Optimization of Passenger Car Design for the Mitigation of Pedestrian Head Injury Using a Genetic Algorithm

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1. ABSTRACT

The complex nature of pedestrian accidents scenarios has resulted in great difficulty when using traditional statistical methods to study the effects of individual parameters of vehicle front-end geometry on pedestrian head injury. This research attempts to apply the emerging field of evolutionary computation to this area of vehicle safety by using a Genetic Algorithm to optimize the shape of a car's front-end for the reduction of pedestrian injury. The fitness of the designs is assessed by creating multi-body models of each one and simulating impacts with different sized multi-body pedestrian models in Madymo, then assessing each impact for both head injury and, to a lesser degree, torso injury.

2. INTRODUCTION

The problem of pedestrian injury is a significant one. Every year in Europe alone, over 7000 pedestrians are killed and hundreds of thousands more are injured [1]. Much research is being done both in Europe and the rest of the world in order to address this problem through changes in road infrastructure, driver legislation and education and through both active and passive safety design of vehicles. It is the area of passive safety design (the mitigation of injury once impact has occurred) to which this paper aims to contribute. Accident statistics have also shown that most severe injuries are caused by contact with the vehicle (primary impact) and not the secondary impact with the road surface [1], [2], [3], particularly at impact speeds over 20km/h [4]. The shape of the front of the vehicle is the primary vehicle characteristic affecting pedestrian kinematics [4],[5] which determines the head impact speed which influences the head injury. The stiffness characteristics of any impacted components has a slight effect on kinematics and a significant effect on injury severity. It is the vehicle shape that is being considered in the current study.

3. VEHICLE GEOMETRY & PEDESTRIAN INJURY

In the majority of cases (67.1% according to GDV data [5]), the vehicle's front-end (as opposed to the side or rear) is the initial impact location for the pedestrian. One of the weaknesses of the current EuroNCAP pedestrian sub-system impact tests as they stand is that they take no account of the vehicle's front-end geometry when assessing head injury. The shape of a vehicle's front-end (traditionally designed according to styling, aerodynamics, manufacturability, engine packaging and occupant safety) is the most important vehicle design related factor (significantly more than the force-deformation characteristics of the vehicle [6]) in determining pedestrian kinematics which in turn determine the impact speed, impact angle and location of the head impact, ultimately affecting the injury outcome.

Some early work has been done on studying the relationship between bonnet leading edge (BLE) height on the head impact speed [7], [6], [8] and also the influence of the bumper lead and bumper height [6]. More recently, the IHRA research project looked at the influence of different vehicle shapes (grouped into 3 main vehicle profile types) on head impact speed, angle and location, relative to vehicle impact speed [3], concluding that this should be taken into account when setting the sub-system head impact test conditions for different vehicle profile types.

4. INTRODUCTION TO GENETIC ALGORITHMS

Science traditionally uses reductionism to study a problem (i.e. by breaking a subject down into its constituent parts) like, for example, the approach towards studying the relationship between pedestrian injury and vehicle geometry of, for example, measuring the effect of changing the bumper height on the head impact speed. Compexity theory (dubbed by Stephen Hawkings as being ‘the science of the 21st century’) looks at how very simple things (such as the basic geometrical parameters that define the shape of a car) can generate very complex outcomes (such as pedestrian kinematics) that could not have been predicted by looking at the parts in isolation. One recent study on pedestrian accident simulation found that even with the Gaussian Process statistical modelling technique, ‘the HIC response could not be modelled due to extreme non-linear behaviour in the results’ [9] and another concluded that pedestrian impact reconstruction was difficult due to the complexity of the pedestrian kinematics [10].

The growing field of evolutionary computation, developed by John Holland in the 1970s, has been found to overcome such problems with the use of Genetic Algorithms or GAs. The GA is an automated optimization technique based on the principles of the Darwinian theory of Natural Selection. It could be described as a “brute-force” search method which generates solutions based upon “survival of the fittest” from a population of competing designs. Through selective breeding it is possible to nurture increasingly appropriate solutions over a number of generations. GAs are particularly suited to complex, multi-dimensional or non-linear solution spaces where more conventional statistical techniques cannot easily be applied, their main advantage being that the mutation and crossover operators allow the global minima of a non-linear function to be found where traditional optimization techniques would find only local minima [11],[12],[13]. Examples of previous applications of GAs include optimizing car aerodynamics and designing jet-engine turbine blades.

