Development and Component Validation of a Generic Vehicle Front Buck for Pedestrian Impact Evaluation

Bengt Pipkorn, Christian Forsberg, Yukou Takahashi, Miwako Ikeda, Rikard Fredriksson, Christian Svensson, Alexander Thesleff

Abstract For evaluation of pedestrian-to-vehicle impacts and pedestrian dummy development, a mathematical and mechanical generic buck corresponding to a passenger vehicle front was developed. The buck consists of the major energy-absorbing structures of a passenger vehicle in a pedestrian-to-vehicle impact. The components are lower bumper, bumper, grille, hood edge, hood and windshield.

Initially, the buck was developed by means of computer-aided engineering (CAE). A CAE model of the buck was refined and tuned. In the current study a physical version of the buck was fabricated. The fabricated buck parts were all tested at the component level. A comparison was made between the mechanical generic buck and the range of results from small family cars in EuroNCAP pedestrian tests to confirm the similarity between the buck and small family cars. Finally, the mechanical test results were used to compare the results with predictions from corresponding simulations with the CAE buck components to confirm correspondence between the CAE model of the buck and the mechanical counterpart.

The pedestrian buck front-end stiffness was within the range of small family car stiffness derived from EuroNCAP pedestrian tests. Therefore, it can be concluded that the pedestrian buck, although a simplified and cost-effective design, is a good representation of small family cars on the European market.

Keywords finite element method, generic buck, pedestrian

I. INTRODUCTION

Pedestrian injuries are a major global health problem. Globally, 270 000 pedestrians are killed in traffic every year and about 10 000 – 20 000 pedestrians sustain disabling injuries every day [1]. The probability for a pedestrian to be injured or killed is much higher than that for a vehicle occupant; 6.7 % of vehicle-pedestrian impacts in the US were fatal, whereas the corresponding fatality rate for occupants in crashes was only 1.3 % [2]. Therefore, there is a need to develop tools for pedestrian impact evaluation and also countermeasures.

To develop and evaluate pedestrian protection systems a whole body pedestrian dummy POLAR II was developed [3]. The tools were developed to be used in the evaluation of pedestrian kinematics and injuries when impacted by a vehicle. To evaluate the biofidelity of the pedestrian dummies, authorized documents containing human response corridors are necessary. Such documents J2782 [4] and J2868 [5] were developed and published by the Society of Automotive Engineers Human Biomechanics and Simulations Standards Committee. The performance of a mid-size male pedestrian dummy was specified in report J2782. In J2868 results from pedestrian dummy full-scale test results were reported and compared to post mortem human subject (PMHS) tests with the same vehicle. A standard passenger vehicle that was available for purchase was used in the tests. The test results were used to develop pedestrian trajectory corridors. However, future reproduction of those tests can be difficult due to the fact that the vehicle used in the PMHS tests will not be available. Therefore, to eliminate the problem of reduced availability of vehicles for testing, a defined pedestrian impact buck was developed, aiming at a simplified vehicle front end with parts that were clearly specified and could be easily manufactured from available materials. In addition due to the fact that the buck is

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simple and consists of a limited number of parts, the repeatability and reproducibility of the impact response can be expected to be improved relative to the impact response of a complex vehicle front.

Two simplified CAE buck models were developed corresponding to a mid-size and a large sedan in a previous study [6-7]. The bucks consisted of the major parts of a vehicle that are engaged in a pedestrian accident. The parts were: lower bumper, bumper, grille, hood leading edge, hood and windshield. The geometry and stiffness characteristics of the parts were similar to those of a mid-size sedan and a large sedan. The stiffness of the parts was generated by FE impact analysis of POLAR II dummy and full-vehicle models. The stiffness of each component of the buck was validated by comparing the predictions of the POLAR II dummy-to-buck impact with POLAR II dummy-to-full vehicle impact predictions. It was found that the simple buck has potential to represent whole-body kinematics and injury measures of a pedestrian impacted by a passenger vehicle.

An evaluation of pedestrian pelvis and lower limb injury measures was carried out [8-9]. Three different vehicles were used to investigate the effect of vehicle stiffness characteristics on injury measures. The importance of front-end geometry and stiffness characteristics on pedestrian kinematics and injuries when impacted was demonstrated. Therefore, vehicle-like geometry and stiffness of the buck is important.

Based on the findings described above the buck was refined to correspond to a sedan, SUV and MPV vehicle [10]. The bucks were validated for impact velocities of 20, 40 and 60 km/h. Finally, the generality of the buck was evaluated by modifying it to correspond to a vehicle with a high score and a low score in EuroNCAP rating. Good agreement between the buck predictions and the results from the EuroNCAP tests was obtained.

Previous buck development was carried out using a CAE model. The intention is that the model will serve as a tool for development of a mechanical buck. A mechanical buck is a prerequisite for development and evaluation of pedestrian dummies. The goal is to develop a mechanical pedestrian buck made of clearly defined and readily available engineering materials that has a repeatable and reproducible response when impacting a pedestrian. The buck is to be used in the development of human response corridors, pedestrian dummy development and evaluation of pedestrian impact kinematics. To develop human response corridors the range of data needed is from initial contact between the occupant and vehicle until head-to-windshield impact. Therefore, the impact response of the buck is to correspond to the impact response of a vehicle from initial impact until head-to-windshield impact.

The aim of this study is to fabricate and test at the component level a generic buck, previously developed in CAE. The buck is to be designed to have a repeatable and reproducible impact response. The impact response of the buck is to correspond to the impact response of a passenger vehicle fleet by confirming that the response of the mechanical buck is within the range of corresponding vehicles in pedestrian component tests. The mechanical test results will be used to compare with the final version of the CAE model of the buck to evaluate the validity of the CAE model.

