EFFECTS OF VEHICLE FRONT DESIGN PARAMETERS ON PEDESTRIAN HEAD-BRAIN INJURY PROTECTION

Jikuang Yang[1,2]
[1]Crash Safety Division, Chalmers University of Technology
SE-412 96 Gothenburg, Sweden
[2]College of Mechanical and Automotive Engineering, Hunan University
410082 Changsha, China

Paper number: 289

ABSTRACT

The objective of the present work is to determine the effect of the vehicle front design on pedestrian head impact responses and injury related parameters based on accident reconstructions and simulation analyses of car-pedestrian impacts.

The accident reconstructions were carried out using selected accident data from an in-depth study with head-brain injuries documented in accident and medical report. The correlations of the output parameters from reconstructions with the injuries described in medical and accident report were analyzed.

The influences of vehicle front structures to pedestrian head-brain injuries were investigated by using computer simulations at varying impact speeds up to 60 km/h. The different sizes of models were used to represent the adult and child pedestrians, including 6, 9 years old children and 5th, 50th, 95th adults. The shapes of the vehicles were investigated and categorized by compact and large passenger cars, mini-van.

The safer vehicle front design for pedestrian protection was analyzed and discussed with focus on the head impact velocity, head impact angle, location and timing of head impact for both adult and child pedestrians.

INTRODUCTION

Pedestrians were primarily impacted by the vehicle front with a high frequency in vehicle-pedestrian accidents. The head brain injuries were over-represented with about 31% of total injuries and often result in fatal consequences[1]. A Prevention Priority Index (PPI) for pedestrian brain injuries was then proposed as 0.336 that is second to car occupants[2]. Since the early 1990s the European Experimental Vehicle Committee (EEVC) has proposed the headform test procedures[3] to evaluate the fronts of passenger cars for pedestrian head protection. The subsystem test procedures can be implemented to detect the vehicle front stiffness and impact energy that are main factors to cause head brain injuries.

In order to develop a new vehicle with pedestrian friendly front that can meet the requirements of the subsystem tests it is necessary to have an effective approach for improvement of a new vehicle front design. In-depth accident analyses and PMHS tests provided valuable information about injury patterns, causation and distribution of the injuries, and injury mechanisms. For further study on improvement of car front design, it requires detail information about the dynamic responses of pedestrians, the loads to body segments from impact with different vehicle types. It also needs some injury related parameters that are usually difficult to measure in either PMHS or dummy tests, and missing even in an in-depth field investigation. Mathematical modeling is one of effective approach to get good understanding of pedestrian impact dynamics and injury biomechanics which forms a basis to improve car front design.

This study aimed at investigating the influences of vehicle front structures on pedestrian head injuries by using mathematical models, and furthermore determining the key injury related parameters and variables to improve car front design for pedestrian head impact protection.

METHOD AND MATERIAL

The pedestrian accident case study was carry out with collected data from both accident site and hospital clinic report. The detail information about both vehicle and injuries as well injury severities. was collected and used for reconstructions of the accidents.

One adult accident and two child accidents were reconstructed by using MADYMO program. The adult pedestrian accident was reconstructed using the validated pedestrian model developed at Chalmers University of Technology in Sweden. The child accidents were simulated using child pedestrian models scaled from the adult model. The correlations of the kinematics and output parameters from simulations with the injuries described in medical and accident report were analyzed.

The influences of vehicle front structures to pedestrian head-brain injuries were investigated by using computer simulations of vehicle-pedestrian impact at varying impact speeds up to 60 km/h. The different sizes of models were used to represent the adult and child pedestrians, including 6, 9 years old children and 5th, 50th, 95th adults. The shapes of the vehicles were investigated and categorized by compact and large passenger cars, mini-van.

PEDESTRIAN ACCIDENTS

An in-depth study [4] on head-brain injuries in crash accidents was conducted from 1998 to 1999 in Sweden, including one adult pedestrian accident and two child pedestrian accidents. The accident cases are summarized as follows.

Accident Case 1

A car-to-child pedestrian collision occurred on a secondary rural road in Sweden. The accident car is OPEL Combi 1985 model. The driver was approaching a group of children playing on the right side of the road at speed about 70 km/h. The driver lifted his foot from the accelerator as he noticed the potential risk. One boy, 7 years old, began running across the road as the car without noticing the car. The driver braked hardly and manipulated the car to avoid an impact. The car, however, still hit the child by the right front corner at an estimated speed about 40 – 45 km/h. The contact dents were visible on the leading edge of the hood and the hood top. The dent on the hood top was identified as the result of the head impact. The measured wrap around distance (WAD) was 1350mm. The throw distance was about 14m from initial impact.

