# A bio-mechanics based methodology to optimize vehicle front profile for pedestrian safety

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## 1. ABSTRACT

Car front design is based on performance and passenger safety requirements by regulatory and rating tests. Pedestrian safety tests are mandatory in regions like European Union and Japan while other regions do not have such regulations. These tests involve impacts of head-form, upper leg-form and lower leg-form to simulate collisions with bumper, bonnet edge and bonnet regions while excluding regions like windscreen. In this paper, we address this issue by the interaction of a complete human body model and not just independent “body-forms”. The focus is to study the human body interaction with the complete front end profile and addressing the front end shape in the perspective of injury reduction. In this process, kinematics of vehicle-pedestrian crash is considered on the basis of a multi-body simulation using MADYMO software. Four different body dimensions are analyzed comprising of one child dummy and 3 adult dummies. The optimization of vehicle shape is based on an “injury cost” measure as a single objective function using indicative cost for various body segments from leg to head. A genetic algorithm based optimization was implemented in MATLAB/MADYMO environment. Constraints of the optimization process denote the geometric limits of the specific car segment. This process has the objective of supporting the initial concept stage of a vehicle design process. An optimization at this stage allows the design to be more pedestrian friendly without compromising the rating and mandatory requirements.

## 2. INTRODUCTION

Cars of today appear in varied shapes and sizes expressing stylistic features combined with features for better performance. The design of front ends is to score better points in New Car Assessment Program (NCAP) tests and pass the regulatory crash tests. Pedestrian fatalities are found to be higher in urban areas in particular across the world (Naci et al. 2009; WHO 2009). In a step to minimize the injury to pedestrians from impacts with vehicle fronts, the pedestrian safety tests were proposed. These tests involve the usage of “body-forms” to assess the threat of vehicle to the pedestrians. The results were based on injury measures calculated from the dynamics of the body-form with vehicle impact.

When NCAP scores are analyzed, one can find cars with two different profiles have

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same rating in the tests, but they do not look similar!! We wish to address the design of shape of the front end of a car, based on safety of a pedestrian considering whole body kinematics and one unified representation of the threat to the pedestrian.

## 3. CRASH SCENARIO SIMULATION

Frontal crash scenario with pedestrian being hit at right side is considered. There is also data epidemiological studies showing major scenarios of pedestrian crash are lateral impact to the front of the vehicle. . The NCAP tests also assume impact with the front end of the vehicle. The pedestrian dummy is positioned with legs at walking position. The speed of impact is assumed 40 kmph reduced by 0.7g due to normal braking up to around 150 ms after contact with the pedestrian. After 150ms of crash, a further deceleration of 7g is introduced to avoid carry over with the vehicle. The focus here is to study due to primary impact and studies have indicated head contact to occur around 100ms from the time of initial contact (Mizuno et al. 2001).

For accounting the variation in population, available MADYMO human pedestrian dummies of 6 year old child, 5th percentile Female, 50th percentile Male and 95th percentile Male are used. The stance considered is based on the values used by Carter et al. 2005. Simulation using multi-body codes is carried for at least 250ms after the first contact with the pedestrian dummy. The dummy is allowed to fall in the field of gravity so as to have a preloading in the legs before crash.

Vehicle representing a car is modeled in segments as hyper-ellipsoids in MADYMO having two ellipsoids for bumper, one each for bonnet leading edge, bonnet, cowl region and windscreen. The contact between vehicle and pedestrian dummy is defined using simplified force-deflection curves based on data from (Mizuno et al. 2001; Rooij et al. 2003). The characteristics as force-deflection used for simulation are to represent body interaction with the car surface. Figure 1shows a screen shot of preprocessor (xMADGIC) application.

Friction between the body surface and vehicle surface is taken as that for a nylon surface with metal as used for dummy ($\mu = 0.61$) (Han et al. 2001). Various friction values have been used but variation of the results significantly was not observed, so the above mentioned value has been used. Friction is also used between the pedestrian foot and ground ($\mu = 0.6$) based contact between sports shoes with road (Feist et al. 2009).

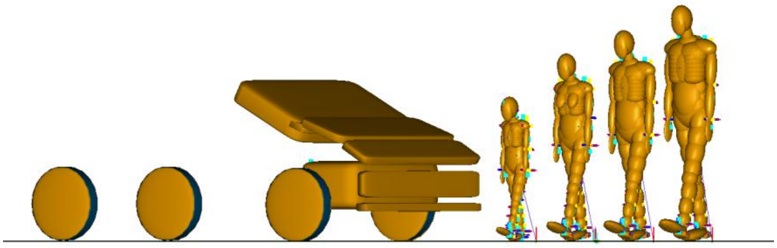

**Figure 1 Vehicle Model and pedestrian dummies before impact**

## 4. MEASUREMENT OF SAFETY TO HUMANS

### 4.1 Injury Measures

Abbreviated Injury Scale (AIS) is a number from 1 to 6 to represent severity of injuries to a particular body part based on the probability of death occurring due to it. It was developed by Association for the Advancement of Automotive Medicine (Gennarelli & Wodzin 2006). The new version was updated in 2008. Measurement of injury is still a researched area. It is understood that the injury measures do not completely represent the injury severity and it's implication to the pedestrian. The nature of injuries varies from soft tissue damage in internal organs to torsional or bending failure of bones.