II. METHODS

The concept of the buck was to represent the fleet of small family cars with generalized stiffness and geometry. Therefore, the buck was designed with a stiffness and geometry that was within the range of small sedan vehicles. The buck was developed to correspond to the geometry and stiffness along the centerline of a vehicle. The centerline was chosen due to the fact that pre-impact position of the subject along the vehicle centerline was used in previous buck developments and vehicle-to-pedestrian PMHS tests. Results from a study, in which the mid profile geometry of 16 European small family cars was measured, was used for the geometry of the buck. The buck geometry was designed to fit within the geometry range of the mid profile of these small family cars. 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.

For the stiffness response a representative vehicle was selected among commercially available vehicles from the small family car category. For the lower bumper, bumper, grille and hood edge stiffness determination human pedestrian model-to-full vehicle impact simulation results were converted into an impactor test configuration that can be reproduced in the laboratory [10]. The impacted area, in the human model-to-vehicle simulations, was cylindrical with a diameter of 160 mm. Therefore, the impactor used was a rigid cylinder with a diameter of 160 mm. The impactor test configuration was developed by iterating the mass of the impactor in the impactor- to-vehicle impacts until the same force and crush characteristics were obtained as in the human model-to- vehicle simulations. Once agreement between results from human model-to-vehicle and impactor-to-vehicle simulations were achieved the impactor test configuration (i.e. impactor mass, impact velocity and impact angle) was used in the development of the buck. In the refinement of the buck the impactor simulation was iterated while varying the design and crush characteristics of the buck until agreement between the model predictions was achieved. The bumper lower, bumper, grille and hood edge were impacted at 11 m/s with a leg impactor with a diameter of 160mm and a mass of 3.19kg for the bumper lower and bumper impact and a mass of 3.0kg for the hood edge impact. In the human model-to-vehicle simulations it was observed that the lower leg was impacted by the bumper and bumper lower horizontally while the upper leg was impacted by the grille and hood edge at an angle of 32 degrees (Fig 1). Therefore the bumper lower and bumper were impacted horizontally while the grille and hood edge were impacted at an angle of 32 degrees.

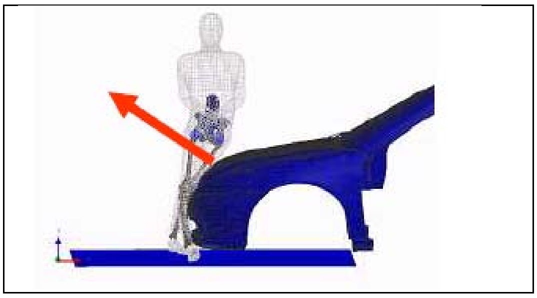

Fig 1. Small sedan to human model impact

For hood stiffness determination hoods from commercially available mid-size passenger vehicles were obtained and tested in-house (Fig 2). For the hood stiffness determination a chest impactor with the effective mass of a 50%-ile male was used. The impact location was selected based on results from in-house vehicle-to-pedestrian dummy impact tests. The hood was impacted with a chest-shaped impactor with a mass of 12.0kg, a length of 500mm and a width of 250mm. The impact velocity was 6 m/s which was found in in-house pedestrian impact tests to be the chest impact speed.

Fig 2. Hood impact test setup of validation tests with real vehicle parts

The materials used for the buck were steel (DC01) with Young’s modulus 210GPa and yield stress of 147MPa, polyethylene (PE300) and polycarbonate (Lexan 9030). Material data were obtained from the manufacturer for the steel, while static and dynamic material coupon tests on polyethylene and polycarbonate were carried out. Based on the material data, material models were developed. The model for steel was without strain rate dependency while the polyethylene and polycarbonate models included strain rate dependency. The design of the buck components was kept simple to keep the variability of the test results as low as possible and to ensure repeatability and reproducibility of the buck response. In addition the simple design made the fabrication of the mechanical buck straightforward. Only a few curved surfaces and simple boundary conditions were defined. The fabricated buck components were tested at the component level according to the method described above.

To confirm the similarity between the buck response and response from a range of small family cars, results from EuroNCAP legform and upper legform impact tests were used (Fig 3) [11]. In the legform tests a 13.2 kg legform impactor was launched horizontally at the bumper of the vehicle at 11 m/s. In the upper legform tests the impactor was launched at the bonnet leading edge of the vehicle. In the testing procedure the upper legform mass, impact velocity and impact angle are varied based on the geometry of the vehicle, according to EuroNCAP procedure [12]. Data from these tests were analyzed and converted to contact force [11]. For the buck the upper legform impactor mass was 10.35kg, the impact velocity was 6.7m/s (24 km/h) and the angle was 42.5 degrees.

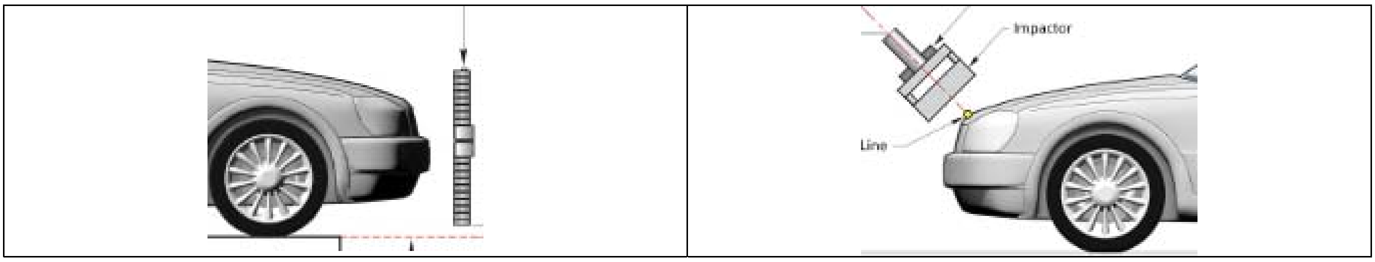

Fig 3. EuroNCAP legform to bumper and upper legform to hood leading edge test procedure

The vehicle with the highest and lowest force in the large and small family car group was selected to demonstrate the similarity between the buck and a passenger vehicle. The contact force and vehicle crush from the leg form tests were mimicked with the buck and used for comparison.

