Development and Validation of a Generic Universal Vehicle Front Buck and a Demonstration of its Use to Evaluate a Hood Leading Edge Bag for Pedestrian Protection

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Abstract A mathematical finite element model of a universal generic buck corresponding to a passenger vehicle front was improved, validated and used. The buck was refined based on a combination of human body model and rigid impactor simulations. The vehicle front geometries that were mimicked were sedan, SUV and MPV and the impact velocities assessed were 20, 40 and 60 km/h. Based on the results from human body to vehicle impact simulations the diameter, mass and impact angle for a corresponding rigid impactor were computed. Thereafter the rigid impactor model was used to improve the force, energy and crush predictions of the buck. The average difference for all impact velocities between the full vehicle to impactor and buck to impactor predictions was 19%. The greatest differences were 71% for peak force, 66% for energy and 34% for total crush.

The universality of the buck was tested by modifying the buck to correspond to the geometry and deformation characteristics of a sedan, an SUV and an MPV with a good pedestrian rating and a sedan, an SUV and an MPV with a bad pedestrian score in the published EuroNCAP vehicle rating. Impact simulations according to the EuroNCAP testing procedures were carried out. There was good agreement between the model predictions and the results from the EuroNCAP tests. Impact simulations with and without a hood leading edge bag were carried out. Significant reductions in leg form force and moment were obtained with the hood leading edge bag.

Keywords pedestrian, universal buck, hood leading edge bag, finite element method

I. INTRODUCTION

Pedestrian injuries are a major health problem in motorized countries. The percentage of pedestrian fatalities ranges from 11% in the United States to about 50% in South Korea [1]. In Japan, the percentage of pedestrian fatalities even exceeds that of vehicle occupants (21%) [2].

Most commonly, the severe injuries that pedestrians sustain were found to be to the lower extremities and head [3]. The percentage of lower extremity injury was found to be high [4]. Severe injury was defined as Abbreviated Injury Scale (AIS) 2-6. Among these lower extremity injuries, pelvic fractures were most important from a viewpoint of threat to life. Pelvic fractures are a substantial factor in pedestrian morbidity and mortality [5, 6]. Pelvic fractures may cause significant blood loss due to the fact that there are major arteries located inside the pelvic ring. Vehicle front-end geometry and stiffness were identified as important causative factors of pelvic injuries in passenger vehicle to pedestrian collisions [5, 6]. In addition it was found that on order to accurately reproduce pelvis deflection, femur bending moment and tibia bending moment in car-pedestrian impact simulations, it is essential to maintain peak crush, absorbed energy and peak force magnitude of the force-

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deflection curves of the bumper lower (lower stiffener), bumper, grille and hood regardless of the levels of details of the stiffness curves represented [7].

For the development of a generic universal buck to be used for vehicle to pedestrian accident evaluation, it is important that the buck mimics the geometry and stiffness of a passenger vehicle. It is also important that the buck mimics the peak crush, absorbed energy and peak force of the passenger vehicle when impacted by a pedestrian.

For evaluation of passenger vehicle to pedestrian impacts an FE model of a simplified vehicle a buck, with geometrical and stiffness characteristics similar to those of a mid-size sedan and a large sedan was developed (Figure 1) [8, 9]. The buck consists of 6 parts: lower bumper, bumper, grille, hood leading edge, hood and windshield. The geometry of the pedestrian buck was approximated according to the contour cross-sections of two sedan vehicles. Dynamic stiffness characteristics of each component of the vehicle front-end structures were validated by comparing the results of impact simulation using the POLAR II dummy to vehicle impact model with the results from the FE buck and impactor model [8]. The impactor was rigid with a mass of 10 kg and the shape was cylindrical. For the bumper lower and bumper impacts the impactor diameter was 220 mm and for the hood leading edge and grill the diameter was 150 mm. The impactor velocity was 40 km/h.

The buck model was further validated by results from human body pedestrian model to full vehicle impact simulations. The human model was developed by Takahashi et al. and it was validated for upper body kinematics, pelvis and lower limb injury measures [10]. The lower limb and pelvis models were extensively validated by means of numerous published human data [11, 12]. It was also found that the injury parameters pelvis deflection, femur bending moment and Medial Colateral Ligament (MCL) tensile strain were generally well reproduced by the buck model [9]. The upper body trajectories of the dummy model generally matched the buck and vehicle models. However, a number of discrepancies were identified. In the 40 km/h impact initially, between 0-5ms, in the full vehicle impact the lower limb was contacted by the bumper lower and bumper, while the lower limb in the buck impact was contacted by only the bumper. Between 5-13ms the grille, the bumper and bumper lower contacted the lower limb in the full vehicle impact, while the bumper and bumper lower contacted the lower limb in the buck impact. The impact force was lower for the bumper lower, and higher for the bumper, grille and the hood for the buck than for the vehicle. The ratio of peak impact force from the bumper face between 20 km/h and 40 km/h was 376% and 256 % for the buck model and vehicle model respectively. This can be attributed to the difference in rate sensitivity of material properties of the bumper and/or the difference in the effective mass of the bumper. At 60 km/h the foam material representing the stiffness characteristics of the hood and grille of the buck model bottomed out, which was not observed in the vehicle.

Therefore, some modifications to the buck were suggested as follows [9]:

modify the geometry of the grill, bumper and bumper lower;
modify the stiffness of the hood, grille, bumper and bumper lower;
include rate sensitivity and effective mass of the bumper; and
modify the crush distance of the hood and grille.

