

Optimization of Car Front Profile Using a Single Objective Function for Safety of Pedestrian in a Car-Pedestrian Impact

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Abstract Car front impacts have resulted in many pedestrian fatalities. Car front is an area designed based on frontal impact and pedestrian body form regulatory and consumer rating tests. To understand the effect of shape of car on injuries, injury measures from kinematics of pedestrian dummy impact is converted to 'injury costs'. 'Injury costs' is calculated as a unitary measure for threat to a human from vehicle profile. We had considered 4 anthropometric sizes of pedestrian dummy in walking stance. We also examined +/-20° angle of pedestrian dummy to the vehicle to the impact. A multi-body simulation of the crash at 40 kmph with braking was considered under a MADYMO 7.4 environment. Optimization codes (in MATLAB) from Illinois Genetic Algorithms Laboratory were used for optimization process. We performed around (4*100*11*3) 13200 simulations. The optimal shapes indicate multiple solutions. With more constraints like some minimum clearance from engine top solution set lead to lesser shapes. The height of bonnet leading edge is to at chest height of a child dummy and length of bonnet is to ensure that taller dummies do not interact with high stiffness lower windscreen region. The data used is not meant for this specific application and injury measures also need to be improved.

Keywords Front-end optimization, pedestrian safety, vehicle design, injury cost

I. INTRODUCTION

Vehicle impact with a pedestrian is highly probable in urban environment with higher pedestrian density and is also observed that urban regions have pedestrian fatalities [1,2]. Regulatory tests in European Union and Japan and consumer tests like Euro-NCAP, J-NCAP provide for pedestrian safety by measuring parameters with impact of body-forms. The tests are based on wrap around distance measurement and impacting with specific body-forms assuming impacts with specific human body segments. These tests also take into consideration child head-form impact. This leads to an assumption in public view, a good rated car is safer for those standard size humans and public in general. But humans are in different sizes and impacts will vary when the kinematics of the body is taken into consideration.

A summary of vehicle design for pedestrian safety was put forward by [3]. Based on data from US Department of Transportation, a majority of injuries and fatalities reported were from frontal impact. Injury distribution shows head to be major injured part for serious and moderate injuries followed by lower extremity including pelvis for moderate injuries. A head impact with windscreen or bonnet is expected within 230ms from impact.

Vehicle front parameterization and optimization was carried out by [4]. They considered the vehicle surfaces in terms of surfaces and crashed with a multi-body pedestrian dummy in MADYMO. They used MATLAB for running an optimization loop and optimized for head injury. The results showed a better shape within the interval considered by varying around one specific car. Reference [5] also addressed the optimization problem considering vehicle front as group of ellipsoids. They used database of 33 different cars of 6 different categories. The vehicle was defined using 11 parameters. Two pedestrian dummies was considered in two different gait positions of near leg forward and far leg forward. One 6 year old child dummy was considered in single stance.

The simulations were for speed of 40 kmph because achieving HIC 1000 above 45kmph was nearly impossible. HIC and contiguous chest acceleration (3ms) were converted to a scale of 100 and used as fitness function in a Genetic algorithm based optimization process. Results converged after 9 generations.

We take this one step further trying to the answer the same design of front end of vehicle problem by including more than just head injury measures. We have attempted to use a unitary measure 'injury cost' to represent the threat of a vehicle profile to a pedestrian. As in previous studies, the variation in stiffness was not considered. Only the effect of shape on the pedestrian primary injury minimization remains the focus of this study.

II. METHODS

Formulation of 'Injury Cost':

Injury cost is a calculated as a representative unitary measure for representing severity of injury on a pedestrian. It was adopted from the ISO 13232: part 5. It does not represent actual loss to human being but a representative number based on the medical and ancillary costs. The data corresponds to cost calculation for motorcycle injury which is adopted. Reference [6] had compared injury costs for representative vehicle profiles to Euro New Car Assessment Programme (Euro-NCAP) pedestrian scores. Injury measures considered are Head Injury Criterion (HIC), Neck Injury Criterion (Nij), Viscous Criterion (VC) for chest, Femur Force Criterion (FFC), shear force below knee, Tibia Index for Lower extremity. It is understood that injury measures chosen do not completely represent the complete set of injuries sustained by a pedestrian. We use table for occupant safety compiled for rail safety in OPERAS project as a reference table in the absence of a comprehensive database for matching Injury measure to Abbreviated Injury Score (AIS) values. The values used are provided in Appendix Table IV, V, VI and VII. Injury cost calculated from AIS is henceforth considered representative of the severity of injury to a pedestrian by a particular vehicle profile. A sample calculation is shown in Table I for a vehicle profile against 95%ile male dummy. Variation of injury costs for some compact car profiles representing cars in market is also shown in [7].