The child sustained unconsciousness due to the head-brain injuries: fracture left orbit, subdural hematomae left frontal lobe. The child recovered the health after 5 days medical treatment. Except some slight outer skin injuries in the lower extremities, no other injuries were reported.

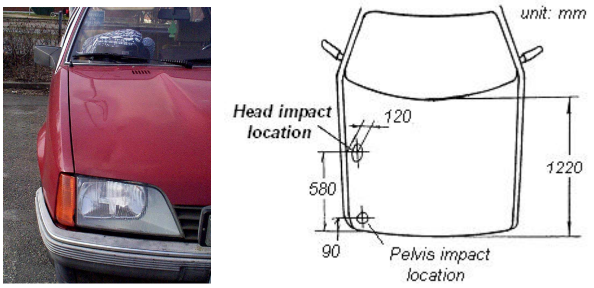


Figure 1. The head impact location on the hood top of the accident car struck a 7 years old child..

Accident Case 2

A 9 year old child was hit by a Volvo car on a crosswalk of street in a residence area. The driver was approaching the crosswalk at speed about 40 km/h. A child was suddenly running through the crossing path to meet his parents standing on the opposite side of the street. The driver braked the car, but he could not avoid a struck to the child. The brake distance after initial impact was about 7–7.5 m. The throw-out distance was about 8.5-9.5m. On the hood top, a very slight dent was found at 630 mm away from the front edge. The measured WAD was 1390mm.

The child pedestrian was injured on the head, and was bruising on the leg. No bone fracture was found. The child sustained slight head injuries (AIS=2) and recovered in 2 weeks.

Accident Case 3

A 52 years old male adult was hit by a VOLVO car. The victim in a running posture was hit at a high speed about 85 km/h even though the driver braked the car. The throw distance of the man was around 42 m. The windscreen was damaged due to the head and upper torso impact (Figure 2). The measured WAD was 2385mm.

The person was seriously injured on the head/brain, including temporal contusion, extra-cranic, facial fracture right side (behind right eye), intraventricular blooding. No severe injury on the lower extremity.

Figure 2. The head impact location on the windscreen of the car in adult pedestrian accident.

RECONSTRUCTION OF PEDESTRIAN ACCIDENTS

The accidents were reconstructed with the data collected from the study. The adult pedestrian accident was reconstructed using the validated pedestrian model [5, 6]. The child accidents were simulated using child pedestrian models scaled from the adult model [7]. The impact speeds of the cars and the pedestrian speed were estimated based on the accident data, considering the car braking skid marks on the road surface and the pedestrian moving postures before the impact. The mathematical models of cars were created based on the drawings of the production cars in the same type involved in the accident. The force-deformation properties of the car models were defined in terms of stiffness properties acquired from Euro NCAP sub-system tests (Figure 4). The injury parameters in head, chest, pelvis and lower extremities were calculated to evaluate the injury severities from the accidents. The correlations of the output parameters from simulations with the injuries described in medical and accident report were analyzed. The threshold of brain injury parameters, such as HIC and angular acceleration, was discussed based on reconstruction results.

The anthropometric data of the pedestrian models used in the reconstructions was summarized in Table 1, which was based on the data from the accident analysis.

Table 1: Anthropometric data

Pedestrian	7YOC	9YOC	Adult
Height (mm)	1227	1301	1820
Weight (kg)	25	30.7	90

Reconstruction of Case 1

The car speed at the moment of impact was defined as 40 km/h according to the brake mark left on the road. The friction coefficient between the wheels and road surface was chosen as 0.7. The diving angle was estimated as 3 degree. Steering effect was also simulated by define an angular velocity of 1 rad/s.

A 7-year-old child was developed by using the scaling method from a validated adult model [7]. The initial posture was adjusted to be running in the direction perpendicular to the car moving direction. The running speed was estimated about 10 km/h.

Reconstruction of Case 2

The car impact speed was defined as 36 km/h. The braking deceleration was chosen as 0.7g, while the diving angle was assumed as 2 degree without steering movement.

The 9-year-old child model was developed with the scaling method mentioned above. The initial posture was adjusted as walking cross the street.

