DEVELOPMENT AND VALIDATION OF PEDESTRIAN SEDAN BUCKS USING FINITE ELEMENT SIMULATIONS; APPLICATION IN STUDY THE INFLUENCE OF VEHICLE AUTOMATIC BRAKING ON THE KINEMATICS OF THE PEDESTRIAN INVOLVED IN VEHICLE COLLISIONS

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ABSTRACT

Previous vehicle-to-pedestrian simulations and experiments using pedestrian dummies and cadavers have shown that factors such as vehicle shape, pedestrian anthropometry and pre-impact conditions influence pedestrian kinematics and injury mechanisms. Generic pedestrian bucks, that approximate the geometrical and stiffness properties of current vehicles, would be useful in studying the influence of vehicle front end structures on pedestrian kinematics and loading. This study explores the design of pedestrian bucks, intended to represent the basic vehicle front-end structures, consisting of five components: lower stiffener, bumper, hood leading edge and grille, hood and windshield. The deformable parts of the bucks were designed using types of currently manufactured materials, which allow manufacturing the bucks in the future. The geometry of pedestrian bucks was approximated based on the contour cross-sections of two sedan vehicles used in previous pedestrian dummy and cadaver tests. Other cross-sectional dimensions and the stiffness of the buck components were determined by parameter identification using FE simulations of each sedan vehicle. In the absence of a validated FE model of human, the FE model of the POLAR II pedestrian dummy was used to validate a mid-size sedan (MS) pedestrian buck. A good correlation of the pedestrian dummy kinematics and contact forces obtained in dummy - MS pedestrian buck with the corresponding data from dummy - MS vehicle simulation was achieved. A parametric study using the POLAR II FE model and different buck models: a MS buck and a large-size sedan (LS) buck were run to study the influence of an automatic braking system for reducing the pedestrian injuries. The vehicle braking conditions showed reductions in the relative velocity of the head to the vehicle and increases in the time of head impact and in the wrap-around-distances (WAD) to primary head contact. The head impact velocity showed greater sensitivity to the different buck shapes (e.g., LS buck vs. MS buck) than to the braking deceleration. The buck FE models developed in this study are expected to be used in sensitivity and optimization studies for development of new pedestrian protection systems.

INTRODUCTION

Pedestrian fatalities comprise a considerable percentage of total traffic fatalities in industrialized nations: from 11 % in USA (NHTSA 2009) to nearly 50 % - South Korea (Youn et al. 2005). Additionally, the probability for a pedestrian to be injured or killed during a traffic accident is much higher than that for a vehicle occupant. In 2007, 6.7 % of vehicle-pedestrian impacts in the US were fatal, whereas the corresponding fatality rate for occupants in crashes was only 1.3 % (NHTSA, 2009).

Protection of pedestrians in vehicle-to-pedestrian collisions (VPC) has recently generated increased attention with regulations implemented or proposed in Europe (EU 2003, EU 2009), Korea (Youn et al. 2005), and Japan (Mizuno 2008). While subsystem experiments are currently being used as the basis of evaluations for these regulations, car-to-pedestrian dummy impact tests (Fredriksson et al. 2001, Crandall et al. 2005) or car-to-human/dummy impact simulations (Untaroiu et al. 2008) provide complementary data that can better characterize whole body response of vehicle-pedestrian interactions.

An advanced pedestrian dummy, called the POLAR II, has been developed and continuously improved by Honda R&D, GESAC, and the Japan Automobile Research Institute (JARI) (Akiyama et al. 1999, 2001; Okamoto et al. 2001, Takahashi et al., 2005, Crandall et al., 2005). The primary purpose of the POLAR II dummy has been to reproduce pedestrian kinematics in a collision with a vehicle. Kerrigan et al. (2005) performed vehicle impact tests on the POLAR II and post mortem human surrogates (PMHS) in identical conditions and showed that the POLAR II dummy generally replicates the complex kinematics of the PMHS.

A FE model of the POLAR II dummy has been developed, validated in component tests (Shin et al. 2006), and verified at the full scale level against kinematic data (Shin et al. 2006, 2007) recorded during the vehicle-dummy impact experiments performed by Kerrigan et al. (2005). The POLAR II FE model was developed using Hypermesh (Altair Engineering) and Generis (ESI) as pre-processors and PAM-CRASH/PAM-SAFE FE solver (version 2001, ESI) was used for impact simulations. The model contains 27,880 elements that represent the head, neck, thorax, abdomen, pelvis, upper arms, forearms, hands, thighs, knees, legs, and feet and has a total mass and height close to that of the 50th percentile male. Recently, injury thresholds for the POLAR II dummy FE model are being established based on FE simulations with a human model (Takahashi et al. 2008) that may extend the applicability of the dummy model to injury prevention applications. While vehicle-to-PMHS tests or simulations may provides a better understanding of new protection devices, the high cost of tests and the lack of a fully validated human models have turned attention of many researchers toward simple tests or models. Vehicle sled bucks were used in pedestrian PMHS tests by Snedeker et al. 2005 to assess the pelvis and upper leg injury risk. While these simplified bucks approximated reasonable the geometric characteristics of current vehicle front-ends, no information about a correlation with the vehicle stiffness was provided. To study the influence of the pre-impact position of pedestrian arms on pedestrian head injury, Ogo et al. (2009) developed a scaled human model and vehicle buck. The values of head injury criteria (HIC) recorded in the vehicle buck-to-dummy tests showed a significant variation with respect to the arm pre-impact position. Neal et al. (2008) developed a simplified buck FE model (rigid surfaces connected by nonlinear springs) to predict the performance of different vehicle front-end designs in pedestrian leg impact tests.

The objective of the current study was to design two FE models of simplified vehicle bucks with geometrical and stiffness characteristics similar to those of a mid-size sedan (MS) and a large sedan (LS). To show a possible application of the buck FE models in the development of new measures for pedestrian protection, a numerical study related to influence of braking on the pedestrian kinematics was performed.

