Full-scale Validation of a Generic Buck for Pedestrian Impact Simulation

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Abstract Due to the lack of the definition of a generic buck for full-scale car-pedestrian impact tests, it was not possible to develop standardized trajectory corridors for validating the biofidelity of a full-scale pedestrian dummy in whole-body kinematics. The objective of this study was to validate the buck representing sedans developed by the authors' group against cars in the sedan category at the full-scale level in terms of the representativeness of car-pedestrian interactions.

Full-scale lateral impact tests were conducted using the buck and the POLAR II pedestrian dummy at 40 km/h, and the tests were simulated using FE models of the buck and the pedestrian dummy to validate the buck model at the full-scale level. The validated buck model was used to simulate a car-pedestrian lateral impact at 40 km/h using a human FE model previously developed by the authors. The representativeness of the buck was validated against a combined dataset from five FE models of production cars and estimation of APROSYS (Advanced Protection Systems) data representing the sedan category, showing that the trajectories, contact forces and injury measures from the buck model generally fell within their variations among the cars in the category represented by the buck.

Keywords Buck, Dummy, Full-body kinematics, Human model, Pedestrian

I. INTRODUCTION

[1]In order to address pedestrian safety performance of vehicles, subsystem test procedures based on the one developed by the European Enhanced Vehicle-safety Committee (EEVC) [1] have been widely used in regulations and new car assessment programs. The test procedures use the subsystem impactors representing isolated body regions including the head (adult and child headforms), the pelvis and the thigh (upper legform), and the lower limb (legform). Subsystem test procedures are beneficial to evaluating vehicle front-end structures in that various impact locations cover a wide range of vehicle front surface area potentially causing pedestrian injuries, along with repeatability and reproducibility of test results due to simplified structure of the subsystem impactors and the impact conditions. When it comes to simulation of actual car-pedestrian interaction, however, it is necessary to use a full-scale pedestrian dummy to investigate pedestrian injury mechanisms. For example, the change in the stiffness of the bumper would result in the difference in lower limb injury measures, which would also alter head injury measures through the change in the upper body kinematics. This sort of interaction between responses of different body regions needs to be simulated using a full-scale dummy rather than subsystem impactors representing isolated body regions individually.

For the purpose of specifying the performance requirements for a full-scale mid-sized adult male pedestrian dummy that can be used to study pedestrian-vehicle interactions, relevant information reports (J2782 and J2868) have been developed and published under the auspices of the Society of Automotive Engineers (SAE) Human Biomechanics And Simulations Standards Steering Committee (HBSSC) that specify performance specifications for full-scale pedestrian dummies [2-3]. J2782 specifies performance requirements for a full-scale pedestrian dummy, including geometric and inertial characteristics, biofidelity, and repeatability and reproducibility of the whole body and the components representing a particular body region. The biofidelity of the whole body is required to be validated by means of a full-scale impact test with respect to the trajectories of

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the head centroid, upper spine, mid-thorax and pelvis, along with the head centroid velocity. However, due to the lack of a standardized vehicle-like buck to be used in the full-scale test, no specific requirements are described in the document and only example test results using a buck mounting a specific production car are presented in J2868. For this reason, there has been a strong need for the development of a generic buck for full-scale impact tests. In addition, the development of a generic buck is beneficial from a viewpoint of pedestrian injury mechanism analysis. As discussed by the authors in their previous studies [4-5], the geometric and stiffness characteristics of a car front-end structure significantly influence the dynamic response of a pedestrian in a full-scale impact with the car. Therefore, a generic buck that allows individual change of geometric and stiffness parameters would significantly contribute to the investigation of the effect of car front-end characteristics on pedestrian loading and resulting injury potential.

The authors' group has been working on the development and validation of a generic buck representing the sedan category to address these practical and research needs. Aiming for generic representation of the characteristics of cars in this category, a generic buck was designed and validated against geometric and stiffness data from cars in the same category at the component level [6]. In the course of the development and component validation, an FE model of the full assembly of the generic buck was developed and used for the validation of the component responses of the buck against the data from the European APROSYS (Advanced Protection Systems) project [7] for the corresponding category. However, the buck still needed to be validated in a full-scale impact configuration, in which the buck is supposed to be used for the biofidelity evaluation of a full-scale pedestrian dummy.

The goal of this study was to validate the generic buck representing cars in the sedan category developed by the authors' group [6] in terms of generic representation of kinematic and kinetic responses of a pedestrian in a full-scale impact configuration. The FE model of the full assembly of the buck developed by the authors' group [6] was validated against full-scale impact tests using the POLAR II pedestrian dummy [9-10]. Using the validated FE model of the buck, a full-scale impact simulation was conducted against a human FE model. Five representative FE models of production cars in the sedan category were also made to collide with the same human model to estimate the results for the cars used in the APROSYS project and compare kinematics and kinetics with the combined dataset of the results from the representative cars and the estimated results of the cars used in the APROSYS project to evaluate how well the generic buck represents cars in the sedan category.

II. METHODS

For the purpose of evaluating full-scale pedestrian dummies in full-scale impact tests, it would be preferred to use a simplified structure of a buck, rather than a complex structure that would increase variability of the test results, to ensure repeatability and reproducibility of the buck responses. For this reason, the buck developed by the authors' group [6] representing cars in the sedan category is not intended to precisely represent one particular car in the category but to represent generic characteristics of cars in the same category. In the current study, therefore, the validation of representation of kinematic and kinetic responses of a pedestrian in a full-scale impact configuration was conducted by comparing the responses from the buck with the response variations from various cars in the category, rather than comparing them with those from a particular car. In other words, if it was confirmed that each of the responses from the buck was within the response variation from different cars in the sedan category, the buck was considered to generally represent the category.

Validation of Buck Model

Validation of generic representation of car-pedestrian interactions from the cars in the sedan category would require response data from multiple cars in the category to be compared with those from the buck. In this study, this was done computationally using FE models of multiple production cars. In order to develop a dataset of a larger sample size to be used for the generality validation, the results from the five representative cars were used to estimate the results from the cars in the APROSYS project and develop a combined dataset of the results of the representative cars and the estimated APROSYS data. Although the study done by the authors' group [6] has validated the components of the buck against experimental data, this study validated the FE model of the full assembly of the buck at the full-scale level against full-scale impact tests using a pedestrian dummy.

Full-Scale Impact Test: The buck represents the front-end structure of cars in the sedan category by six components; lower bumper, bumper, grille, hood edge, hood and windshield. The energy-absorbing components representing the lower bumper, bumper and grille were all made of polyethylene (PE-300). The hood edge and hood were made of steel with a yield stress of 230 GPa, and polycarbonate (Lexan® 9030) was used for the windshield. These components were rigidly mounted on a steel frame. Further details of the buck specifications are given in Pipkorn et al. [6]. Six full-scale impact tests were conducted using the full assembly of the buck and the POLAR II pedestrian dummy [9-10]. The test conditions were determined in accordance with the test methods for whole body biofidelity evaluation specified in SAE J2782 [2] as illustrated in Figure 1. The buck was made to collide with the POLAR II pedestrian dummy [9-10] at 40 km/h (average: 40.15 km/h, standard deviation: 0.08 km/h) laterally from the right. The posture of the dummy was determined in accordance with SAE J2782. The release mechanism for the tether supporting the dummy was activated 35 ± 5 ms prior to the impact. The dummy was initially positioned on a polystyrene block with a plastic sheet on top simulating the ground, which collided with the buck after the feet of the dummy came off the simulated ground after impact. Photo targets were rigidly mounted on the back of the dummy at upper spine, mid-thorax and pelvis positioned in accordance with the requirements specified in SAE J2782 (Figure 1). High-speed video was recorded using a posterior view of the pedestrian dummy. The trajectories of the photo targets along with the head centroid with respect to the buck were calculated using the film analysis procedures specified in SAE J2782. The buck was equipped with load cells to measure the reaction forces of the components as presented in Figure 2. Uniaxial load cells were used on both sides of the lower bumper and the bumper, and tri-axial load cells were used on both sides of the grille and the hood edge.