Reconstruction of Case 3

The accident case 3 was reconstructed even though it occurred in a high impact speed that is seldom in pedestrian accidents. It is meaningful to investigate the surviving reason of the person. The car impact speed was defined as 85 km/h according to the brake mark left on the road. The friction coefficient between the wheels and road surface was chosen as 0.7. The diving angle was estemated as 3 degree. Steering effect was also simulated by define an angular velocity of 2 rad/s.

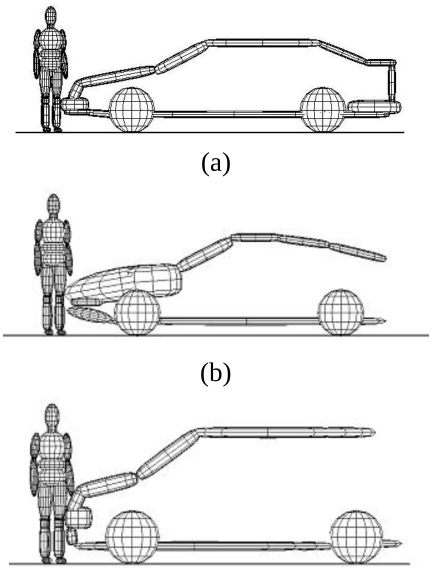
An adult pedestrian model was used to simulate the accident. The initial posture was adjusted to be running in the direction perpendicular to the car moving direction. The running speed was defined about 20 km/h.

STUDY ON HEAD IMPACT RESPONSES

There is a need of the information about injury related parameters for pedestrian protection by improving vehicle front design. A study is therefore carried out on pedestrian dynamic responses at different impact speeds with different types of vehicles. In this paper, the analysis is focused on the head impact responses, including timing of head impact to hood top, location of head impact, head velocity during impact to hood top, and head impact angle. These are main parameters to be considered in new car design for head impact protection.

The Vehicle Geometry and Mechanical Properties

The geometry of the vehicle models was based on the drawings of the production cars and the chosen variables of the vehicle front structure (Table 2). The following dimensions on the vehicles are measured in Y0 axis. The examples of the base models of car-to-pedestrian impact are shown in Figure 3a the Sedan 1, in Figure 3b the Sedan 2, and in Figure 3c the SUV.



(c)

Figure 3. Example of the baseline models for parameter study on head responses in car-pedestrian impacts.

Table 2: Passenger car shape for simulation

		Sedan1	Sedan2	SUV	Box
BL	mm	60	40	127	180
BCH	mm	498	420	516	600
LEH	mm	725	580	839	900
Hood length	mm	1175	1400	635	360
Hood angle	deg	12	15	18	40
Windscreen angle	deg	29	27	38	42

The mechanical properties of the car front was partly calculated from EuroNCAP subsystem impact tests. The stiffness data from EuroNCAP tests were used to define the characteristics of car front in MADYMO models.

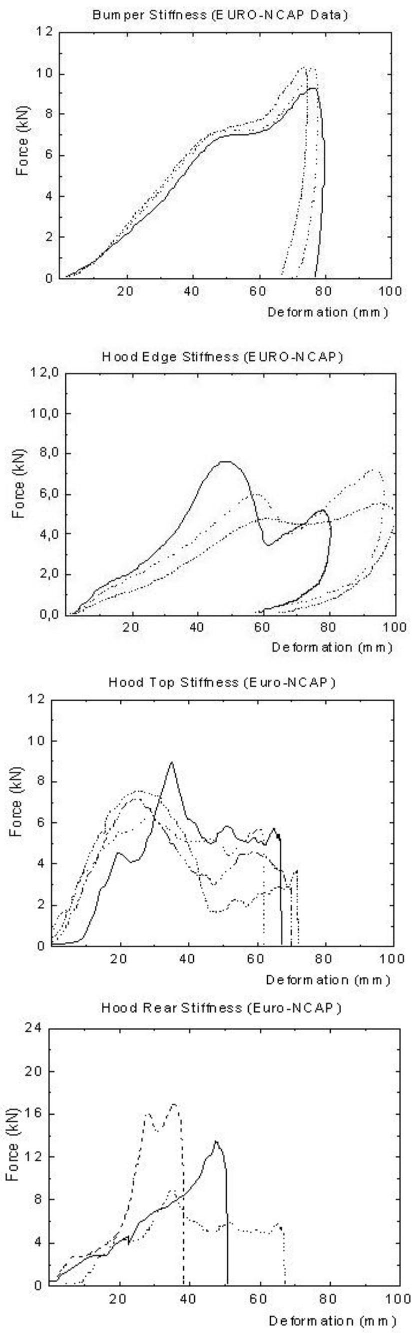


Figure 4. Mechanical properties of car front at varying location based on subsystem impact tests of Euro NCAP.