METHODOLOGY

The pedestrian kinematics during impact with a vehicle are generated by the vehicle-dummy contact forces. These loads highly depend on the geometry and stiffness properties of the front-end structures of the vehicle involved in the crash. Since a pre-impact position of the dummy along the vehicle centerline has been used in previous vehicle-to-pedestrian dummy/PMHS tests (Kerrigan et al. 2005, Kerrigan et al. 2007), the vehicle geometry and stiffness properties along the centerline were used in current study for the development of MS and LS bucks. It was hypothesized that five vehicle components (lower stiffener, bumper, hood leading edge and grille, hood and windshield) can reasonably approximate the front-end of the vehicle during a pedestrian impact. Each component was designed as a combination of deformable parts connected to a rigid part. Since a physical implementation of the pedestrian buck is ultimately planned, material selection for the deformable components of the buck was based on readily available materials: steel, Expanded Polypropylene Particle (EPP) foam (JSP Japan), and polypropylene fascia (Boedeker Plastics, TX, US). The shape and locations of buck components were defined based on the exterior geometry of the MS and LS vehicles used in previous testing (Kerrigan et al. 2005, Kerrigan et al. 2007). The material used for each deformable component of the buck was chosen based on the stiffness characteristics of corresponding sedan component determined by FE simulations. Then, FE simulations in similar conditions were run to calibrate the thickness of deformable parts of the bucks. Detailed information about the development of each vehicle component is provided in the following sections.

Development of a mid-size sedan (MS) pedestrian buck

A pedestrian simulation was performed using the POLAR II FE model (Shin et al. 2006 and 2007) and the FE model of a MS vehicle in order to determine the maximum level of dummy-vehicle forces during a 40 km/h impact. In addition to the upper body kinematics of pedestrian recorded at specified locations (head center of gravity (CG), T1, T8, pelvis – Untaroiu et al. 2008), the time histories of resultant force were calculated at the contact points of the dummy with four components (lower stiffener, bumper, leading edge and grille, hood – Figure 1).

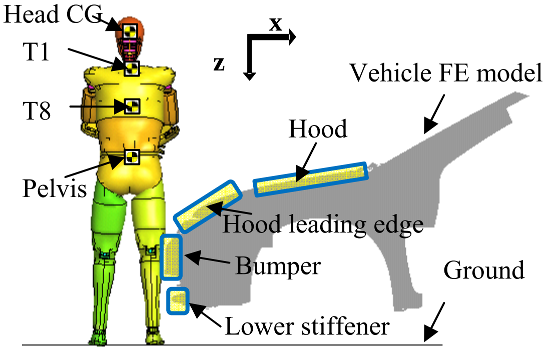

Figure 1. Pedestrian - mid-size (MS) sedan vehicle FE simulation setup

To determine the stiffness characteristics of the lower stiffener and bumper, a cylindrical rigid impactor (220 mm length, 120 mm diameter, and 10 kg mass) was launched freely with a 40 km/h initial velocity toward the vehicle at the middle sections of the lower stiffener (Figure 2), and then at the corresponding section of the bumper (Figure 3). The time histories of the resultant force in the impactor were calculated during the simulations, and then were normalized with the sum of the highest forces calculated in these components in the POLAR II – vehicle simulation.

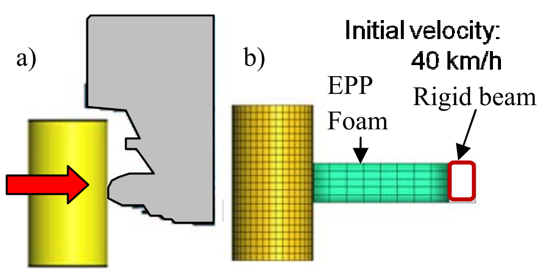

Figure 2. Impactor – vehicle/buck FE simulations at lower stiffener location a) MS vehicle and b) MS buck

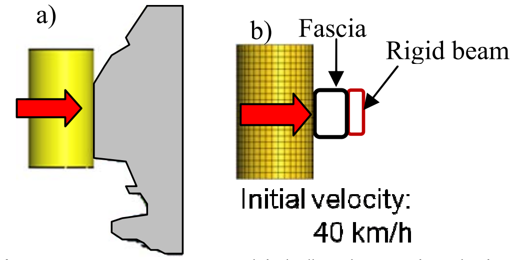

Figure 3. Impactor – vehicle/buck FE simulations at bumper location a) MS vehicle and b) MS buck

It was observed that the EEP foam and the fascia could approximate the stiffness characteristics of the lower stiffener, and the bumper respectively. While the vertical lengths of the chosen deformable components were approximated from the vehicle cross-section (Kerrigan et al. 2007), the other dimensions were adjusted to match the stiffness curves of vehicle components.

A cylindrical rigid impactor (350 mm length, 150 mm diameter, and 10 kg mass) was also used to determine the stiffness of the hood leading edge-grille region of the vehicle. The impactor was launched freely at 40 km/h with an angle of 40 degrees towards the hood vehicle leading edge (Figure 4). The time histories of the resultant forces in the impactor were calculated during the simulations, and then were normalized with the sum of the highest forces calculated in the hood leading edge and grille components in the POLAR II – vehicle simulation. After evaluating several different potential solutions, it was determined that two EFF foam parts (20g/l density) covered with a steel sheet could reasonably represent the leading edge and the grille stiffness.

