A Method to Compare and Quantify Threat to Pedestrian Using Injury Cost Measure

Hariharan Sankarasubramanian, Sudipto Mukherjee, Anoop Chawla, Dietmar Göhlich

Abstract Crash report-based studies indicate Vulnerable Road Users (VRUs) to still be at risk of severe injury /fatality on our roads. These studies also indicate frontal crashes to be the most frequently occurring crashes. This work proposes a method to quantify the "threat" from a vehicle front shape to a pedestrian. Injury indices were computed using impact simulations of finite element models of car profiles against multi-body pedestrian models at a speed of 40km per hour. 3 adult pedestrian models (95th %le and 50th %le Male, 5th %le Female) and one 6 year old child model were considered in crash scenario simulations. Five injury indices, namely, HIC (15ms) for head injury, Viscous Criterion (VC) and resultant peak linear accelerations for chest, peak forces in femur and tibia for lower extremity were recorded from these simulations. An "Injury Cost" (IC) measure was then calculated by mapping injury indices to Abbreviated Injury Scale-based scores and then mapping them to cost implications. MAIS and ISS have also been discussed for comparison of threat. Ford Taurus (a pre- Euro-NCAP rated car, and named Profile 1), and Toyota Yaris (a post- Euro-NCAP rated car with 21 points, and named Profile 2) profiles were evaluated using the proposed IC measure. Equi-weighted IC showed Profile 2 to be safer than Profile 1 but specific population-based weighted IC indicated Profile 1 to be relatively safer.

Keywords Injury Cost Scale, injury threat to pedestrian population, vehicle front-end design

I. INTRODUCTION

Since pedestrians have the lowest level of protection amongst Vulnerable Road Users (VRUs), they are known to have a higher injury and fatality risk from automobiles than motorcyclists and cyclists [1]. Vehicle crash trends in India show pedestrian fatalities to be substantially more than that in higher income countries [2]. Globally approximately 22% of the road crashes involve pedestrians [3]. With these crash trends, it becomes important to design a vehicle for protection of pedestrians.

Studies on the regions of a passenger car interacting with a pedestrian during a pedestrian-automobile crash have shown the bumper, bonnet, windscreen and the cowl region to be prominent contact points affecting the kinematics of the struck pedestrian. The kinematics can be correlated to the different injuries sustained [4]. Through input of contact stiffness data, phenomenon like enhanced injury risk to the head from contact with "A" pillars and the windscreen lower region can be captured. Analysis of threat from car profiles has shown that passenger cars (sedan) pose a lesser threat than a SUV or light truck profile [5-6].

Consumer ratings such as Euro-NCAP [7] perform impacts with separate body forms against the vehicle front at different locations to assess potential passive pedestrian safety and provide a discrete "star" rating. A reduction in severity of pedestrian crashes and reduction in fatality was reported to show a correlation between Euro-NCAP pedestrian compliance and increased pedestrian safety [8]. The body forms used in these tests represent a statistically significant measure in properties of individual body components. The head form impact tests are designed to consider impact points based on wrap-around distance (WAD) corresponding to adult and child populations.

Crash reconstruction studies use multi-body pedestrian models to estimate the pre-impact configuration and kinematics that best correlate with the known impact locations. Rigid body modelling technique is seen to be sufficient for replicating the kinematics in a crash and can be used for estimating some of the injury indices.

A vehicle-front designer can predict the kinematics of a pedestrian in a vehicle crash, given the vehicle

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profile. It would be ideal if one could define a criterion to evaluate the vehicle profile for a particular pedestrian and then use it to assess the suitability of a profile to a known statistical pedestrian population. In this work, an attempt is made to develop a methodology to provide such a measure.

The objective of this study is to develop a way to quantify the suitability of a vehicle profile to a known pedestrian population through evaluations using single pedestrian impacts. Demonstration through comparison of potential threat from two different vehicle profiles is targeted.

II. METHODS

Measurement of threat to pedestrian

Threat to a pedestrian is computed from correlations of potential injury or fatality risk obtained from the injury criteria of the different body parts. These injury criteria are typically based on linear accelerations, velocities, penetrations or peak resultant forces. For instance, fracture risk for bones is measured using bending and compressive forces, moments or a combination of both; injuries to soft tissues and ligaments under blunt impact can be measured by the strain produced.

The specific injury indices used for measurement of threat for a particular body region/organ are constantly updated. The Abbreviated Injury Scale (AIS), developed by the Association for the Advancement of Automotive Medicine (AAAM), is a scale formulated for standardization of injury severity measurement [9]. Injury risk curves for different injury indices have been developed to predict the likelihood of specific AIS level injuries for the respective index. Payne and Patel [10] give a detailed coverage of the indices and the injury risk curves for the same. The injury risk curve is discussed further in subsequent sections.