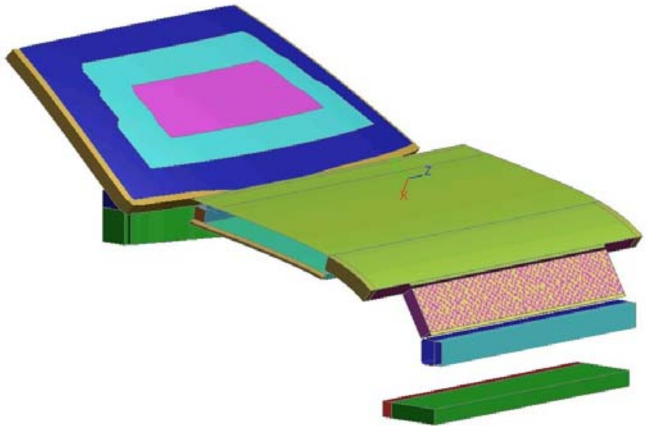

Figure 1
Original Buck

The aim of this study is to modify the mathematical pedestrian buck to represent a sedan, an SUV and an MPV front at 20, 40 and 60 km/h vehicle to pedestrian impact velocity and to demonstrate its universality. An extended aim is to use the universal buck to evaluate the potential injury reducing benefits by a hood leading edge bag.

II. METHODS

The pedestrian kinematics during an impact with a vehicle are influenced by the inertial properties of the pedestrian and by vehicle–pedestrian interactions. These interaction loadings highly depend on the geometry and stiffness properties of the front-end structure of the vehicle involved in the crash. Since a pre-impact position of the dummy along the vehicle centerline has been used in previous buck development and vehicle-to-pedestrian PMHS tests, the vehicle geometry and stiffness properties along the centerline were used in the current study [8, 13, 14].

The buck will be physically fabricated and mechanical tests for model validation will be carried out in the future. Therefore human model to full vehicle impact simulation results were converted into a rigid impactor model that can be physically reproduced in the laboratory. The impactor model was developed for 3 vehicle types, a sedan, an SUV and a MPV. The impacted area, in the human model to vehicle simulations, was cylindrical with a diameter of 160 mm. Therefore the impactor model used was a rigid cylinder with a diameter of 160 mm. The impactor mass and angle was developed by iterating the mass and angle of the impactor in the impactor to vehicle impact simulations until the same energy, force, crush and horizontal and vertical force ratio were obtained as in the human model to vehicle simulations (Figure 2). Once agreement between results from human model to vehicle and impactor to vehicle simulations was achieved, the impactor test configuration was used in the development of the buck. The predictions were considered to be in agreement when the human model to vehicle and impactor to vehicle force and crush were within 15%. The rigid impactor test configuration used to refine the buck was for the bumper lower and bumper impact a horizontally launched impactor with a mass of 3.9 kg for the sedan, 4.0 kg for the SUV and 5.5 kg for the MPV. For the refinement of the grille and hood edge the mass of the impactor was 3.0 kg launched at an angle of 32 degrees for the sedan, the mass for the SUV was 14.8 kg launched at an angle of 22 degrees and the mass for the MPV was 11.7 kg launched at an angle of 14 degrees.

In the refinement of the buck the impactor model was iterated, while varying the design and crush characteristics of the buck until agreement between the model predictions was achieved. Using the method described above the buck was modified to correspond to a Sedan, an SUV and an MPV. The cylindrical impactor with a diameter of 160 mm was launched at the vehicle at 3 impact velocities 20 km/h, 40 km/h and 60 km/h (Figure 2).

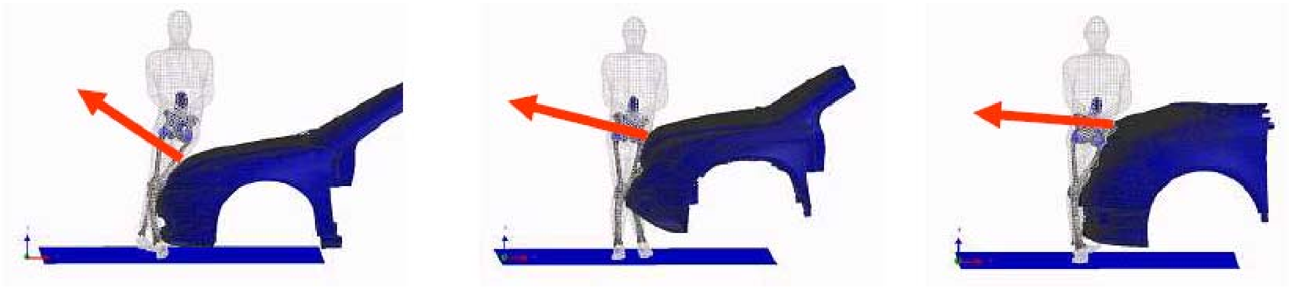

Figure 2
Sedan, SUV and MPV to Human Model Impact

A validation criterion was defined based on peak deflection, absorbed energy and peak force magnitude, due to the fact that it was found that these parameters were correlated to pelvis deflection, femur bending moment and tibia bending moment in passenger vehicle to pedestrian impacts [7]. The model was considered valid when the predicted value from the buck was within 20% of the vehicle value. Generally for the bumper lower and bumper, the shape of the force deflection curves was either one step or two step constant crush force. For the grille and hood edge the shape of the force deflection curves was generally one step constant crush force.