Finally, the predictions from the CAE model were compared to the results from the mechanical component tests. The average results from the component tests were used for the evaluation of the CAE model predictions. The model predictions were evaluated for crush at peak force, total crush and energy at peak force.

III. RESULTS

The buck was fabricated (Fig 5). Dimensions of the buck can be found in Appendix A. For the geometry of the buck there was correspondence between the outer surface of the buck and European small family cars (**Error! Not a valid bookmark self-reference.**). The mid profile of the buck was similar to the smaller vehicles in the group.

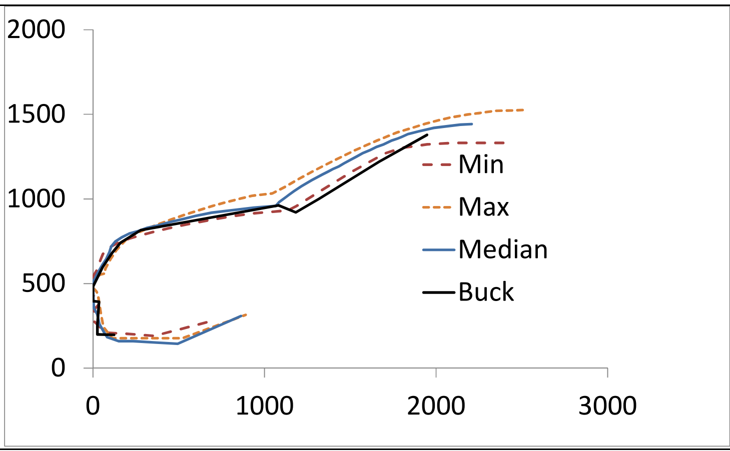

Fig 4. Small European family cars (buck in black)

In the fabricated buck the lower bumper, bumper and grille were all made of polyethylene (PE-300). The hood edge and hood were made of steel (DC01). The windshield was made of polycarbonate (Lexan 9030). The bumper and bumper lower were closed sections in a 2-layer design allowing for 2-step force displacement behaviors when loaded. The grille was a closed section, while the hood edge was an open section with a support in each end and the upper edge resting on the hood with an overlap. The deformable hood was a square steel sheet with a rectangular support welded around the edge. The hood was held by gravity within four fixed connection supports that prevented translation of the hood in the x-, y- and negative z-direction (**Error! Reference source not found.**). The engine block was modelled as a rigid structure 130mm below the hood. The windscreen was a straight square design clamped to a steel frame. All buck components were rigidly attached to a frame by means of thick steel beams.