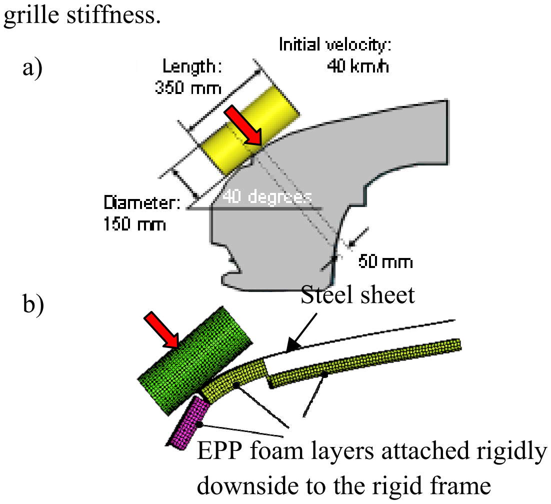

Figure 4. Impactor – hood leading edge FE simulations a) MS vehicle and b) MS buck

Since the stiffness of the hood varies from the leading edge to the cowl, two locations were chosen to determine the hood stiffness, and then were used in the buck calibration: 1) the middle region at a wrap-around distance (WAD) = 1200 mm – the location frequently struck by the dummy upper extremities and 2) the cowl region at WAD = 1500 mm – the location often struck by the dummy shoulder or head. A head impactor FE model developed by Untaroiu et al. (2007) and validated against static and dynamic tests reported by Matsui and Tanahashi (2004) was used in the hood impact simulations (Figure 5). The head impactor was launched freely at an impact angle of 65◦ in agreement with the requirements of the International Organization for Standardization (ISO) and the European Enhanced Vehicle Safety Committee (EEVC) protocols for a sedan type vehicle (Untaroiu et al. 2007). The time histories of the resultant forces in the impactor were calculated during the simulations, and then were normalized with the maximum force calculated in the hood in the POLAR II – vehicle simulation.

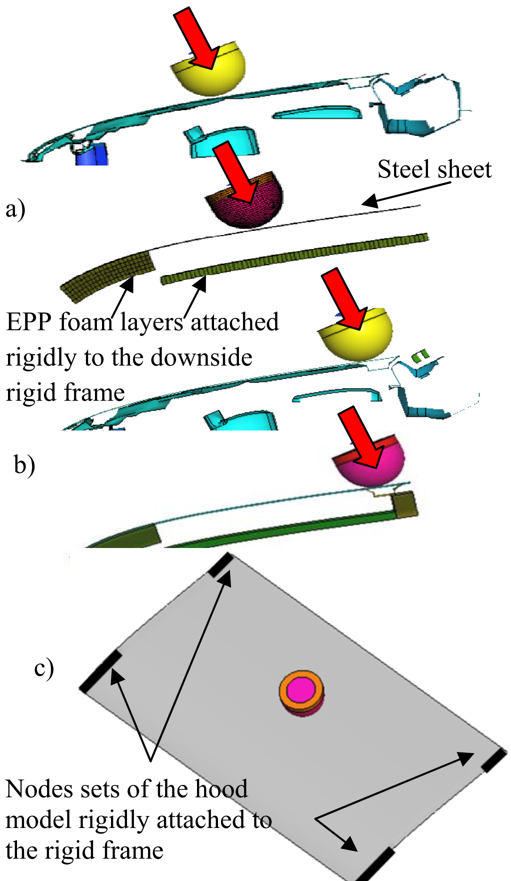

Figure 5. Head adult impactor – Hood FE simulations a) at WAD = 1200 mm, b) at WAD = 1500 mm, and c) The attachment of hood to the rigid buck frame

A glass windshield similar to that of the MS vehicle was used in the MS buck. All deformable parts were rigidly connected to the buck frame, with the total mass adjusted to that of the actual MS vehicle.

To verify the MS buck model, an impact simulation was performed with the POLAR II FE dummy with a configuration matched to those used in the POLAR II - MS vehicle simulation (Figure 1). The kinematics of the POLAR II and the reaction forces with the buck were calculated and then compared with the corresponding data from the POLAR II - MS vehicle simulation.

Development of a large-size sedan (LS) pedestrian buck

A similar design approach to that used for the MS pedestrian buck was utilized in the development of the LS pedestrian buck. The geometry of the LS buck was approximated based on the exterior contour of the LS vehicle (Kerrigan et al. 2007). Following Kerrigan et al. (2008), the rigid impactors were constrained to move in the impact direction with a prescribed velocity of 40 km/h. The stiffness curves obtained by FE simulations of that vehicle (Kerrigan et al. 2008) were used to calibrate the lower stiffener, the bumper, and the hood leading edge-grille components of the LS pedestrian buck. In the lower stiffener impact test, a cylindrical impactor (220 mm length, 120 mm diameter) was used. While a similar design to the MS buck was able to reasonably approximate the stiffness characteristics in the lower stiffener component of the LS buck (Figure 6 a), a different design approach was required for the LS bumper component. As in Kerrigan et al. 2008, an impact simulation with a rigid cylindrical impactor (800 mm length, 120 mm diameter) striking the MS buck complex of lower stiffener and bumper at 40 km/h was performed (Figure 6 b). The structure consisted of two EPP foam layers that were shown to provide the best approximation of the LS vehicle bumper in terms of the stiffness characteristics during the impact simulation.

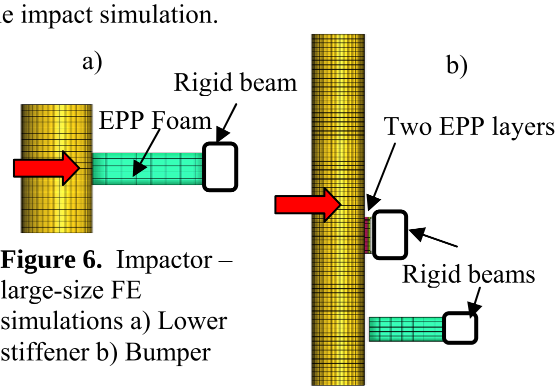

Figure 6. Impactor – large-size FE simulations a) Lower stiffener b) Bumper

A similar structure consisting of one EPP foam layer covered by a steel sheet was used for the hood leading edge–grille LS buck model. A impact simulation with a cylindrical impactor (300 mm length, 200 mm diameter) at a 40 degree angle from the vertical was performed as in Kerrigan et al. (2008) (Figure 7). The thickness of the foam layer and the steel sheet was adjusted to approximate the stiffness characteristics of the leading edge structure of the LS vehicle. Since stiffness of the hood structure in the LS vehicle model was not directly available, the hood design determined for the MS buck was also applied to the LS buck.