Fig. 1. Calculation of Injury Cost

TABLE I
CALCULATION OF INJURY COST

Injury Values obtained	Car 1_95		
	Value	AIS	Cost
HIC	135	1	3448
Nij	0.667	1	0
VC	0.002	0	0
FFC (kN)	9.09	3	
TI	0.339	0	128302
Force above knee on femur (kN)	12.24	4	
Lower Extremity PPI	0.27		
Total Injury Cost (USD)			131750

MADYMO set up

We considered a set up similar to [7] with a varied force-deflection (FD) characteristic to Windscreen. Reference [8,9] produced the FD characteristics for a typical sedan vehicle and it was used as basis for simplified FD characteristics used in [7]. There were also works by [10] showing a corridor of European vehicles. Reference [11] used a characteristic to study head injury. We are taking a generic characteristic in our study and intend to take a characteristic based on [9]. Our point of view is that bonnet is to have minimum stiffness followed by windscreen, though it will change after some penetration from impact. So, for primary impact we assume all the characteristics of [7] with a windscreen FD given in Fig 2. The characteristic assumed is to have a high stiffness at the beginning and same force is assumed to be provided on further penetration though it reduces in actual tests. This characteristic assumption makes windscreen hits more costly and hence it is bound to be minimized. Fig 3. shows a screenshot of MADYMO crash scenario showing vehicle and pedestrian dummy positions.

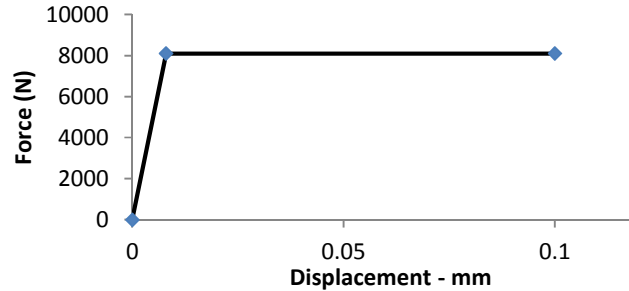


Fig. 2. Force Deflection characteristic for Windscreen

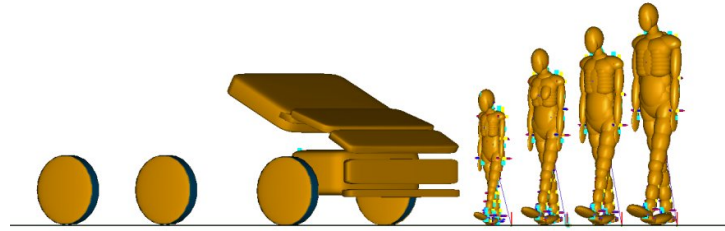


Fig 3. Vehicle Model and pedestrian dummies

Methodology of Optimization

We begin the optimization process with MATLAB GA codes deciding the values for 18 variables which describe the position, inclination and size of ellipsoids describing vehicle front. The range chosen is decided based on table of data used in [6]. We decided on a geometrical limit of compact segment and smaller cars with conventional Internal Combustion (IC) engine power source. With inputs of the variables, MATLAB creates a XML file forming input to the MADYMO solver. MADYMO solver computes the kinematic variables and provides output in various files. We read the PEAK files of MADYMO and obtain our injury measures by codes in MATLAB. The values obtained are converted to AIS equivalents and then Injury cost computed. We consider injury limits same for children and adults in these simulations. The data available corresponds to a 50th %le Male size dummy; hence we use the same across all four sizes. We also consider equal weightage of all pedestrian sizes by considering total injury cost as the sum of all four injury cost computed. The expected output from the optimization loop is a set of injury costs which forms the fitness function of the Genetic Algorithm optimization process.

Whole process is shown as a flow diagram in fig 4. This methodology represents the cycle for one angle of pedestrian to the vehicle. The process is repeated independently for zero, +20° and -20° of the pedestrian dummy with the vehicle. The process was repeated independently to cover the design space better and search.