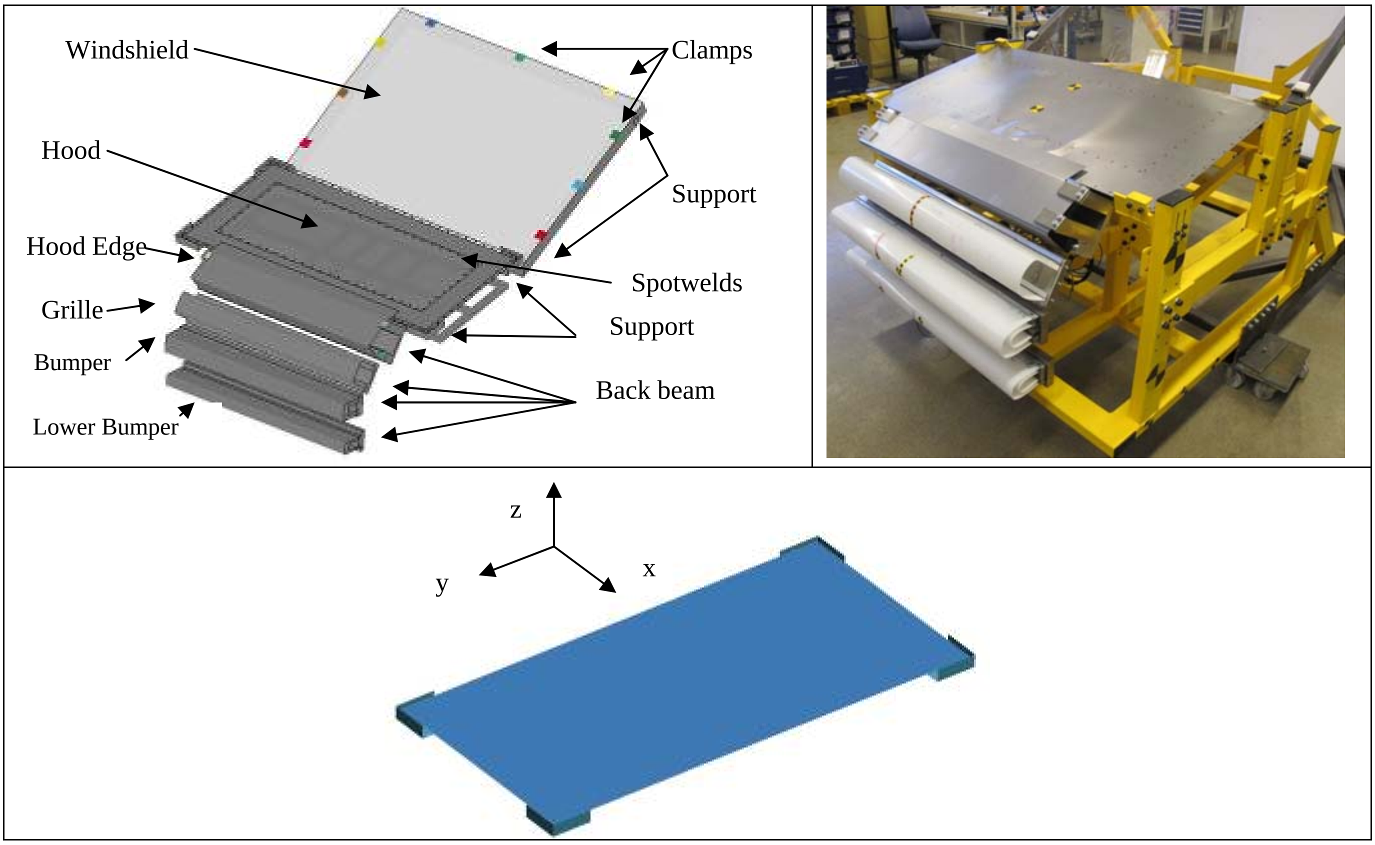

Fig 5. Buck and Hood

The fabricated buck components were tested at the component level (Fig. 6). All mechanical buck bumper lower, bumper, grille, hood edge, hood and windshield impact tests were repeated three times.

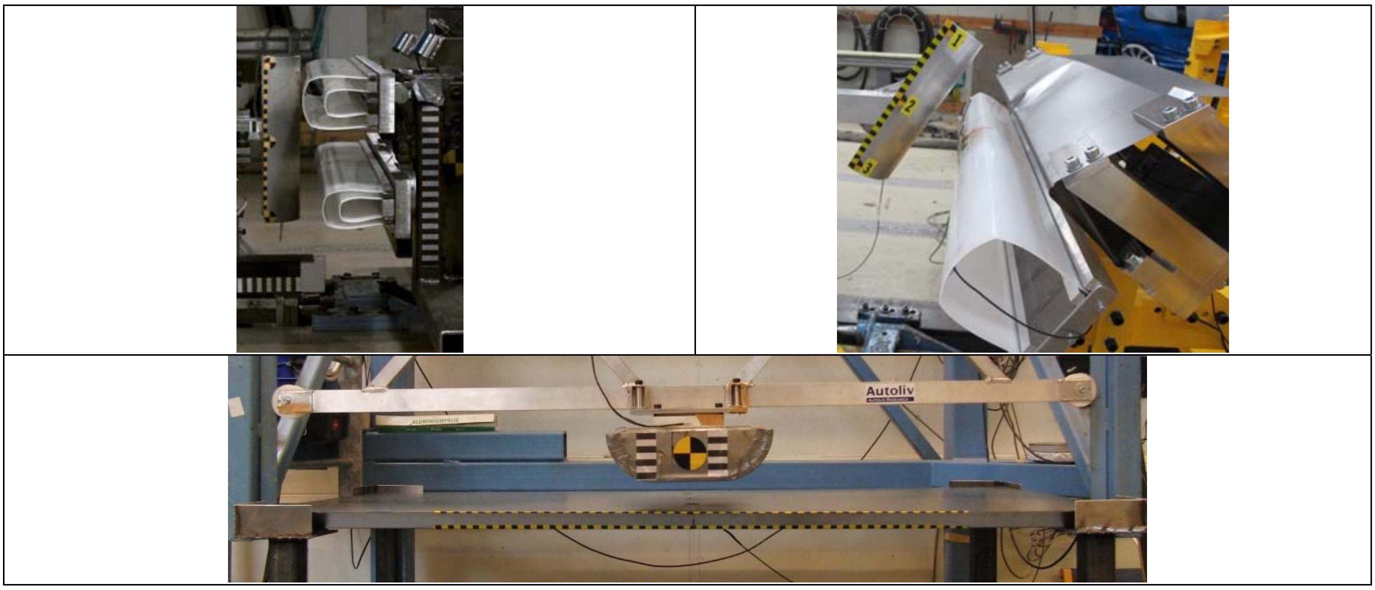

Fig 6. Test setups of bumper and bumper lower impact (top left), grille and hood edge impact (top right), chest to hood impact (low left)

For the lower bumper and bumper impact the peak displacement varied from 55 to 65mm and peak force from 4.8 to 5.8kN (Fig 7). For the grille and hood edge impact, peak displacement varied from 70 to 78mm and peak force from 3.9 to 4.0kN. For the hood impact peak displacement varied from 74 to 82mm and peak force from 12.1 to 12.3kN