5. METHODOLOGY

5.1 Pedestrian models

TNO’s pedestrian human body models were used in the Madymo simulations. These have been extensively validated by TNO with reference to PMHS subjects (both by blunt impact tests on body segments and full-body car-pedestrian tests) [14]. Recent validation studies against published cadaver data, have found multi-body models to be reliable for pedestrian kinematics but with limitations in the assessment of injury criteria [9]. As the present study is mainly concerned with the effects of geometry on pedestrian kinematics (using the HIC and Torso injury criteria only as comparative measurements for fitness testing), these limitations should not significantly affect the results of the study. The choice of the size of the models used was based on epidemiological studies [15]. As Figure 1 shows, the most common age groups sustaining serious injury or death are the 20-29 and 12-15 year-olds. The first group is best represented by the 50th percentile male model and the second by the 5th percentile female model (approximately equivalent in height to a 12-year-old German but closer to the height of a 13-year-old in the UK) [16]. Although relatively few pedestrians killed or seriously injured fall into the 5-7 age group, this group has also been represented in the study by the 6-year-old child model. This is in part due to the fact that a car shape optimized for taller pedestrians would be done so at the expense of this age group (as seen by the results of the study). Also, when considering the rate of KSI pedestrians per population, this vulnerable age group (who have underdeveloped peripheral vision, directional hearing and poor vehicle awareness [17]) actually rank 5th out of 12. The 3-year-old model has not been used as very few struck pedestrians fall into the 0-4 age group probably due to tighter parental control at this age. The greater the number of models used to test the fitness of the design, the greater the internal conflict of the fitness function leading to a reduced scope for optimization. It is therefore important to keep the number of pedestrian models as low as possible while still achieving a solution which protects as many ‘at risk’ people as possible.

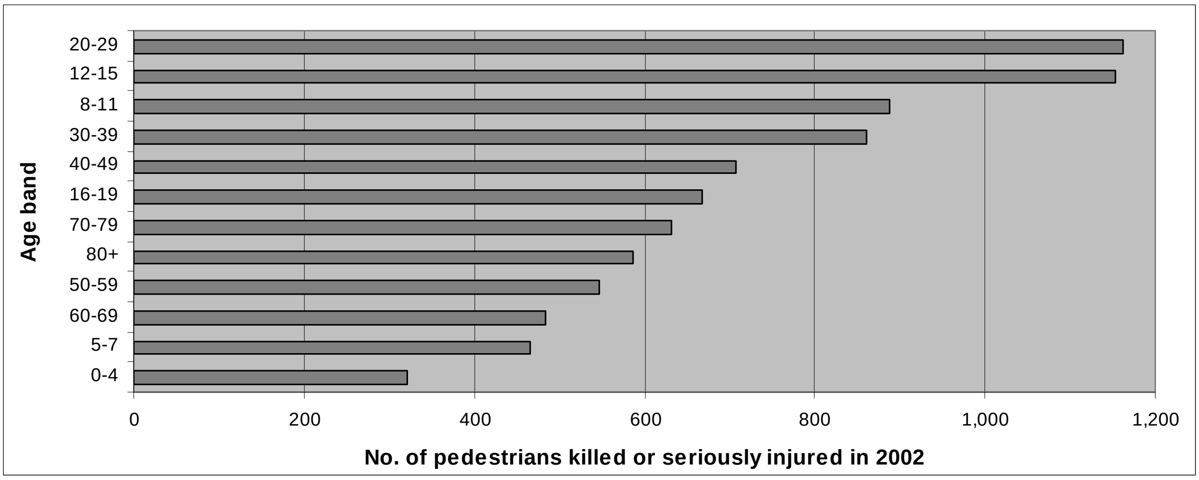

Figure 1 – Pedestrians killed or seriously injured in Great Britain [15]