A parameter study with the representative configurations was carried out with adult and child pedestrian models at impact speeds of 15 up to 60 km/h.

The Pedestrian Models

The available pedestrian models and anthropometric data used in the parameter study are shown in Figure A1 and Table A1 in Appendix.

RESULTS AND DISCUSSION

Accident Reconstruction

The kinematics of the pedestrian models in simulations are comparable with that in corresponding accident in terms of the head impact location and throw distance.

7 years old child - Figure 5 showed the kinematics of the 7 years old child. Head impact occurred at around 60 ms after the initial contact. The head impact location was 580 mm away from hood leading edge and 150 mm away from right fender. The throw distance was calculated as 13.5m.

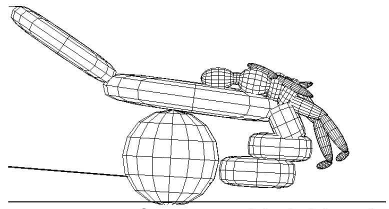


Figure 5. Kinematics of 7 years old child and the head impact location on hop top at 60 ms after initial contact.

9 year old child - The throw distance of the child was properly simulated as 8.9m (Figure A2 in Appendix). It was close to the results found at accident scenes. The head impact location was about 640 mm from the hood leading edge, and 420 mm from the right fender, which matched well with the inspection result of the accident car.

Adult Pedestrian - The impact speed was determined as 83 km/h. The calculated throw distance of the adult was 41m in simulation. The head impact location was up middle of the windscreen (Figure 6) which matched well with the inspection result of the accident car.

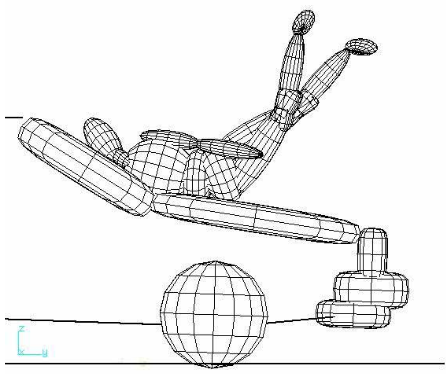


Figure 6. kinematics during of adult and the head impact location on the windscreen at 75 ms from initial impact.

Calculated WADs are comparable with that measured from accident cars (Table 3). It is also noticed that the WADs measured in accident are general a little higher than that calculated from simulations. The ratio of the WAD to the pedestrian height was calculated in the simulations.

Table 3. Comparison of WAD

Injury Parameters	Case 1 7YOC	Case 2 9YOC	Case 3 Adult
WAD_A (mm)	1350	1390	2385
WAD_R (mm)	1306	1364	2300
Height of head CG (mm)	1113	1184	1680
$WAD_A/H_{head\ CG}$	1.21	1.17	1.42
$WAD_R/H_{head\ CG}$	1.17	1.15	1.37

The head injury parameters calculated from accident reconstructions are presented in Table 4. The corresponding head-brain injuries from accidents are summarized in Table 5.

Table 4. Results from accident reconstructions

Injury Parameters	Case 1 7YOC	Case 2 9YOC	Case 3 Adult
HIC	1200	760	12669
HLAC (g)	110	87	281
HAV (rad/s)	72	42	99
HAA (rad/s^2)	8000	5200	20400
HV (km/h)	39	32	101
HIA (degree)	55	65	39
Head contact time (ms)	60	90	78

Table 5. Summary of head-brain injuries

Case 1 7YOC	Case 2 9YOC	Case 3 Adult
Skull facture at left orbit and subdural hematoma at left frontal lobe	Bleeding in left thalamus and diffuse axonal injury in brain stem	Temporal contusion, extra-cranic, facial fracture right side (behind right eye), intraventricular blooding

The head injury severity was evaluated with HIC value and angular acceleration. The calculated HIC values are 1,200 and 760 for the 7- and 9-year old child, respectively. In accidents, skull fracture occurred at the left orbit of the 7-year-old child, but no fracture was observed in the 9-year-old child. It seems that the HIC value of 1000 appears to be a good indicator for skull fracture of children.