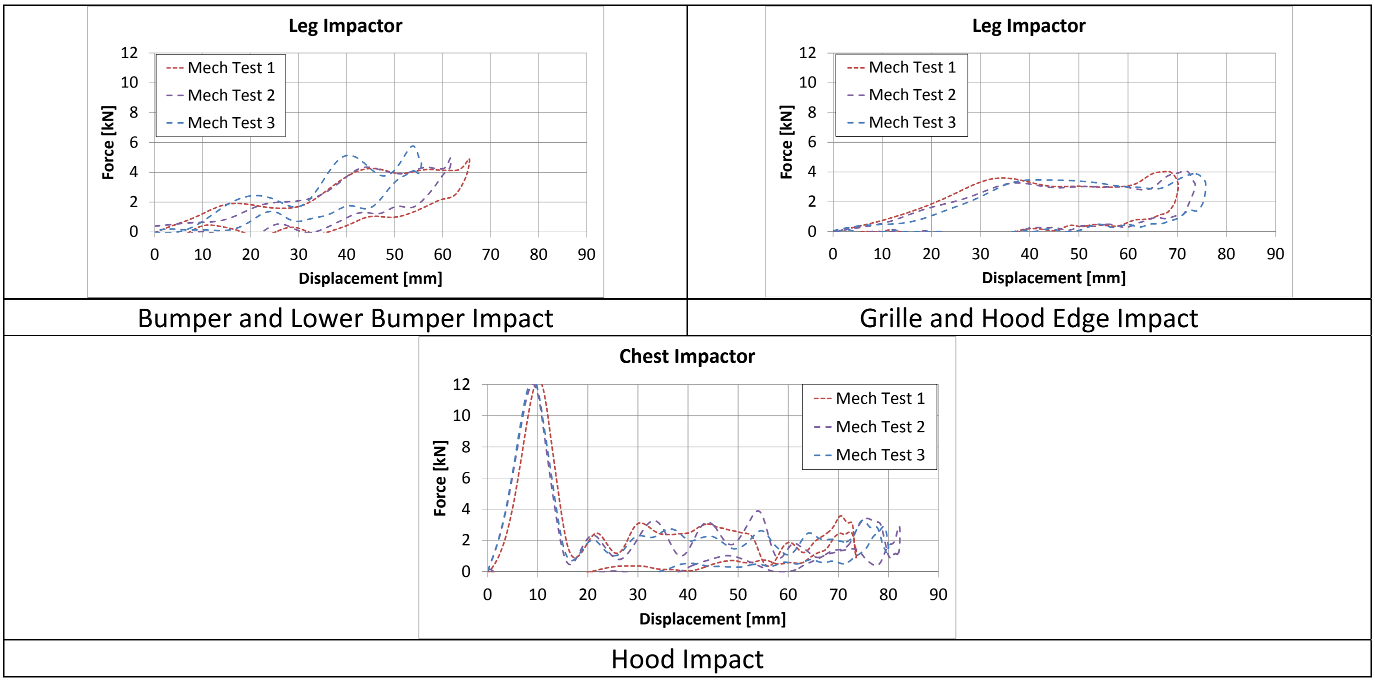

Fig 7. Impactor Results for Buck Component Tests

To demonstrate the similarity between the front-end stiffness and the stiffness of the average European vehicle fleet, results from EuroNCAP testing was used. The test results were converted to contact force and intrusion by multiplying the measured acceleration with the mass of the impactor, and the intrusion was obtained by double integration of the acceleration [11]. The vehicle with the highest and lowest force in the small family car group was selected to demonstrate the similarity between the buck and a passenger vehicle (Fig 8). It can be observed that the response of the buck was between the vehicles with a high and a low score in the rating. Therefore, the buck impact stiffness was considered to be representative of the impact stiffness of the European vehicle fleet.

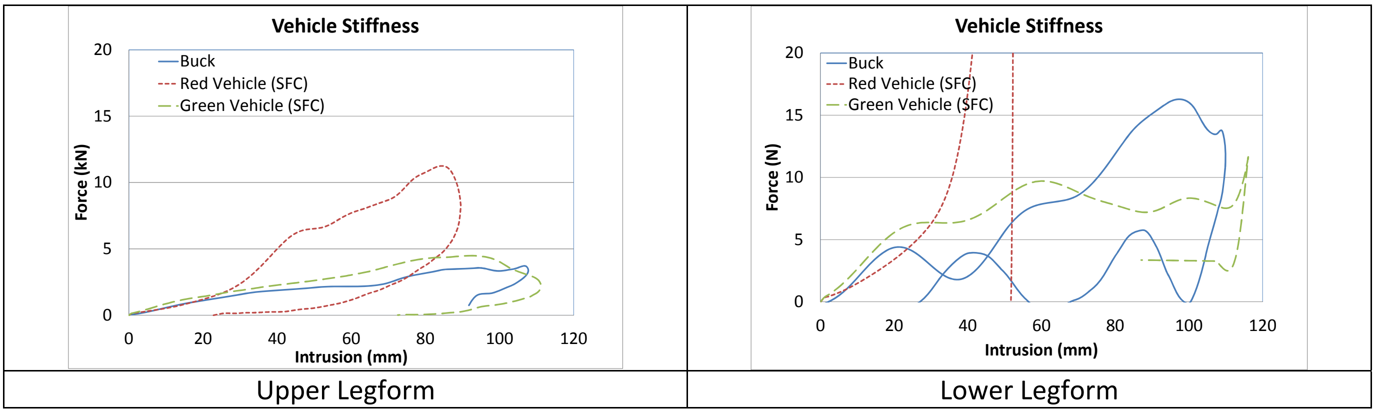

Fig 8. Buck upper and lower legform impact results. The vehicle with a high score in the EuroNCAP pedestrian rating is marked with a green curve and the vehicle with a low score is marked with a red curve

The average test results from the mechanical component tests were used for the evaluation of the CAE buck impact predictions. The time history results from the mechanical tests and the predictions can be found in Appendix B. For the bumper lower and bumper validation there was less than 20% difference between the model predictions and test results for crush at peak force and total crush while for peak force and energy at peak force the difference between predictions and results were 43 and 39%, respectively (Table 1). The grille and hood edge peak force and total crush predictions were within the 20% of the mechanical test results. The difference between the predicted energy at peak force and the crush at peak force were 57 and 54%, respectively. For the hood the difference between the predicted and measured peak force, energy at peak force, crush at peak force and total crush were 48, 53, 39 and 6%. For the timing there was a difference in 14% for peak force in the lower bumper and bumper impact. For the grille and hood edge impact and hood impact the difference in impact time between predictions and test results was -70% and 50%, respectively. For the total crush the difference in impact time was less than 10% for all impact configurations.

