OPTIMIZATION OF VEHICLE FRONT FOR SAFETY OF PEDESTRIANS

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ABSTRACT

During impact with an automobile, a pedestrian suffers multiple impacts with the bumper, hood and the windscreen. Optimisation of the car front using a scalar injury cost function has been demonstrated. The results for impacts simulated in MADYMO show good co-relation with Euro-NCAP ratings for existing vehicles. Optimization of the car front to minimise the injury cost converges to vehicle profiles with features known from earlier studies to be pedestrian friendly. A method to design car fronts for pedestrian safety is evolved.

INTRODUCTION

Vulnerable road users, which include pedestrians and non-motorized two wheeler riders, have been found to be the major constituent in road fatalities in developing countries. Fatalities due to vehicle-pedestrian crash are found to be higher in urban areas in India (Mohan, 2010). In India, the predictions for vehicle sales for the year 2011 show an increased demand for LCVs, utility vehicles and passenger cars (SIAM, 2010). By addressing the design of the front of these automobiles one can contribute a major step in the safety of the vulnerable road users without compromising on the safety of the occupants. In this work, the issue of vehicle-front design for safety of pedestrians is addressed.

MEASURES OF INJURIES

"The abbreviated injury scale (AIS) is the only dictionary specifically designed as a system to define the severity of injuries throughout the body" mentioned by (Gennarelli & Wodzin, 2005). The combined effect of multiple injuries to a particular body part is better represented by Maximum-AIS (MAIS) and Injury Severity Score (ISS). ISS denotes the sum of squares of worst 3 AIS injury scores to a body part and it is number that varies from 0 to 75.

Crash injury databases like German In-Depth Accident Study (GIDAS), Pedestrian Crash Data Study (PCDS), and Advanced Protection Systems (APROSYS) use AIS measure. Studies conducted using these crash databases suggests that the majority of pedestrian-vehicle crash has been frontal impact with pedestrian being hit from the side (Erik& Sander, 2010; Rikard & Erik, 2010)

Multiple measures like Head injury criterion (HIC), Neck injury criterion (N_{ij}), Thoracic Velocity Criterion (VC), Abdomen Peak Force (ABF), Femur Force Criterion (FFC), Tibia Index (TI) and knee bending angles are used to quantify the impact in terms of kinematic and dynamic parameters. The New Car Assessment Program (NCAP) rates vehicles for pedestrian safety through head and leg form impactor tests and the outputs are in terms of points based on forces or torques and other related measurements on impactors. Newer systems of injury measurement, specifically for pedestrian safety during regulatory test, VREPS (Kuehn et al., 2005), using HIC has also been proposed.

Most of injury databases show that injuries in lower extremities and chest are significant. The injury measures for each of these body regions namely head, thorax, abdomen, and lower extremities hence need to be quantified in one score for giving a better picture of the effect of the vehicle front to overall pedestrian safety. To study the effect of a vehicle profile on a pedestrian, it is proposed to consider the effect of injuries on all major segments of the body, in addition to the head.

Work presented here uses a scalar measure "injury cost", calculated as a sum of medical and ancillary cost given in ISO: 13232: part 5, indicator of crash severity on a pedestrian during a vehicle-pedestrian impact. Pedestrian lateral impact with vehicle front using MADYMO^{TM} (TNO Automotive, Netherlands) 50th percentile pedestrian male dummy in 50% gait stance is simulated. A sample application of this measure is presented on the context of vehicle front shape optimization for safety of pedestrians. The injury risk functions considered are based on limits for occupant safety.

Formulation of "Injury cost"

In motorcycle safety systems research standard (ISO13232, 2002) ISO 13232: part 5, a "cost" measure is defined to estimate the effectiveness of a safety component to motorcycle rider, Probable crash clusters are based on crash data from Los Angeles and Hannover. The "cost" factor is formulated using hospital data linked to the injury severity in AIS. The "injury cost" includes a medical cost and ancillary cost which accounts for partial impairment and even an indicative cost for death (AIS 6).