Injury measures like HIC, Nij, and VC for Torso with head and peak forces with index for long bones are considered for this study. There are further injury measures like Angular acceleration based injury measurement on head (Schmitt et al. 2007) to represent injuries better. We restrict to these measures which can be computed with simple multi-body simulations of a vehicle pedestrian crash in a manner of representing one major injury measure for each of the body regions namely head, neck, thorax, upper leg, knees and lower leg.

## 4.2 Unitary Measure - Injury Cost

There have been attempts to optimize based on one measure or two of injury measures (Carter et al. 2005; Linder et al. 2004). The optimizations were based on HIC and HIC with chest accelerations. We take it further by considering the method of calculating 'injury cost' used in ISO 13232: part5 and formulate a representative cost based on the injury AIS values. The 'injury costs' involve medical costs and auxiliary costs, both based on AIS level of injury. For our study, we had considered the limit values based on the Injury limits used in (Payne A R, 2001). A sample calculation is shown in Table 1. This attempt of 'injury cost' can represent the injuries to whole body rather than just specific parts. It is understood that the data quoted for finding reference AIS values from injury measures was for a different application. Our objective here is to have an initial representative values for illustrating the procedure.

**Table 1 Sample Calculation of the Injury Cost**

| | Car 1_95 | | | Car 1_50 | | | Car 1_05 | | | Car 1_6c | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Injury Values obtained** | Value | AIS | Cost | Value | AIS | Cost | Value | AIS | Cost | Value | AIS | Cost |
| HIC | 135 | 1 | 3448 | 793 | 2 | 14625 | 357 | 1 | 3448 | 896 | 2 | 14625 |
| Nij | 0.667 | 1 | 0 | 0.369 | 1 | 0 | 0.47 | 1 | 0 | 0.267 | 1 | 0 |
| VC | 0.002 | 0 | 0 | 0.002 | 0 | 0 | 0.001 | 0 | 0 | 0.007 | 0 | 0 |
| FFC (kN) | 9.09 | 3 | 128302 | 10.9 | 4 | 128302 | 10.2 | 4 | 128302 | 4.15 | 1 | 128302 |
| TI | 0.339 | 0 | | 0.31 | 0 | | 0.29 | 0 | | 0.977 | 1 | |
| Force above knee on femur (kN) | 12.24 | 4 | | 11.17 | 4 | | 10.72 | 4 | | 3.53 | 1 | |
| Lower Extremity PPI | 0.27 | | | 0.27 | | | 0.27 | | | 0.27 | | |
| **Total Injury Cost (USD)** | | | 131750 | | | 142927 | | | 131750 | | | 142927 |

## 5. PROCESS OF OPTIMIZATION

The whole design of vehicle front design can be formulated as a function of single objective namely 'injury cost'. The injury cost measure is an indicative number and it has been shown to have inverse relationship with Euro-NCAP scores (Sankara subramanian et al. 2011). A higher injury cost means a profile with higher risk for injury to a pedestrian. So, we formulate the problem vehicle front design to be a problem of minimization of injury cost.

Optimization algorithm is used to control the shapes of car fronts and MADYMO solver is used to simulate the vehicle pedestrian crash. MATLAB codes are used to compute the AIS equivalent for the injury measure and the injury cost from it .With outputs from solver the optimization cycle continues till stopping criteria is reached.