Table 1. Buck validation results

	Peak Force [kN]	Time [ms]	Energy @ Peak Force [kNmm]	Crush @ Peak Force (mm)	Crush (total) [mm]	Time [ms]
Lower Bumper & Bumper						
Mech	4.7	7	138	57	61	10
CAE	6.8	8	192	60	60	9
Difference (%)	43	14	39	5	-1	-10
Grille & Hood Edge						
Mech	4.0	10	165	71	73	12
CAE	3.5	3	71	33	72	13
Difference (%)	-11	-70	-57	-54	-1	8
Hood						
Mech	12.0	2	54	10	78	31
CAE	6.3	1	26	6	73	30
Difference (%)	-48	-50	-53	-39	6	-3

IV. Discussion

A previously developed finite element model of a vehicle front, a generic buck, to be used for vehicle-to-pedestrian impact evaluations was further developed, validated and fabricated. The buck was generic in the sense that simple geometries and few parts were used in the buck design. In the design of the buck it was strived to achieve simple manufacturing by minimizing the number of curved surfaces of the parts. In addition care was taken to use materials that were clearly defined and readily available worldwide. However, a sufficient number of parts and geometric complexity were used to accurately represent the properties of a passenger vehicle fleet when impacting a pedestrian. The intention was to get properties matching a range of real vehicles. It was demonstrated that the geometry and stiffness of the refined buck in this version were similar to that of small European vehicles.

The mechanical impact tests were repeated 3 times. Small variations in the test results were observed. Therefore the buck was considered to be repeatable. To date only one buck was manufactured. However, due to the fact that the design of the buck was simple, and only clearly defined and readily available engineering materials were used, a reproducible buck response can be expected.

For the hood part of the buck, Aprosys data were not available regarding the stiffness of the range of vehicles [15]. Therefore standard hoods from three current vehicles, similar to the small family car category, were tested and used for comparison. The impact response of the hood of the mechanical buck was stiffer than the response of the hood for the vehicles evaluated (Fig 9). The design of passenger vehicle hoods is complex. The surface is curved and there are stiffness-optimized reinforcements under it. The generic hood did not capture the maximum force of the mechanical hoods. However, the maximum displacement was captured. Further, for a real vehicle the under-hood parts, such as engine and suspension, are more important for the response, and it is the distance to those parts that often determines injury outcome. This distance was represented in the buck by a rigid surface at a constant distance of 130 mm, which represents vehicles with high protection performance. Since the buck hood shows good correlation in peak displacement and thereby the risk for impacting underlying stiff structures was captured, the impact response of the generic hood was considered representative for the vehicle fleet.

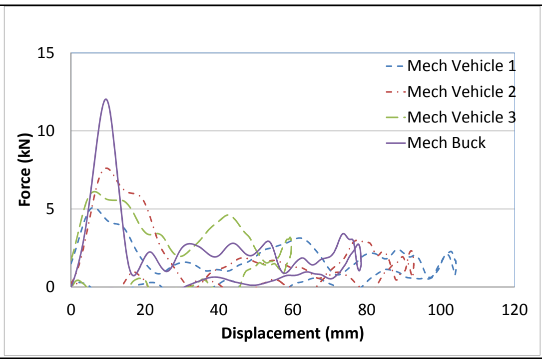

Fig 9. Impact response of the hood

For the leg impactor-to-grille and hood edge impact there were 2 local force peaks in the test results and CAE predictions (Appendix B). The peaks were similar in magnitude. In the simulation the maximum force was the first peak which was at 30ms. In the mechanical tests the maximum force was the second peak at about 70ms. Due to the significant difference in time at peak force for the test results and predictions, the energy at peak force and crush at peak force differed significantly (Table 1). However, the two local predicted peaks were close in magnitude. If the second local peak had been slightly greater, that peak would have been the maximum value and the difference in energy at peak force and crush at peak force would have been small.

For material characterization of the polyethylene, uni-axial static and dynamic coupon tensile tests were carried out. The data were used to develop and validate the material models. Due to the fact that the bumper structures are loaded mainly in compression a material test in which the polyethylene is loaded in compression can improve the predictions. In addition the behavior of the material in shear loading and bi-axial tension is not known. Therefore, bi-axial tensile tests and shear tests can also improve the capability of the CAE model of the buck to predict the mechanical buck impact response. For the steel used only quasi-static tensile test data were available. Therefore, strain rate dependency was not included in the material model. Future improvements of the CAE buck model can be to carry out dynamic tensile material tests and use the data to include strain rate dependency for the steel material model.

In the project a generic buck was developed. The buck consists of 6 simplified parts: lower bumper, bumper, grille, hood edge, hood and windshield. The buck was evaluated at the components level by means of impactor tests. The impact response of the buck corresponded to the response of a European family vehicle and was found to be repeatable and reproducible. The performance of the CAE and mechanical buck will in the next step be evaluated by full-body POLAR II impact tests [13].

V. Conclusions

A mechanical generic vehicle front end (buck), based on a CAE developed buck representing a small family car, was manufactured in this study and tested in component tests and compared to a range of small family cars from the European vehicle fleet. It was concluded that the pedestrian buck front-end stiffness was within the range of small family car stiffness derived from EuroNCAP pedestrian tests. Therefore, it can be concluded that the pedestrian buck, although a simplified and cost-effective design, is a good representation of small family cars on the European market.