For scenarios involving multiple injuries to a particular body region, the Maximum AIS (MAIS), identifying the highest AIS value amongst multiple injuries in a particular body region, was proposed. The Injury Severity Score (ISS) measure for poly-trauma represents a squared addition of the highest MAIS values in three ISS body regions. ISS remains the only scale used in medical emergency management in hospitals which has a linear correlation with morbidity, mortality and expected hospital stay after trauma of a patient [11] . As a limit, ISS > 17 was proposed in [12] to classify injury as poly-trauma or syndrome of combined injuries. Since both these measures are derived from the AIS, using the same processing methodology, MAIS and ISS from potential AIS would be obtained to present a similar scale of injury severity estimation as a result of a vehicle crash simulation.

Previous studies on Injury Cost

The cost implication of injuries to humans has been estimated [13] in four categories; namely, hospital cost as direct restorative cost, nonmedical cost as indirect restorative cost, loss of resources as morbidity cost and a cost for fatality as Mortality Cost. The Injury Cost Scale (ICS) and ICS Lethal (ICSL) were proposed to provide a direct implication of severity of injury to a human from automotive crashes. A potential problem with ICS using an example of facial laceration and plastic surgery was explained and it was recommended that ICS/ICSL be used as a supplementary tool with AIS.

A study by [14] estimated costs based on medical, police and fire services, household work, wage work, insurance administration, legal/court, property damage and quality of life. The cost estimations were based on AIS 90 coding or MAIS values of injuries. The compiled cost validations were not complete for considering data as direct cost implications.

(Potential) Injury Cost (PIC)

For the purpose of assessing threat to pedestrians from a particular car profile, a methodology for calculating potential injury cost from simulations was proposed by the authors [15]. This potential Injury Cost (IC) was used as a representative unitary measure of threat to a pedestrian. The process for IC calculation is summarized in Figure 1. This measure was used to optimize vehicle profiles using computer simulations.

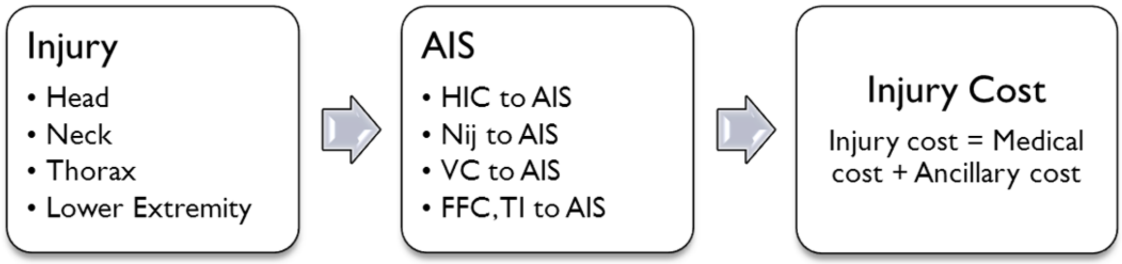


Figure 1. Injury Cost calculation from [13]

In estimating the injury cost, potential risk to the well-being of a pedestrian in terms of health and threat to life are estimated using injury indices mapped to their estimated Abbreviated Injury Scale (AIS) values. The injury indicator to head is estimated using the Head Injury Criterion (HIC), neck using Nij, Thorax using the viscous criterion (VC) measure and chest acceleration (3ms) at sternum, lower extremities using Femur Force Criterion (FFC) and tibia index (TI). The injury indices were correlated to the AIS using limits of Table 13 in [10] for HIC, VC limits from [16], chest acceleration limits from [17], Nij limits from [18] and lower extremities limits from Table 38 in [10].

The potential AIS values were mapped to the potential injury cost based on hospital and ancillary costs data reported in part 5 of ISO:13232 [19]. The cost increases with severity of AIS and a very high cost is assigned for AIS 6 (Non-survivable). There are higher cost implications for a potential impairment. The costs were used as a "representative" measure and do not imply a potential absolute cost figure for the threat to a particular pedestrian model during a simulated crash scenario.

Comparison of IC and Euro-NCAP measures

The Euro-NCAP pedestrian safety rating is based on assessing threat from impacts on different points of the vehicle front based on the wrap-around distance (WAD). A variation of WAD is used to address the safety to the pedestrian population as well as variations in crash scenarios. In Euro-NCAP, injury indices are compared to a target specification for "pass" or "not pass". A weighted sum of the "pass"es determines the star ratings of the vehicle profile. The transition from pass to not-passed, being discreet, makes it difficult to operate through gradient-based optimizers, though it is well suited as a legislative and social tool. The proposed Chinese NCAP [20] assigns points based on a linear interpolation between the injury index limits and so is continuous. The limits used in both NCAP measures are based on injury risk curves.