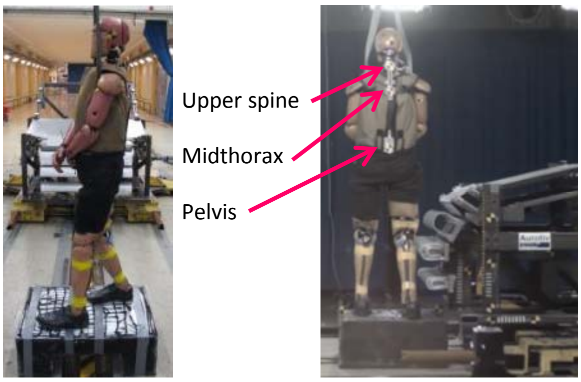

Fig. 1. Setup of full-scale impact test

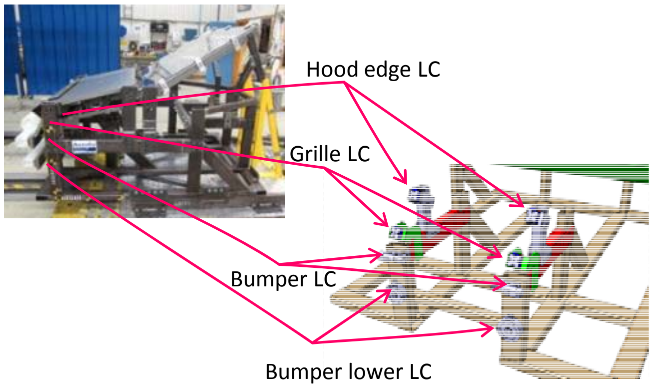

Fig. 2. Location of load cells

Full-Scale Impact Simulation: The full-scale impact tests using the full assembly of the buck was simulated using FE models of the buck and the POLAR II pedestrian dummy. Figure 3 shows the FE model for the buck developed by Pipkorn et al. [6]. Although the original model was developed in LS-DYNA, the model was converted to that in PAM-CRASH because the generality of the buck was validated by means of impact simulations against the human FE model developed in PAM-CRASH. The lower bumper and the bumper with a double-layered structure of polyethylene were modeled using shell elements attached to the back beam modeled by solid elements. Similarly, the grille with essentially the same structure as that of the lower bumper and the bumper but with only one layer of polyethylene was modeled using shell and solid elements. The hood edge made of steel was modeled using shell elements and the back beam with support columns was modeled using solid elements. The steel hood modeled with shell elements and the steel frame behind the hood modeled using shell elements were connected at riveted locations by means of nodal constraint that fixed all translational degree of freedom without any restriction in rotational degree of freedom. The hood assembly model was supported at the corners by the support rigs modeled as rigid bodies. The polycarbonate windshield was modeled using shell elements backed up with a frame consisting of a steel rectangular tube modeled using shell elements. The windshield was rigidly attached to the back-up frame at several locations corresponding to the clamp locations. Considering that the steel frame of the buck to which these components are attached is virtually rigid, the frame was not modeled, except the part of the frame behind the hood assembly which was modeled as a rigid body. 1500 kg nodal mass was applied to the node located at the center of gravity of the buck. The node was rigidly connected to the rear ends of the load cell attachments of the back beam for the lower bumper, bumper, grille and hood edge, four support rigs for the hood assembly, the frame behind the hood assembly and four corners of the frame supporting the windshield. Elasto-plastic material model was applied to the back beam for the lower bumper, bumper, grille and hood edge. Elasto-plastic rate-dependent material model was applied to the lower bumper, bumper, grille, hood edge, hood, windshield and back-up frame for the windshield.

The FE model of the POLAR II pedestrian dummy developed by Takahashi et al. [11] and Shin et al. [12] illustrated in Figure 4 was used. The deformable parts of the dummy such as the flesh/skin, abdominal insert, deformable part of the neck, thoracic and lumbar joints, shoulder pad, shoulder stopper rubber and tibia shaft were modeled using deformable solid elements. Other rigid components were modeled as rigid bodies by specifying the mass and moment of inertia of the rigid segment around its center of gravity. The rigid components were connected using joint elements except for the knee joint constrained by a combination of bar (representing the ligament wires) and spring elements. Similarly, the neck ligaments were modeled using a combination of bar and spring elements. The models of the deformable components were individually validated against experiments with various loading configurations quasi-statically and dynamically. The knee joint response was validated against dynamic lateral loading tests in the knee bending and shear setups. The torso model was validated against thoracic and abdominal impact tests. The trajectories of the head CG, upper spine, mid-thorax and pelvis were validated against the full-scale impact tests using the same dummy and a small sedan.

The buck model was made to collide with the POLAR II model laterally at 40 km/h by specifying the initial velocity to the node with a concentrated nodal mass and allowing only translation in the longitudinal direction of the buck. The trajectories of the head CG, upper spine, mid-thorax and pelvis with respect to the buck along with the reaction forces measured at the load cell locations for the lower bumper, bumper, grille and hood edge were compared between the experiment and the FE simulation to validate the FE buck model in a full-scale car-pedestrian impact configuration.

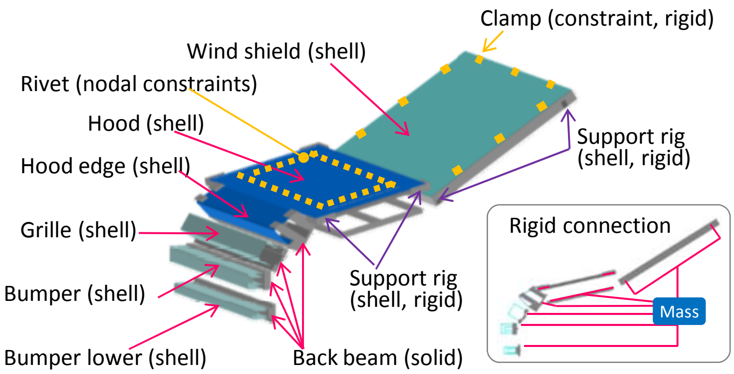

Fig. 3. Sedan buck FE model

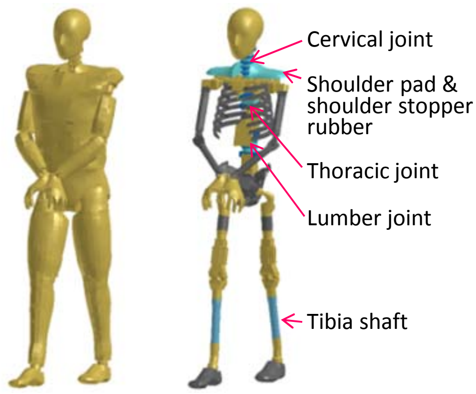

Fig. 4. POLAR II FE model

Validation of Generality of Sedan Buck

Using the validated FE buck model, a full-scale impact simulation was conducted against a human FE model. In order to enhance the generality of the buck representation, the thicknesses of the PE sheets of the lower bumper and the steel plate of the hood edge of the buck model were changed from 2.0 mm to 1.5 mm and from 0.5 mm to 1.0 mm, respectively, relative to the model developed by Pipkorn et al. [6]. Five representative production cars were chosen from the sedan category to compare the kinematic and kinetic responses of the human model in a full-scale impact simulation and validate generality of the buck representation. FE models of these five production cars were also made to collide with the same human model to compare kinematics and kinetics to evaluate the generality of the buck representation of the sedan category.

Representative Cars in Sedan Category: Figure 5 shows the FE models for the five production cars chosen for the study. Car-1 is a relatively old model from the US market with the bumper complying with the bumper damageability requirements. Car-2 through Car-5 are newer models all released within 10 years. Although not subjected to official Euro NCAP tests, four out of five cars are rated green with a full score for the upper legform and legform tests when tested at the mid-section based on the results of the computer simulations of these tests. The hood edge of Car-3 is much higher than the other four cars. Figure 6 compares the contours of the mid-section of the five cars with those from the report of the European APROSYS (Advanced Protection Systems) project [7] for the sedan (small family car) category, confirming that the geometry of the five representative vehicles are within the variation of the cars in this category in terms of geometry. The upper legform and legform impact simulations were conducted using the FE models of the five cars, and stiffness characteristics were calculated using the force and linear acceleration data from the upper legform and legform simulations, respectively, by following the procedure specified by the APROSYS report [8]. Figure 7 compares the force-deflection response from the upper legform and legform impact simulations of the five representative cars with the average, upper bound and lower bound of the force-deflection curves determined from the APROSYS report [8] for the cars rated green by Euro NCAP for the corresponding tests. The cars rated green were chosen based on the recent advancement of pedestrian safety technology. The comparisons show some difference in the stiffness characteristics of the five cars from the APROSYS data particularly for the upper legform test. This difference most likely comes from higher safety performance of the newer models included in the five representative cars. Considering the larger sample size in the APROSYS report [8], it was decided to compare the buck with the combined dataset of the four out of five representative cars rated green and the data estimated for the cars rated green in the APROSYS report [8] from the four representative cars. The estimation was necessary due to the lack of the results of the human model impact simulation for the cars in the APROSYS report [8]. Similarly, the trajectory corridors used to compare with the buck results were also determined from the combined dataset of the five representative cars and the estimated results of the cars in the APROSYS report [7].