The universality of the buck was tested by using results from EuroNCAP pedestrian impact testing [15]. In the tests a leg impactor was launched at the vehicle front. Data from these tests was analysed and converted to contact force [15]. In the EuroNCAP testing procedure the leg form mass and impact angle were varied based on the geometry of the vehicle (Figure 3).

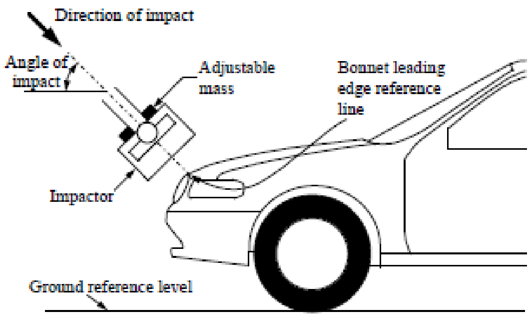

Figure 3
EuroNCAP Upper Leg Form to hood Leading Edge Test Procedure

The data was divided into three vehicle groups, Sedan, SUV and MPV. The vehicle with the highest and lowest force in each group was selected for the universality testing. The EuroNCAP pedestrian score for the vehicle with the highest force was poor while for the vehicle with lowest force the score was good. Therefore, the vehicles with the highest force will be referred to as bad vehicles and the vehicles with lowest force will be referred to as good vehicles. The geometry of the buck was modified to correspond to the specific sedan, SUV or MPV for which the contact force corresponded (Figure 4) [16]. Impact simulations in which the EuroNCAP upper leg form was impacting the buck were carried out [17]. The contact force and vehicle crush from the leg form tests were mimicked with the buck. Based on the geometry of the vehicle front the mass, impact angle and initial velocity of the leg form were calculated based on the EuroNCAP test specification [18]. The impact velocity was 23-40 km/h, the impact angle was 28-37 degrees and the leg form mass was 9.8-12.6 kg.

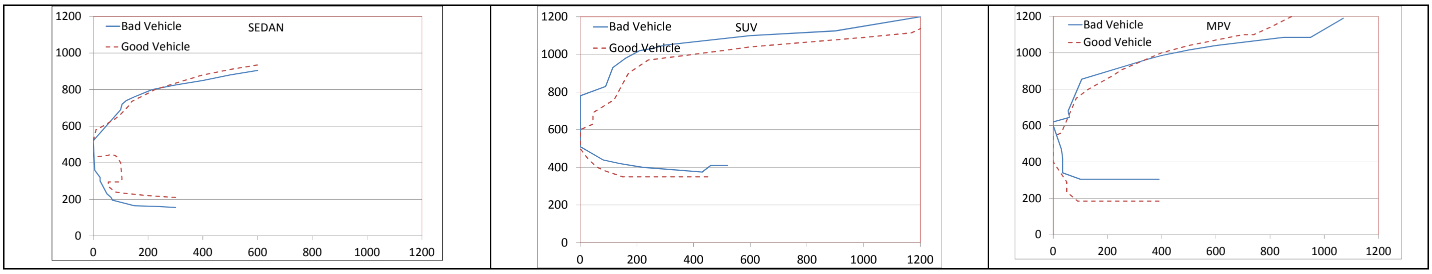

Figure 4
Vehicle Geometry for the Sedan, SUV and MPV Used in the Universality Development

The potential injury reducing benefits of a hood leading edge bag for a pedestrian were evaluated with the buck (Figure 5). The bag was mounted to the hood leading edge of the buck representing the bad Sedan, SUV and MPV in the EuroNCAP tests. The EuroNCAP leg form with the same mass, impact velocity and impact angle as described above was impacting the buck with the hood leading edge bag. The volume of the bag was 106 liters and the pressure when loaded was 30 - 45 kPa, depending on vehicle type. The pressure of the bag varied due to the fact that the mass, impact angle and impact velocity of the leg form varied between the vehicle types.

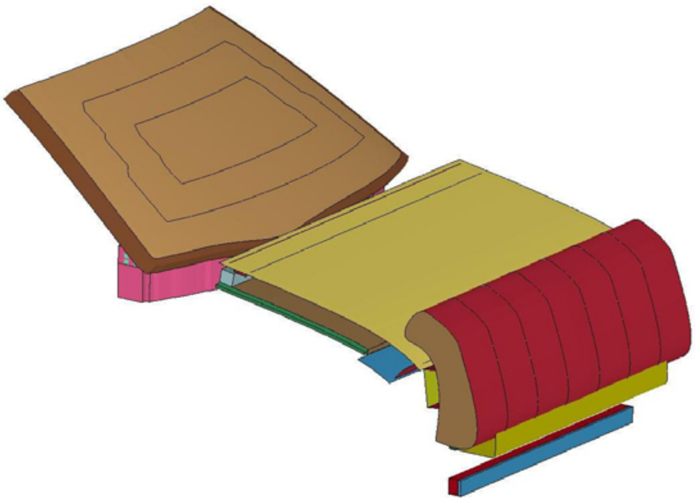

Figure 5
Hood Leading Edge Bag

III. RESULTS

The modified universal generic vehicle front buck consists of bumper lower, bumper, grill, hood edge, hood and windshield (Figure 6). The design of the bumper lower, bumper, grille and hood edge were all modified. For the bumper lower and the bumper a dual layer plastic design was used.