An injury risk function based on dummy response however entails using lookup tables by (Payne, Patel 2001), to convert the respective kinematic, dynamic and derived measures to corresponding AIS scores.

Vehicle-pedestrian crash simulation

Kinematics of interaction between pedestrian and vehicle during impact are modelled effectively using multibody codes in MADYMO (Mizuno, 2005). The time-history output of such codes can be post-processed to obtain injury scores and force measures. The 50th percentile pedestrian dummy in Madymo has been previously used for reconstruction of a vehicle-pedestrian crash scenario by (Rooij et al., 2003) for speed of 40 kmph in a lateral impact.

It has also been reported (Carter et al., 2005) that the pedestrian kinematics post impact is primarily dependent on the vehicle geometry and stiffness has a secondary role. A frontal crash scenario with pedestrian being hit laterally by the vehicle at a speed of 40 km/hr is modelled. The car profile is simplified to 5 sections shown in Figure 1.

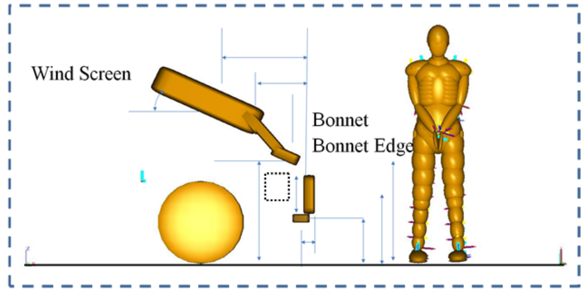

Figure 1 Ellipsoid model of simplified Car profile with pedestrian

The engine is modeled as a rigid mass with high stiffness to have a clearance of minimum of 70 mm from the bonnet of car at the minimum allowed bonnet height. Only the lateral central section of the vehicle is considered (Linder et al., 2005; Carter et al., 2005) A sample population of 12 "in-production" passenger cars across segments from compact to large sedan was considered with details as in Appendix A.

The force deflection characteristics are based on simplification of data from (Rooij et al., 2003) in line with that considered by (Linder et al., 2005). Specifically, negative slopes of the loading curve have been removed and contact damping has not been modelled. The force-deflection relationships are shown in Figure 2, Figure 3, Figure 4, Figure 5 and Figure 6.