Fig. 5. FE models for the five production cars

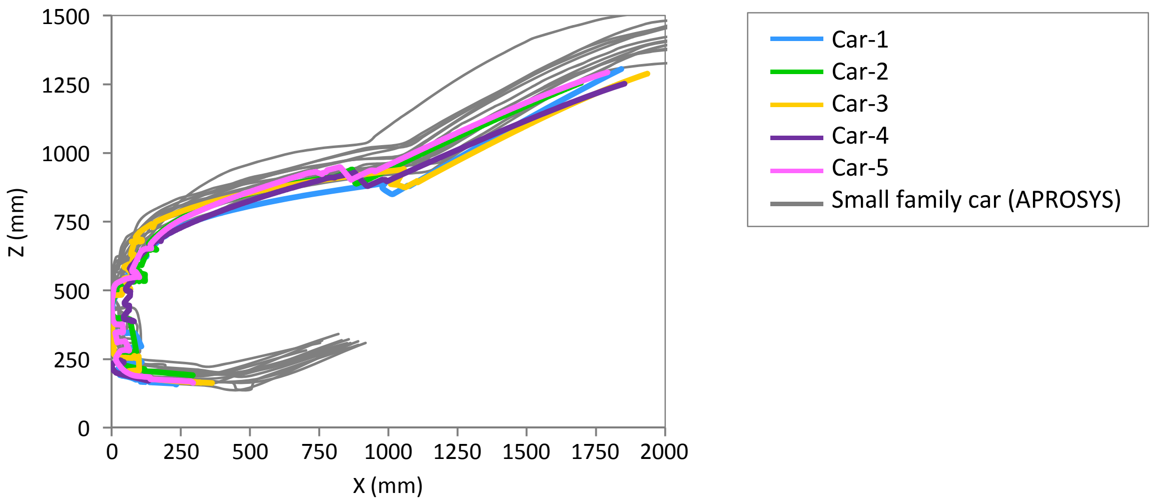

Fig. 6. Comparison of the mid-section of the five cars and sedans from APROSYS

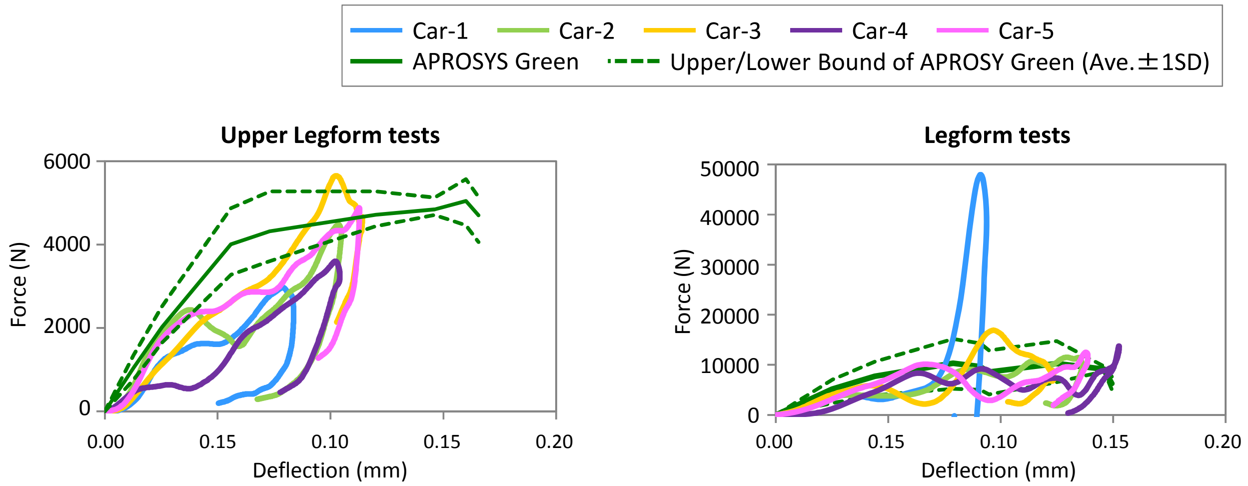

Fig. 7. Comparison of the force-deflection responses from the upper legform and legform impacts

Human Model Impact Simulations: The human FE model approximating the anthropometry of an average male developed by the authors in their previous study [4] was used in full-scale impact simulations. The pelvis and the lower limbs are modeled with shell and solid elements to allow evaluation of the probability of injuries based on tissue level injury metrics. The pelvis model and the lower limb model have been extensively validated under quasi-static and dynamic conditions against published experiments, including lateral compression of the pelvis in acetabulum and iliac loadings, 3-point bending of the thigh, femur, leg, tibia and fibula at multiple loading locations, tension of the individual knee ligament and 4-point valgus bending of an isolated knee joint. The upper body is modeled using articulated rigid bodies with all of the seven cervical and five lumbar vertebrae individually modeled to represent flexibility of these regions. The assembled full-body model has been validated against published full-scale pedestrian impact tests in terms of the trajectories of the head CG, upper spine, mid-thorax and pelvis, along with the comparison of predicted injuries with those from the experiment in collisions with a sled buck mounting the body of a small sedan and a large SUV.

FE models for the five representative cars along with the sedan buck were made to collide with the human model laterally from the right at 40 km/h. Figure 8 shows the configuration of the impact simulations. Similar to the full-scale impact tests and simulations for the POLAR II dummy, the human model was positioned in accordance with SAE J2782. The target points at the head CG, upper spine, mid-thorax and pelvis shown in Figure 8 were used to determine trajectories with respect to the car and buck models. The time histories of the pelvis and lower limb injury measures, including the pelvis deflection, femur bending moment, MCL tensile strain and tibia bending moment, were measured at the locations specified in Figure 8. In addition, the contact force time histories between the human model and each of the lower bumper, bumper, grille and hood (including hood edge) were measured. Since the models for the five representative cars were full FE models of production cars, these car models did not have a separate hood edge component. For this reason, the contact force between the human model and the hood edge was included in the contact force of the hood, although there was a clear definition of an individual hood edge component exclusively for the buck model.

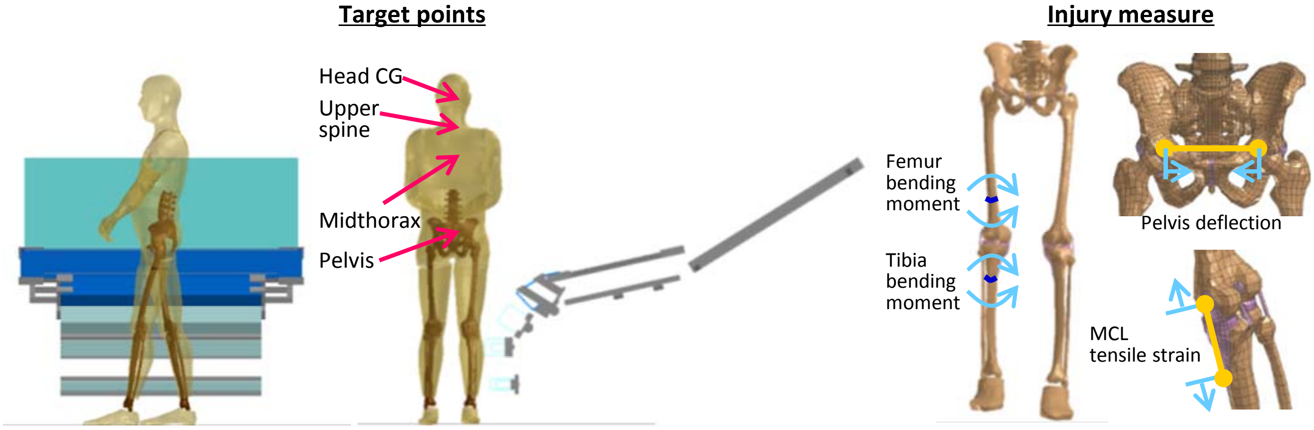

Fig. 8. Setup of impact simulation

The trajectories with respect to the car or buck model along with the peak values of the pelvis and lower limb injury measures and the contact forces were compared between the buck model and the combined dataset of the representative car models and the APROSYS data to validate the generality of the buck representation of the cars in the sedan category. As discussed earlier in this paper, this study aimed to compare the buck results with the variations of the car results. Since the number of representative cars was limited, comparisons were made with the combinations of the representative cars and the cars from the APROSYS report [7-8]. Due to the lack of the results of the human model impacts, however, the results for the cars in the APROSYS report [7-8] were estimated from those of the representative cars. To this end, procedures to estimate the trajectories and the peak values of the injury measures and the contact forces for the cars in the APROSYS report [7-8] from the representative cars were utilized to validate the generality of the buck. All of the five representative cars were used to estimate trajectories from the cars in the APROSYS report [7] considering that the front-end geometry of the five cars falls within the variation of the APROSYS cars, and that the geometry would be the most significant contributor to pedestrian whole-body kinematics. In contrast, only four out of five representative cars were used to estimate the injury measures and the contact forces from the cars in the APROSYS report [8] because recent advancement of pedestrian safety technology would require the representation of higher-performance cars in the sedan category, and thus only the cars rated green in the Euro NCAP tests were chosen from the five representative cars and the cars in the APROSYS report [8].