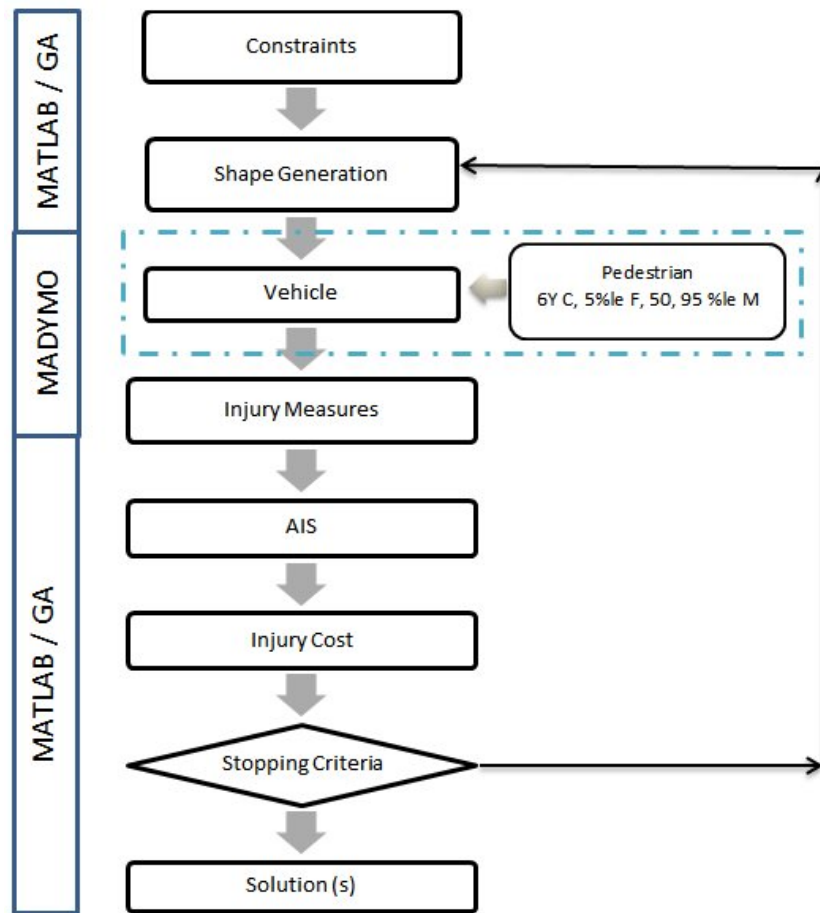


Fig 4. Methodology of Optimization

Genetic Algorithm configurations

Genetic Algorithm (GA) codes written in MATLAB by Illinois Genetic Algorithms Laboratory were used in SGA process. Total injury cost of four profiles is considered as fitness function. The stopping criteria was set to 10 generations, effectively (1+10) 11 generations would be computed. Every generation was to have 100 as population. A random selection of population for the first generation as chosen and a replacement proportion of 0.9 were chosen. We chose following values after the suggestions by [5] to use higher population of 30 – 100, mutation operators, fitness function revision to account real injury severities. Crossover and mutation were set to default values and their role in the solution search was not considered within the scope of this study.

Discussion on Constraints to Vehicle Front end

We placed first set of constraints on optimization process in geometrical limits for evaluation of all shapes within the design space. At the second level we address the vehicle shape in following levels.

Under bonnet Packaging:

In a conventional IC engine powered car, one of the major components to be accommodated in packaging is the engine with gearbox and its ancillaries like Radiator for cooling and battery. We examined the approximate volume occupied by these components from FE model used for crash simulation which is available at [12]. One of the vehicles with engine capacity around 1 litre is shown in Table III. A 1 liter engine is considered because it is the average engine capacity for a compact segment and below it suitable for urban transport. Since we are still at an extended 2D view of a vehicle, we consider the upper limit of bonnet to be limiting value with extra space above engine to allow deflection of bonnet. The height of floor sill from the ground was found to be 135 mm. With 150mm space above engine for deflection of bonnet, the minimum height of the bonnet should be $(466+135+150 = 751 \text{ mm})$.