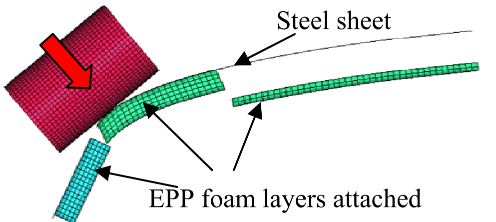

Figure 7. Impactot-to- hood leading edge – grille FE simulation (LS sedan)

Application: Study the influence of pre-braking and vehicle shape on the pedestrian kinematics

A study of the influence of braking and vehicle shape on the pedestrian kinematics was performed. A constant deceleration (1.0 g) and a forward pitching rotation (1 deg) were applied to the vehicle bucks based on the test data recorded in a large sedan during an in-house braking test (Autoliv). Two FE simulations with braking and non-braking conditions were run using MS and LS bucks, and POLAR II dummy in the same initial posture (Figures 1 and 8). The pedestrian dummy kinematics and the contact forces with the buck were calculated and compared among the cases.

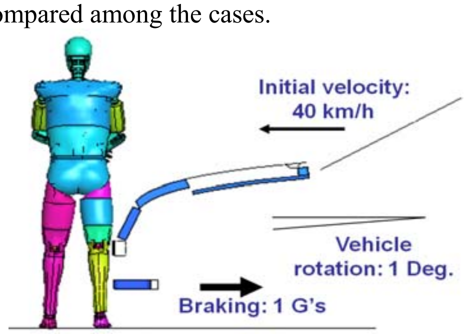

Figure 8. Pre-Impact Configuration of POLAR II – MS Buck impact FE simulation with braking condition

RESULTS

Development of a mid-size sedan (MS) pedestrian buck

A nonlinear trend was observed in the force time history in the lower stiffener impact simulation of the MS vehicle (Figure 9a). A rectangular prismatic part (200 x 55) made of EPP foam (20 g/l) and connected rigidly to the frame (Figure 10) provided an almost linear force time history which was considered to reasonably approximate the corresponding curve of the lower stiffener in MS vehicle. For the force time history of the bumper, a slightly increasing force was obtained until about 3 ms, followed by a high spikes in force at later times (Figure 9b). A fascia sheet with a 1.7 mm thickness (Figure 10) and a rectangular shape (34 mm x 67 mm) was used to model the bumper and exhibited a trend similar to the MS vehicle.

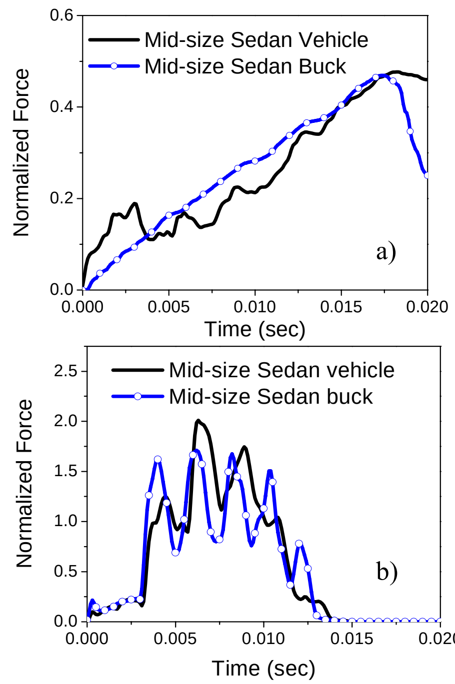

Figure 9. Time histories of the normalized contact force in FE simulations at a) lower stiffener and b) bumper locations

The force time history obtained in the impact with the MS vehicle at the hood leading edge location showed an almost linear increasing force (above the maximum force recorded in the pedestrian impact) that was followed by a plateau region at later times (Figure 11). Several designs of the buck hood leading edge which matched well the linear part of this curve in the component test were proposed. However, these designs recorded in the POLAR II – buck simulation much higher force levels at the hood leading edge location than the levels recorded in the POLAR II – vehicle simulation. The impact force obtained using a hood leading edge design of two rectangular prismatic layers of EPP foam 20 g/l (the final design) also showed a linearly increasing force trend , but with a lower slope than that of MS vehicle (Figure 11).

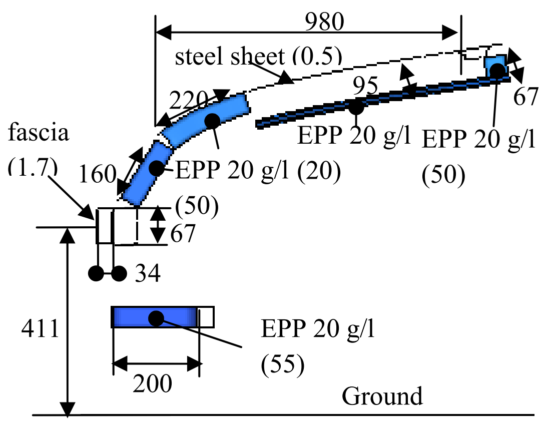

Figure 10. Schematic drawing of the MS pedestrian buck. All dimensions are in mm (thickness in parenthesis)

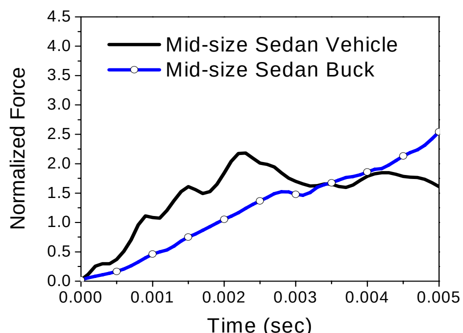

Figure 11. Time history of the normalized force in impactor-hood leading edge FE simulations

The time history of force at the interface between the head impactor and the hood showed a peak at about 4 ms followed a second slightly higher peak. The impactor simulation using a MS hood design, which consists of a steel sheet (0.5 mm thickness) connected at its corners (Figure 10), showed a very good match in the first part of the impact force time history. An EPP foam layer (20 g/l) was added under the hood in order to reduce the second peak of impact force (Figure 12). Several peaks were observed in the time history of impact force at the headform-cowl region impact (Figure 13). In the ME buck design, the force levels of the first and the last peaks were adjusted by changing the gap under the steel sheet and the thickness of EPP foam, respectively (Figure 10).