VI. References

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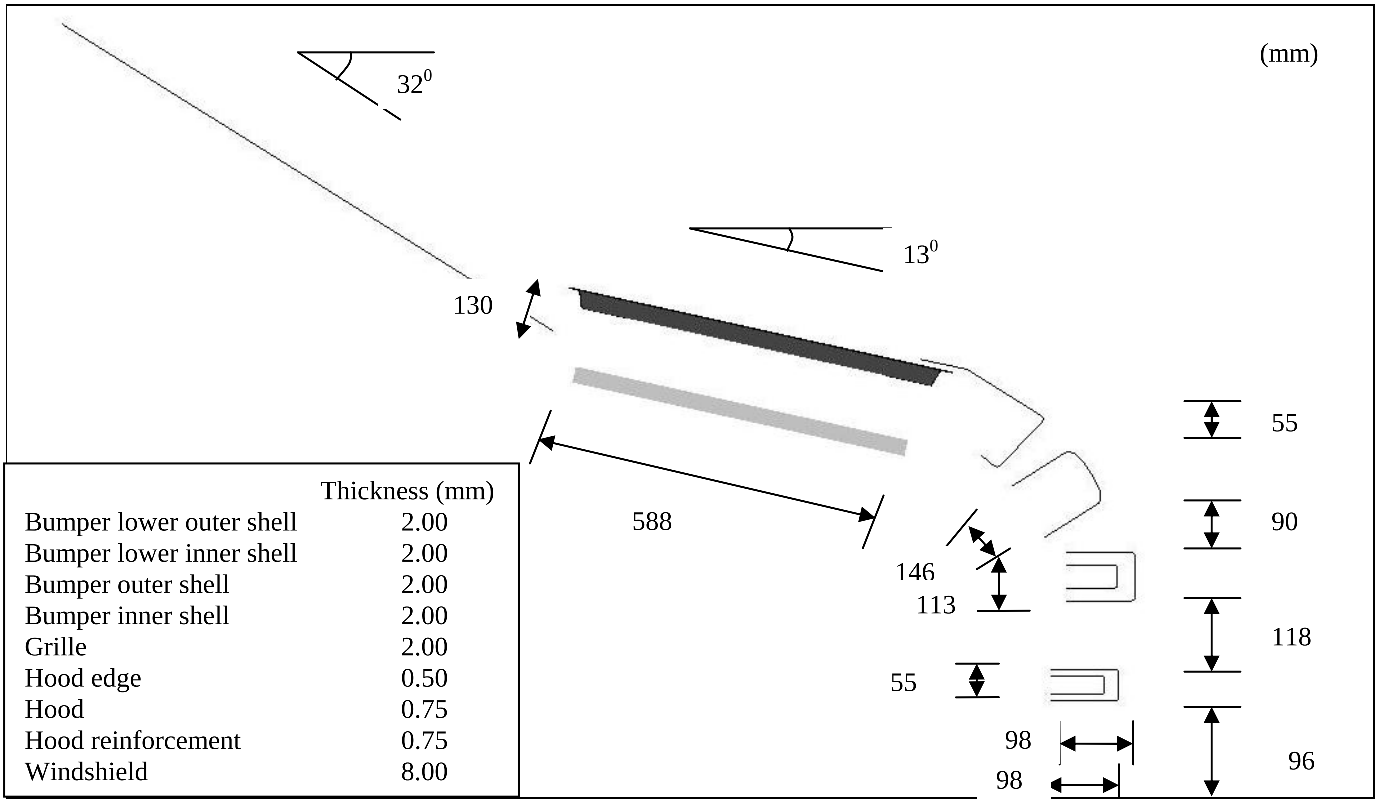
APPENDIX – A Dimensions of the buck



	Thickness (mm)
Bumper lower outer shell	2.00
Bumper lower inner shell	2.00
Bumper outer shell	2.00
Bumper inner shell	2.00
Grille	2.00
Hood edge	0.50
Hood	0.75
Hood reinforcement	0.75
Windshield	8.00

Fig A-1. Cross section of buck

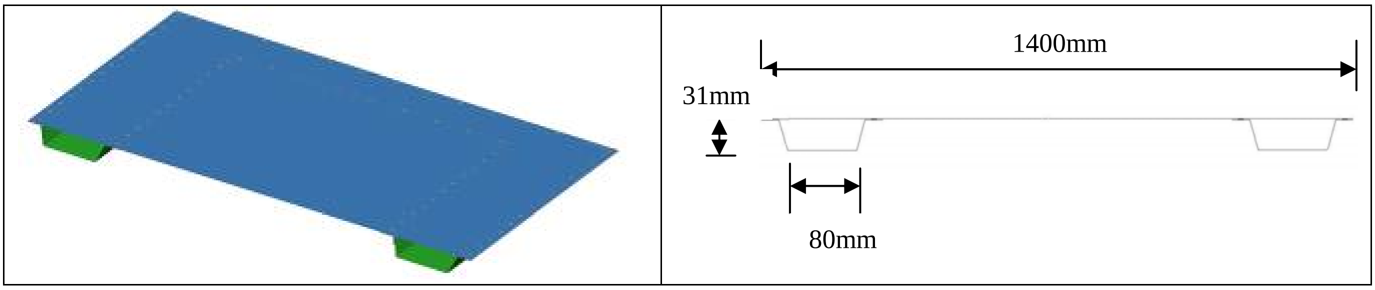
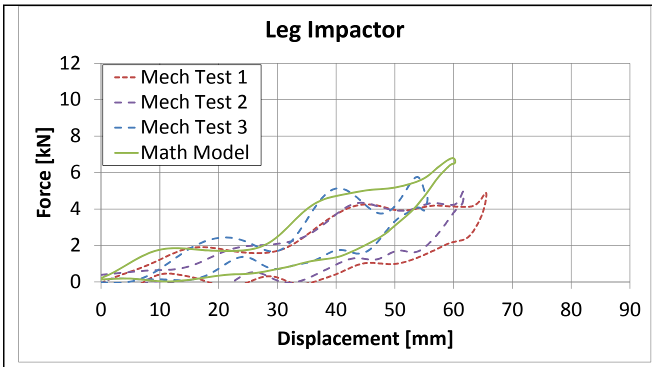
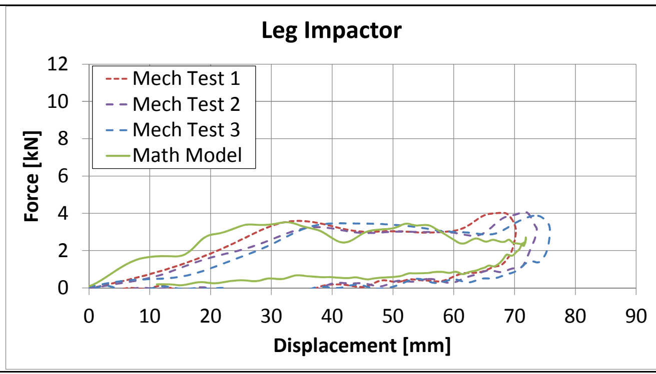