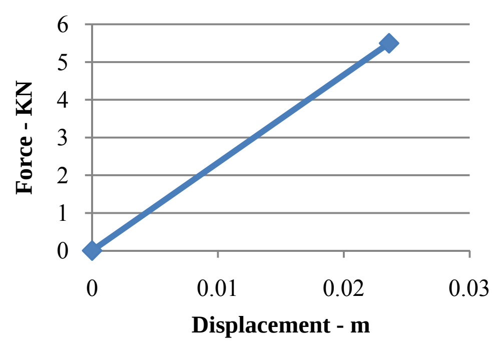

Figure 2 Load-deflection curve of Bonnet Ellipsoid

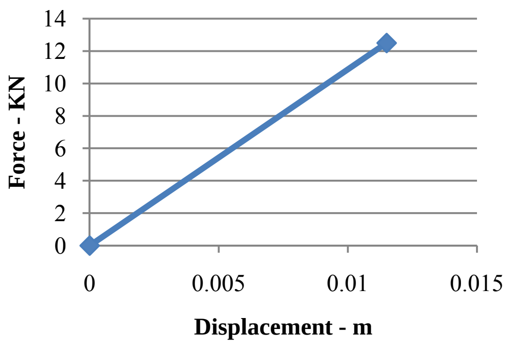

Figure 3 Load-Deflection curve for Leading Edge

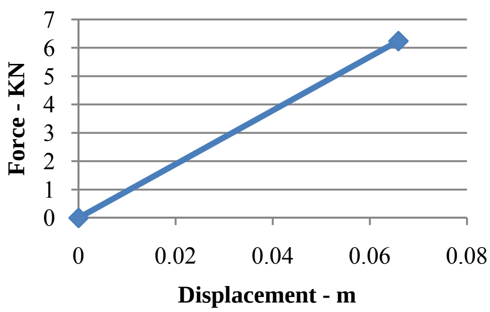

Figure 4 Load-Deflection curve for Windscreen

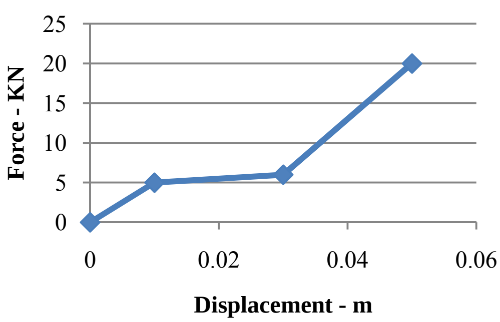

Figure 5 Load-Deflection curve for Cowl Region

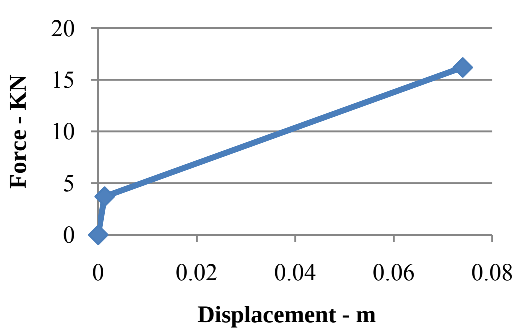

Figure 6 Load -Deflection curve for bumper (lower and stiffener)

Friction between pedestrian and vehicle surface is same as in (Rooij et al., 2003). Braking deceleration of 0.7g is considered all through the impact which is the average braking deceleration on a dry asphalt road. The pedestrian dummy is placed with hands in front and in the 50 % gait stance described in (Kerrigan et al., 2008). An 80 ms period of stabilization is allowed for the dummy to settle under gravity load after which the interaction with vehicle component begins. The crash is simulated for 300 ms of impact

"Injury Cost" Calculation

Table 1 Sample "Injury cost" calculation

Injury Values obtained	Value	AIS	Cost (USD)
HIC	1700	5	583877
Nij	0.52	1	0
VC	0.01	0	0
Pelvis lateral force (kN)	6.22	3	41198
Femur force criterion (kN)	4.72	1	128302
TI	1.511	3	
Force above knee (kN)	8.63	3	
Lower Extremity PPI	0.27	-	-
Total Injury Cost			**753377**

Table 1 shows the cost calculation of one particular geometric profile in a MADYMO crash simulation. For the upper extremity, HIC, neck injury criterion on the neck, viscous criterion on the thorax, lateral peak force for the pelvis, femur force criterion, tibia index and lateral force on knee considered as injury scores for determining the "injury cost".

HIC is formulated as a weighted integration of linear acceleration of head over a time interval specified (15 ms) so it can indicate the direct injury on head. The neck injury criterion is also based on ratio of forces and moments. It is taken as the maximum of combination of four parameters, tension, compression, degree of flexion and extension. The major N_{ij} score observed during crash simulation was for tension-extension. This injury measure was developed as an indicator for occupant neck injury during a frontal collision. For sedan and long bonnet cars, it has been observed that chest contacts do occur with the vehicle and have used the viscous criterion to calculate the injury score.

For accounting the abdomen region, peak pelvis force in lateral direction is considered. The lower extremity injury cost is based on three separate ratings, the femur force criterion, Tibia Index and force above knee with factor for partial impairment (PPI). These measures were used to calculate injury cost using procedure stated in ISO 13232:part5.

INJURY COST WITH EURONCAP

Euro-NCAP pedestrian scores are based on responses of headform and legform over vehicle profiles at specified wrap around distances (WAD) obtained from crash data analysis (Hobbs & McDonough, 1998). Vehicle designers target to achieve higher NCAP pedestrian scores of their vehicles to prove them to be "safer" cars.

With the sample population of 10 cars (two cars were not tested in Euro-NCAP), a trend of increase in "injury cost" as the pedestrian NCAP points decrease is observed. An increase in "injury cost" implies that the specific geometric profile has a greater cost implication to the pedestrian during an impact as the force-deflection properties are remaining the same not varied.