Validation of a mid-size sedan (MS) pedestrian buck in vehicle-to-pedestrian impact

The time histories of the impact forces calculated in the lower stiffener during POLAR II - MS buck simulation showed similar overall trend to the corresponding data calculated from the POLAR II - MS vehicle simulation (Figure 12). However, the force time history of the buck lower stiffener showed a slightly higher load peak, corresponding to the impact with the right leg (about 10 ms), and less fluctuation at the later times than the corresponding data from the vehicle simulation (Figure 14 a). A pattern of bi-modal peak forces, corresponding to the impacts with the right knee and then the left knee regions, were observed in both simulations (Figure 14 b). While the first peak had similar values to those in the MS vehicle simulations, the second peak in the MS buck simulation was about 40% higher.

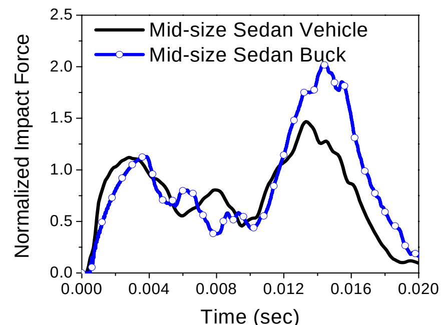

Figure 12. Time history of the normalized force in impactor-hood simulations at WAD =1200 mm impact locations

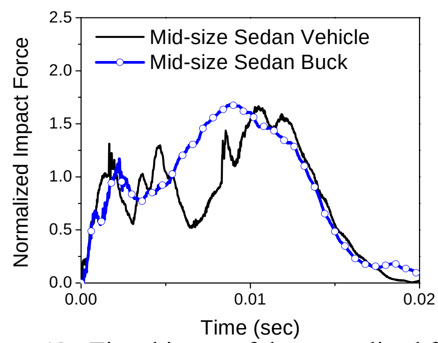

Figure 13. Time history of the normalized force in impactor - hood simulations at WAD = 1500 mm impact locations

The time histories of the forces at the hood leading edge and grille location showed a similar trend in the vehicle and buck simulations with a uniformly increasing force response during pelvis loading, and a decreasing force during the rebound of the pelvis (after 30 - 50 ms). However, the peak forces in the hood leading edge and the grille were higher in the MS buck simulation than in the MS vehicle simulation (Figure 14 c). The contact between the upper extremities and the hood occurred at the last part of the dummy- MS vehicle (buck). The time histories of the hood contact showed a similar trend in the vehicle and buck simulations, with slightly lower values in the buck simulation (Figure 14 d).

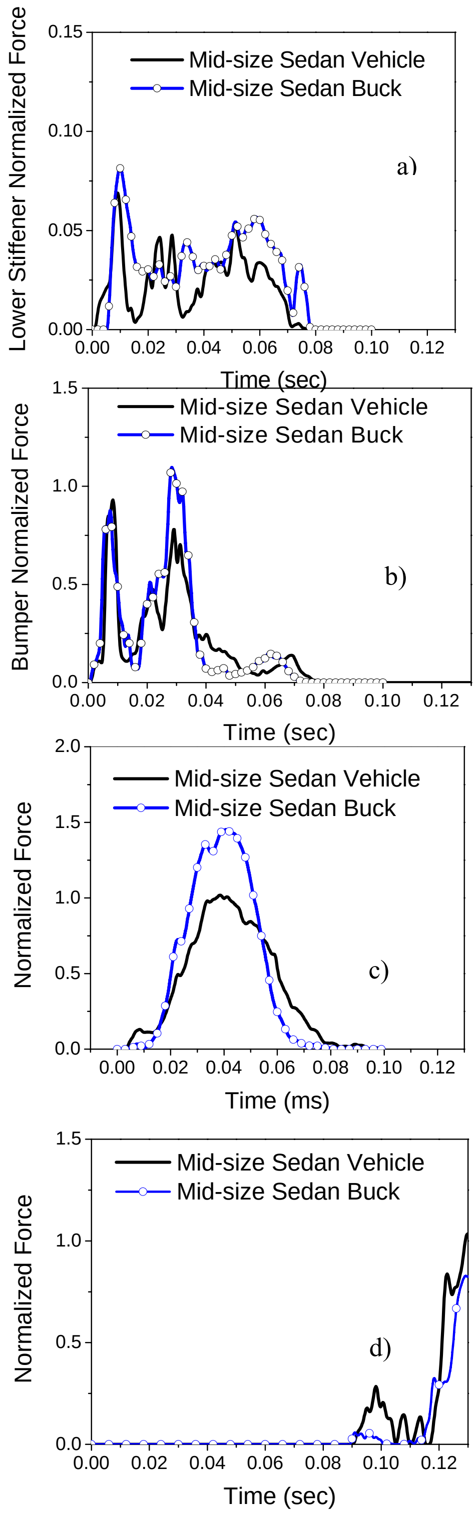

Figure 14. Time history of the normalized forces in POLAR II - vehicle/buck simulations a) lower stiffener contact b) bumper contact c) hood leading edge + grille contact, and d) hood contact