For computing the IC, the injury measures are converted to potential AIS measures using the injury risk curves. The potential AIS obtained is then compared with the likely treatment/rehabilitation costs obtained from [19]. An assumption in the IC-based measure is that a "severe injury" to a pedestrian implies a higher financial liability. The IC-based measure is hence a direct method to assess the financial implication of a specific pedestrian crash scenario.

Euro-NCAP pedestrian head tests over a range of WAD potentially cover the range of head impacts with a targeted range of population height and other factors. Simulations provide an advantage over experiments in that multiple scaled models of pedestrians can be simulated so as to enable understanding about a population of pedestrians. It is expected that in the future virtual human models will be available and more specific population crash scenarios can be simulated to measure threat to a population.

Vehicle Model

Two detailed Finite Element (FE) models of passenger cars, Ford TAURUS-v3 (Profile 1) for representing a typical sedan and Toyota YARIS -v1 (Profile 2) for representing a subcompact car, were used for the study. As shown in Table I these models have similar levels of complexity in terms of number of parts and elements. Both these models have been validated against experimental results for US regulatory frontal crash tests [21-22].

The accurate geometrical representation of the car outer profile and locations of prominent under-bonnet components like engine, radiator and battery are considered important for this study. References [21] and [22] report that both the models were generated using reverse Engineering data of vehicles procured; hence it is assumed that both are close representations of the actual locations of significant points in a real car.

Profile 1 does not have a Euro-NCAP pedestrian rating. Profile 2 has a Euro-NCAP pedestrian score of 21 points (60%) in the year 2011 corresponding to a 5-star rating.

TABLE I
Details of FE models from NCAC reports

Profile 1		No. of Parts	778
		No. of Elements	805505
		No. of shells	1057113
Profile 2		No. of Parts	771
		No. of Elements	974383
		No. of shells	950560

Pedestrian Model

Four anthropometric pedestrian ellipsoid multi-body models from [18] representing the 95th%ile Male (95M), 50th%ile Male (50M), 5th%ile Female (5F) and 6 year old child (6C) shown in Figure 2 were used. These multi-body models have been validated by TNO for kinematic prediction against Post Mortem Human Surrogate (PMHS) tests [23]. MADYMO models have also been used for crash reconstruction studies exhibiting capability to predict injury indices based on crash dynamics [24-25].

Figure 2. MADYMO^{TM} multi-body models from TNO [18]

Simulation Scenario

A lateral collision of a pedestrian with the vehicle front was simulated with a pedestrian model positioned in front of the vehicle model as shown in Figure 3. The pedestrian legs were positioned with an angle of 0.4 radian between the legs to represent a walking position. The pedestrian model was allowed to fall under gravity to load the legs before impacting with the vehicle. A scenario of the crash is depicted in a simplified way in Figure 3 in both front and top view.

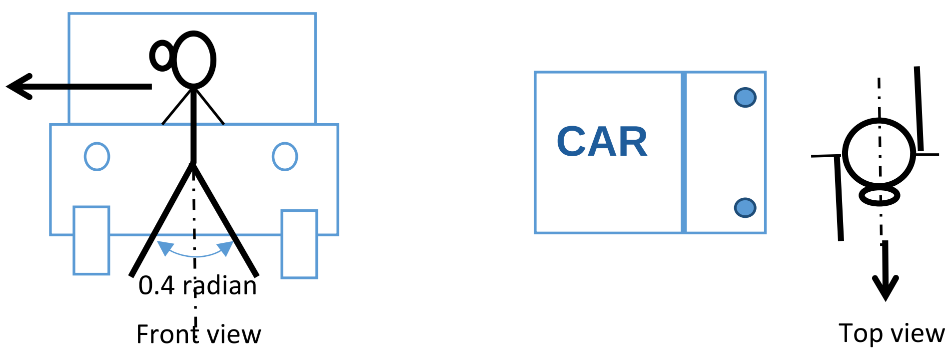


Figure 3. Simplified scenario of pedestrian-vehicle crash

It is known that an impact speed of around 40+ km per hour (kmph) is likely the upper limit for pedestrian safety relative to head injury, throw distance and head contact time [26]. For simulations, vehicle speed was 40 kmph (11.1 m/s) and braking was not modelled. Contacts were defined between vehicle front surfaces, under-bonnet components like engine, radiator, suspension housing, battery and bumper. In the simulation, tracking was limited to the primary contact with the car.

The rigid-FE coupled simulation results in force transfer from the FE solver to MADYMO™ solver which is applied to the rigid bodies. MADYMO™ output files record estimates on the injuries to the pedestrian in the form of injury indices processed from kinematic parameters as well as force parameters, and LS-DYNA™ output files relate to the damage to the car.

