Mathematical modelling of pedestrian crashes: Review of pedestrian models and parameter study of the influence of the sedan vehicle contour

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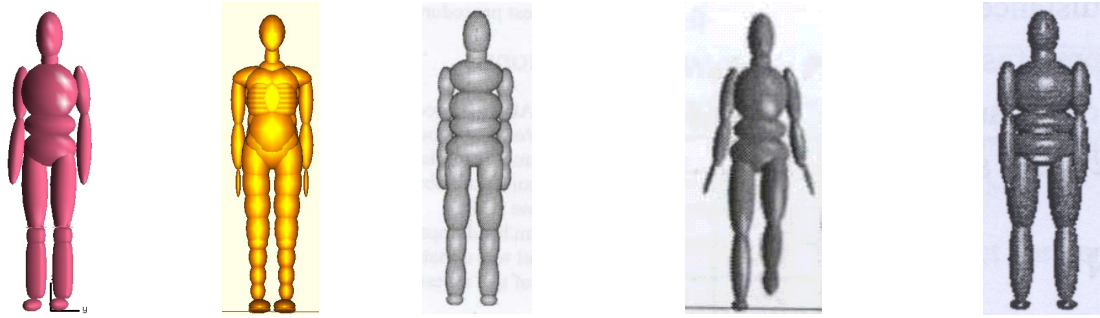
INTRODUCTION

Road crashes result in a substantial number of pedestrian fatalities and injuries worldwide. Statistics from 35 European countries have shown that pedestrian fatalities represented on average 25% of road users killed throughout Europe (ECMT, 2003). In Japan, pedestrian fatalities accounted for 28% of the road toll (ECMT, 2003), while in Australia approximately 16% of road fatalities were pedestrians (ATSB, 2003). Pedestrian fatalities as a proportion of road fatalities were estimated at 13% in the USA to as high as 40-50% of the annual road toll in India and Thailand (Mohan and Tiwari, 2000). The most common cause of such fatalities is head injuries sustained by the pedestrian. Other severe injuries sustained in such impacts are injuries to the chest, spine and abdomen and the lower extremities (Anderson and McLean, 2001, Fildes et al., 2004). Computer simulations for studying methods of reducing the loading to the pedestrian in a crash is a powerful tool especially considering the great cost associated with mechanical optimization of designs. Numerous pedestrian computer models are described in the literature. These models vary in complexity, published validation and availability. For the study of overall human kinematics in a crash, computer models based on rigid bodies connected to each other by joints provide a powerful tool.

Pedestrian multibody models described in the literature can be divided into two categories, models with and without frangible legs. In the category of frangible leg models two widely used models are the Chalmers Pedestrian Model (Chalmers PM) (Yang et al., 1997) and the TNO Pedestrian Model (TNO PM) (TNO, 2004). In the category of non-frangible leg models there are a larger number of models, such as the JARI Pedestrian Model (JARI PM) (Neale et al., 2001), the University of Adelaide Pedestrian Model (Garrett, 1998) and the Honda Pedestrian Model (Honda PM) (Okamoto et al., 2000). The UA PM is also referred to as the RARU i.e. Road Accident Research Unit of Adelaide University, model in the literature in, for example, Mizuno (2003). Figure 1 shows these models as 50th percentile male. All the above mentioned models, except for the Honda PM, require a MADYMO working environment. The Honda PM is run on PAM-CRASH. Validations of these pedestrian models are performed against various cadaver tests. A comparison of the validation of these models was not part of this review, as each validation focuses on a different set of parameters thus limiting the ability to compare them.



Chalmers Pedestrian Model (Yang et al., 1997) | TNO Pedestrian Model (TNO, 2001) | JARI Pedestrian Model (Neale et al., 2003) | University of Adelaide Pedestrian Model (Garrett, 1998) (picture from Mizuno, 2003) | Honda Pedestrian Model (Okamoto et al., 2000)

Figure 1 Multibody models of 50th percentile male pedestrians.