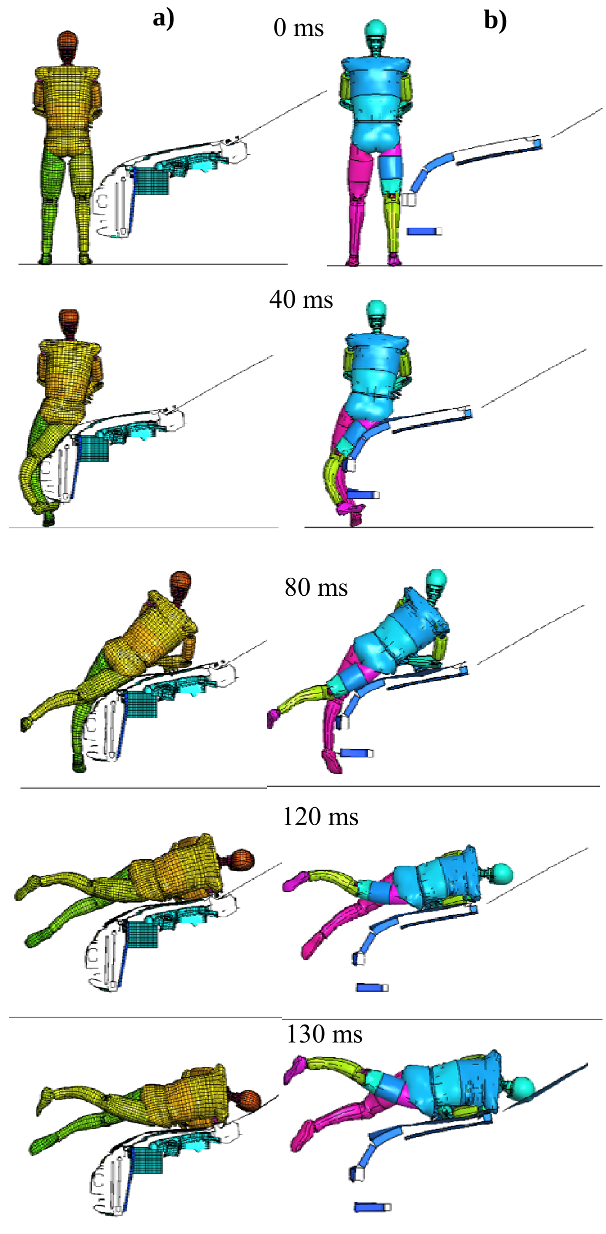

Figure 15. POLAR II dummy kinematics during the impact with a) mid-size sedan FE model and b) mid-size sedan buck FE model

The overall kinematics of the dummy during the impact with the MS buck model showed good visual correlation with the corresponding data from the MS vehicle impact simulation. However, at 120 ms and 130 ms it was observed that the right leg and the pelvis exhibited higher vertical displacements in the MS buck simulation than in the MS vehicle simulation.

The design of the MS lower stiffener was also used in the LS buck design (Figure 16). Although the time histories curves of the LS vehicle LS buck (Figure 17

a) have different trends (linear in LS buck, and nonlinear in LS vehicle), relatively small differences were observed up to about 1.5 kN. Similar trends and relatively small differences were observed in the stiffness curves of the LS vehicle and buck calculated during impact simulations at bumper plus lower stiffener (Figure 17 b) and hood leading edge plus grille (Figure 17 c) locations.

Good correlation can be observed between the trajectories of the upper body trajectories of the POLAR II dummy in the MS buck and vehicle simulations. The T1 and T8 trajectories for the MS vehicle and buck simulations are similar. However, the higher rotation of the POLAR II in the sagittal plane for the MS buck simulation compared to the MS vehicle simulation (Figure 15) generated a slightly lower and higher trajectory of the head location (Figure 18 a) and the pelvis location (Figure 18 d), respectively.

Significant differences are observed between the POLAR II upper body kinematics obtained in the LS and MS buck simulations. While the location of head-vehicle impact was at almost the same vertical level (about 1.1 m) in the LS and MS simulations, the horizontal level in the LS simulation was approximately 100 mm lower than in MS simulations. In addition, the dummy head contact for the MS vehicle occurred in the windshield region (Figure 19 a), while the dummy head - LS vehicle was observed in the cowl region (Figure 19 c). While the trajectories of T1 and T8 calculated in the impacts with MS and LS vehicles were almost identical, the horizontal level at head impact was shorter in the LS simulation than in MS simulation. A higher trajectory of the pelvis marker impact was observed after pelvis-buck interaction in the simulation with LS buck than with MS buck (Figure 18 d).

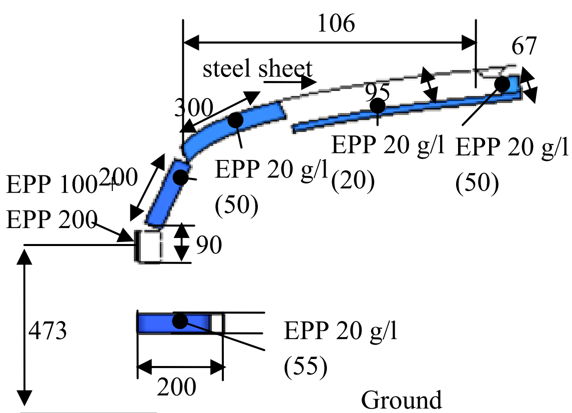

Figure 16. Schematic drawing of LS pedestrian buck. All dimensions are in mm (thickness in parenthesis)

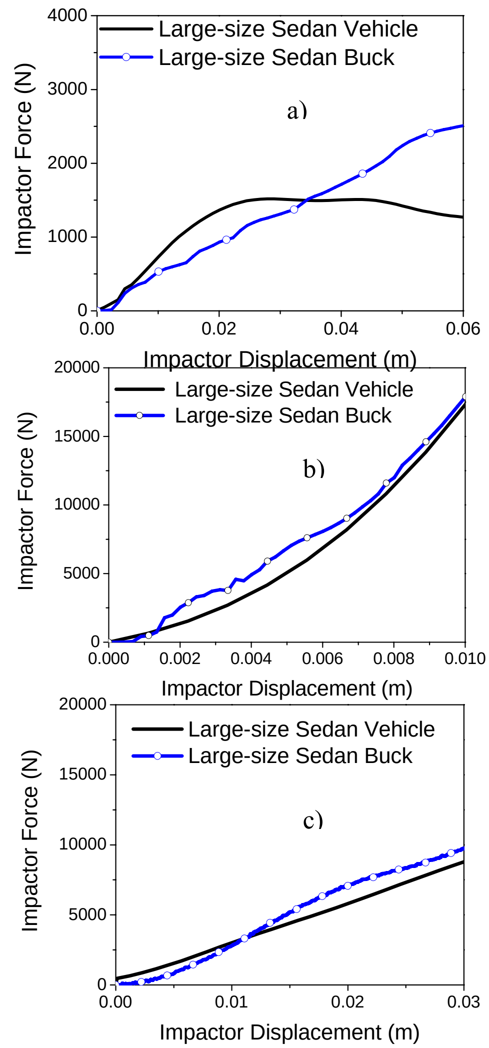

Figure 17. Force-displacement curves in impactor simulations a) lower stiffener b) bumper, and c) hood leading-edge