TABLE III
SAMPLE MEASUREMENT OF PACKAGING UNDER HOOD FOR COMPACT CAR – GEO METRO

CAR 1	Dimensions			Volume mm ³
	X mm	Y mm	Z mm	
Engine + gear box +Diff	523	800	466	1.95E+08
suspension (single)	254	250	300	3.81E+07
Radiator	40	615	335	8.24E+06
Batteries	200	270	180	9.72E+06
Inlet Manifold	265	390	120	1.24E+07
Outlet Manifold	130	280	200	7.28E+06
Air filter	190	360	250	1.71E+07
			Total	2.88E+08

Driver Visibility:

There are no direct regulations in this regard. But, it would act as a constraint for front end design to allow better visibility for the driver. For constraints, the bonnet edge should not be at a height more than average height of bonnet edge available in market for a given length of bonnet. We are to also ensure that bonnet edge height is lower than the height of 'bonnet ellipsoid' center. We used the database of VC-COMPAT project for obtaining the details of location of structural members [13-<http://vc-compat.rtdproject.net/>]. The location of upper cross member shows the location of bonnet leading edge.

III. RESULTS

With optimization loop, we found a variation in injury cost to vary from around 1.5 Million USD in first generation to minimum of 0.2 Million shown in Fig 5, 6, 7. A trend curve of second order also shows reduction in the average value of the injury cost. The number of peaks reduces as we move from left to right showing a shift towards minimum injury cost profiles by the end of 10th generation. The minimum value obtained was 218736 USD and it was found to be a combination of 54684 USD for each of the size of pedestrian dummy considered indicating an equally threat for all. The total number of shapes including all the three different angles at the end of 10th generation having the minimum injury cost of 218736 USD was over 100.

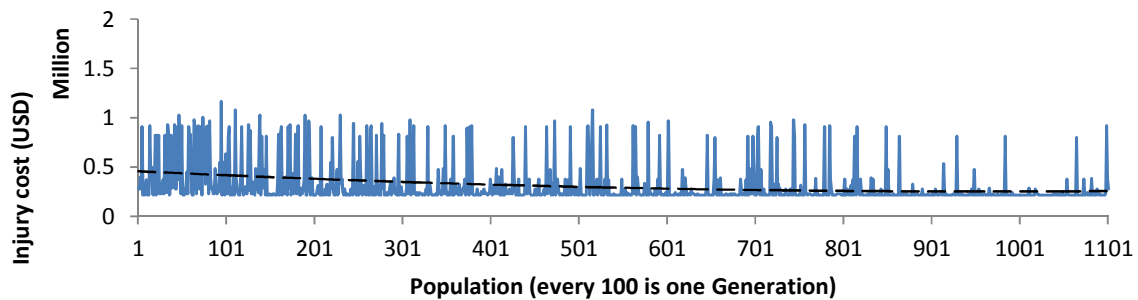


Fig. 5. Variation of Injury cost (pedestrian hit laterally)

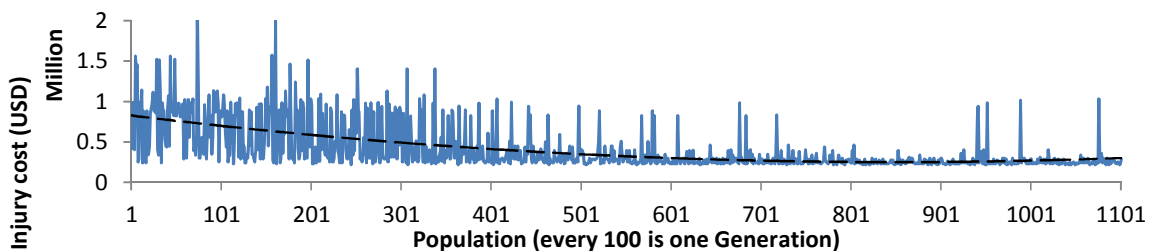


Fig. 6. Variation of Injury cost (pedestrian hit +20deg laterally)

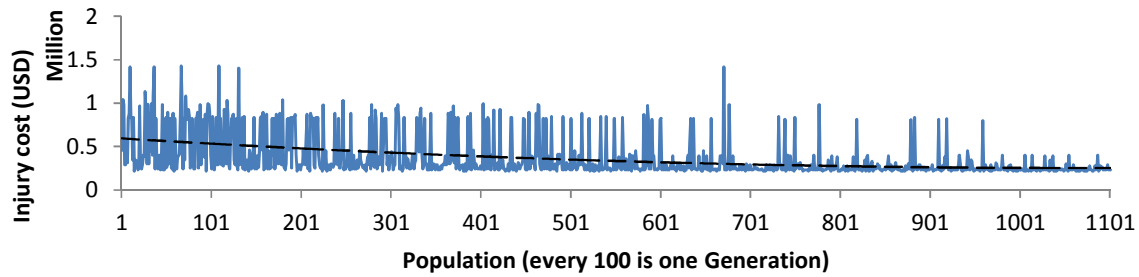


Fig. 7. Variation of Injury cost (pedestrian hit -20deg laterally)