5.2 Pedestrian position, orientation and gait

The PCDS study on pedestrian accidents found that 72% of the pedestrians were hit on either their right or left side [18]. German studies found that in 81.1% of cases, the pedestrian was crossing the road, and therefore likely to be hit side-on, and that for 61.1% of accidents, the front of the vehicle was the initial impact location [5]. The PCDS study also found that 56% of the pedestrians were walking prior to impact and 38% were running [18] (50% and 13.8% respectively according to the German data [5]). Based on these and other similar studies, the pedestrian model has been placed at 90° to the vehicle and in line with the centre of the bumper (as only the vehicle profile is under study).

The initial position of the leg (i.e. the leg nearest the bumper being either forward or behind) has a significant and unpredictable influence on the pedestrian kinematics [10] and the manner in which these leg positions affects the kinematics varies according to the shape of the vehicle (see Fig. 2) so it was important to test the designs with both these basic leg positions. The chances of being struck with either the near leg or the far leg forward are obviously equal, so for both the adult models, simulations were carried out both with the far leg forward and the near leg forward as shown in Table 1.

Table 1 – Simulation matrix

Test No.	Model	Gait
1	6-year-old child	‘Far leg forward’ (near leg rotated back 0.4 rad.)
2	5th % female	‘Far leg forward’ (near leg rotated back 0.5 rad.)
3	5th % female	‘Far leg forward’ (near leg rotated back 0.5 rad.)
4	50th % male	‘Near leg forward’ (near leg rotated forward 0.5 rad.)
5	50th % male	‘Near leg forward’ (near leg rotated forward 0.5 rad.)

5.3 Vehicle model

One of the requirements for design optimization using evolutionary methods is the ability to express the form of the design (the phenotype) as a string of numerical parameters (the genotype or chromosome). Also, in order to test several hundred different car front geometries in a relatively short space of time, the phenotype needed to be automatically created from the genotype and as all the ellipsoids in Madymo are positioned relative to a global origin, a mapping system had to be developed so that a random change to some or all of the parameters still resulted in something resembling a passenger car without the need for any manual modifications. In total, six ellipsoids were used to form the front of the vehicle; spoiler, bumper, bonnet leading edge, bonnet, windscreen and roof defined by a total of 11 parameters (BLE height, length of bonnet etc.). The original population of cars was based on measurements of a wide range of recent popular car models including SUVs, roadsters, superminis, MPVs, family cars and luxury cars with some parameters altered in an attempt to avoid large gaps in the design space that may then not be explored by the GA.

As the geometry of the vehicle front was under study and not the stiffness of the vehicle front components (which although greatly affecting HIC values, has only a secondary influence on pedestrian kinematics [4],[5]), these values were kept constant throughout the study. The force-deformation characteristics used for each of the ellipsoids representing the main vehicle front components were based on those used in similar studies [6],[19],[20],[21],[22]. A coefficient of friction of 0.5 was used between the pedestrian and vehicle and 0.7 between the pedestrian and road surface [23]. The initial vehicle speed of the vehicle was set at 11.1 m/s (40km/h). According to GDV data, 80.3% of pedestrian impacts occur at an impact speed of <=40km/h. This is also the speed chosen for the EuroNCAP pedestrian head impact tests [24] based on accident statistics and the fact that for impacts over 45km/h, a HIC<1000 would be nearly impossible to achieve. To simulate braking (PCDS data shows 56% of vehicles braking before hitting a pedestrian and GDV data found that to be 55% [5]), a deceleration of 8m/s^2 (corresponding to full braking on a dry road surface [5],[4],[10]) was used, bringing the actual impact velocity down to 10.5m/s (approximately 38km/h). Both of these values were kept constant throughout the study.