Pedestrian models with frangible leg

The Chalmers PM consists of 15 ellipsoids (Yang and Lövsund, 1997) and frangible legs with a human-like knee. The human-like knee comprises a number of major knee ligaments. The model can therefore be used to assess how aggressive the car front is to pedestrians. The Chalmers PM has been validated against cadaver experiments by Yang and Lövsund (1997) and Yang et al. (2000) and is not commercially available. In addition to the 50th percentile male, this model has been scaled to represent a 95th percentile male, a 5th percentile female and a 3, 6, 9 and 15-year-old child (Liu and Yang, 2002). The 50th percentile male pedestrian and the 9 and 6-year-old child models have been used in reconstructions of real-world crashes by Yang (2003).

The TNO PM consists of 52 rigid bodies and includes six frangible leg joints in each leg (TNO 2001). An overview of the validation of the TNO PM model against cadaver experiments is found in TNO (2001). The TNO PM can be scaled to any required body size (TNO 2001) and is commercially available from TNO. The TNO PM is available in the MADYMO database and represents a 95th and 50th percentile male, a 5th percentile female and a 6 and 3-year-old child. The 50th percentile male model and the scaling of the TNO PM have been used in the reconstruction of real-world crashes by van Rooij et al. (2003).

Pedestrian models without frangible leg

The most common type of multibody pedestrian model is that without frangible legs. In this category there are the JARI PM, UA PM and the HONDA PM, with an ongoing developmental process for most of these models. All these models represent a 50th percentile male and none are commercially available.

The JARI PM comprises 27 segments whose dynamic response has been compared to that of cadavers by Neale et al. (2003). The JARI PM has been used as the basis for further improvements by IHRA (Neale et al., 2003) and resulted in the development of the IHRA-PED Pedestrian Model (Mizuno, 2003).

The UA PM consists of 17 rigid segments, whose dynamic response has been compared to that of cadavers in several studies, by among others Garrett (1998) and Anderson and McLean (2001). The UA PM has been used in the reconstruction of real-world pedestrian impacts by, for example, Garret (1998), Anderson and McLean (2001), and Anderson et al. (2003) and as a result has been scaled to the appropriate anthropometric data (segment dimensions, masses and motion of inertia) for each pedestrian case.

The HONDA PM comprises 15 rigid bodies whose dynamic response has also been compared to that of cadavers by Yoshida et al. (1998). The HONDA PM has been scaled to represent, in addition to the 50th percentile male, a 95th percentile male, a 5th percentile female and a 6-year-old child (Okamoto et al., 2000).

Previously performed optimization for a generic vehicle shape has shown that with one vehicle parameter kept fixed, head and pelvic loads can be reduced (Niederer and Schlumpf, 1984). Various vehicle shape parameters, such as the front of the hood edge and the bumper lead, have been shown to affect in the loading to the pedestrian in a crash (Higuchi and Akiyama, 1991) in such a way that the variation of one parameter can be influenced by the other. Furthermore, the hood edge height has been shown to influence the kinematics of the pedestrian (Ishikawa et al., 1991) and the head responses to impact (Yang and Lövsund, 1997). Simulations by Yang (2003) indicate that head impact conditions were affected by bumper lead and height, hood leading edge height, hood length, hood angle and windscreen angle for a child and an adult pedestrian model in impact speeds of 15 to 60 km/h. Corridors representing sedans, light trucks and sports vehicles have recently been published (Mizuno, 2003). Using mathematical modelling, the optimum vehicle contour for minimizing the load to the pedestrian within such corridors could be investigated.

AIM

The aim of this study was to optimize the front contour of a sedan vehicle in order to minimize the loads to the head of the pedestrian in a vehicle-pedestrian crash.

METHODS AND MATERIALS

As an initial step in the investigation of the influence of vehicle-specific features on the loading to the pedestrian in a crash, the influence of the contour of a sedan vehicle was examined using mathematical modelling. In this pilot study an optimization of the contour of the vehicle was obtained for three different pedestrian head output measurements.