In this study, X and Z directions were defined as the car longitudinal and vertical directions, respectively. Figure 9 shows the procedure to estimate the trajectories with respect to the cars for the cars in the APROSYS report [7] from the results of the five representative cars. The procedure included the following steps;

Step-1: The trajectories of the head CG, upper spine, mid-thorax and pelvis of the human model with respect to the car model were created for the five representative car models. The head trajectories were terminated at the time of head contact with the car. The trajectories for other locations were terminated at the time of peak contact force between the corresponding body region and the car.

Step-2: For each of the five car models, the contour of the mid-section of the car model was created and the hood edge height was measured. In addition, the end points of the four trajectories were projected normally onto the contour to determine the Wrap Around Distance (WAD) of each of the projected points.

Step-3: For each of the four measurement locations for the trajectories, a linear correlation function was determined from the plot of WAD against the hood edge height for the five cars.

Step-4: The hood edge height was measured for each of the 14 cars from the APROSYS report [7]. The hood edge height was then converted to WAD of each of the four measurement locations for the trajectories using the correlation function of the corresponding location determined in Step-3. This step determined the points on the car contour corresponding to WAD for the four measurement locations of the trajectories. These points were interpreted as the projection of the end points of the trajectories. The points were then moved normal to the surface of the car contour by a half of the width of the corresponding body region to determine estimated end points of the four trajectories for the car.

Step-5: For each of the four measurement locations of the trajectories, the variation of the combined dataset of the end points estimated for the 14 cars from the APROSYS report [7] and the end points for the five representative cars was determined using the average and 1SD of the combined end points. The upper right and lower left corners of the rectangle representing the variation of the combined end points were used to determine the upper and lower bounds of the trajectory corridor estimated for the APROSYS data by scaling normalized trajectories determined from those of the five car models.

The definition of the termination time in Step-1 was necessary to estimate the end points of the trajectories for the cars in the APROSYS report [7] as performed in Step-4. The linear correlation function determined in Step-3 was used to account for the difference in sliding of a pedestrian body due to the difference in the hood edge height, assuming that the sliding motion of a pedestrian is determined by the hood edge height. The procedure used to estimate the end points of the trajectories in Step-4 approximated the distance between the contact point on the car surface and the measurement location on the human model located in the mid-sagittal section with a half of the width of the corresponding body region of the measurement location. 1SD was used to estimate the variation of the combined dataset of the estimated APROSYS data and the results of the five representative cars to represent the variation of the car in the category.

The procedure to calculate the normalized trajectories is presented in Figure 10. The procedure includes the following steps;

Step-1: For each of the four measurement locations of the trajectories, five trajectories with respect to the car were created. The trajectories were the same as those created in Step-1 presented in Figure 9.

Step-2: For each of the four measurement locations of the trajectories, the X and Z coordinates of the end points of the five trajectories with respect to the initial measurement location were normalized by their coordinates. As a result, normalized X and Z coordinates become 1.0 for all of the five trajectories.

Step-3: For each of the four measurement locations of the trajectories, the normalized trajectories from Step-2 have the same start and end points for all of the five trajectories. The normalized five trajectories were averaged for Z coordinates to determine the average normalized trajectory.

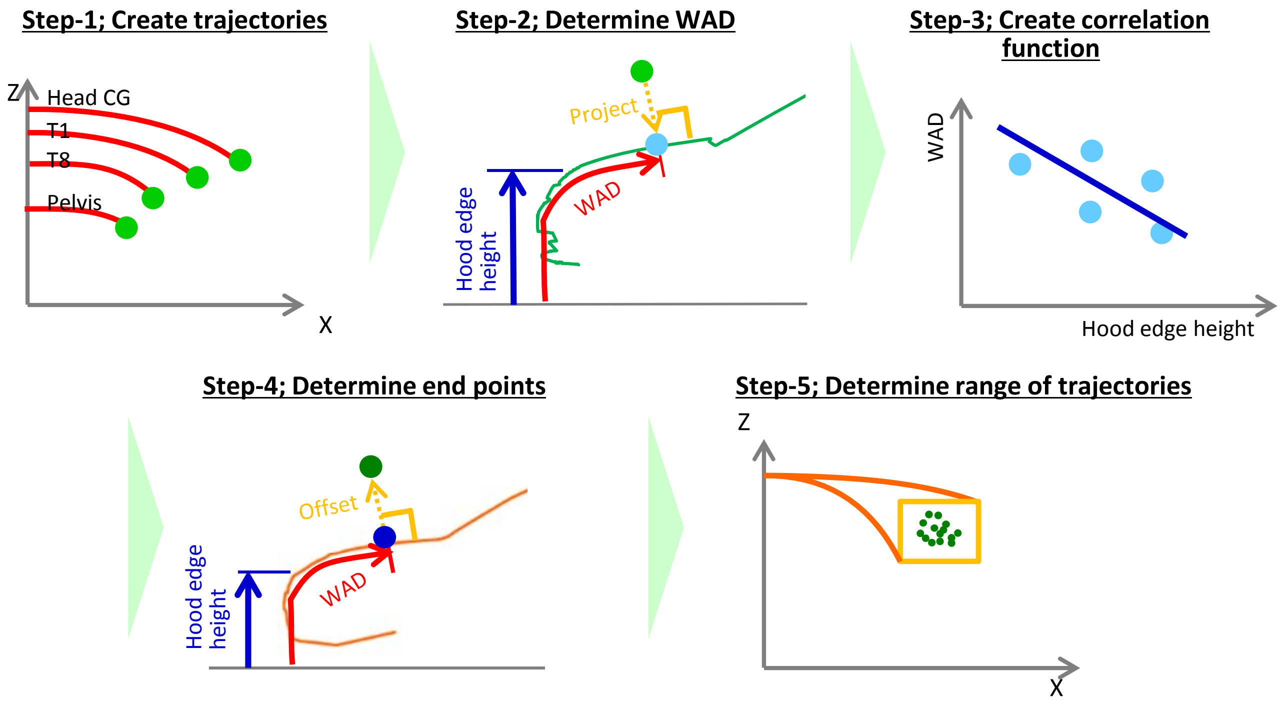

Fig. 9. Procedure to estimate the trajectories for the cars in the APROSYS report [7]

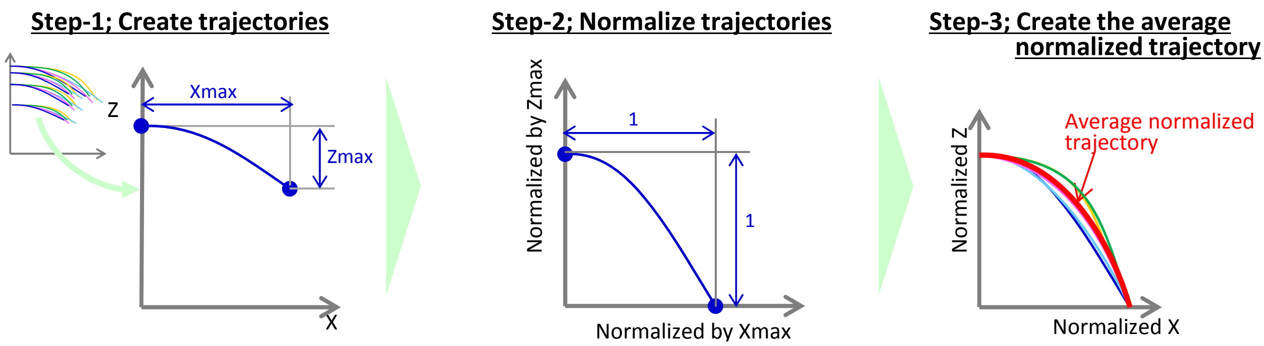

Fig. 10. Procedure to calculate the normalized trajectories

The average normalized trajectory for each of the four measurement locations of the trajectories was scaled by multiplying the X and Z coordinates (with respect to the initial measurement locations) of the upper right and lower left corners of the rectangle representing the variation of the end points.