Methodology to address a Pedestrian Population

Existing estimates of threat posed by a car front is based on the perceived threat to a particular anthropometric size of the pedestrian model. We go on to show through simulations that threat perceptions are not uniformly graded with change in the anthropometry across car front profiles. Hence, threat estimates for a pedestrian population as opposed to a specific anthropometry become relevant. Design of a profile that is optimal for a whole pedestrian population must necessarily consider a weighted measure that is biased towards safety of more frequently occurring configurations. With the best known knowledge of distribution of pedestrian crash impact (CI) configurations, a threat perception can be estimated for the population, knowing the CI of the individual configurations.

Figure 4 outlines the methodology adopted for this work. A clustering of pedestrian crash cases based on height and weight distribution of the crash population is performed. The IC calculated for each cluster is weighted linearly with the cardinality of each cluster in a geographical region.

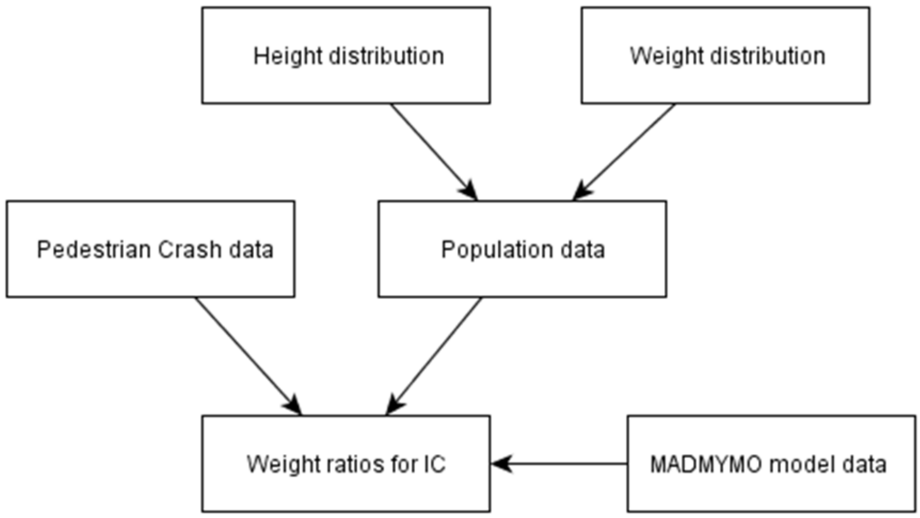


Figure 4. Methodology for calculation of weighting ratio for IC

Pedestrian crash data from the Department of Transportation, Michigan, USA were considered for this study. Table II has been constructed from bar charts in the report [27]. The data as shown in Table II were interpolated linearly between the intervals to operate on similar data ranges as with the data range available from US census on population height and weight. The gender distribution of the data shown in Table II was 64% for males and 36% for females [27]. This ratio is assumed to carry across within each range when correlating with census data.

TABLE II
Michigan data on pedestrian crashes (Revised) from [27]

Age distribution	% Crash (revised)
Under 20	33.08
20-29	17.77
30-39	11.86
40-49	12.44
50-59	10.50
60-74	7.01
75 and above	2.91
Unknown	4.45
Total	100.00

The age of crash victims (pedestrians) along with gender was compared to the population distribution in height and weight obtained from US census data [23]. The document reports height and weight data along with their standard deviation for the population considered for the study.

A "*Z*" factor of a data point in this work is defined as the deviation of the value from the mean of the population divided by the standard deviation. With standard deviation and mean from [28], the "*Z*" factor is computed based on the height and weight of available TNO pedestrian models. Our set of pedestrian models consists of scaled pedestrian models; namely, 6C, 5F, 50M and 95M.

Data of mean and standard deviation recorded for height and weight variation of people less than 20 years of age were found to be within specified limits for pedestrian model 6C. The strange phenomenon of 6C representing a population below 20 years is due to large variance in anthropometry in the population below 20 years, which was 29.15 kgs for weight. We obviously need more models, ideally a continuum of models, to address such issues. Similarly, a male population of age 20 years to 75 years fits with the 50M size of pedestrian model. The female population above the age of 75 years fits with the 5F model. A detailed tabulation is provided in Table IX of the Appendix. The female population from 20 years to 75 years of age could not fit within the specification (Table III).

The unknown category in Table II is not considered for calculation of the ratios to be discussed in the next section.

It is seen that 74.1% of the population is represented using the four TNO models The ratios are calculated assuming similar mix of male and female in every segment as observed for the whole population.