One sample shape is shown in Table II with screen shots at specific intervals of initial impact at the lower extremity, impact with pelvis and impact with upper extremity. For the shape shown, the impact with upper extremity was not observed in 5th %le Female (5F) and 50th %le Male (50M). These screen shots provide a better picture of the interaction between a particular vehicle front shape and all the 4 size of pedestrian dummies. In this particular case, height of bonnet leading edge is near the shoulder height of a 6 year old child (6YC) and exactly near the pelvis of 5F and 50M where as it is almost near center of femur of a 95%le Male (95M) dummy. Similarly, the length of bonnet in this configuration ensures that 5F head will land on cowl region whereas 50M and 95M will hit windscreen. The region where bumper makes contact with child is near the knee region, whereas it is below knee for all others. The height of bumper is found to influence the kinematics of pedestrian, like in some cases the legs remain caught below the bumper resulting in almost complete wrap-around of the pedestrian dummy with vehicle.

TABLE II
SAMPLE SCREENSHOTS SHOWING ONE OPTIMAL SHAPE 'S1' WITH PEDESTRIAN HIT LATERALLY

	6 y.o. child	5%le Female	50%le Male	95%le Male
First Contact				
Pelvic Contact				
Contact with Upper body / extremity		-	-	

With 100+ samples showing minimal injury cost, we compared the results from three different angle of pedestrians and shortlisted the ones with similar combination of values. A minimum of 0.01 m was used as a tolerance in matching the profiles. We had used double precision in our optimization process to compute the distances. We found 6 different profiles at the end of application of the two extra constraints specified and the combination process which is shown in Fig. 8.

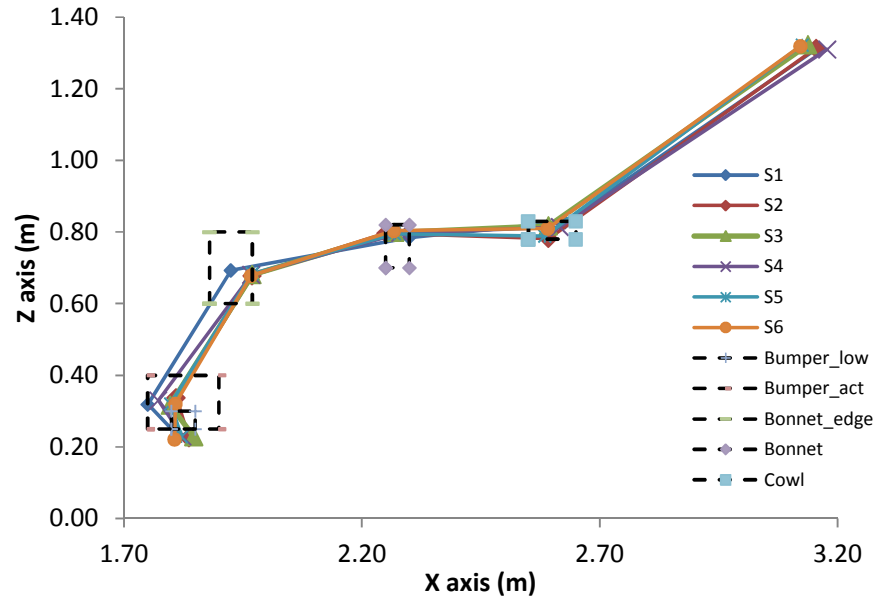


Fig. 8. optimal shapes

IV. DISCUSSION

We had examined only 3 different orientations of pedestrian and within these, multiple solutions to vehicle-front end design seem to exist. The process of shortlisting for common dimensions was chosen as a step outside the loop because it allowed evaluation of more profiles. In our calculations, injury cost was insensitive to chest and neck injuries. This trend was observed because the injury was not severe enough to be shown. The trend in pedestrian crashes shows presence of severe chest injuries. With a multi-body model detection of surface injuries and bone fractures may not be possible.

In the context of setting a limit to the bonnet height to 0.751m, the values assumed are possible to be designed. Data from [14] shows a car with engine height within this range. Bonnet leading edge around 0.70m is a good compromise to the child impact below shoulder avoiding head impact. But, in our calculation the angular acceleration related injury measurement of head is not taken into consideration. The results with rotational injury criterion may lead to a different cost implication. The length of bonnet for an urban car is not so long. The length now is around 0.8m.