Pedestrian Model

The pedestrian model used for this study was the Chalmers Pedestrian Model of a 50th percentile male pedestrian (Yang et al., 1997) and is run in MADYMO 5.4. This model was made available for the simulations through a collaborative research project aiming to improve pedestrian protection. The pedestrian model was positioned in a walking stance, angled away from the vehicle at 15°. The left upper leg (vehicle strike side) was angled forward 6°, with the right upper leg angled 5° backwards. The arms were positioned out of phase with the legs in human gait cycles (Figure 2).

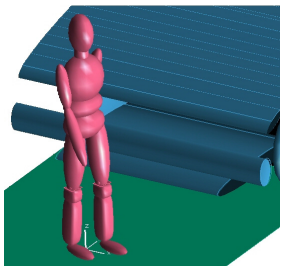


Figure 2 Pedestrian model (Yang et al., 1997) in the posture used in the optimization.

Design of the Mathematical Vehicle Model

The shape of the sedan model was optimization to fit within the sedan, light and sports vehicle corridors developed by Mizuno (2003), which included 33 vehicles. As a starting point for the simulations, a baseline vehicle profile that represented an average large Australian passenger vehicle was designed. To represent this type of vehicle, modifications were required to the hood length and windshield rake of the average vehicle within the Mizuno (2003) corridor (Figure 3). In addition, the vehicle was given a smooth aerodynamic shape. Furthermore, the bumper was divided into an upper and lower section to represent the split bumper for radiator cooling found in most vehicles. The vehicle geometry was then allowed to shift within pre-defined limits of the corridors defined by Mizuno (2003). Furthermore, the upper and lower bumper was allowed to move outside the IHRA corridor as there was very restricted motion for these components allowed for within the corridor.

The curvature of the hood was constructed from a series of eleven planes using the software Easi-Crash. Three cylinders were used to model the hood edge and bumper systems. Contact interaction between the large leg ellipsoid and the small hood edge plane required the use of a hood edge cylinder to allow appropriate contact forces to be transferred, as previously observed by Ishikawa et al. (1993). An additional plane was placed between the hood and the windshield to represent the stiffer scuttle while a single flat plane was used to represent the vehicle windshield. To prevent unrealistic multiple contact forces from occurring, the evaluations command was applied where multiple contact interactions were expected. Friction coefficients were applied to the pedestrian to vehicle contact (0.3) and the pedestrian to ground contact (0.7), as well as damping.

Vehicle stiffness values were obtained from Yang et al. (2001). The hood edge cylinder and corresponding planes were given a higher stiffness value than the hood to represent the large box cross member located directly below the hood leading edge (Yang et al., 1997). In addition to the stiffnesses in Yang et al. (2001) a difference between upper and lower bumper stiffness was used since it was considered that the lower bumper is typically less well supported, and hence a lower stiffness value was applied (Figure 4). Furthermore, the higher hood edge stiffness value was applied to the scuttle plane to represent a strike to the head on the stiff scuttle, relative to that of a softer hood. In the simulations where the scuttle plane was impacted, additional simulations were performed with a model of the hood that continued up to the windshield so that the impact involved structures with the same stiffness.

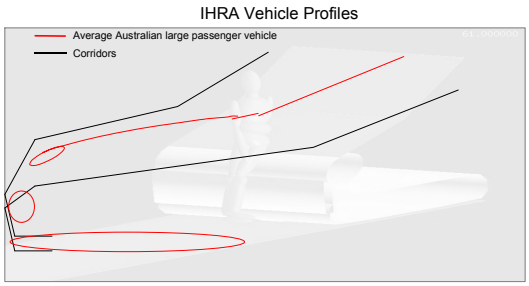


Figure 3 IHRA vehicle front shape corridor (Mizuno et al., 2001) and the average large Australian vehicle shape used as the baseline vehicle shape.