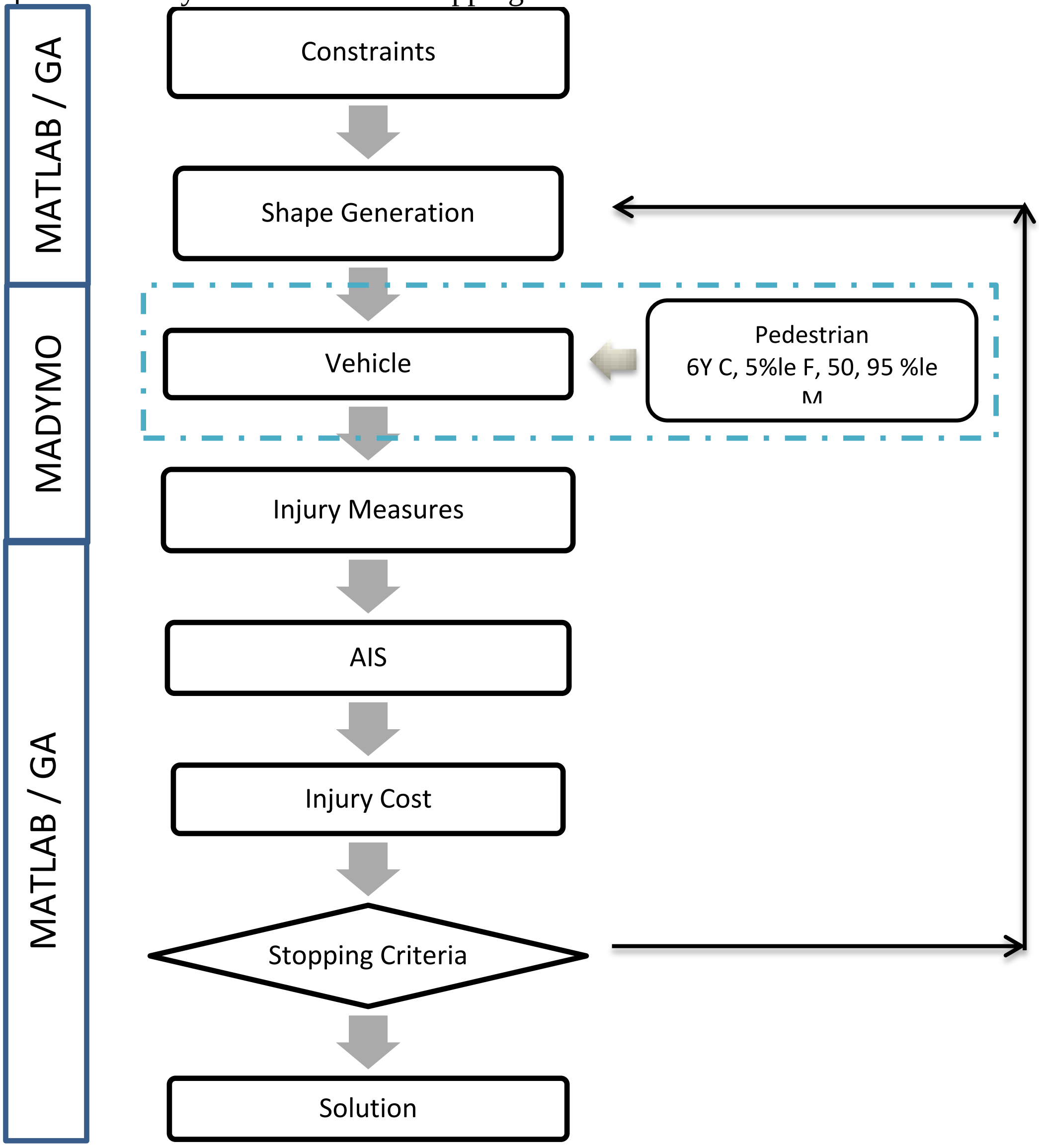

**Figure 2 Methodology of Optimization**

## 5. SAMPLE APPLICATION

A specific problem of urban car with conventional engine is addressed in this study. The design space for centers of ellipsoids is set in red box shown in Figure 4. The limits are based on the measurements of 6 compact car fronts. Optimization cycle stopping criteria is set with number of generations to be computed as 10. The number of samples in one generation is 100; effectively (10*100*4 = 4000) simulations are computed. It has been observed in previous calculations that median costs approach the minimum cost by the end of 9th generations in the trials conducted.

Constraints are placed in the length variations and angle variations of ellipsoids are restricted to represent only conventional shapes.

Injury cost is computed as the sum of injury costs of all four anthropometric sizes of humans. The injury cost is expected to serve as an indicator and not actual cost.