Application: Study of pre-braking and vehicle shape on the pedestrian kinematics

A comparison between the dummy configurations at the times of head-to-vehicle impacts showed that vehicle (buck) shapes and braking conditions have a significant influence on the head-to-vehicle contact locations (Figure 19) and to the velocity of dummy head relative to the vehicle (buck) (Figure 20). The contact points on the buck for the head-to vehicle impacts were located in the MS windshield regions (Figure 19 a-b) and the LS cowl regions (Figure 19 c-d) for both the braking and no-braking conditions. However, the braking conditions introduced a delay in the head contact time, and generated an increase in the WADs. In addition, both vehicle/buck shape and the braking conditions influenced the head velocities relative to the vehicle/buck (Figure 20). The velocity of the head relative to the vehicle was lower in the LS simulations than in the MS simulations and in the braking conditions relative to the no-braking conditions (Figure 20).

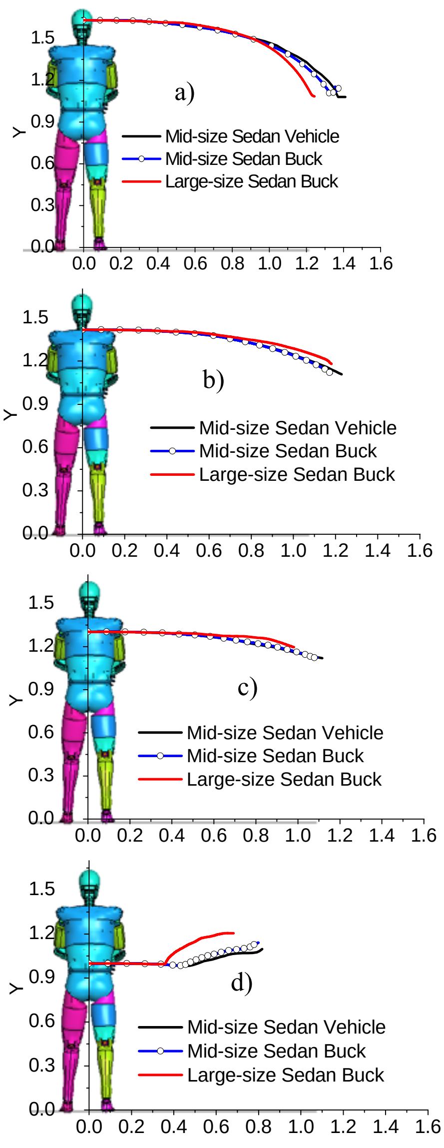

Figure 18. Comparisons of POLAR II upper body trajectories during the impacts with mid-size sedan vehicle, mid-size sedan buck, and large-size sedan buck. a) head, b) T1, c) T8, and d) pelvis

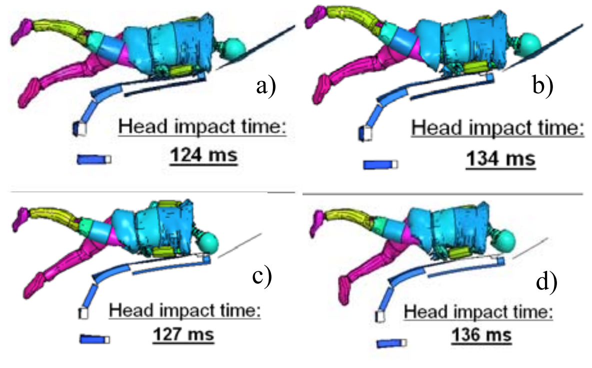

Figure 19. POLAR II - pedestrian buck configurations at the times of head-vehicle impacts a) mid-size buck b) mid-size buck with braking c) large-size buck and d) large-size buck with braking

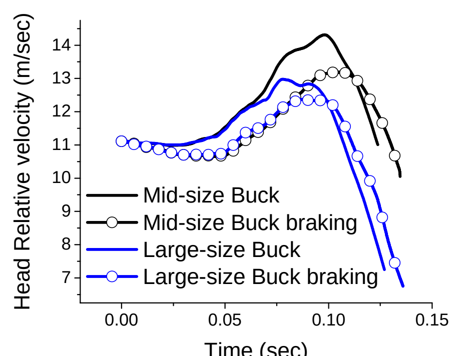

Figure 20. Head velocity relative to the mid/large -size sedan buck in braking/non-braking conditions

DISCUSSION

In addition to the pedestrian impactor tests used currently in regulations and consumer tests, the pedestrian dummy-to-vehicle impact test is a complementary way of investigating pedestrian protection. Given the high cost of experimentally testing a large number of vehicle front-end concepts, an alternative solution could be replacing the vehicle front end with a pedestrian buck that allows simple design changes in terms of vehicle shape and component stiffness parameters.

The design of a generic pedestrian buck (MS and LS configurations), which may reasonably replicate the behavior of sedan front ends in a pedestrian impact, was investigated in the current study. The deformable parts of the bucks were designed using three types of currently manufactured materials: steel, EPP (Expanded PolyProylene) foam (JSP Japan), and plastic fascia used in vehicle bumpers, which allow manufacturing the bucks in the future. While the contour cross-sections of the bucks were approximated based on the corresponding data of vehicles (Kerrigan et al. 2006, 2007), other cross-sectional dimensions were determined using FE simulations to approximate the stiffness characteristics of front end structures. Impactor-to-vehicle simulations were used to determine the dynamic stiffness of main components of vehicle front ends, such as: lower stiffener, bumper, grille, hood leading edge and hood.