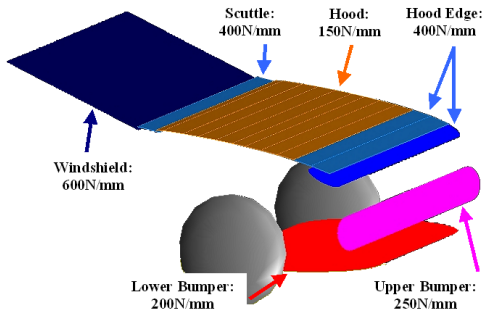


Figure 4 Vehicle stiffness from Yang et al. (2001) and the scuttle plane and upper and lower bumper values used for the simulations.

Vehicle components such as A-pillars, engine and strut towers, known to be pedestrian unfriendly hard-points, were not modelled in this simulation for simplification. Vehicle stiffness was not modified throughout the scope of this analysis. In addition, no deceleration or nose-dive due to braking was included in the vehicle dynamics.

The mathematical optimization program

A non-stochastic optimization program was designed to generate the optimum vehicle contour for one pedestrian output parameter at a time. The optimization program was written in MATLAB, as schematically described in Figure 5. The program was designed to reduce the pre and post processing time required to manually optimize vehicle structures. Designed as an automated logic optimization program, the program optimizes geometry based on one selected pedestrian model output for each optimization. The program was designed to minimize the output parameter. One output parameter was optimized at a time due to that the complexity of tracking multiple variables was beyond the scope of this pilot study.

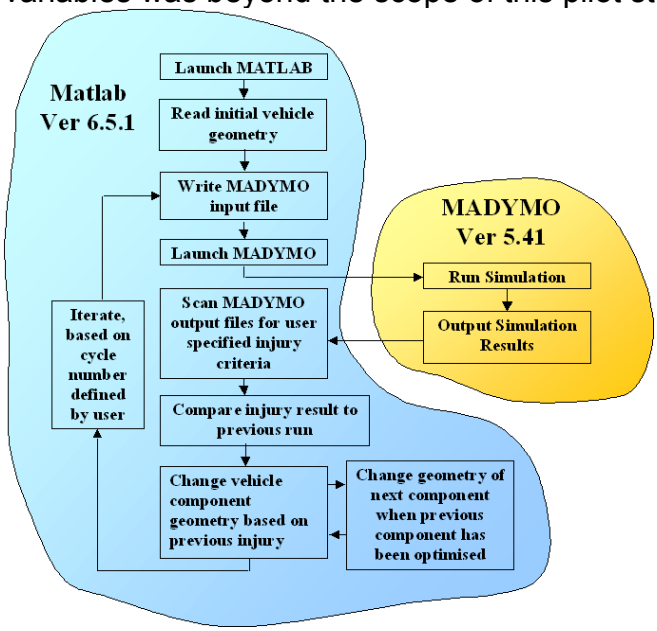


Figure 5 Schematic structure of the mathematical optimization program

The optimization program evaluated a given geometric configuration based on the increase or reduction of the pedestrian model output, after which the program made decisions as to the next geometry modification. The program worked sequentially on each vehicle component, such as lower bumper optimization then upper bumper optimization. Each component was iterated a user specified number of times or until the solution converged. In this way, the program cycled between 20-50 geometric solutions before reaching an optimized solution for any given model output.

The optimization was carried out at the impact velocity of 40 km/h since at this impact velocity the probability of fatal injuries for the pedestrian is significant (among others Mizuno (2003), and Fildes et al. (2004)). In addition the baseline contour was run at the impact velocity of 30 km/h to quantify the influence of impact velocity compared with the influence of the contours found in the optimization. The optimization program was run by minimizing three different head parameters; head

to vehicle resultant velocity ratio, head linear acceleration and head angular acceleration. Within each optimization, peak outputs were recorded and presented as a ratio to the baseline vehicle shape. All recorded peak values were checked for consistency through graphs filtered at CFC 1000 and were only filtered at higher rates (CFC 180) if erroneous spikes were observed in the time history file of the output data.

RESULTS

The results of the simulations show the potential for designing the contour of a vehicle in so as to reduce the loads to various body parts of the pedestrian in the event of a pedestrian crash.