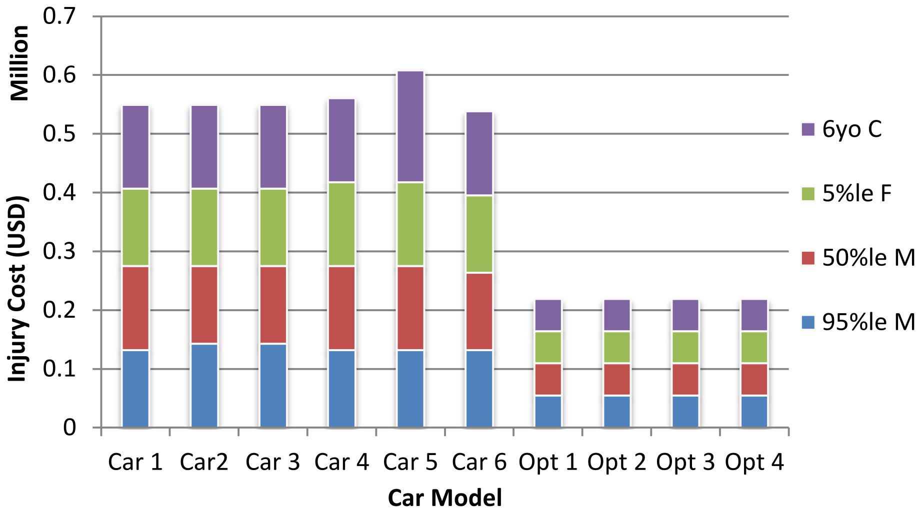

Figure 3 Injury cost variation

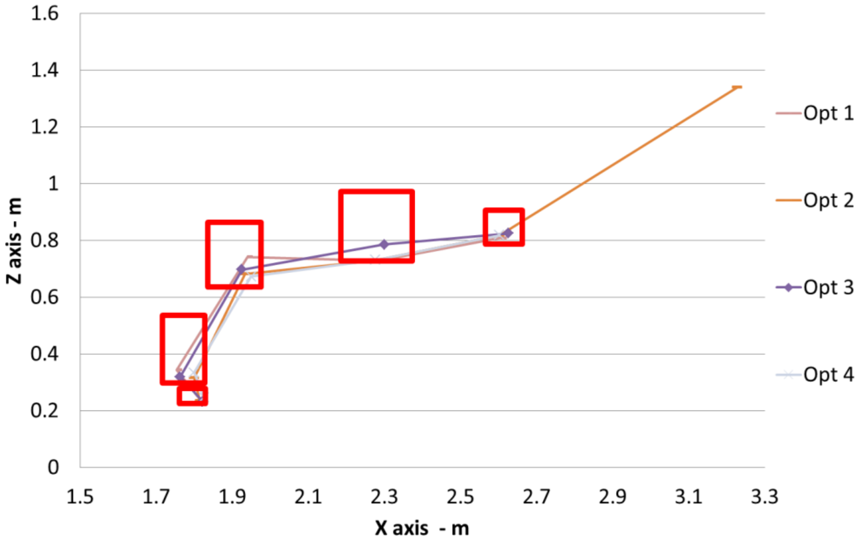

Figure 4 Best 4 Shapes at the end of optimization

## 6. RESULTS AND DISCUSSION

Figure 3 shows injury costs for six reference car profiles and 4 optimized profiles with shares of the various sizes of pedestrians indicated in different color. The resulting optimal shapes show injury costs around 30 to 40% of the shapes of cars considered. This reduction has been observed with variation of the shapes alone and not altering the stiffness characteristics. A further deeper analysis on the contribution of various costs showed a trend of severe injuries in lower extremity for the taller (95% Male) and more severe upper extremity injury for the child and shorter (5% Female). All 4 optima have nearly equal injury cost for the four dummies considered, hence they should cause minimal injury for adults and children.

Figure 4 shows the shape of vehicle as a line chart connecting the center of the hyper-ellipsoids. The actual shape would involve the ellipsoids with their inclinations included forming a conventional looking vehicle front.

It is known that the hood is the softest part in the body of the car and windscreen denotes a harder part followed by hood edge. The new shapes show a shift of the vehicle hood down and hood leading edge to a point where the head of child impacts the hood and point of first impact with hood edge is below the shoulder. Within the limits of the our design space, the head hits of all the other sizes of humans are found to be on the windscreen and not on the high stiffness cowl region below the windscreen or above the windscreen. Peak lateral force exceeding the limits of large bone failure was observed for all the standard car profiles considered. There was a reduction in this force also observed in the new profiles. The height of hood leading edge is found near 0.75m.

The contribution of thorax VC measure and the Nij measure of injury cost was not significant in almost all simulations indicating the requirement of a better measure.

This injury cost based optimization addresses the threat of a particular vehicle shape factor to a human assuming no variation in stiffness across profiles. The role of stiffness in vehicle parts impacting is critical in fine tuning for injuries to specific body parts. Though more than one solution is found, the trend shows grouping towards local minimal points.

With better data from epidemiological studies, ‘injury cost’ can represent in a better way the injury threat to humans. A finite element Human body model would be essential for calculation of specific injury measures to carry out in depth study. Since this method shows some probable results, the next step is to use a three dimensional model of the vehicle considering more detailed packaging considerations. In combination, the vehicle design problem can be better addressed for minimizing injury to pedestrians at concept stage without interfering with design for the rating and regulatory tests.

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