5.4 Fitness function

The fitness function of a genetic algorithm is crucial to its success. It is the measure by which each design is ranked and the ranking of a design determines how likely it is to ‘breed’, passing on some of its characteristics to the next generation. Finding a suitable fitness function for the complex area of pedestrian injury is not an easy task. As mentioned previously, there are many conflicting requirements when considering pedestrian safety. For example, a characteristic which may reduce head injury for a child may increase the torso injury for a child and also increase head injury for an adult. The fitness function therefore needs to cover as many scenarios as possible without overloading the GA with so many conflicting requirements that no optimization can occur. The fitness function developed for the current study is in the form of a scoring system which adds up weighted head injury and torso injury scores for all of the five Madymo simulation tests in Table 1.

5.4.1 Head injury

Several epidemiological studies have found the head to be the most common site of fatal injuries to a pedestrians hit by passenger cars [1],[25] and the most common site for injuries greater than AIS2 [26]. Also, studies have found that head impact with the car is more likely to be the cause of significant brain injury to a pedestrian than contact with the road surface [27]. Therefore, head injury due to primary impact with the vehicle forms the basis of the fitness function. The Head Injury Criterion (HIC), the universally recognised method of quantifying head injury severity, is used in the study to measure the degree of head injury likely to be sustained for each impact scenario. HIC assumes linear acceleration and duration of impact to be the main determinants of head injury severity, but does not account for rotational acceleration or linear acceleration in planes other than the sagittal plane or the area of the head receiving the impact. The complexity of head injury associated with pedestrian trauma is clearly beyond the scope of HIC but it is still used by virtue of the facts that it is entrenched in worldwide vehicle safety legislation and a better alternative has yet to be developed. A HIC of < 1000 is deemed 'safe' in that it is unlikely that a fatal head injury will result but it has not yet been related to an actual injury definition. Studies on rear and frontal crash occupant injuries found that there is approximately a 38% chance of sustaining a MAIS 3 head injury or a 16% chance of sustaining an MAIS 4 head injury for HIC <1000 [28]. Scoring for the fitness function has taken account of these HIC / MAIS relationships (e.g. $HIC<800$ scores the maximum 20 points, $900<HIC<1000 = 17$, $1900<HIC<2000 = 7$ etc.).

5.4.2 Thoracic injury

Unlike occupants, pedestrians are also likely to have sustained fatal injuries in other body regions as well as the head [1] and it is recognised that the thorax contains, after the head, the next most critical organs to protect from injuries [29] and since the design for mitigation of head injury can conflict with that of thoracic injury, a measure of thoracic injury has been included in the fitness function but with approximately half the weighting than that of head injury. A commonly stated human tolerance level for severe chest injury ($AIS>= 4$) is a maximum linear acceleration in the centre of gravity of the upper thorax of 60g sustained for 3ms or longer [29]. This result is taken from the Madymo peak file (in m/s^2) and scored for the fitness function, taking into account the 60g tolerance level.

5.5 The Genetic Algorithm

Once the original population of vehicles have been tested in MADYMO and ranked according to fitness, the genotypes are input in order of rank into the Genetic Algorithm for 'breeding'. The GA was designed to accommodate a population of 30 cars (the larger the population size, the more variety in the gene pool but the longer it takes to test each solution and 30 was deemed to be a reasonable compromise). Cars were bred with the higher ranking given a higher probability of breeding. The probabilities for each rank were such that while the best performers were often used as parents, there was still a reasonable likelihood of lower ranking genotypes being used (ensuring that some potentially good features of lower ranking genotypes were retained). A method know as 'elitism' was used wherein the top two ranking cars were preserved for the next generation (ensuring the top score from each generation is at least as high as that of the previous one). In order to breed the cars, the algorithm incorporated a 'crossover' operator which effectively split each string of parameters (the chromosome) into at least two parts which are then swapped between parents (mimicking the combination of the male and female chromosomes in nature). The number of crossover points used (between 1 and 3) was determined each time by a probabilistic operator and the positions of the crossovers was selected randomly but always between parameters (never in the middle of a parameter). Another operator used, key to enabling the GA to escape from local minima scenarios thus providing a greater chance of finding the globally optimal solution, was the mutation operator. Each parameter had a 2% probability of mutating with the degree of mutation specified as proportionate to each parameter range. In order that the vehicle offspring made spatial sense (e.g. didn't have a bumper higher than the BLE) and would be a viable design (e.g. the vertical component of the windscreen was sufficient to see out of), certain constraints were built into the GA. If any cars failed the constraint tests or were found to already exist (clone cars) they were aborted and another bred in their place so that the next generation always contained 30 genotypes. Since at each iteration, the previous generation was discarded, the population always remained constant at 30 cars.

