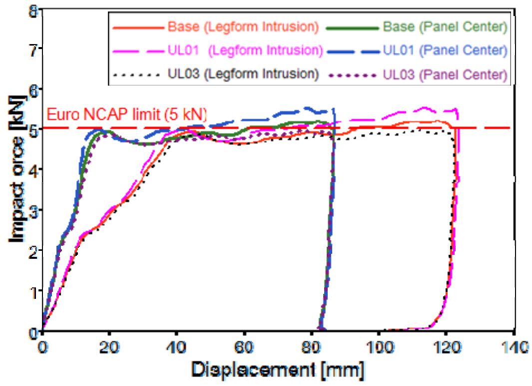
Figure 7. Distribution of all the test points for upper legform impacts.

Table 2.
Required minimum EA space for different impact energy levels

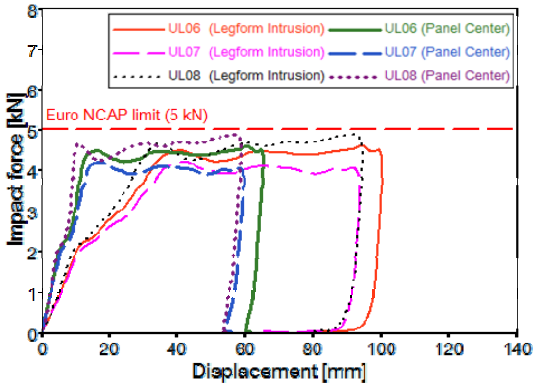
Case	E_{ini} [J]	m [kg]	v_{ini} [m/s]	D [mm]	E_2 (t_R) [J]	EA space [mm]
Base	700	14.00	10.00	127.8	257.9	86.5
UL01	700	16.66	9.17	128.6	258.0	86.9
UL02	700	13.82	10.06	127.7	256.0	86.5
UL03	700	12.57	10.56	127.4	255.6	86.4
UL04	700	11.34	11.11	126.8	254.1	86.1
UL05	700	18.34	8.61	126.8	254.0	84.9
UL06	515	12.26	9.17	105.5	215.5	65.4
UL07	470	9.94	9.72	98.9	202.4	59.7
UL08	460	16.98	7.36	99.6	206.0	58.9
UL09	400	13.22	7.78	90.7	189.5	51.0
UL10	365	15.14	6.94	84.0	178.0	44.6
UL11	340	11.24	7.78	81.6	173.2	42.8
UL12	270	12.15	6.67	69.4	156.3	30.7
UL13	200	9.39	6.53	57.7	135.4	20.0



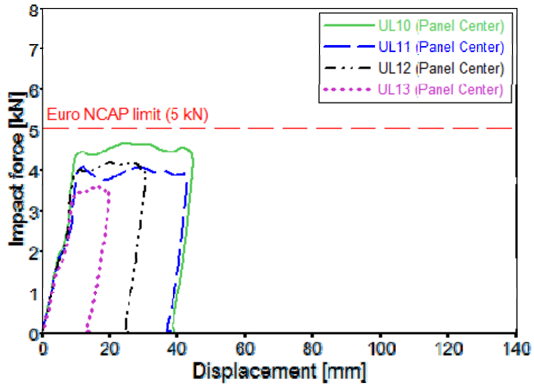
(a) Relationship between initial impact energy and EA space requirement



(b) Input energy 700 J



(c) Input energy from 460 J to 515 J



(d) Input energy lower than 400 J

Figure 8. Upper legform impact responses from the semi-ideal model.

regression of the calculation results. The minimum EA space requirement monotonically increases with the initial energy input.

Figure 8 (b) and Figure 8 (c) show the calculation results for the highest level (700 J) and the mid-level (from 460 J to 515 J) groups of initial energy, respectively. The impact responses exhibit similar shape with 5 kN peak force value as plateau. The results demonstrate that, for these two groups of the initial energy input, the semi-ideal simplified model behaves as expected for estimating the minimum EA space to fulfill the Euro NCAP full score rating requirement.