The "injury cost" was compared with the Euro-NCAP for 10 different passenger car models of 1998 to 2005 The two measures shown in Figure 7 had a linear correlation coefficient of -0.9, indicating a strong inverse relationship between the two factors.

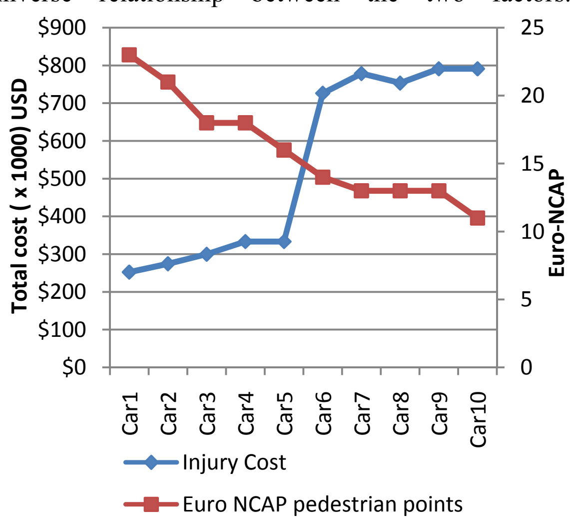

Figure 7 Correlation of "Injury cost" with Euro NCAP pedestrian points

To illustrate the usage of "injury cost" measure, two simple optimization processes for vehicle profile are presented.

VEHICLE PROFILE OPTIMIZATION

There have been earlier attempts to establish the ideal front profile of a passenger car using multibody simulations. Optimization of vehicle font for minimization of head injury using linear programming converging to a solution suggesting a very good reduction in HIC (Linder et al., 2005) was found to be a "local" minimum in their sample space. Simulations with multiple pedestrian dummies representing different gaits and sizes and varied vehicle sizes (Mizuno & Ishikawa 2001) were optimised for multiple objectives using genetic algorithms (Carter et al., 2005). The solution did not converge satisfactorily. Optimization of vehicle front profile based on linear optimization and genetic algorithm formulated to minimise a single objective, the injury cost function has been considered here.

Optimization using MADYMIZER

The MADYMIZER™ is a central linear sequential optimization tool with MADYMO™. The constraints used are listed below:

- HIC to be below 1000
- FFC less than 10kN
- Tibia index below 1
- Distance between ellipsoids constrained based on a dimensions variation within one segment of cars rather than whole domain from compact to a large luxury car.

When constrained to compact car dimensions, the leading edge and hood length resulted in the profile shown in Figure 8. The optimal geometric profile has enough space to accommodate the engine packaging and requires minimal or no change to the structural elements. The "injury cost" value is compared in Table 2.

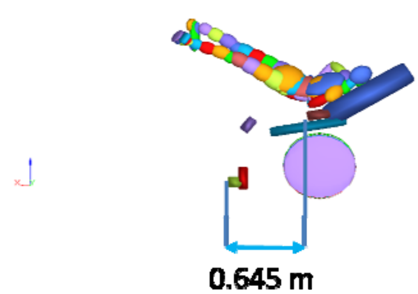

Figure 8 Optimal geometric profile with compact car segment constraints

A comparison of injury cost suggests that by varying the geometry of the vehicle front, a safer vehicle can be obtained. In this case, the distance of the windscreen was the major cause of reduction on the injury cost. The position of the bumper ellipsoids minimised the Tibia Index. The leading edge was allowed to rise up to 0.8m; and resulted in increase of injury to the pelvic region. Bumper ellipsoids were significantly shifted down in (Carter et al., 2005).