Fig A-2. Details of hood and hood reinforcement

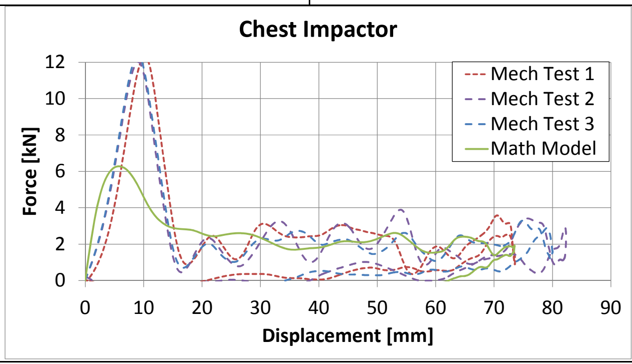
APPENDIX – B Impactor Validation Results for Buck Component Evaluation



Bumper Lower and Bumper



Grille and Hood Edge



Hood

Fig B-1. Impactor Validation Results from Buck Component Evaluation

APPENDIX – C Material Model Validation

For the development of the material model static and dynamic coupon tests were carried out for both the polyethylene (PE300) and the polycarbonate (LEXAN). The results were used to develop the material models for the materials. The coupon tests were replicated and the material model was validated.

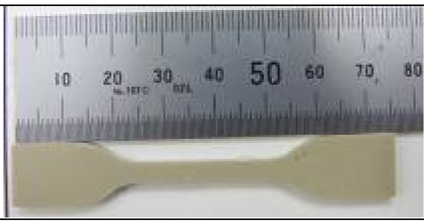


Fig C-1. Coupon

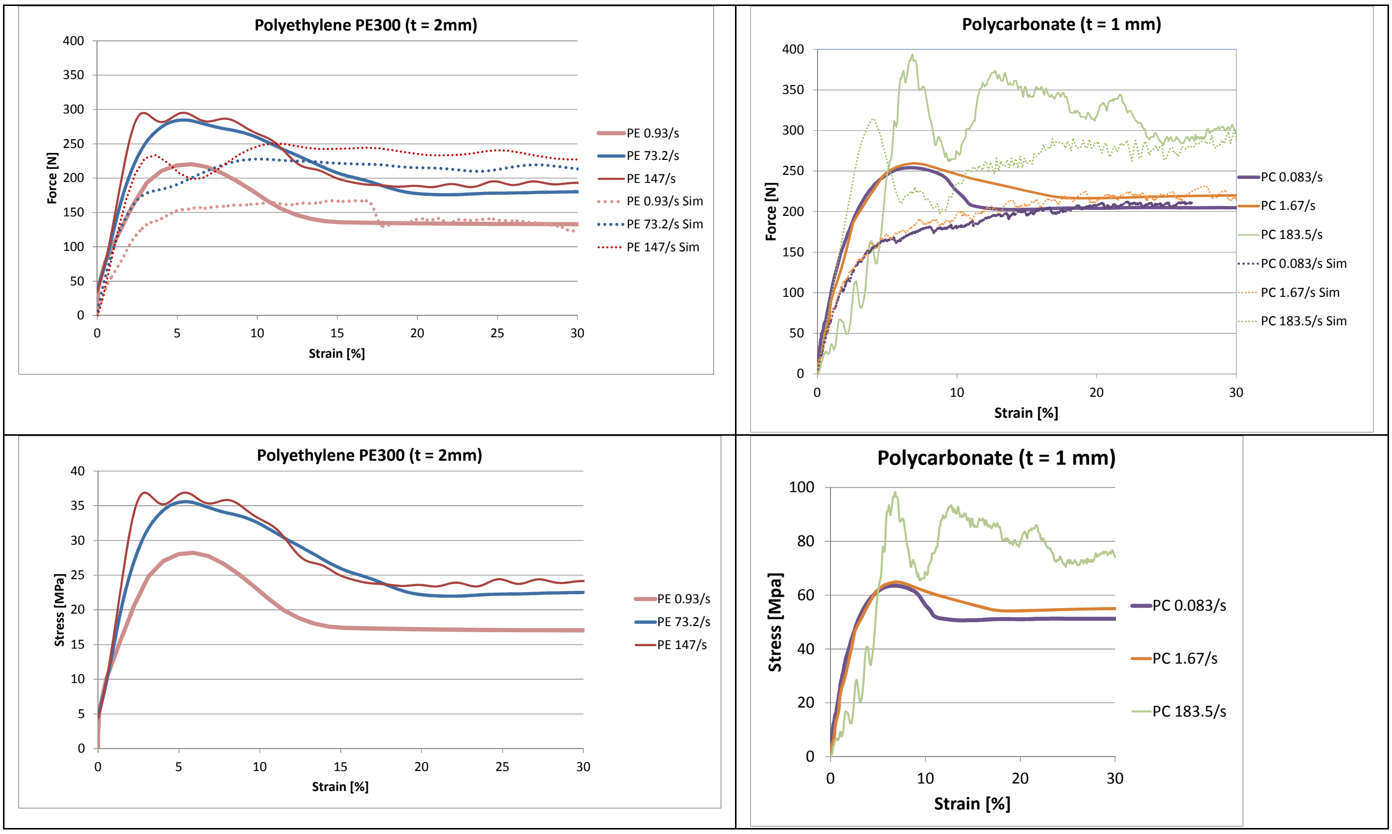


Fig C-2. Results from Polyethylene and Polycarbonate Static and Dynamic Coupon Tests