The lower stiffener is located below the bumper system, and prevents the pedestrian's leg from moving underneath the vehicle. Its main role for pedestrian interactions is to reduce the risk of severe knee joint injuries such as ligament ruptures by limiting the knee bend angle (Schuster 2006). A buck component with a prismatic shape (55mm x 200 mm in cross-section) and made of EPP foam (20 g/l) was chosen in the buck design. The force time histories and stiffness curves of the vehicle lower stiffeners showed a nonlinear increasing trend in impactor tests, in contrast to linear trend observed in the lower stiffener of the buck. However, the time history of lower stiffener force in dummy - MS buck simulation had similar trend like the corresponding data from MS vehicle impact, but slightly higher peaks values. Although the lower stiffener component have a low influence on the pedestrian kinematics (especially on upper body) by low load applied during the impact, future studies should try to improve the current design, especially if the buck will be used in prevention studies of lower extremities injuries.

The bumper is the first vehicle component to contact the pedestrian and the level of impact force is high. The bumper system in sedan vehicles usually consists of an energy absorber component (bumper cover, deformable foam etc.) in front of a semi-rigid beam. A fascia sheet (1.7mm thickness) connected to a rigid beam approximated the MS bumper up to the maximum force observed in the dummy-MS simulation. In addition, the time histories of the bumper force in the dummy-MS buck simulation showed similar trends and values as the MS vehicle simulation. The higher peak values predicted at 30 ms may be caused by the higher stiffness of buck bumper at larger deformations. The stiffness of the LS bumper showed an increasing trend, which was well matched using a two-layer bumper design (EPP foams with densities of 100 g/l and 200 g/l, respectively). Although current designs of buck bumpers showed to approximate well the stiffness properties of vehicle bumpers, better designs can be obtained using optimization techniques (Untaroiu et al. 2007).

The leading edge of the hood is the vehicle component that usually contacts the pelvis of adult pedestrian during the impact. Depending on its position relative to the hip joint, the pelvis can slide along the hood or can be pinned at the contact point (Kerrigan et al. 2007, Untaroiu et al. 2007). Since the pelvis-to-vehicle contact is complex, the design of this region was the most challenging task of the pedestrian buck design. After trying several design concepts, it was decided that a design consisting of two low densities EPP (20 g/l) blocks, which approximate the shape of the hood leading edge and the grille, reasonably replicate this vehicle component response in the buck design. The time history of MS buck force shows a linear trend with values relatively close to the curve obtained from the MS vehicle impact which has an initial slope followed by a plateau region. However, the results of the dummy-MS vehicle simulation showed a higher stiffness for the MS buck in the contact with the dummy pelvis, especially in the grille region. While the MS buck was softer than the vehicle in the impactor test, this finding suggests that the leading edge impactor test may poorly approximate the conditions of a dummy pedestrian impact. Therefore, a new impactor test or even the whole dummy-vehicle simulation should be used for a better stiffness calibration of this region in a future design. The stiffness curve, obtained from the impact between the constrained impactor with a constant impact velocity (40 km/h) and the hood leading edge - grille component of the buck, showed a closed trend to the stiffness curve reported by Kerrigan et al. (2008).

A steel sheet rigidly connected at its corners, with one EPP foam layer showed to approximate well the hood behavior during simulations with adult headform impactor at both middle and cowl impact locations. Although the hood contact force in MS vehicle and MS buck showed good correlation with the corresponding data from the POLAR II - MS vehicle simulation, the level of force between shoulder and hood was low because the head impacted the windshield. Therefore, future studies of MS vehicle impacts with a dummy having a different anthropometry (e.g., the 5th female used in Untaroiu et al. 2008) may be used to verify the hood design of buck in a dummy-vehicle simulation.

Since previous pedestrian studies have investigated the pedestrian kinematics until the head-to-vehicle contact (Kerrigan et al. 2005, 2007), the windshield was included as a buck component but stiffness studies of this component were not performed in the current study. FE models of the buck may be improved in future studies by using recently developed material model of laminated glass (Timmel et al. 2007) when dynamic test data of the sedan windshields will be available.

A parametric study using the same dummy FE model, but different buck shapes (MS and LS) showed a possible application of buck models in the study of an automatic braking system for reducing pedestrian injuries. While the pre-braking condition showed reductions in the relative velocity of head with the vehicle at the head-vehicle impact and increase the pedestrian WAD, the vehicle shape showed a significant influence on the velocity speed and the vehicle component impacted by the pedestrian head. More parametric studies may be run in the future, with different braking parameters, and dummy anthropometries. The simplified FE models of vehicle can be easily used in different optimization studies of vehicle shape and stiffness and restraint systems for pedestrian protection. In addition, a physical buck developed based on the design concepts of this study may be manufactured and used to validate the new pedestrian protection design in dummy-pedestrian buck crashes.

CONCLUSIONS

This numerical study showed that a simplified pedestrian buck consisting of five components: lower stiffener, bumper, hood leading edge-grille, hood and windshield; can reasonably approximate the vehicle front structures during the lateral impact of a POLAR II dummy. The geometry of the buck FE models was developed based on the contour-cross-sections corresponding to a mid-size and a large-size sedan vehicle used in previous vehicle-to-dummy and cadaver tests. The material properties of current polymeric products were used for the FE models of the buck components in order to allow manufacturing a physical implementation of the generic pedestrian buck in the future. Simulations of interactions between impactors and vehicle component were used to correlate the dynamic stiffness of buck components with the corresponding data of vehicle models. The hood lower edge-grille component designed based on impactor simulations showed poor correlation during the dummy –vehicle impact simulations. This poor correlation may be caused by the complex contact between the pelvis and vehicle which is poorly reproduced in the component test. In a parametric study using FE impact simulations of POLAR II dummy and pedestrian buck models, it was shown that the vehicle braking conditions reduce the relative velocity of the head to the vehicle and increase the time of head impact and wrap-around-distances (WAD) to primary head contact. In addition, different buck shapes (e.g. MS buck and a large-size sedan - LS buck) showed a higher sensitivity to pedestrian kinematics (e.g. relative head impact velocity) than to the braking conditions over the range of conditions examined in this study. The pedestrian buck models developed in the current study may be used for future optimization studies of pedestrian protection systems (e.g. airbags, automatic braking etc) and in manufacturing a physical pedestrian buck, which could, in turn, be used to validate pedestrian protection systems.

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