The peak values of the pelvis and lower limb injury measures and the contact forces for the cars from the APROSYS report [8] were estimated by adjusting the difference in their average and variation between the four out of five cars rated green in the Euro NCAP testing and the data of the same rating from the APROSYS report [8]. Considering the recent enhancement of pedestrian safety performance of the vehicle fleet, only the data for the cars rated green in the Euro NCAP testing were used. For both the average and Coefficient of Variation (CV) values, human model results for the cars from the APROSYS report [8] were estimated by multiplying the upper legform or legform results of the APROSYS data by the ratio of the average upper legform or legform results of the four representative cars to the average human model results of the four cars. The sum of the upper legform forces was used for the estimation of the pelvis and femur injury measures and the grille and hood edge contact forces. The acceleration from the legform was used for the estimation of the MCL and tibia injury measures and the lower bumper and bumper contact forces. The SDs for the APROSYS data were then estimated by multiplying the estimated CV values by the average results. The estimated APROSYS data were then combined with the results of the four representative cars to calculate the average and SD of the combined dataset. Similar to the comparison of the trajectories, 1SD was used for the comparison with the buck results to represent the variation of the cars in the sedan category.

III. RESULTS

Validation of Buck Model

In order to validate the buck model developed by Pipkorn et al. [6] at the full-scale level, kinematic and kinetic responses of the POLAR II pedestrian dummy were compared between the experiment and the computer simulation. Figure A-1 compares the time sequence of the dummy kinematics (front view of the dummy) between the experiment and the computer simulation. Although some difference was seen in the upper body angle, the overall kinematics of the dummy was generally represented by the computer simulation. Figure A-2 compares the trajectories of the head CG, upper spine, mid-thorax and pelvis with respect to the buck between the six tests and the computer simulation. Although the trajectories for one of the six tests (test 1) were slightly different from other tests particularly for the head CG, upper spine and mid-thorax, probably due to the variation in the test setup for the first test, the model well represented the trajectories of most of the tests. In addition to the trajectory comparison, the time histories of the reaction forces measured at the load cells installed behind the lower bumper, bumper, grille and hood edge were compared between the experiment and the computer simulation as presented in Figure A-3. Since uni-axial load cells were used at both ends of the lower bumper and bumper, the sum of the forces from both ends was compared. The sum of each component of the reaction forces was used to calculate the resultant forces for the grille and the hood edge where tri-axial load cells were installed to compare the resultant forces for these components. Only three test results were available for the grille reaction forces (tests 4 through 6). The wave profile and the peak force level were generally represented by the model except for the hood edge.

Validation of Generality of Sedan Buck

Since the current study aimed to develop a buck for a generic representation of the cars in the sedan category, the validation of representation of kinematic and kinetic responses of a pedestrian in a full-scale impact configuration was conducted by comparing the responses from the buck with the response variations from various cars in the category. The results of the trajectories along with the peak values of the pelvis and lower limb injury measures and the contact forces of the buck components were compared between the buck model and the combined dataset of the results from the representative car models and the estimated APROSYS data [7-8]. The actual data plots of the relationship between the WAD and hood edge height used in the procedure to estimate the trajectories from the cars in the APROSYS report [7] were provided for the four measurement locations in Figure A-4. Figure A-5 illustrates the time sequence of the human model kinematics between the buck and the five cars. Although some small differences are seen due to the difference in the geometry of the car front-end, no significant difference was identified between the buck and the five cars. Figure A-6 compares the trajectory of the head CG, upper spine, mid-thorax and pelvis between the buck and the trajectory corridors obtained by combining the results of the five cars with the data estimated for the cars in the APROSYS report [7], confirming that the buck represents the trajectories with respect to the car within the variation of the cars in the sedan category. Figures A-7 and A-8 compare the buck results with the combined dataset of the results from the four out of five cars and the data estimated for the APROSYS data [8] for the peak values of the pelvis and lower limb injury measures (pelvis deflection, femur bending moment, MCL tensile strain and tibia bending moment) and the contact forces between the human model and the buck components (lower bumper, bumper, grille and hood edge), respectively. The individual results from the five representative cars were also compared for reference. Although the buck results were out of 1SD corridor from the combined dataset for the tibia bending moment and the grille contact force by 19% and 4%, respectively, the comparisons generally showed that the values from the buck represent the results in the variation of the cars in the sedan category.

IV. Discussion

In the validation of the buck model, it was found that the hood edge reaction force time history was significantly different between the experiment and the model prediction in terms of both the level of oscillation and the peak force level. However, it was also found from the human model impact simulations that the peak reaction force of the hood edge was similar between the buck model and the five representative models. Although the buck model may need to be further investigated, the difference in the hood edge reaction force between the experiment and the model prediction could be due to the dummy model, which also needs further investigation.

Relative to the buck model developed and validated at the component level by Pipkorn et al. [6], the current study changed the thicknesses of the lower bumper and the hood edge components to enhance the generality of the buck representation at the full-scale level. This discrepancy between the component and the full-scale validations would show the limitation of the simplified buck due to the difference in the loading direction from a pedestrian body. The choice of the thickness of these components determined in the current study from the full-scale validation would provide a practical solution considering that the buck is designed to be used in impact tests against a full-body pedestrian dummy.

This study used some assumptions when adjusting the results from the representative cars to the APROSYS data, including the assumptions that WAD is solely dependent upon the hood edge height, and that the distance between the end point of the trajectory and the contact point of the corresponding body region is a half of the width of the body region. These assumptions need to be validated in a future study when numerous results of human model simulations are available for a number of different cars in the category.

The results of the generality validation of the buck developed in this study for the injury measures and the contact forces showed that the tibia bending moment and the grille contact force were out of the 1SD corridor of the combined dataset. The differences of these parameters from the average values of the combined dataset were 19% and 4% for the tibia bending moment and the grille contact force, respectively. These differences correspond to 1.4SD and 1.1SD of the combined dataset that cover 73.5% and 83.9% of the population when normally distributed. These results suggests that, although the buck representation was out of the 1SD corridor, the buck still represents pedestrian kinetics and contact interactions that can take place in car-pedestrian impacts against various cars with a high performance of pedestrian protection.

The validation of the generality of the buck representation was conducted by means of the comparison of the trajectories and pelvis and lower limb injury measures and contact forces. However, SAE J2782 incorporates requirements for the time history of the head velocity relative to the car in addition to those for the trajectories. The current study chose not to validate the head velocity due to the lack of the validation of the head velocity of the human model used in the study. Considering the relevance of the head velocity in the requirements specified in SAE J2782, a future study needs to validate the human model for head velocity and validate the generality of the head velocity representation using the sedan buck developed in the current and relevant studies. The upper body of the human model used in this study consists of articulated rigid bodies rather than finite elements. For this reason, the generality of the buck representation was validated by comparing the injury measures for the pelvis and below. Considering the significance of the injuries to the upper body in pedestrian accidents, such as thoracic injuries which are second or third most frequent in fatal pedestrian accidents, a future study would need to investigate the generality of the buck representation in terms of upper body injury metrics.

V. CONCLUSIONS

This study validated the buck model representing the sedan category against a full-scale pedestrian dummy impact test, and subsequently the buck model and five car models in the sedan category were used to run impact simulations against a human FE model. The results of the comparisons of the trajectories and the peak values of the pelvis and lower limb injury measures and the contact forces with the car components with the combined dataset of the five representative cars and the data estimated for the cars in the APROSYS reports showed that the pedestrian responses from the buck fell within 1SD of the combined dataset except the tibia bending moment and the grille contact force that fell within 1.4SD and 1.1SD of the same dataset, respectively, showing the generality of the buck representation at the full-scale level.