TABLE III
Selection of MADYMO pedestrian Models

	Scaled Pedestrians Model from MADYMO by TNO							
Pedestrian Group	6C		5F		50M		95M	
(Age –years)	Height	Weight	Height	Weight	Height	Weight	Height	Weight
Under 20	X	X	-	-	-	-	-	-
20-29	-	-	-	-	X	X	-	-
30-39	-	-	-	-	X	X	-	-
40-49	-	-	-	-	X	X	-	-
50-59	-	-	-	-	X	X	-	-
60-74	-	-	-	-	X	X	-	-
75 and over	-	-	X	X	X	X	-	-

'X' represents the pedestrian model represented in characteristics of the pedestrian population within one standard deviation of the population.

Weighted IC

The weighting ratios are calculated to reflect specific distributions of the models within a mix of a population of pedestrians in calculating the IC measure. We define

Total potential IC for a population = x_1 * IC 6C + x_2 * IC 5F + x_3 * IC 50M + x_4 * IC95M

Where,

x_1 = weighting factor for IC calculated from 6C

x_2 = weighting factor for IC calculated from 5F

x_3 = weighting factor for IC calculated from 50M

x_4 = weighting factor for IC calculated from 95M

A general case giving equal importance to all sizes of pedestrians is as follows,

Equi-weight IC (EIC) = 0.25 * IC 6C + 0.25 * IC 5F + 0.25* IC 50M + 0.25 * IC95M

The processing of the data in Table III using a point measure to obtain a set of ratios for a particular pedestrian model resulted in the weighted IC measure. Every successful "fit" within one standard deviation for both height and weight results in one point for a particular pedestrian model. Analysis of the data and "fit" with all the considered pedestrian models from TNO resulted in a match of 7 points a total of 16 points (maximum possible) (from Table VIII in Appendix).

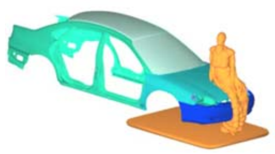
From Table II, the percentage of population is split using ratios of 64:36 for Male:Female since specific data are not available. Such a calculation yields Table XI and it is processed as explained in the Appendix to obtain

Weighted IC for a population (WIC) = 0.45 * IC 6C + 0.08 * IC 5F + 0.47* IC 50M + 0.0 * IC95M

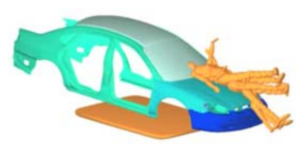
III. RESULTS

Coupled LS-DYNA / MADYMO - Overall kinematics

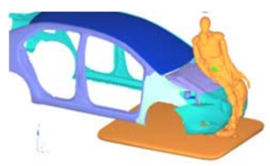
The simulations performed with four different sizes of pedestrian models with struck leg forward showed kinematics as observed in [29] with qualitatively similar motion. This is pictorially shown for 55s and 180s time frames in Figure 5 for both profiles. Each frame consists of four pedestrian models superimposed on each other. The head impact for the tallest pedestrian (95M) was observed on the lower part of the windscreen for Profile1 while in the case of Profile2 the impact was above the middle of the windscreen. This is as expected with these categories of vehicles based on wrap around distance (WAD)-based measurements.



Profile1- 55ms after initial impact



Profile1 -180ms after initial impact



Profile2- 55ms after initial impact

Profile2 -180ms after initial impact

Figure 5. Comparison of kinematics of profile1 and profile2 for 6C, 5F, 50M and 95M

Analysis of Injury threat

During initial runs, Head Injury Criterion (HIC) calculations with 36ms and 15ms window had no significant differences for the pedestrian head impact with vehicle front. Consequently, only the 15 millisecond value has been tracked.

Head impacts observed in Profile2 indicated a higher threat for 50M, primarily due to the impact location being in a region at the edge of the bonnet corresponding to the cowl region which in our nomenclature was the structural member called "engine top shield". A HIC of 1246 (highest) was observed in this scenario. The other taller models had a head impact following a shoulder impact, thereby reducing the impact threat to a HIC value of 805. The shorter models scored relatively well for head impacts. In the case of Profile1, threat to head by primary impact was higher for the child model and less overall for the adult models. The HIC values for 6C showed the highest value of 952 corresponding to a direct impact of the child's head with the stiff structural member at the bonnet edge. By working with a population, using the IC as a measure, singularities such as the 50M hitting the "engine top shield" do not unduly bias a design.

Threat to the chest is conventionally represented in units of 'g's for the peak chest acceleration measured at the sternum and Viscous Criterion (VC). Since both these measures scaled the same way for the crashes considered, the VC measure has been omitted in the analysis. Chest acceleration measured at the sternum is separately included in the IC calculation as it can also increase understanding of the threat during a crash scenario.