For the impact velocity of 40 km/h, the optimization of minimum linear and angular head acceleration resulted in a reduced head velocity of 6% and 3% respectively and a reduced HIC value by 81% and 53% respectively (Table 1) compared to that of the baseline vehicle contour. These optimizations resulted in the largest increase of pelvic loads and accelerations. When the contour minimizing head velocity was created, head linear and angular acceleration as well as HIC increased. The largest reduction in resultant head velocity was 13% compared to the baseline contour, which was obtained when optimizing for minimum head resultant velocity.

Table 1 The pedestrian output parameters from the baseline vehicle and the ratio of the pedestrian parameters for each optimization as a ratio to the baseline vehicle shape for the Optimizations at 40 km/h impact velocity.

	40 km/h	Baseline Vehicle	Optimizing for Minimum Head to Vehicle Resultant Velocity Ratio	Optimizing for Minimum Head Linear Acceleration	Optimizing for Minimum Head Angular Acceleration
Head	HIC 16	3115	1.46	0.19	0.47
	Head Velocity Resultant Ratio	1.24	0.87	0.94	0.97
	Head Linear Acc. (g)	215	1.41	0.49	0.70
	Head Angular Acc. (rad/s^2)	19103	1.37	0.56	0.78
Pelvis	Pelvis Impact Force Value (kN)	5.65	0.96*	3.70	3.28

*Filtered with CFC 180 instead of CFC 1000

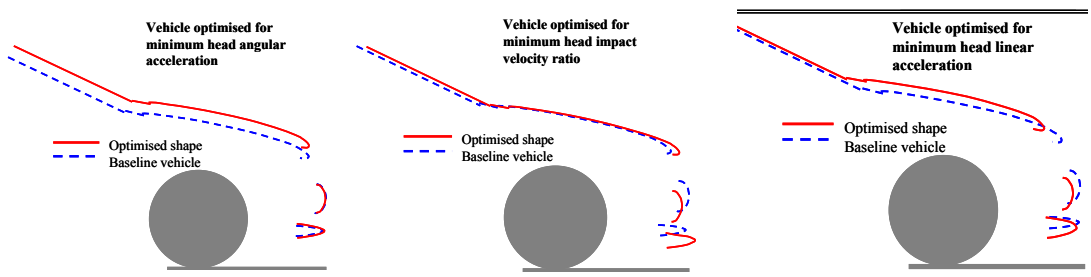


Figure 6 The vehicle contours generated for the impact velocity of 40 km/h in the optimizations compared to the baseline vehicle shape that was used as a starting point for the simulations.

In the animation of the optimizations (Figure 7) it was found that in the case of the optimized vehicle shape on head velocity, the head struck the scuttle plane and therefore this case included head interaction with a stiffer structure than the other cases. This particular case was rerun with a hood continuing up toward the

windshield to facilitate a direct comparison between all contours generated in this study (Table 2).

Figure 7 The animations of the optimized cases and the base line vehicle at the impact velocity of 40 km/h.