The head-brain injuries of the adult victim are obviously due to the high impact speed with very high injury parameters.

The brain injuries were observed for both 7- and 9-year-old child. The predicted head angular acceleration of the 7-year-old child is 8,000 rad/s^2 with a change of angular velocity of 72 rad/s. The 9-year-old child experienced a head angular acceleration of 5,200 rad/s^2 with a change of angular velocity of 42 rad/s. The calculated HAA in combination with a change of HAV are within the proposed brain injury corridor as shown in Figure 7 [8, 9].

Acceptable corrections were achieved between calculated injury parameters and actual injuries in accidents.

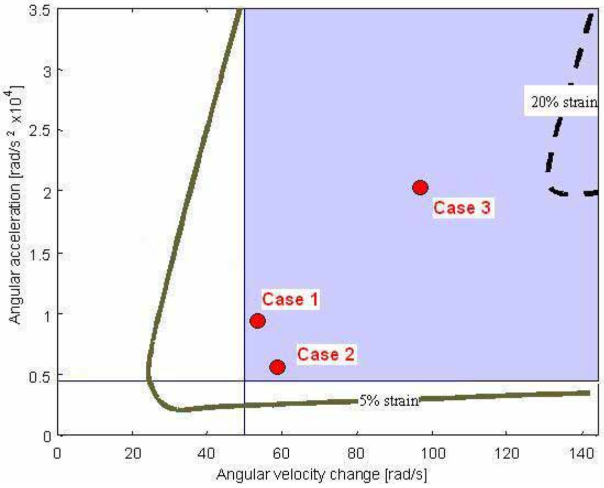


Figure 7. Comparison of the calculated HAA/HAV with proposed tolerance level of brain injuries [8, 9].

Head Responses in Parameter study on Car-to-Pedestrian Impacts

The results from parameter study in simulations of vehicle-pedestrian impacts are partly presented Tables 6a through 6d in terms of the following parameters: the timing of the head impact, the head contact location, the head impact velocity with respect to the car, the head impact angle with respect to horizontal line. In the tables the head contact with windscreen were distinguished with star marks.

Table 6a: The calculated parameters of head impact to the Sedan 1 at 40 km/h

	WAD (mm)	Time (ms)	Vel (km/h)	Angle (deg)
*95th male	2163	136	52	59
*50th male	2132	137	42	67
5th female	1560	98	42	71
9YOC	1294	66	45	56
6YOC	1064	49	39	54

* Indicated a head-windscreen contact in table 5.

Table 6b: The calculated parameters of head impact to the Sedan 2 at 40 km/h

	WAD (mm)	Time (ms)	Vel (km/h)	Angle (deg)
*95th male	2090	157	44	67
50th male	1901	148	34	87
5th female	1575	114	37	70
9YOC	1236	65	44	62
6YOC	931	42	43	49

Table 6c: The calculated parameters of head impact to the SUV at 40 km/h

	WAD (mm)	Time (ms)	Vel (km/h)	Angle (deg)
*95th male	1863	102	51	53
*50th male	1730	98	44	57
5th female	1402	70	47	59
9YOC	1167	51	35	58
6YOC	961	22	40	17

Table 6d: The calculated parameters of head impact to the Box at 40 km/h

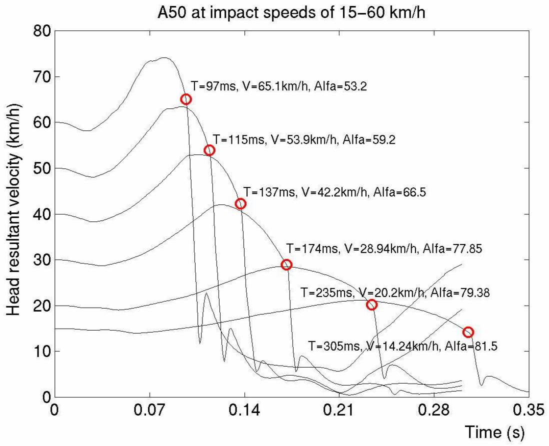
	WAD (mm)	Time (ms)	Vel (km/h)	Angle (deg)
*95th male	1841	82	48	37
*50th male	1752	78	45	39
*5th female	1430	58	45	29
9YOC	1197	40	27	22
6YOC	1006	24	32	19

The timing of the head contact - Analysis of the head contact to the corresponding car front part indicated that the contact timing on the car front varied in a wide range due to car impact speeds, pedestrian sizes, and car front shape, especially for the height of the hood leading edge. For instance the head contact timing is 22 ms in case of6 years old child to a SUV, and 157 ms for 95th male adult to Sedan 2.