6. RESULTS & DISCUSSION

6.1 Results of Genetic Algorithm optimization:

The GA stabilised after 7 generations. The score for the best car in the original population was 66 and the score of the best car overall (in the 7th generation) was 73, an improvement of around 11%. After the optimization was completed, the cars were also scored just for their performance in the 6-year-old child and small female simulations – the best car shape was reached by the 4th generation (after which the need for better scores for the male pedestrian conflicted with those for the smaller models, driving this score down). Both shapes are shown in Figure 2.

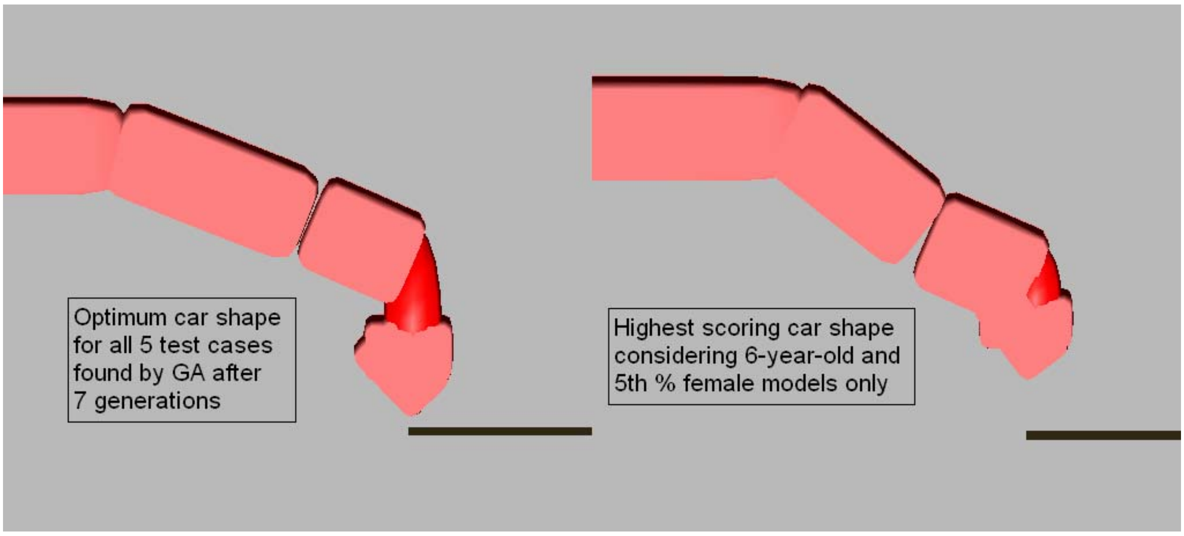

Figure 2 – Optimum car shapes

6.2 Other observations:

6.2.1 Effect of initial leg position

The pedestrian's leg position had varying effects on HIC results for the different car shapes. Some of the designs resulted in very similar kinematics and resulting injury scores for both leg positions while some designs resulted in hugely different outcomes for either position.