For the lowest level group of initial energy (lower than 400 J), Figure 8 (d) shows that the semi-ideal simplified model predicts the impact force from 3.6 kN to 4.6 kN, depending on the initial energy input levels. The prediction is lower than the 5 kN injury threshold, indicating that the calculated EA space may be further reduced for the 5 kN target. The reason for over-estimating the EA space is because the parameters of the semi-ideal simplified model have been tuned for the initial energy level of 700 J (Figure 6). In the next steps, we will investigate if a simplified model applicable in a broader range can be developed.

CONCLUSIONS

Pedestrian upper leg impact protection design is related to the early stage of a vehicle product development process in at least two aspects. One is the front-end styling design since there are two styling related geometry parameters determining the initial impact energy level of the legform impactor, and a high initial energy input would require large energy absorption (EA) space underneath the bonnet lead. The other is the components packaging design underneath the bonnet where enough EA space should be reserved. In this study, a simplified model has been developed for analyzing the upper legform impact with the bonnet lead and for estimating the EA space requirement in the early stage of the vehicle development process when other structural details may not have been available. The simplified model represents equivalent vehicle structure stiffness in the bonnet lead area where the upper legform impacts with the vehicle.

The model is referred to as the semi-ideal model. An ideal model represents a square-wave shape force-deformation response of the upper legform impact, while the semi-ideal model includes the legform foam soft contact stage and the initial ramp-up stage of vehicle structure stiffness. The impact response of the semi-ideal model consists of a quick force ramp-up in the early stage of the impact process followed by a force plateau close to the injury threshold force (Figure 6), which can be considered as the vehicle design target for obtaining the full rating score in the Euro NCAP upper legform impact test. It is possible to design an EA device placed underneath the bonnet lead such that the upper legform impact response follows that of the semi-ideal model. The response would be the lump-sum contribution from that of the legform, the vehicle bonnet lead and the EA device.

Using the simplified model, the upper legform impact force and intrusion can be calculated. For the initial energy level greater than 400 J (up to the highest limit of 700 J), the impact force is close to the 5 kN injury threshold of the Euro NCAP requirement, and the EA space underneath the bonnet lead can be estimated from the legform intrusion. For the initial energy level lower than 400 J, the EA space estimate value is greater than the needed since the simplified model is tuned for the high initial energy level.

The analysis results based on the simplified model have shown that the minimum EA space is linearly correlated with the initial energy level. This study also reveals that the compression of the upper legform foam can absorb roughly 20% - 40% of the total impact energy (Table 1), and therefore, the required EA space underneath the bonnet lead is only part of the total EA space. In the semi-ideal model, as a simplification, the legform is assumed to be in full contact with the impact target in the height direction (Figure 5). In real situation, however, the contact starts around the middle section of the legform and the contact area increases during the impact but may never reach the full contact area status, and so the foam contribution to the EA should be smaller than that calculated by the simplified model. Therefore the model only gives a lower bound of the EA space. Smaller contact area in real situation would require larger EA space underneath the bonnet lead for the 5 kN injury threshold. This also provides a guide in bonnet styling and structure design: making sure that the upper legform contact area with the bonnet lead as large as possible.

This study has provided a tool for estimating the EA space requirement underneath bonnet lead in the early stage of vehicle development. It may eliminate or reduce the iterations between styling design, packaging design and structure design for meeting the Euro NCAP upper legform impact performance requirement. In further study, more effort will be made on making the simplified model applicable in a broader range of initial energy levels and accounting for more realistic contact characteristics during the impact process. Designs of several embodied countermeasures will also be carried out to demonstrate the effectiveness of the EA space estimate based on the simplified model.

ACKNOWLEDGEMENTS

The authors would like to thank LSTC for providing us with the educational license of LS-DYNA. We also appreciate that Altair provides us with the educational license of HyperWorks.

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