The acceleration was found to be higher for 5F and 95M for the Profile2 FE model, resulting from direct contact, and was above the threshold of 80g. The chest accelerations for the Profile1 FE model was above the threshold for 5F, but the rest of the population did not show substantial threats. The high acceleration recorded can be attributed to contact with stiffer structural members under the bonnet as mentioned in the case of head impacts.

Threat to the lower extremity was measured as peak force on the tibia and femur, on the way to failure. Evaluation of this as a measure is however somewhat limited by the capability of the pedestrian model considered.

Some injury indices for comparing threat to lower extremity, head and chest are compiled in Table IV and Table V. Comparing the threat to the lower extremity, the peak force observed at the femur and tibia of the tallest pedestrian (95M) was highest for the Profile2 FE model.

TABLE IV

INJURY MEASURED OBSERVED WITH PROFILE2

Pedestrian Model	Femur peak force (kN)	Tibia peak force (kN)	HIC _ 15ms	Chest acceleration (g)
6C	5.7	2.6	307	32
5F	4.5	3.2	490	137
50M	7.0	4.9	1246	27
95M	9.6	5.2	805	210

TABLE V

INJURY MEASURED OBSERVED WITH PROFILE1

Pedestrian Model	Femur peak force (kN)	Tibia peak force (kN)	HIC _ 15ms	Chest acceleration (g)
6C	7	4.5	952	48
5F	4.2	2.7	578	75
50M	8.5	5.6	474	30
95M	9.3	4.6	538	32

ISS and MAIS

From the injury indices of the simulations, a potential AIS level for the injuries sustained was obtained as expressed in Table IX and Table X. With these AIS levels as input, MAIS and potential ISS were calculated for comparing the threat levels to a pedestrian from the vehicle profile. The ISS value was calculated with available AIS values and not strictly with the codes of AIS primarily due to the limitations in models chosen for simulation.

The values in Table VI show that MAIS and ISS levels are the same for all adult pedestrian models. In both profiles, taller pedestrians tend to have higher threat as shown in 95M and 50M ISS values. The 5F model has least perceived threat from both profiles. The 6C model has a significant difference in threat from the two profiles. ISS of 14 from profile 1 is significantly higher than 6 from Profile 2.

TABLE VI
COMPARISON OF MAIS AND ISS

	95M		50M		5F		6C	
	MAIS	ISS	MAIS	ISS	MAIS	ISS	MAIS	ISS
Profile2	4	21	3	14	2	6	2	6
Profile1	4	21	3	14	2	6	3	14

Injury cost calculations

Injury cost has been calculated from the injury measures tabulated in the Appendix as Table IX and X. IC variation showed that Profile2 posed maximum threat to a 50M pedestrian while Profile1 posed maximum threat to a child.

With an assumption that every cluster was equally important, a population IC can be calculated using a weight of 1 for all pedestrian sizes. EIC was 217664 USD for Profile2 and 218404 USD for Profile1. The threat level by Profile1 was slightly higher than Profile2. WIC calculation with ratios for a pedestrian population using the Michigan crash distribution shows the value to be 226190 USD for Profile2 and 203895 USD for Profile 1. This shows a trend not in line with EIC, as shown in Table VII.

TABLE VII
COMPARISON OF TOTAL IC WITH WEIGHTED IC (USD)

	IC 95M	IC 50M	IC 5F	IC 6C	Weighted IC (WIC)	Equi-weighted IC (EIC)
Profile2	209357	256720	195222	209357	226190	217664
Profile1	209357	198180	209357	256720	203895	218404

IV. DISCUSSION

Observations from Injury Measures

A child model 6C showed higher threat from Profile1 compared to Profile2. A taller pedestrian model, the 50M on the other hand, had a high HIC value in Profile1 whose magnitude is the highest observed among all crash scenarios simulated. The 5F model of pedestrian had a potentially higher threat to the chest region from both profiles. The two profiles clearly seem to be potentially more threatening to taller as well as shorter (6C) pedestrian models than those of intermediate height.

Injury measures can be correlated to threat of a pedestrian using injury risk curves indicating probability of a particular AIS level of injury. In our study, the implication of injury measures on pedestrian safety is measured using the potential AIS values. Both profiles show varying levels of threat to adults based on height differences. More significantly shorter height of the bonnet leading edge resulted in severe head injury for 6C for Profile 1. A relatively shorter bonnet resulted in severe head injury for 50M in profile 2. This phenomenon suggests that a longer bonnet profile need not always be perceived as safer than a shorter bonnet profile. The rest of the injury measures in isolation also do not convincingly indicate a safer vehicle profile.

MAIS/ ISS measure

Comparison of the MAIS or ISS values does not indicate any difference between pedestrian population category 95M, 50M and 5F. But, in case of 6C, the MAIS and ISS indicate a clear difference of Profile1 causing a higher threat than Profile1.