Table 2 Comparison of "Injury cost" variation in compact car with optimized shape

S No.	Vehicle	Injury cost (USD)
1	Compact 1	274498
2	Compact 2	753377
3	Compact 3	778609
4	Compact 4	791312
5	**Optimized Shape**	**172948**

Optimization using Genetic Algorithm

A vehicle-front optimization problem was formulated using simple genetic algorithm (Sastry, 2007). Vehicle profiles are shown below with lines joining the centres of the ellipsoids in the vehicle front profile as indicative of the profile. The point on windscreen denotes the top edge of the windscreen and not its centre. A population of 40 is chosen randomly to start with. Dimensional limits based on the car population considered are used to ensure profiles generated resemble a conventional car front.

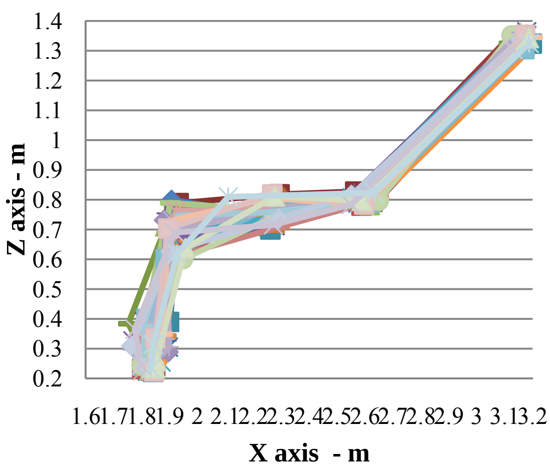

Figure 9 Initial Population for the vehicles - Genetic Algorithm

The initial Population showed a large variation in injury cost, varying from 215081 to 647815 USD. Figure 9 shows the variation of the geometry.

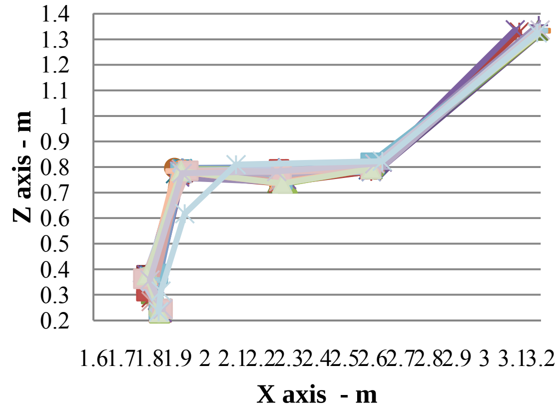

Figure 10 Population at the end of tenth generation - Genetic algorithm

Figure 10, shows the profiles at the end of 10 generations, where the population seems to converge towards one solution and has a variation of injury cost of 113223 to 215081 USD. One isolated solution of 635112 USD was observed.

DISCUSSION

Optimization results

From the linear sequential optimization tool, a local solution for the profile is obtained but it cannot be an indicator for the global minimum as the algorithm works in minimizing every variable separately. The output reflects minimal values for individual variables, with the process repeated a finite number of cycles. As a technique for optimization, this may not lead us to the global minimum. The changed profiles generated had the chest and torso impacting the windscreen first. This makes intuitive sense as the windscreen is a region of lower stiffness. The upper edge of the windscreen is a region of high stiffness but it can removed from the design altogether as shown in Figure 11.

Figure 11 Opel Astra 2006 - new windscreen concept, taken from (Kuehn et al., 2007)

Genetic algorithms based optimization; on the other hand allow starting of search from a random set of population. The optimization problem with the genetic algorithm codes show convergence in tenth generation for the case of 50th percentile male dummy to a single profile. Additionally injury measures for the pedestrian injuries are more comprehensive with consideration for the lower extremity and pelvic region also. The results are not comparable directly with the results of (Carter et al., 2005) because they have also modeled the roof of the vehicle and consequently the stiff member on top of the windscreen.

CONCLUSIONS

Earlier methods used optimization based on single injury measure to obtain a better vehicle profile. In subsequent levels, one additional injury measure was combined using weight factors and optimization extended.

The procedure is built upon and a single objective optimization is proposed. The objective function is derived from multiple injury parameters obtained from statistical analysis of crash and hospital data. It is a better indicator of the "actual" loss to the pedestrian in terms of cost. A direct co-relation of the individual injury severity as well as the gross effect of injuries is possible with this new measure. Analysis of the "injury cost" shown in Table 3 shows the relative distribution of injuries in two regions of body.