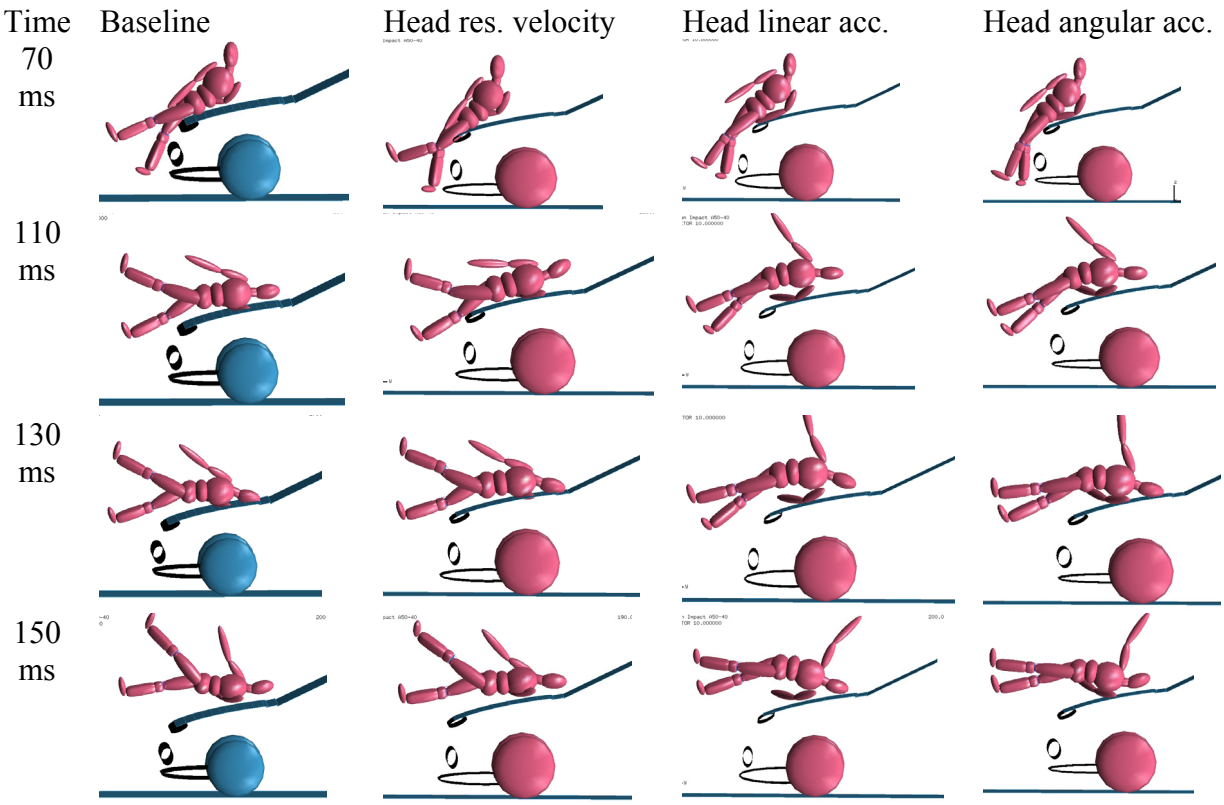


Table 2 The pedestrian output parameters from the base line case and the ratio of these parameters for the optimization for the impact velocity of 40 km/h with the hood continuing to the windshield as a ratio to the baseline vehicle shape.

	40 km/h	Baseline Vehicle	Optimizing for Minimum Head to Vehicle Resultant Velocity Ratio
Head	HIC 16	**3115**	**0.83**
	Head Velocity Resultant Ratio	**1.24**	**0.87**
	Head Linear Acc. (g)	**215**	**0.94**
	Head Angular Acc. (rad/s^2)	**19103**	**0.87**
Pelvis	Pelvis Impact Force Value (kN)	**5.65**	**0.96***

***Filtered with CFC 180 instead of CFC 1000**

The influence of the impact velocity for the baseline vehicle is shown in Table 3. In this table the pedestrian output parameters from the 30 km/h impact are divided by those from the 40 km/h impact.

Table 3 The pedestrian output parameters from the baseline vehicle and the ratio of these parameters for each optimization for the impact velocity of 30 km/h divided by the results from the 40 km/h baseline simulation.

Pedestrian output parameters	HIC 16	Head resultant velocity	Head linear acc.	Head angular acc.	Pelvis Force
Ratio between baseline 30 km/h and 40 km/h case	0.36	0.93	0.69	0.68	0.23

DISCUSSION

The results of the mathematical optimization of the vehicle's contour indicate that loading to the head of the pedestrian can be reduced with alteration to the design within the corridors of an average sized vehicle. Both angular and linear acceleration of the head and HIC were considerable reduced for a number of the contours generated, indicating a potential for reducing these parameters by the contour of the vehicle. Some designs identified in this study reduced the loads to the head and distributed them to the pelvis.