ISS above 17 was regarded as potential poly-trauma. Using this measure, the 95M would result in serious complex injuries for both profiles.

ISS provides information on potential morbidity, mortality and hospital stay related to the injured pedestrian. However, more information is needed than what can be gleaned from such injury measures. In most crashes resulting in severe injuries to pedestrians, the length of hospital stay, for example, is not always indicative of the severity of an injury resulting in long-term disability.

IC measure

An IC measure provides an indication of the hospitalization cost similar to the ISS, but it also provides information on ancillary costs for injuries resulting in long-term impairment or disability, thus underscoring the potential threat to a future normal life of an injured pedestrian.

For estimating threat to a population, the EIC which gives equal weighting to all pedestrian models, indicated Profile1 to be marginally better than Profile2.

WIC indicated Profile1 to be safer than Profile2 for a specific population. It is also noted that Profile2 has a Euro-NCAP pedestrian score of 5 stars whereas Profile1 does not have a published Euro-NCAP pedestrian test result. The car with Profile1 is from a period before the Profile2 car, when the design effort was not focused on high pedestrian ratings.

Noted also is the fact that the minimum value of IC observed in WIC for Profile1 was less than the IC for Profile2 in the EIC calculation (both EIC and WIC represent normalized weighting factors applied). WIC was able to clearly differentiate the two profiles in terms of cost.

Limitations

The existing pedestrian model is restricted in prediction of soft tissue failures; hence the calculation of a cost measure in this region was not performed. Similarly, injury associated with soft tissue damage, joint dislocations and stress-related are not computed due to restrictions in modelling. Two car models used in this study were considered only for illustration and do not limit the application of the same methodology across a variety of cars/motor vehicles. The two Finite Element models of the cars chosen have not been validated for pedestrian safety-related tests.

The present work demonstrates a methodology to compare threat to a pedestrian using a variation in population, two vehicle types and only one crash configuration. The variation in crash scenarios has not been addressed in this work. Using a population of crash scenarios and vehicles of the kind available in [1] is a logical extension and needs to be taken up using a consistent database.

The costs calculation in this process has been based on converting injury measures to AIS and then back again. This method was preferred to address the variations of injury and associated cost, but it has limitations in terms of sensitivity. Other scales to convert observed trauma into cost such as ICS and ICSL have not been attempted due to limitation in estimating them from the pedestrian model considered. These can also be considered as supplementary measures with more detailed FE Human Body Models.

V. CONCLUSIONS

The MAIS/ISS measures present potential injury severity to a pedestrian but an IC-based measure was able to provide more direct information on vehicle threat to a pedestrian in terms of potential cost implications. A cost scale with higher cost indicating severe threat to a population was proposed as WIC/EIC. All the above mentioned secondary measures were computed from AIS values obtained from computer simulations. The procedure adopted for IC calculation had similarity to the methodology used in the Euro-NCAP rating system for the initial injury measure, but it provides better insights into implications of a crash with a pedestrian.

The injury indices considered in this study were not exhaustive. The limitations of the chosen pedestrian model stipulated the limit to the injury measures chosen. To represent threat to pedestrians using better injury indices, a better validated pedestrian human body FE model would provide a more accurate starting point.

Within the constraints of simulations and limited accuracy in pedestrian modelling, the WIC measure was able to provide better information of the threat to a pedestrian from a vehicle profile, taking into account specific population distributions. In our study, Profile2 can be concluded to be of a lesser threat to a pedestrian population than profile1.

VI. ACKNOWLEDGEMENT

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VIII. APPENDIX

1 point is allocated for Male and 1 point for Female in one age range. For category with just height or weight having a one 'Z' score less than 1, but other 'Z' score greater than 1, weightage (points) allocated is 0.

TABLE VIII
SELECTION OF SCALED MODEL FOR SIMULATION – 'Z' score to weightage points