VI. REFERENCES

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Appendix

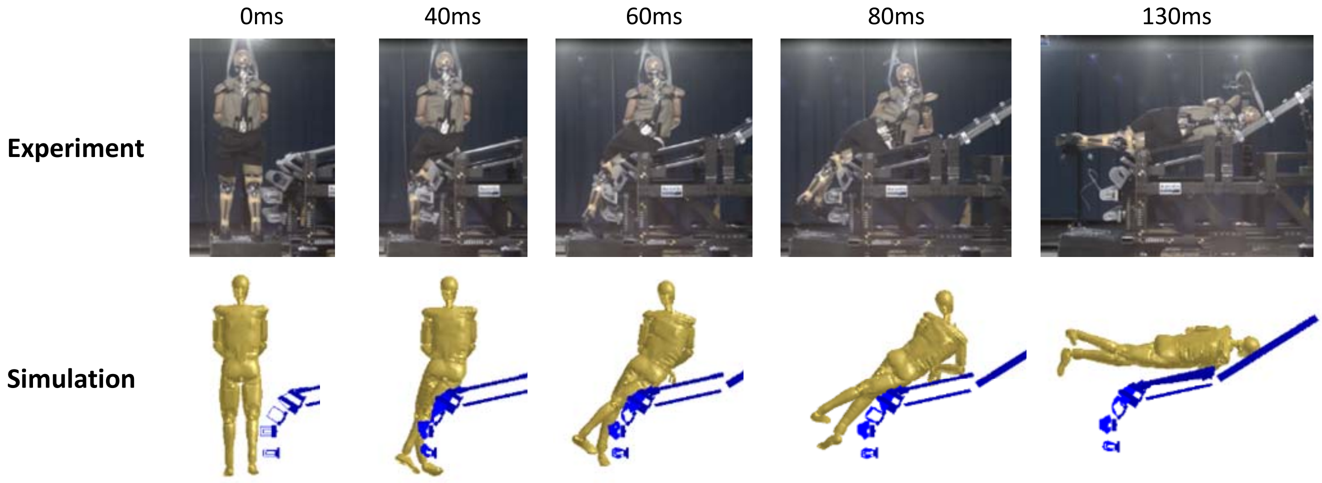

Fig. A-1. Comparison of the dummy kinematics between the results from experiments and simulation

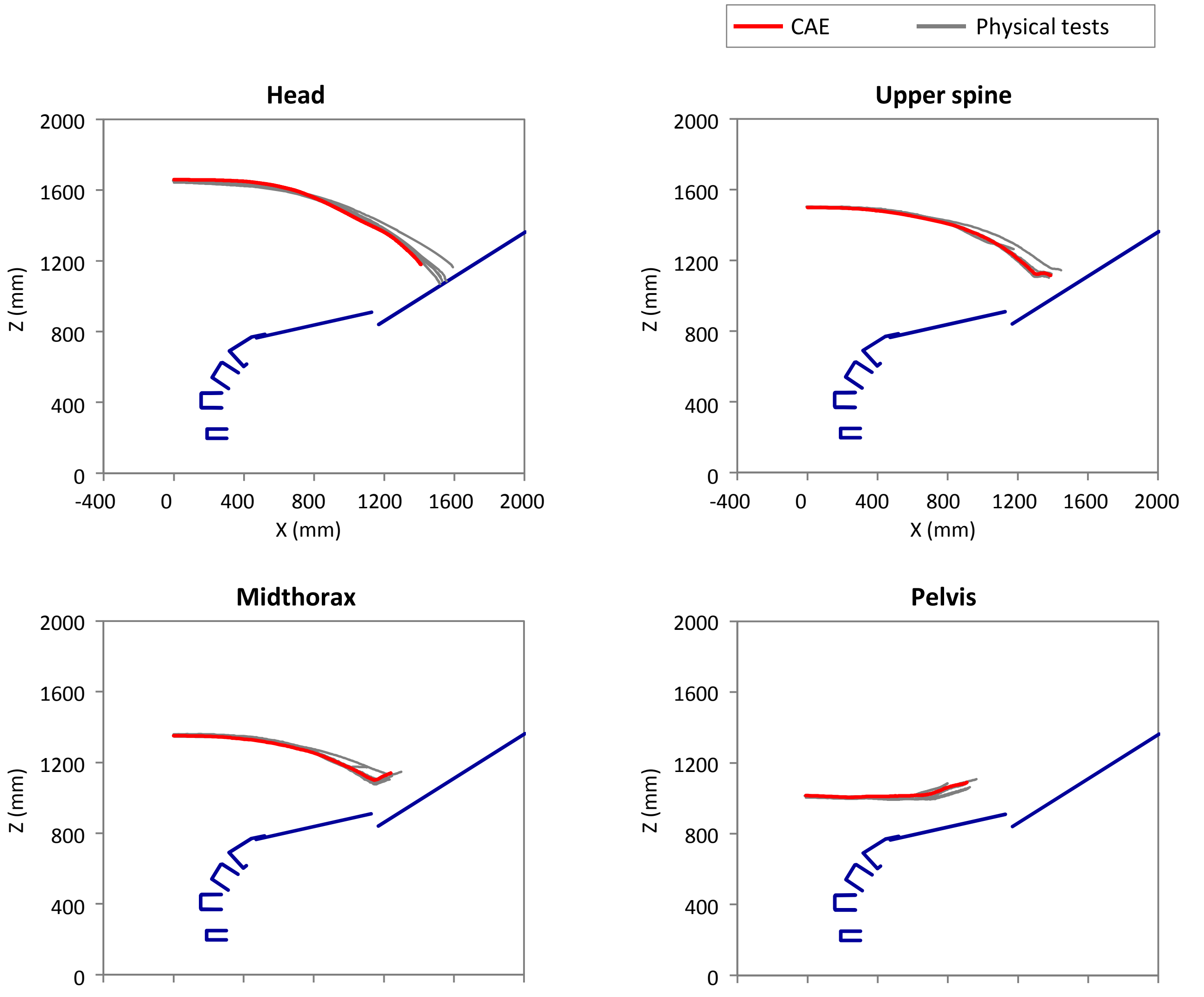

Fig. A-2. Comparison of the dummy trajectories between the results from experiments and simulation

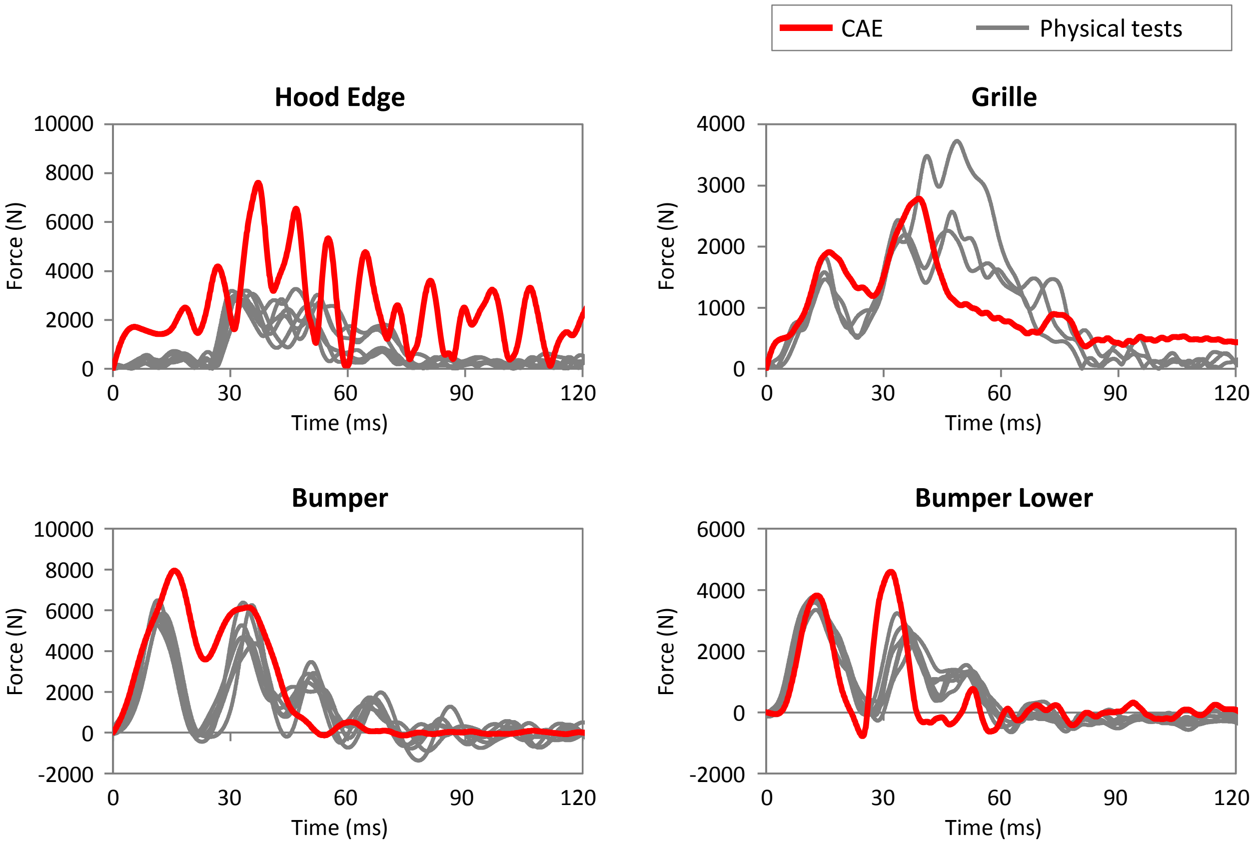

Fig. A-3. Comparison of reaction forces between the results from experiments and simulation