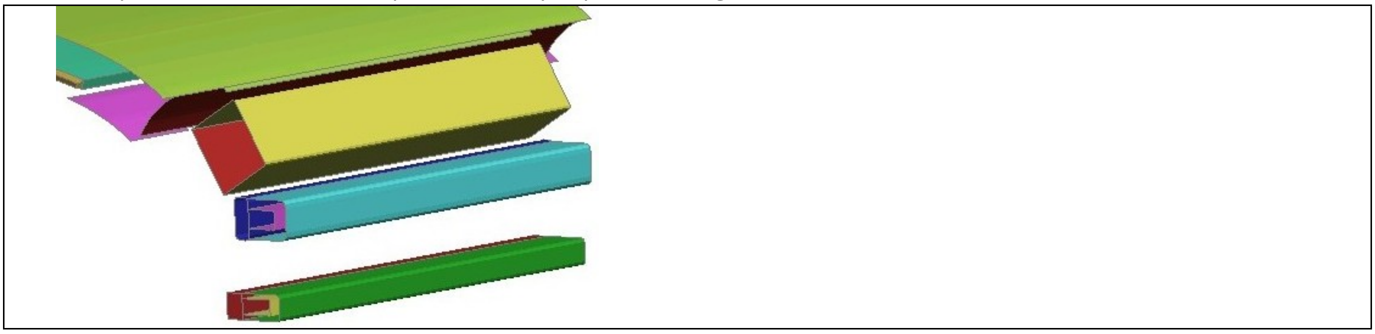

Figure 7). The thickness was varied based on the type of vehicle modeled. The grill was plastic and the design was U-shaped. The hood edge design was a curved steel shape. The boundary conditions for the hood were similar to a vehicle. The hood was constrained at the hinges and at the hood lock in the front of the hood.

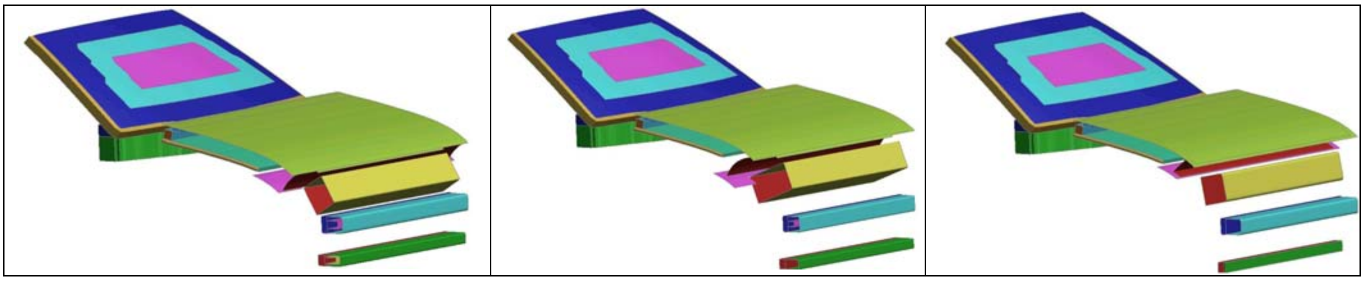

Figure 6
Universal Buck Corresponding to a Sedan, SUV and MPV

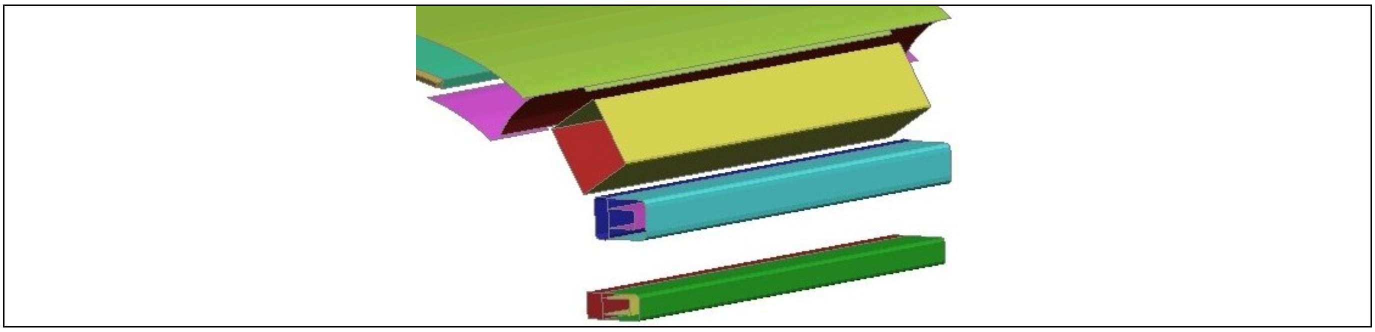

Figure 7
Bumper, Bumper Lower, Grille and Hood Edge Design

The modified buck model was validated by comparing force, energy and crush predictions from the impactor to buck impact simulations with the results from impactor to vehicle impact simulations. The force deflection results for impactor to sedan, SUV and MPV vehicles at 20, 40 and 60 km/h impact velocity can be found in Appendix A.

For the sedan validation at 20, 40 and 60 km/h impact velocity the total average difference between the peak force, energy at peak force and max crush predicted by the impactor to buck impact model and the impactor to vehicle impact model was 14% (Table 1). The average difference was 19% for peak force, 12% for energy and 10% for crush. The greatest difference was 42% for peak force, 45% for energy and 20% for crush.