The car shape for which HIC was most sensitive to leg position (pictured in Figure 3 on the left) shows the pedestrian being thrown facing completely opposite directions after the primary impact with the vehicle, whereas the scenario pictured on the right resulted in almost identical HIC values for both leg positions:

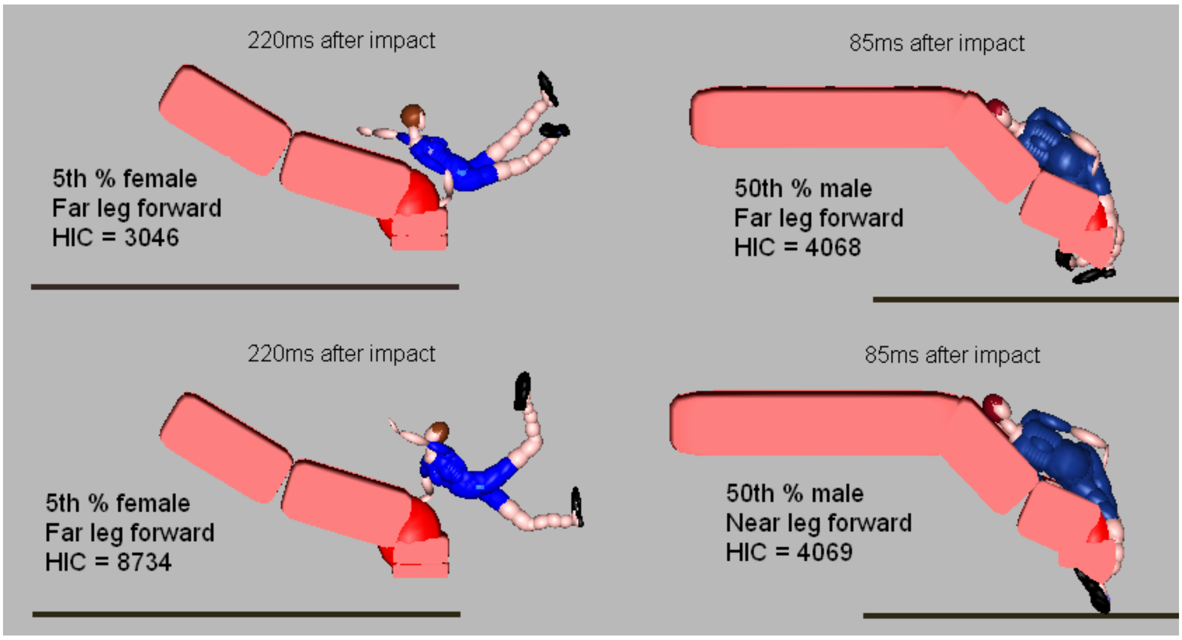

Figure 3 – Effect of initial leg position on HIC

For the average passenger car with a relatively low Bonnet Leading Edge height, pedestrians hit side-on with their near leg forward would rotate so that the back of the head impacts the vehicle, as shown in Figure 4 on the left. But for the increasingly popular SUV style cars with slightly higher BLE heights, the opposite was observed (see Figure 4). This illustrates how a slight change in the front-end geometry can dramatically affect the pedestrian kinematics. These differences observed in the pedestrian kinematics between the high and low BLE heights agree with results from earlier research by Niederer & Schlumpf [4].