The head contact location – The head contact to the car front was measured with WAD from the ground to the contact point of the head CG along the Y0-axis of the car front.

The head contacts with windscreen area represent a large proportion of head impact to car front, especially for adults and old children.

The head velocity and impact angle - Figure 8 illustrates the time history plots of the head resultant velocity relative to the car with Sedan 1 at different impact speeds of 15 to 60 km/h.



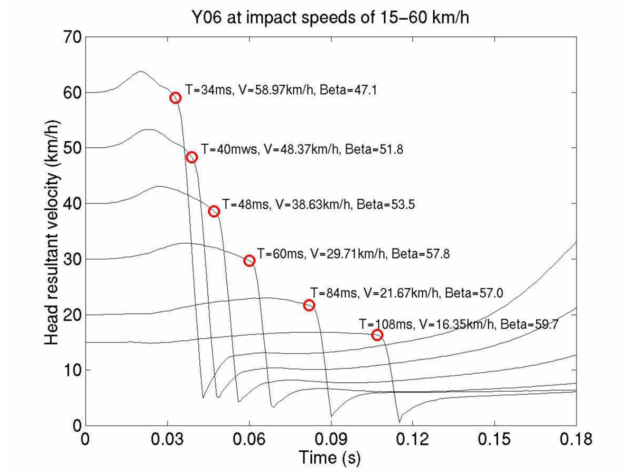


Figure 8. The time history plots of the head resultant velocity for 50th adult and 6 years old child with respect to the car-front

GENERAL REMARKS

In depth analysis and reconstructions of real-world accidents are important means pedestrian safety research. A better understanding of injury mechanisms and tolerances of the living human body can be achieved via the correlations of the calculated parameters with actual injuries. These valuable information are generally difficult to acquire from other sources.

The both linear and angular accelerations were calculated in accident reconstructions. It seems that the HIC was not sufficient for assessment of brain injuries in Case 2 with relative low value. It is necessary to use rotational acceleration as complement injury criterion to evaluate the brain injuries.

The conditions of the head impact to the vehicle front were investigated in the present study for both adult and child pedestrians, including the head impact velocity relative to the vehicle, head impact angle with reference to the horizontal line, location and timing of head contact to the front part.

The results from present work indicated that the head impact conditions in vehicle pedestrian collisions are dependent on the vehicle travel speed, the front shape, the size of pedestrians, the initial posture of pedestrian at the moment of impact.

The main variables of front shape affected the head impact conditions are:

- bumper lead and height
- hood leading edge height
- hood length
- hood angle (one box passenger car)
- windscreen angle.

A rather big amount of head impacts to the windscreen area which could include the windscreen frame and A-pillar. No test procedure was proposed to solve this problem which was raised for years. It is necessary to consider a new test procedure or a extend test method based on the headform test against the hood top.

The EEVC headform test procedure specified impact conditions at 40 km/h and an angle of 65 degrees. It is necessary to point out that the head impact velocity and impact angle could be varied due to car front geometry parameters. For instance, the presented results in this study indicated that at car speed 40 km/h the 50th percentile adult head impact velocity is 34 km/h for Sedan 2, and 45 km/h for 1BOX. The impact angle is 87 degrees for Sedan 2, and 39 degrees for 1BOX. The similar effects due to the car front structures could be found for other configurations.

REFERENCES

[1] Mizuno, Y. and Ishikawa, H. (2001). Summary of IHRA Pedestrian Safety WG Activities – Proposed Test Methods to Evaluate Pedestrian Protection Aforded by Passenger Cars. *Proc. of the ESV* in Amsterdam, The Netherlands. Paper 280.

[2] Viano, D.C. (1989) Biomechanical Responses and Injuries in Blunt Lateral Impact, *Proc. 33rd Stapp Car Crash Conference*, pp. 113-142.

[3] EEVC (1998). Improved Test Methods to Evaluate Pedestrian Protection Afforded by Passenger Cars. Report, European Experimental Vehicle Committee, working group 17, Document No. 100.