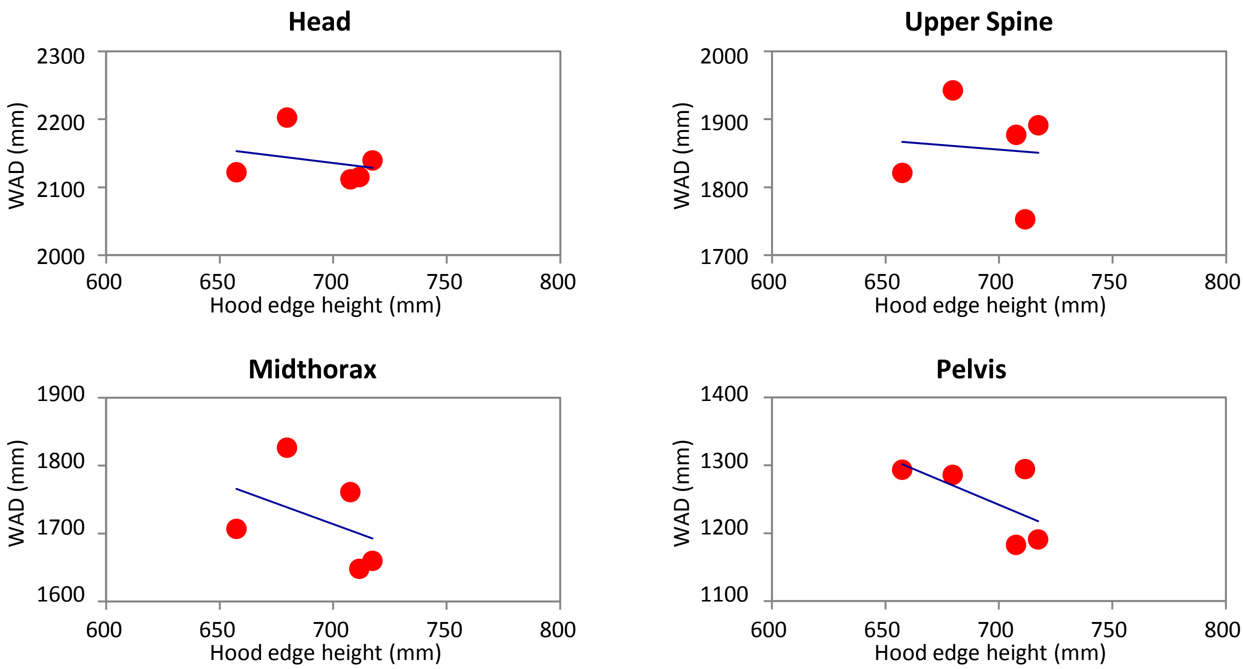

Fig. A-4. Correlation of WAD and hood edge height

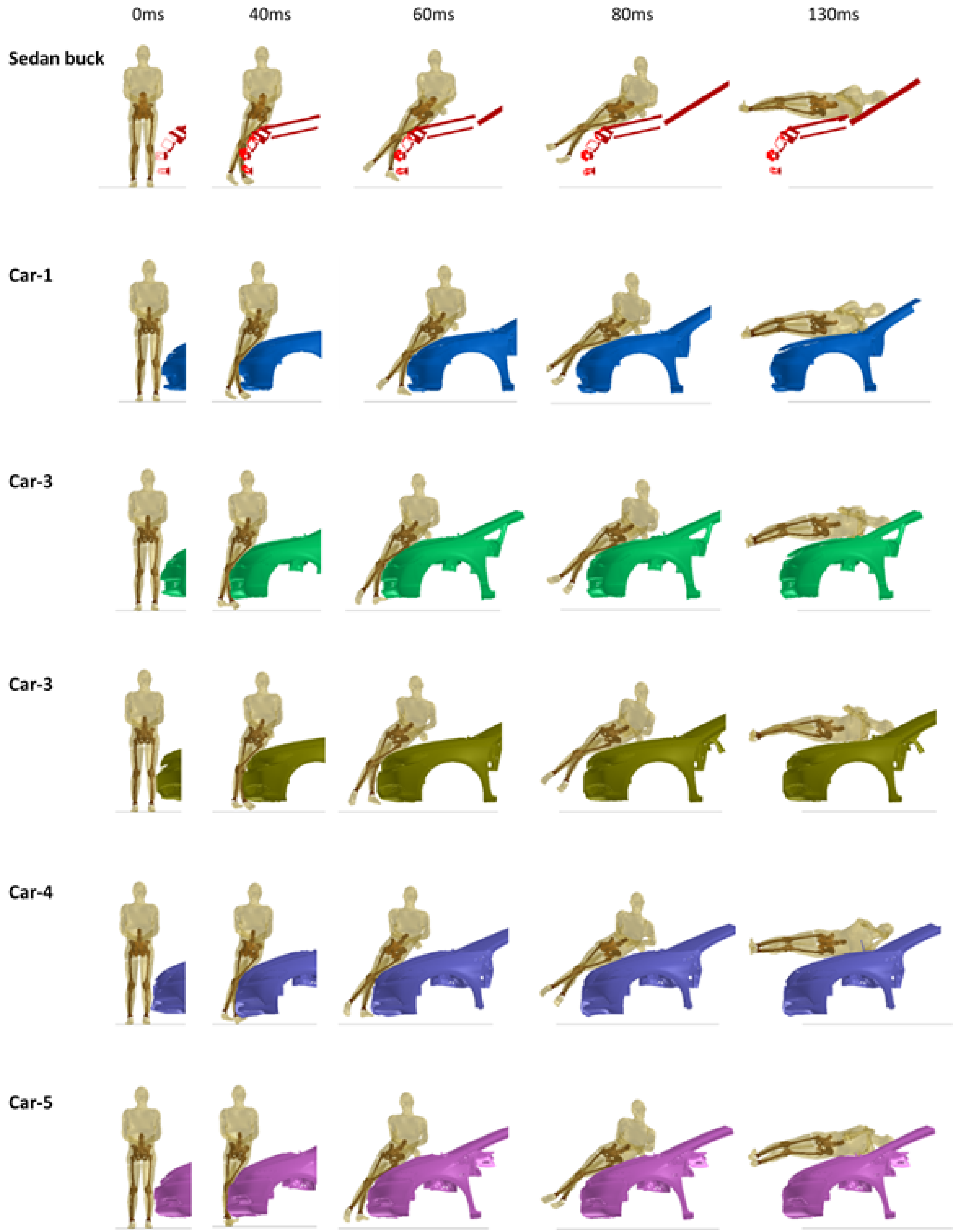

Fig. A-5. Human model kinematics in impact simulations

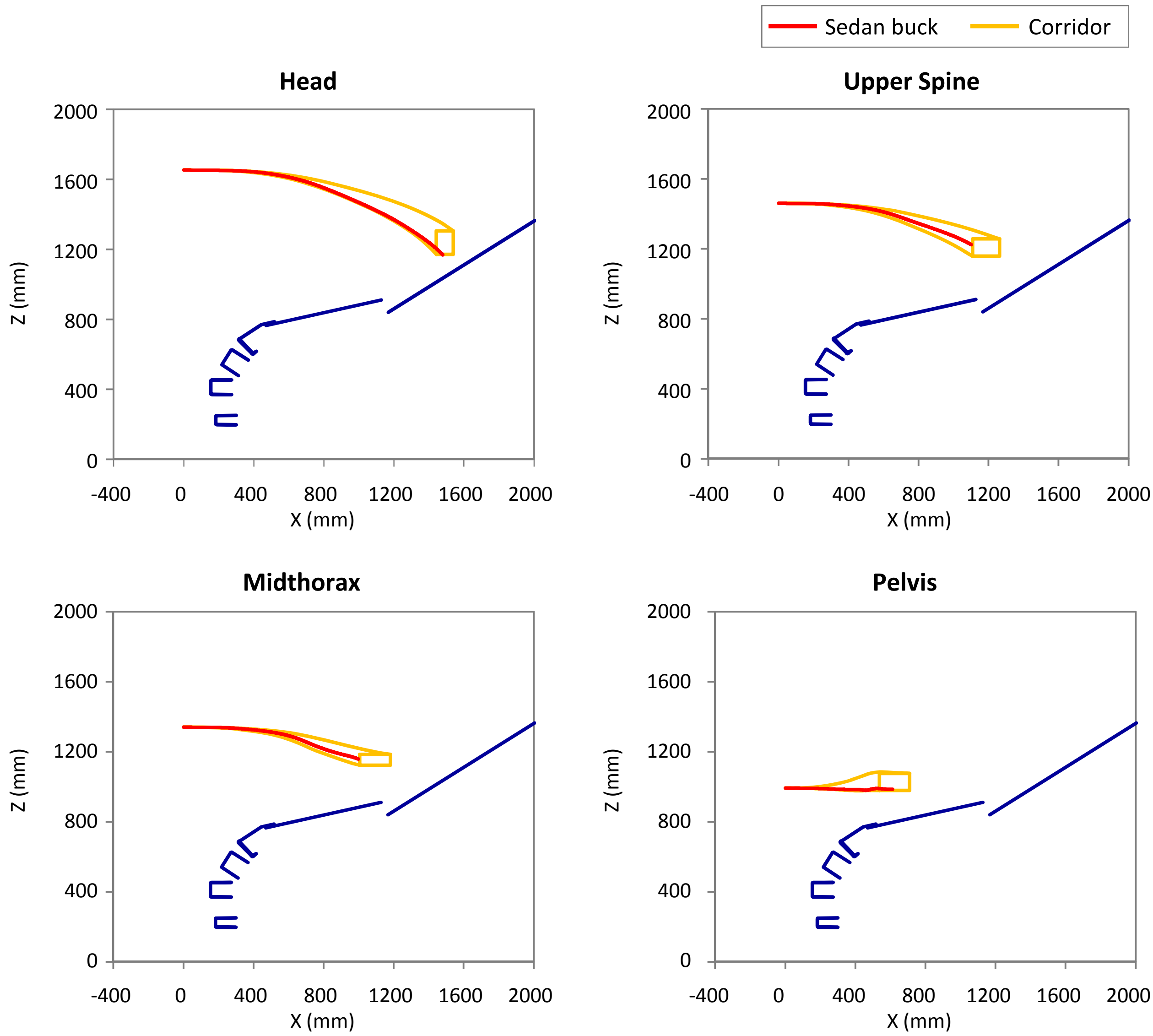

Fig. A-6. Comparison of the trajectories between the sedan buck and the sedan cars