Table 1.
Sedan Validation

	20kph			40kph			60kph		
	Peak Force [kN]	Energy @ Peak Force [kNmm]	Crush (total) [mm]	Peak Force [kN]	Energy @ Peak Force [kNmm]	Crush (total) [mm]	Peak Force [kN]	Energy @ Peak Force [kNmm]	Crush (total) [mm]
Bumper Lower									
Difference	25%	35%	3%	2%	3%	7%	0%	23%	14%
Bumper									
Difference	10%	7%	3%	10%	3%	7%	22%	1%	14%
Grille									
Difference	13%	11%	4%	28%	4%	13%	42%	4%	20%
Hood Edge									
Difference	5%	45%	4%	35%	4%	13%	39%	7%	20%

In the human body pedestrian model to SUV impact simulations there was no contact between the pedestrian leg and the bumper lower. Therefore no impact evaluation was carried out for the bumper lower for the SUV.

For the SUV validation at 20, 40 and 60 km/h impact velocity the total average difference between the peak force, energy at peak force and max crush predicted by the impactor to buck impact model and the impactor to vehicle impact model was 26% (Table 2). The average difference was 40% for peak force, 28% for energy and 11% for crush. The greatest difference was 71% for peak force, 66% for energy and 34% for crush.

Table 2
SUV Validation

	20kph			40kph			60kph		
Bumper	Peak Force [kN]	Energy @ Peak Force [kNmm]	Crush (total) [mm]	Peak Force [kN]	Energy @ Peak [kNmm]	Crush (total) [mm]	Peak Force [kN]	Energy @ Peak [kNmm]	Crush (total) [mm]
Difference	55%	31%	31%	15%	17%	17%	0%	10%	34%
Grille									
Difference	21%	17%	4%	64%	54%	2%	71%	66%	3%
Hood Edge									
Differece	36%	36%	4%	26%	6%	2%	70%	12%	3%

For the MPV validation at 20, 40 and 60 km/h impact velocity the total average difference between the peak force, energy at peak force and max crush predicted by the impactor to buck impact model and the impactor to vehicle impact model was 18% (Table 3). The average difference was 28% for peak force, 20% for energy and 7% for crush. The greatest difference was 50% for peak force, 48% for energy and 13% for crush.

Table 3
MPV Validation

	20kph			40kph			60kph		
Bumper Lower	Peak Force [kN]	Energy @ Peak Force [kNmm]	Crush (total) [mm]	Peak Force [kN]	Energy @ Peak [kNmm]	Crush (total) [mm]	Peak Force [kN]	Energy @ Peak [kNmm]	Crush (total) [mm]
Difference	32%	40%	13%	38%	48%	1%	28%	4%	1%
Bumper									
Difference	3%	13%	13%	17%	7%	1%	0%	1%	1%
Grille									
Difference	34%	41%	12%	33%	13%	7%	50%	13%	7%
Hood Edge									
Difference	34%	30%	12%	35%	5%	7%	28%	26%	7%

The buck was modified to correspond to a sedan, an SUV and an MPV with a good and bad score respectively in the EuroNCAP pedestrian rating. Both the geometry and the stiffness of the buck were modified. Simulations with the EuroNCAP upper legform impactor were carried out. For the vehicles with good EuroNCAP pedestrian impact scores the upper leg form max bending moment was less than 300 kNmm and the total force was less than 5 kN (Figure 8). For the vehicle with bad EuroNCAP pedestrian impact scores the max bending moment was greater than 380 kNmm and the total force was greater than 6 kN. The highest force for the bad vehicles was for the MPV vehicle, where peak force was 16 kN and total crush was 90 mm. The lowest force was for the sedan vehicle, where peak force was 4.5 kN and peak crush was 111 mm.

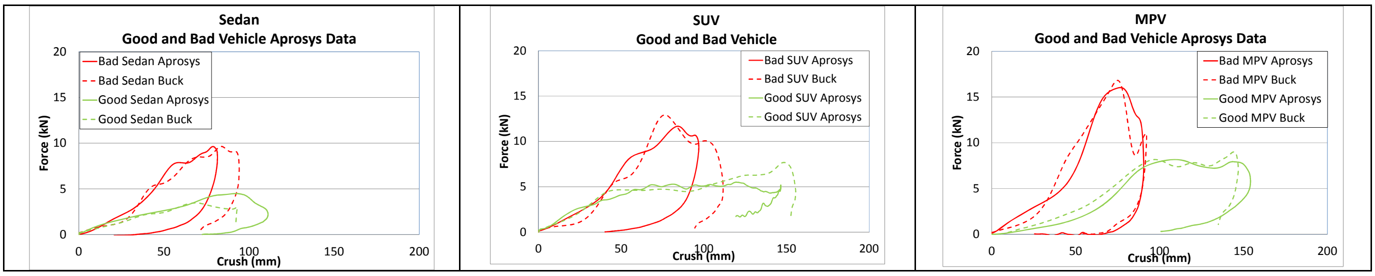

Figure 8
Sedan SUV and MPV Universality Demonstration
The vehicle with a good score in the EuroNCAP Pedestrian rating is marked with a green curve and the vehicle with a bad score is marked with a red curve

The buck was capturing the Sedan, SUV and MPV responses, meaning that all buck predictions were inside the 20% range of the vehicle responses for all but the bad sedan vehicle (Table 4). For the sedan there was a discrepancy between the predicted peak force and the peak force from the EuroNCAP sedan test.