[4] Thomson, R.W., Lövsund, P., Jakobsson, L., Boström, O., Håland, Y. (2001): Brain Injuries in Real World Accidents: A Multidisciplinary Investigation, Inter. IRCOBI Conference, October, 2001.

[5] Yang, J.K. (1997). Injury Biomechanics in Car-Pedestrian Collisions: Development, Validation and Application of Human-Body Mathematical Models. Doctoral thesis. Dept. of Injury Prevention, Chalmers University of Technology, Göteborg, Sweden

[6] Yang, J.K., Lövsund, P., Cavallero, C., Bonnoit, J. (2000). A Human-Body 3D Mathematical Model for Simulation of Car-Pedestrian Impacts. *Journal of Crash Prevention and Injury Control*, Vol. 2(2), pp. 131-149.

[7] Liu, X.J. and Yang, J.K. (2002): Development of Child Pedestrian Models and Evaluation with Accident Reconstruction. *Traffic Injury Prevention*, Vol. 3(4), pp. 321-329.

[8] Löwenhielm, P. (1974). Sprain Tolerance of the Vv. Cerebri Sup. (Bridging Veins) Calculated from Head-on Collision Tests with Cadavers. *Z. Rechtsmedizin*, 75, pp. 131-144.

[9] Margulies, S. S. and Thibault, L. E. (1992) A Proposed Injury Criterion for Diffuse Axonal Injury in Man, *Journal of Biomechanics*, Vol. **25**(8), pp.917-923

APPENDIX

Table A-1: Anthropometric data of the pedestrian models

Pedestrian Model	A95	A50	A05	Y09	Y06
Height (mm)	1850	1750	1522	1310	1150
Weight (kg)	87	78	50	32.1	21.3

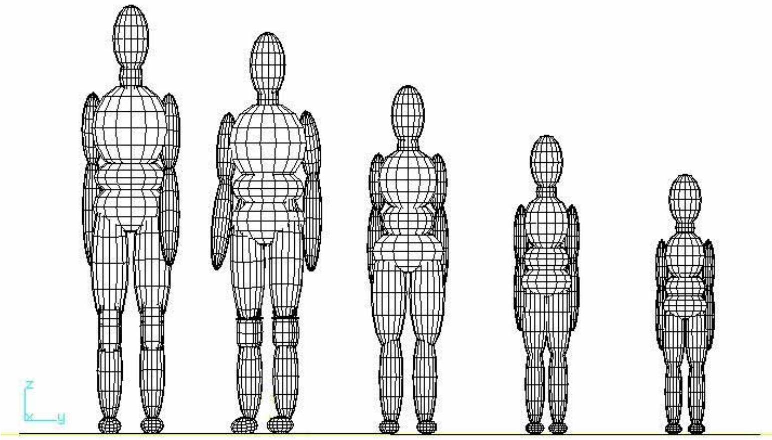


Figure A-1. The pedestrian models developed and validated at Chalmers were used in the parameter study with different production vehicles

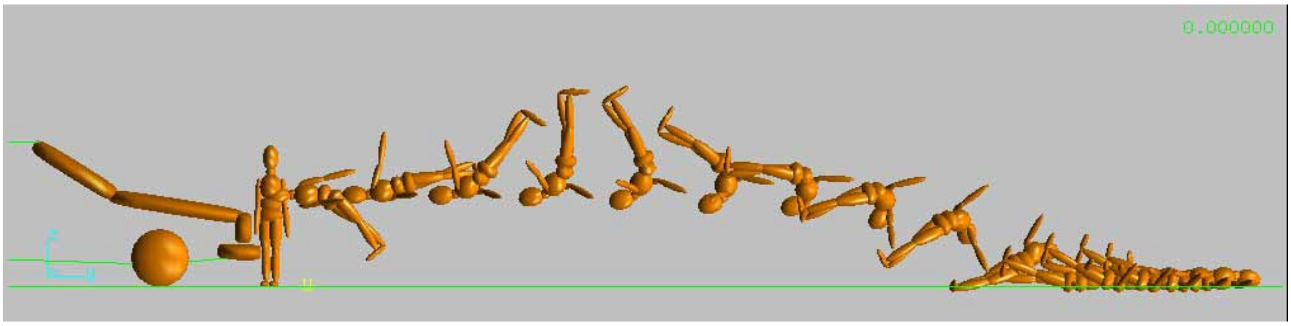


Figure A-2. Overall trajectory of 9-year-old child in accident case 2, the calculated throw distance is 8.9m.