20-29 years	Male		Female		Weightage points		
Z scores	Height	Weight	Height	Weight	Male	Female	Total
6C	-7.40	-3.21	-5.93	-2.08	0	0	0
5F	-2.94	-1.79	-1.27	**-0.92**	0	0	0
50M	**-0.33**	**-0.41**	1.45	**0.20**	1	0	1
95M	1.77	0.94	3.65	1.29	0	0	0
30-39 years							
6C	-7.39	-2.61	-5.76	-2.13	0	0	0
5F	-2.91	-1.50	-1.25	-1.02	0	0	0
50M	**-0.30**	**-0.43**	1.38	**0.07**	1	0	1
95M	1.82	0.63	3.51	1.13	0	0	0
40-49 years							
6C	-7.17	-3.37	-8.23	-1.73	0	0	0
5F	-2.88	-2.01	-1.85	**-0.86**	0	0	0
50M	**-0.38**	**-0.68**	1.88	**-0.03**	1	0	1
95M	1.64	**0.61**	4.90	**0.79**	0	0	0
50-59 years							
6C	-8.00	-2.98	-6.16	-2.00	0	0	0
5F	-3.10	-1.77	-1.26	-1.01	0	0	0
50M	**-0.24**	**-0.59**	1.59	**-0.04**	1	0	1
95M	2.07	**0.56**	3.90	**0.90**	0	0	0
60-74 years							
6C	-6.02	-3.36	-6.79	-2.73	0	0	0
5F	-2.24	-1.96	-1.10	-1.32	0	0	0
50M	**-0.04**	**-0.60**	2.21	**0.04**	1	0	1
95M	1.74	**0.73**	4.89	1.38	0	0	0
75 years and over							
6C	-6.04	-4.12	-5.81	-2.09	0	0	0
5F	-2.04	-2.13	**-0.63**	**-0.81**	0	1	1
50M	**0.30**	**-0.21**	2.39	**0.44**	1	0	1
95M	2.19	1.68	4.83	1.65	0	0	0

TABLE IX

CALCULATION OF INJURY COST – PROFILE2

Injury Values obtained	Profile2_95			Profile2_50			Profile2_05			Profile2_6c		
	Value	AIS	Cost	Value	AIS	Cost	Value	AIS	Cost	Value	AIS	Cost
Head _HIC	805	2	14625	1246	3	61988	307	1	490	696	2	14625
Chest _VC	0.04	4	66430	0.06	4	66430	0.04	4	66430	0.04	4	66430
Sternum acceleration(g)	210			27			137			32		
Femur peak force (kN)	9.6	4	128302	7	2	128302	5.7	2	128302	4.5	1	128302
Tibia peak force (kN)	5.2	1		4.9	1		2.6	1		3.2	1	
Lower Extremity PPI	0.27			0.27			0.27			0.27		
Total Injury Cost (USD)			142927			190290			128792			142927
Lower Extremity cost (USD)			128302			128302			128302			128302

TABLE X

CALCULATION OF INJURY COST – PROFILE1

Injury Values obtained	Profile1_95			Profile1_50			Profile1_05			Profile1_6c		
	Value	AIS	Cost	Value	AIS	Cost	Value	AIS	Cost	Value	AIS	Cost
Head_HIC	538	2	14625	474	1	3448	578	2	14625	952	3	61988
Chest _VC	0.06	4	66430	0.07	4	66430	0.04	4	66430	0.04	4	66430
Sternum acceleration(g)	32			30			75			48		
Femur peak force (kN)	9.3	4	128302	8.5	3	128302	4.2	1	128302	7	2	128302
Tibia peak force (kN)	4.6	1		5.6	2		2.7	1		4.5	1	
Lower Extremity PPI	0.27			0.27			0.27			0.27		
Total Injury Cost (USD)			142927			131750			142927			190290
Lower Extremity cost (USD)			128302			128302			128302			128302

TABLE XI
CALCULATION OF PERCENTAGE POPULATION REPRESENTED BY PEDESTRIAN MODELS

Age	Male	Pedestrian Model	Female	Pedestrian Model	Total
20-29	**11.37**	50M	6.40	-	17.77
30-39	**7.59**	50M	4.27	-	11.86
40-49	**7.96**	50M	4.48	-	12.44
50-59	**6.72**	50M	3.78	-	10.50
60-74	**4.48**	50M	2.52	-	7.01
75 and above	**1.86**	50M	**1.05**	5F	2.91

From Table XI, population represented by the pedestrian models are indicated in bold font. The models represented Male population from 20 years to above 75 years and Female population 75 years and above.

Percentage of adult population (>20 years) represented = 41.03 %
Percentage of pedestrians under 20 years is completely represented (From Table II) = 33.08 %

Total percentage of pedestrians involved in crashes represented by the set of models = 74.11 %

Population represented by 6C = 33.08 %
Population represented by 50M = 39.98 %
Population represented by 5F = 1.08 %

A distinction is made to consider people below 20 years in a separate category as children and young population. The data availability made it convenient to split at 20 years of age and no other reason was considered for this specific age. The distinction would be necessary as the injury measures and other cost implications will differ from young population to adult population. Ratio of children and young pedestrian population is approximately 45%. To calculate the weighting ratios, the population is normalized to the total population represented.

Weighted IC of population = Weighted IC of young population + Weighted IC of adult
= 0.45 * IC of young + 0.55 * IC of adult
= 0.45*IC of 6C + 0.47*IC of 50M +0.08*IC of 5F