Table 4
Sedan, SUV and MPV Universality Testing

	Force @ APROSYS Peak [kN]	Energy @ APROSYS Peak [kNmm]	Crush (total) [mm]		Force @ APROSYS Peak [kN]	Energy @ APROSYS Peak [kNmm]	Crush (total) [mm]		Force @ APROSYS Peak [kN]	Energy @ APROSYS Peak [kNmm]	Crush (total) [mm]
Sedan Good	4,5	235	111	MPV Good	8,2	349	154	SUV Good	5,5	467	147
Buck Good	3,0	199	93	Buck Good	7,4	405	147	Buck Good	6,0	459	156
Difference	50%	18%	19%	Differece	10%	14%	4%	Difference	9%	2%	6%
Sedan Bad	9,6	355	81	MPV Bad	16,0	498	91	SUV Bad	11,7	452	97
Buck Bad	8,9	334	94	Buck Bad	16,4	529	92	Buck Good	11,4	439	112
Difference	8%	6%	14%	Difference	2%	6%	1%	Difference	1%	3%	13%

The hood leading edge bag was mounted on all vehicles with a bad score and the vehicles were impacted with the EuroNCAP legform at 23 – 40 km/h. The bag reduced peak force and peak bending moment significantly for all vehicle types (Table 5). Without a hood leading edge bag all vehicle responses were above the injury assessment reference value (IARV) of a peak force of 5 kN and a peak moment of 300 kNmm. With the bag the responses were below the IARVs. For the sedan vehicle peak force was reduced from 7.6 kN to 3.2 kN and peak moment from 416 kNmm to 134 kNmm.

Table 5
Results Upper Leg form Impacts with Hood Leading Edge Bag Mounted on Buck

	Peak Force	IARV	Peak Moment	IARV
	(kN)	(kN)	(kNmm)	(kNmm)
		5		300
Sedan bad	7,6		416	
Sedan bad with Bag	3,2		134	
SUV bad	10,0		621	
SUV bad with Bag	4,6		194	
MPV bad	13		722	
MPV bad with Bag	4,3		175	

IV. DISCUSSION

A previously developed finite element model of a vehicle front, a buck, to be used for vehicle to pedestrian impact evaluations was further developed (Figure 1). The model consists of both solid and shell elements. The typical element size was 10 mm. It was demonstrated that the model can be tuned to correspond to pedestrian to vehicle front impact characteristics of a sedan, an SUV and an MPV vehicle front. The model was evaluated for 20, 40 and 60 km/h impact velocities.

There were significant differences for some of the peak forces, energies and max crush values between the impactor to buck and impactor to vehicle simulations (Table 1-3). In particular there were differences in peak force. The reason for the disagreement was that some of the responses from the vehicle to impactor simulations were very noisy, significantly more noisy than the corresponding buck to impactor responses. Making the vehicle to impactor responses more smooth will improve the agreement between the buck to impactor and vehicle to impactor responses. In addition in the human pedestrian and impactor to vehicle analysis there were components that were breaking in the vehicle front. In particular for the higher impact velocity there were parts that were breaking. The current buck was designed without the capability to include breaking of parts. Therefore including breaking of parts can improve the agreement between the impactor to buck and impactor to vehicle predictions. However, such a modification makes the buck more complex and less robust.

The total average difference of 14% in force, energy at peak force and max crush seems to be a broad measure for the universal generic buck mimicking a specific sedan, SUV and MPV (Table 1-3). However, the aim of the buck was to develop a tool capable of mimicking a fleet of vehicles. Therefore the 14% difference was considered adequate when modeling a specific vehicle type. In addition adding more detail to the buck reducing the difference between the specific vehicle results and buck predictions would make the buck less generic and less universal. Therefore there is a tradeoff between the universality of the buck and the capability of it to predict specific vehicle results.

Bumper lower, bumper, grille and hood edge were all modified in the universal generic buck relative to the original buck. It was observed that the force deflection characteristics for the bumper lower and bumper were a two step constant crush force shape (Appendix A). To capture the two force levels the bumper lower and bumper were designed by means of two u-shaped plastic profiles with air between the profiles (Figure 7). However, for the SUV only the outer plastic profile was deformed and there was no need for the inner profile. In the original buck the bumper lower and bumper consisted of constant crush force foam. A two step constant crush force shape using foam was not achieved; therefore, the bumper lower and bumper were redesigned using two u-shaped plastic profiles.

The deformation characteristics for the grille were generally constant crush force. In the modified buck a U-shaped plastic profile design for the grille was chosen (Figure 7). With that design the constant crush force characteristics of the grille observed in the human body and impactor to vehicle simulations were captured. However, with the foam design of the grille in the original buck the constant crush force characteristics were also captured.

For the hood edge the combination of compressive and transverse crush forces observed in the human body and impactor to vehicle simulations were not obtained with the foam hood edge design of the original buck. Therefore the hood edge was redesigned using a curved shaped steel beam (Figure 7). With that design the combination of compressive and transverse crush forces of the hood edge was achieved.

The buck model was considered valid for the hood leading edge bag evaluation, due to the fact that generally there was a close match between the buck to leg form predictions and the results from corresponding EuroNCAP tests (Figure 8). The difference between the buck to leg form predictions and the results from the leg from to vehicle EuroNCAP test results were less than 19% for all vehicle types and responses but the peak force for the good sedan and good buck comparison (Table 4). The difference in measured peak force for the good sedan and the predicted peak force for the good buck was 50%. The force level in that test was very low. Therefore, despite the fact that the predicted value was close in absolute numbers to the measured value in the EuroNCAP test, the difference in percent between the measured and predicted value was 50%.

In the EuroNCAP leg form tests the impact can be anywhere on the vehicle front and not necessarily in the middle. Therefore, if the leg form impact is towards the side of the vehicle in which the vehicle geometry can be different from the middle of the vehicle the boundary conditions for the test can also be different. The leg form can impact headlamps and other vehicle components, which are not addressed with the current version of the buck. Future modifications of the buck can include characteristics of components, such as head lamps.