In our study, we do not measure the wrap around distance to determine the head impact point like the conventional methods. We observed that wrap around could be applicable till bonnet leading edge but after that point, we would need the help of kinematics to predict head impact. A kinematic simulation would allow a more accurate positioning of head impact and in our simulations the head impact has been shifted to either windscreen or to bonnet and not in the bottom of windscreen. We had marked bottom of windscreen as high stiffness area.

The 'injury cost' based method is based on injury limits which represent frontal impact limits for occupants and costs are not representative of pedestrian injuries but motorcycle injuries. With this combination, we may not obtain the exact trend. This methodology may not be completely misleading because the cost distribution shows higher weightage for head injuries, followed by lower extremity injuries and thorax injuries. There is also a very high cost associated with death in this scale. For lower extremities, there is a factor for partial impairment which adds extra in case of severe injuries.

We did not include the pelvic peak force into consideration but it was monitored. The pelvic force was not included because the cost available was for abdominal injury. The trend in pelvic force variation was found to be directly influenced by the position of bonnet leading edge. Effectively, the optimization was representing head and lower extremity, two major regions of injury reported.

V. CONCLUSIONS

The method for optimization is direct and follows a logical sequence. With better data, the methodology can produce results which have better accuracy. The model and solver used for quicker results for explanation of

the concept. With more detailed Finite element human body model, addressing injury measures in a more close to real way will be possible. The conversion measures used in this process do not represent the injury limits for a pedestrian in lateral impact but with better data on it we can improve upon it. Never the less, it does provide a good starting point on an idea of shape of vehicle for vehicle concept generation process with an optimal safety for pedestrians inbuilt into the design. Because this process does not involve stiffness measures, it would not interfere with the conventional pedestrian safety design of a vehicle development process.

VI. ACKNOWLEDGEMENT

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VIII. APPENDIX

TABLE IV
HIC TO AIS CONVERSION TABLE

Head Injury Criteria	AIS Code	Level Of Brain Concussion And Head Injury
135 – 519	1	Headache or dizziness
520 – 899	2	Unconscious less than 1 hour – linear fracture
900 – 1254	3	Unconscious 1 – 6 hours – depressed fracture
1255 – 1574	4	Unconscious 6 – 24 hours – open fracture
1575 – 1859	5	Unconscious greater than 25 hours – large haematoma
> 1860	6	Non survivable

Data from [13]

TABLE V
VC to AIS conversion table

Injury Criteria	Unit	Tolerance Levels	Injury Level	Reference
VC max	Ms-1	<1.0	AIS 0-2	Cavanaugh
Half thorax		>1.0	AIS 4,5	
VC max	Ms-1	1.47	25% AIS 4	Viano
Whole thorax				

Data from [13]

TABLE VI
LOWER EXTREMITY CONVERSION TABLE

Injury Level	Injury Tolerance Level	Equivalent AIS	Equivalent Legislation	Equivalent EuroNCAP Frontal	Equivalent EuroNCAP Frontal
Fracture of the Femur, tibia and fibula	Fracture Index	-	-	Equivalent Femur Force	Tibia Index
0 (No Injury)	<1	0	-	-	-
1 (No Injury)	<1	0	-	Green < 3.8 Yellow < 5.6	Green < 0.4 Yellow < 0.7 Orange < 1.0
2 (Simple Fracture)	1 – 1.3	2	-	Orange < 7.6	Brown <1.3
3 (Complex Fracture)	>1.3	3-4	FMVSS208 European Frontal Impact 96/79/EC	Brown <9.1 Red > 9.1	Red > 1.3

Data from [13]

TABLE VII
COST CONVERSION TABLE

	Severity	Medical Cost (USD)	Ancillary Cost (USD)	Total	
Head	1	784	2664	3448	
	2	3807	10818	14625	
	3	14169	47819	61988	
	4	72349	91497	163846	
	5	263306	320571	583877	
	6	596580			
Neck	3	20509	76267	96776	
	4	440037	391007	831044	
	5	530695	463314	994009	
Thorax	1	696	1372	2068	
	2	3410	10886	14296	
	3	10147	31051	41198	
	4	19577	46853	66430	
	5	32790	64256	97046	
Lower Extremity	2	7881			PPI
	3	22732	27370		0.07
			58650		0.15
			86020		0.22
		For two AIS 3	105570	128302	0.27
		For >two AIS3	148580	171312	0.38

Table complied with data from ISO 13232: part 5