Table 3 Injury cost split up for cars

CAR	Total "injury cost" (USD)	Pelvic and below (USD)	Torso region (USD)
Sedan1	252367	237742	14625
Sedan2	299730	237742	61988
Sedan3	333346	169500	163846
Sedan4	333346	169500	163846
Sedan5	726475	142598	583877
Compact1	274498	212510	61988
Compact2	778609	194732	583877
Compact3	753377	169500	583877
Compact4	791312	194732	596580
Compact5	791312	142598	648714
Compact6	252367	237742	14625
Compact7	778609	194732	583877
MADYMIZER optimized	172948	110960	61988
GA optimized	113223	98598	14625

A larger sedan is expected to score better in headform tests indicating less severe head injury of pedestrians as it has a larger bonnet region with comparatively low stiffness. A similar trend is observed with the "injury cost" distribution.

MADYMIZER optimized model showed a 31% reduction from the minimum injury cost observed in production vehicles. The convergence is however to a local minimum within the range specified.

The model optimized using genetic algorithms approach was able to operate on a wider range of dimensions and it showed a reduction of 55% from minimum injury cost observed. It was also observed that the model optimized by genetic algorithm was able to combine the benefits obtained from a longer bonnet car with better bumper and leading edge locations to reduce injuries for pelvic and lower regions. The injury cost for torso shows the minimum observed in the whole population. Similarly, the injury cost for the pelvic and region below is also found to be least.

"Injury cost" is a hence good candidate as a unitary measure of severity of injury to pedestrian in the event of a pedestrian-vehicle crash. It can be used in the vehicle front-profile optimization for reduced pedestrian injury as it acts as a direct indicator of injury severity. Further, this method potentially allows optimisation to be carried across a population of impact cases by weighing the injury cost from each impact case.

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APPENDIX A

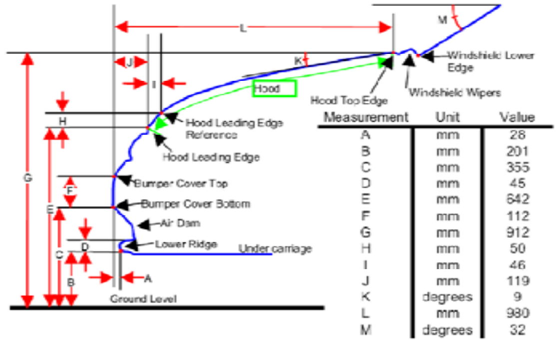

Figure 12 Vehicle dimensions taken from (Kerrigan et al., 2008)

Vehicles were measured using tapes based on the template shown in Figure 12 from (Kerrigan et al., 2008). The vehicles were photographed and processed using PC-RECT to extract the geometry. The dimensions for 12 types of passenger cars are shown in the Table 4.

Table 4 Sample "in-production" vehicle details

Vehicle	A	B	C	D	E	F	G	H	I	J	K	L	M
	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	deg	mm	deg
Car1	0	263	414	35	601	111	995	222	131	13	20	703	28
Car2	0	237	389	37	535	146	994	136	77	33	16	676	30
Car3	-26	215	451	26	696	86	963	151	171	85	11	761	30
Car4	25	230	391	36	694	142	1010	84	95	83	14	800	25
Car5	19	326	470	43	799	166	1130	116	114	78	16	820	30
Car6	56	314	431	30	686	141	1120	180	83	66	50	375	25
Car7	15	188	368	95	650	128	955	100	50	85	8	890	25
Car8	0	0	259	0	745	320	1040	105	137	116	11	1085	27
Car9	0	280	439	31	727	139	993	114	78	49	3	1064	30
Car10	25	196	440	70	588	98	860	110	0	90	9	1053	26
Car11	98	198	403	57	571	137	937	113	50	90	3	1205	30
Car12	0	259	423	47	623	130	1000	200	128	60	10	983	27