The largest influence on resultant head velocity from these simulations was a reduction of 13% from the baseline vehicle contour while the other optimizations had minor influence on the resultant head velocity. These results indicated that within the IHRA corridor for light trucks, sport and sedan vehicles (Mizuno, 2003), major reductions in resultant head velocity at 40 km/h for a 50th percentile male pedestrian might be limited. The contour generated when minimizing the resultant head velocity resulted in the pedestrian model moving closest to the vehicle during the impact. The two other optimizations caused the pedestrian to become airborne before striking the head on the vehicle and therefore considerable loads to the neck and spine could be expected. In these cases there was little or no chest impact (Figure 7).

The reduction of impact velocity has been shown to have a significant effect on injury severity for children (Lui and Yang, 2002). This study shows similar results for a 50th percentile male when the contour of the vehicle was optimized within the IHRA corridor. Compared to the optimizations of vehicle contours at 40 km/h (Table 1 and 2), the head and pelvic output parameters were reduced for the baseline vehicle contour when the impact velocity was reduced from 40 to 30 km/h (Table 3).

Due to the non-stochastic approach of the optimization program, a minimum for the chosen output parameter was found. This approach will not necessarily identify the absolute minimum, but a local minimum. Therefore, additional minima than those identified from the optimization could exist. This is exemplified by the results in the optimization for minimum head angular acceleration at 40 km/h, where a local minimum for head angular acceleration was found. However, an even lower minimum for head angular acceleration was identified in the optimization for the minimum head linear acceleration, as shown in Table 1. For some of the impacts, oscillations occurred in the output signals. This required increased filtering to CFC 180 to remove anomalies generated by these oscillations (Table 1) and highlighted the importance of closely examining the time history events from mathematical simulations.

A conflicting design phenomenon was observed for competing injury parameters. In the 40 km/h study, minimum head velocity was generated by an extended lower bumper, whereas minimum head acceleration requires the lower bumper to be as the baseline vehicle. The minimum head velocity was generated by a lowering and shifting forward of the hood, as opposed to minimum head angular and linear acceleration, which was obtained by a retraction and rising of the hood (Figure 6).

The optimization program was originally developed to allow changes to the shape of the hood. This resulted in the hood forming corrugations to accept the model's thorax, pelvis and head ellipses to successfully distribute the load as shown in Figure 8. It was necessary to control this, and resulted in the hood geometry confined to a continues line without the corrugations.

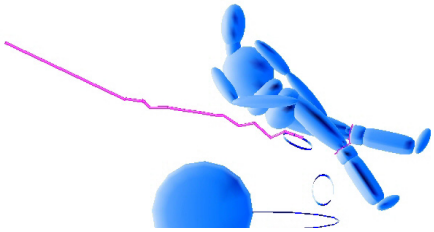


Figure 8 The corrugations of the hood that occurred in the originally developed program that allowed individual changes in the orientation of the planes of the hood.

The influence of vehicle front design and the size of pedestrians have been studied by Yang (2003). In this study it was shown that of the two different sedan models used in the simulations, one of the models reduced the head impact velocity relative to the vehicle for all the tested pedestrian sizes with one exception. The influence of pedestrian size should be taken into consideration in order to make recommendations about optimum vehicle design and will be aimed at in future optimizations. Further optimizations should also include various vehicle front stiffnesses, a larger range of impact velocities and lower extremity measurements. Such Optimizations would be needed in order to make recommendations on the vehicle design with the largest potential for reducing critical loads to the pedestrian in a vehicle-pedestrian crash.

CONCLUSIONS

Reducing the head resultant velocity by optimizing the contour of a sedan vehicle within the IHRA profile, at a 40 km/h impact velocity, resulted in a maximum reduction of 13 % compared to the baseline vehicle contour. The largest reduction in HIC was 81 %, the head linear acceleration was 51% and the angular acceleration of the head was 44 %. The reduction of pedestrian head output parameter by changing the contour of the vehicle increased in some of the cases the pelvic load.

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