The buck was found to be capable of mimicking the impactor to vehicle and also EuroNCAP legform to vehicle impact characteristics for a sedan, an MPV and an SUV with a good and a poor score in the EuroNCAP rating (Table 4). However, the buck was not evaluated for whole body pedestrian impact kinematics. Therefore the buck will also be evaluated in the future for whole body kinematics using a human body model, as well as a mathematical model of the POLAR III dummy.

A limitation with the impactor method used in the study was that only one vehicle component at a time was impacted. In a pedestrian to vehicle impact all components of the vehicle front such as the bumper lower, bumper, grille and hood edge are loaded by the pedestrian lower body. Therefore the kinematics of the pedestrian is a result of a combination of the loads from the various vehicle components. These combined effects are not addressed with the impactor method used in the study. In future development of the buck such combined effects will be evaluated. In addition, future development of the buck will include refinement of hood and windshield.

The universal generic buck was found to be a good tool to mimic the pedestrian impact characteristics for various vehicle types at various impact velocities. For development of pedestrian impact countermeasures the buck will be used with pedestrian substitutes such as the POLAR III dummy or other human body pedestrian models. Therefore the buck will in the future be used to develop robust pedestrian impact countermeasures.

V. CONCLUSIONS

The total average difference between full vehicle to impactor and buck to impactor predictions was 19% for all impact velocities and all measures.

The average difference between full vehicle to impactor and buck to impactor peak force was 28%, energy was 20% and total crush was 7%.

The greatest difference between full vehicle to impactor and buck to impactor peak force was 71%, energy was 66% and total crush was 34%.

The universal generic buck can be tuned to correspond to a sedan, an SUV and an MPV in a pedestrian to vehicle impact evaluation in analysis using mathematical simulations models.

The hood leading edge bag reduced the thigh (femur) force by 4.4 kN for the sedan, by 5.4 kN for the SUV and by 8.7 kN for the MPV.

The hood leading edge bag reduced the thigh (femur) bending moment by 282 Nm for the sedan, by 427 Nm for the SUV and by 547 Nm for the MPV.

The universal generic buck can be used in analysis using mathematical simulations models to develop robust pedestrian impact countermeasures for sedan, SUV and MPV vehicles.