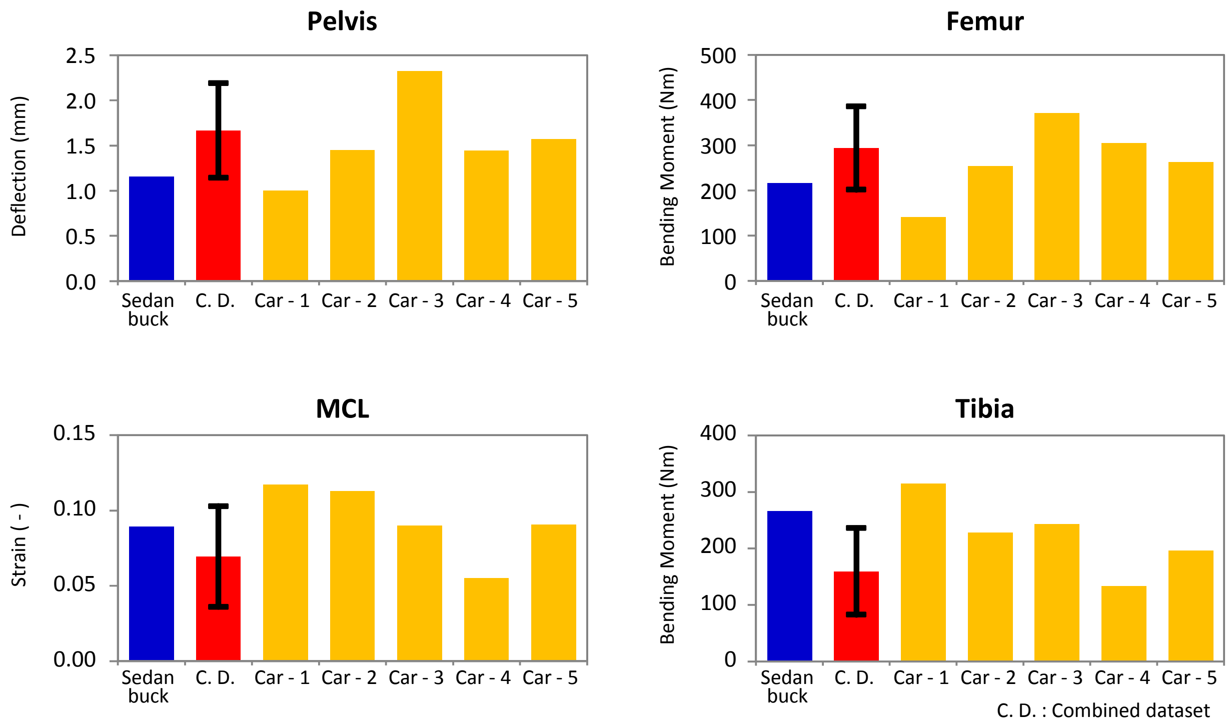

Fig. A-7. Comparison of injury measures between the sedan buck and the sedan cars

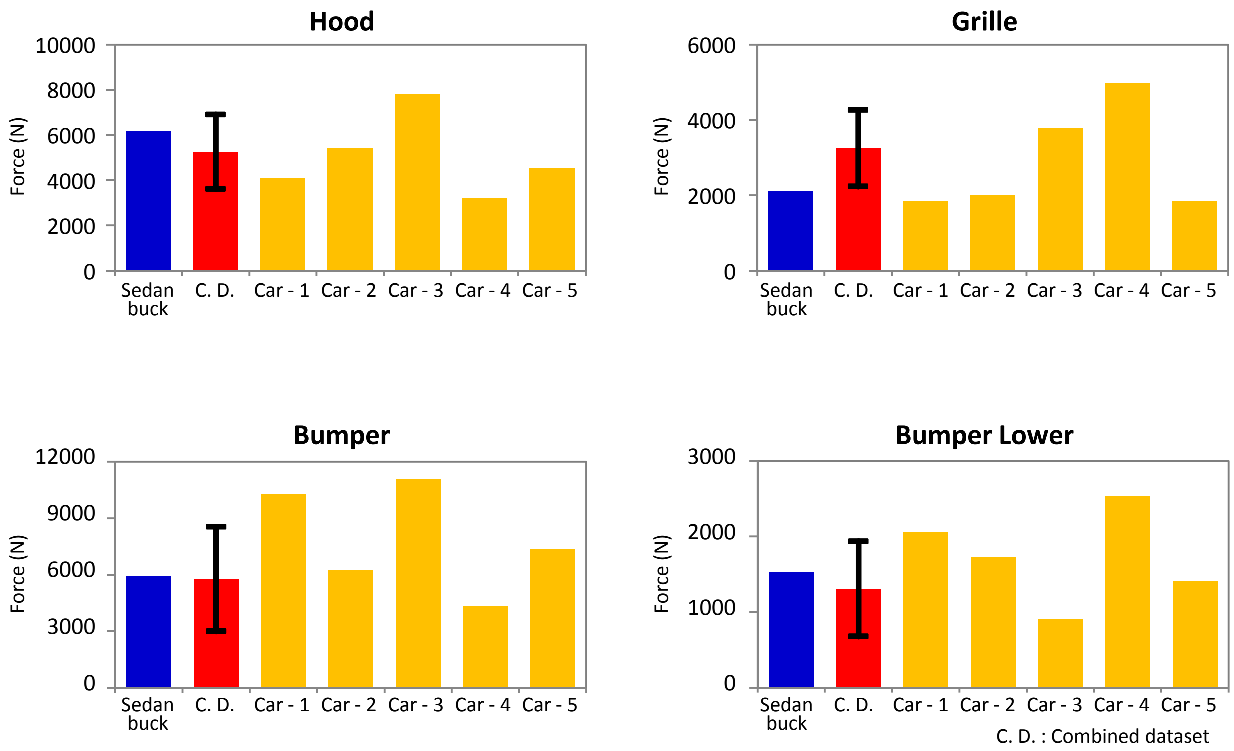

Fig. A-8. Comparison of contact forces between the sedan buck and the sedan cars