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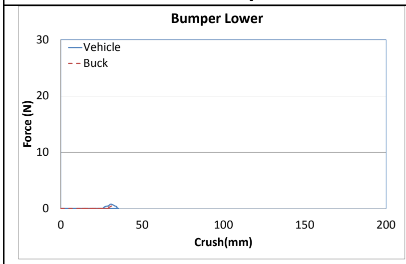
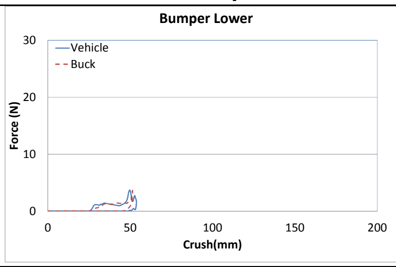
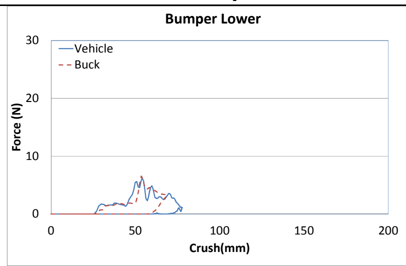
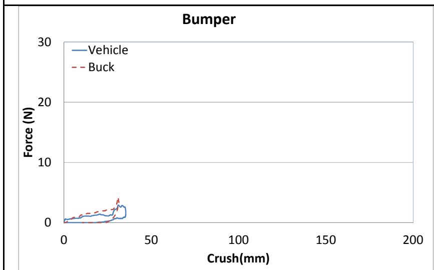
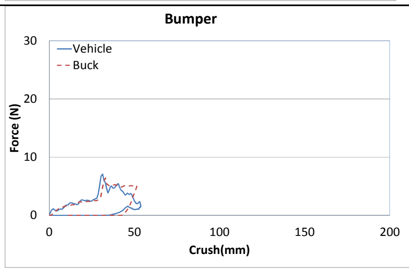
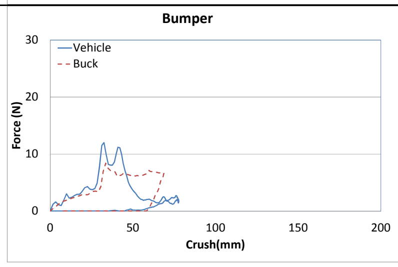
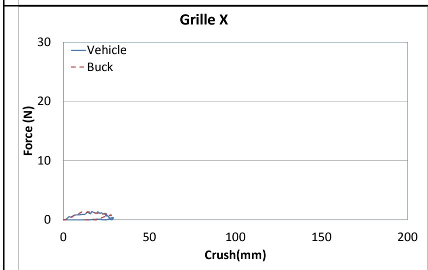
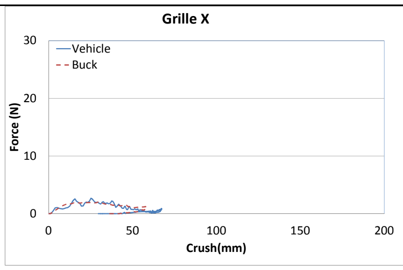
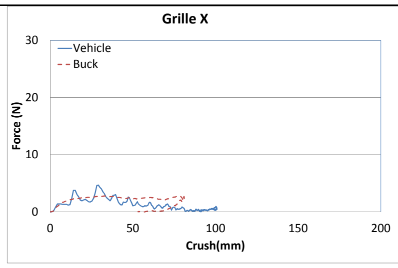
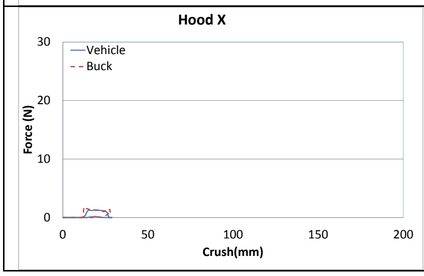
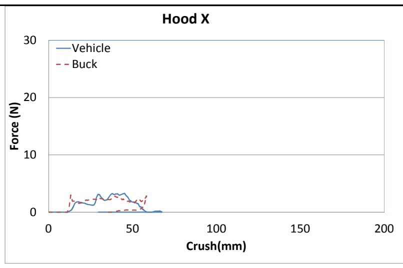
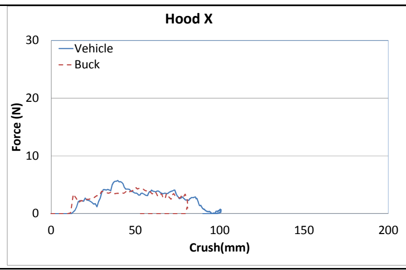
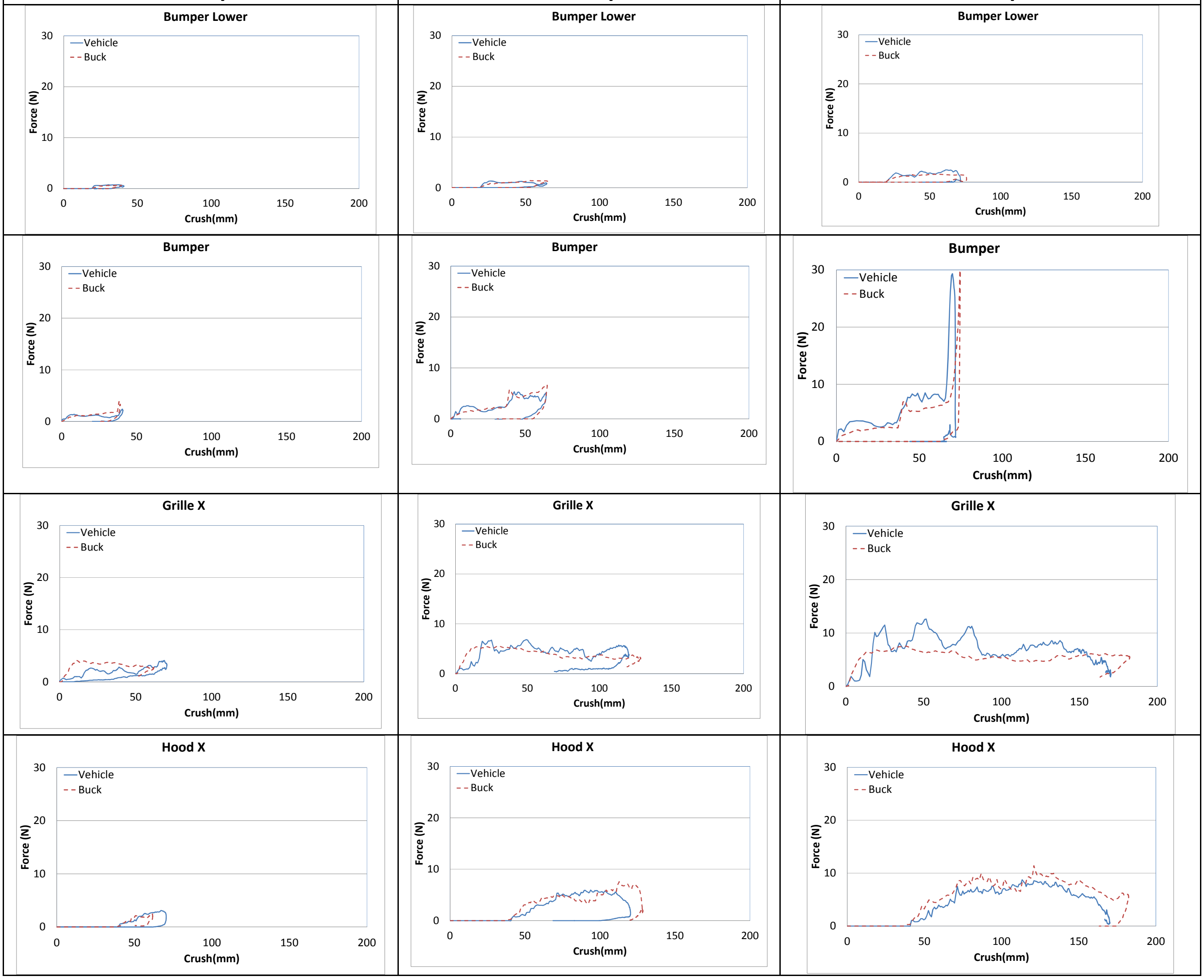
VII. Appendix

APPENDIX A – Sedan, MPV and SUV Vehicle Rigid Impactor Results at 20, 40 and 60 km/h impact velocity

	Sedan	
20 km/h	**40 km/h**	**60 km/h**
		
		
		
		

	MPV	

20 km/h	40 km/h	60 km/h



SUV		
20 km/h	**40 km/h**	**60 km/h**