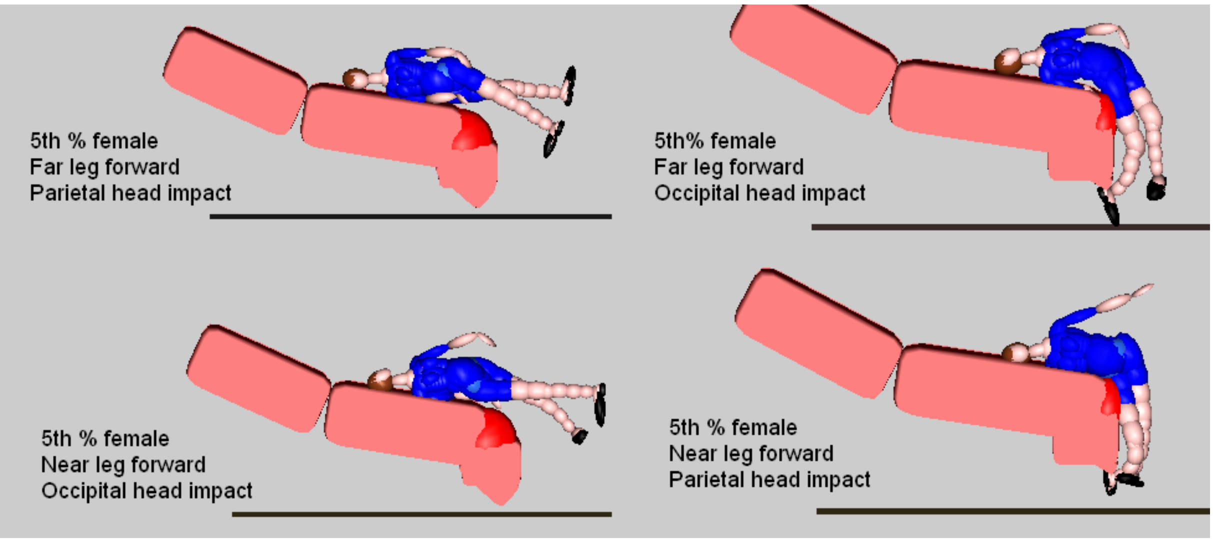

Figure 4 – Effect of initial leg position on area of head impacting vehicle

6.2.2 Effect of BLE height

This is certainly one of the most influential parameters with regard to head impact speed [4]. Earlier studies on the relationship between BLE height and head impact speed found that the higher the BLE height, the lower the head impact speed, with the exception that it is not higher than a child's head. (A direct head impact with the bonnet edge would produce extremely high HIC values even at relatively low speeds) [8]. The results of the GA optimization would back this up as the top scoring cars have high bonnet leading edges which remain just below the head of the 6-year-old child model. However, finding an actual correlation between BLE and either head impact speed or HIC was not obvious for any of the pedestrian sizes. For example, Figure 5 shows no relationship between BLE height and HIC for the 6-year-old other than the sharp increase once the bonnet edge reaches the child's head height.

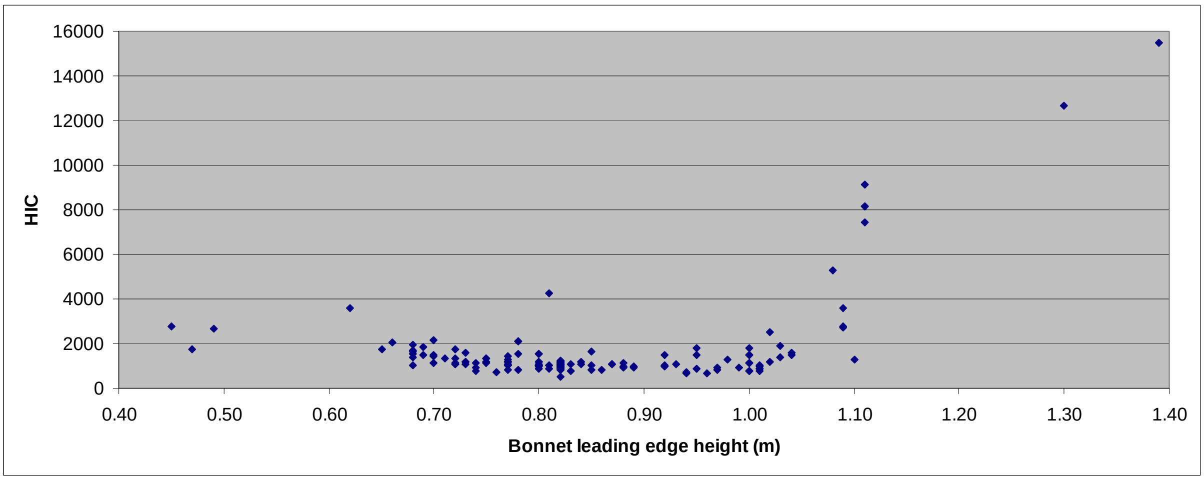

Figure 5 – BLE height vs HIC for the 6-year-old child model

6.2.3 HIC vs. head impact speed

Previous studies have found a correlation between HIC and head impact speed [7], similar to that found in the current study (which covers a wider range of HIC values and impacts speeds). The emerging pattern (Figure 6) fits reasonably well with a 3rd order polynomial.

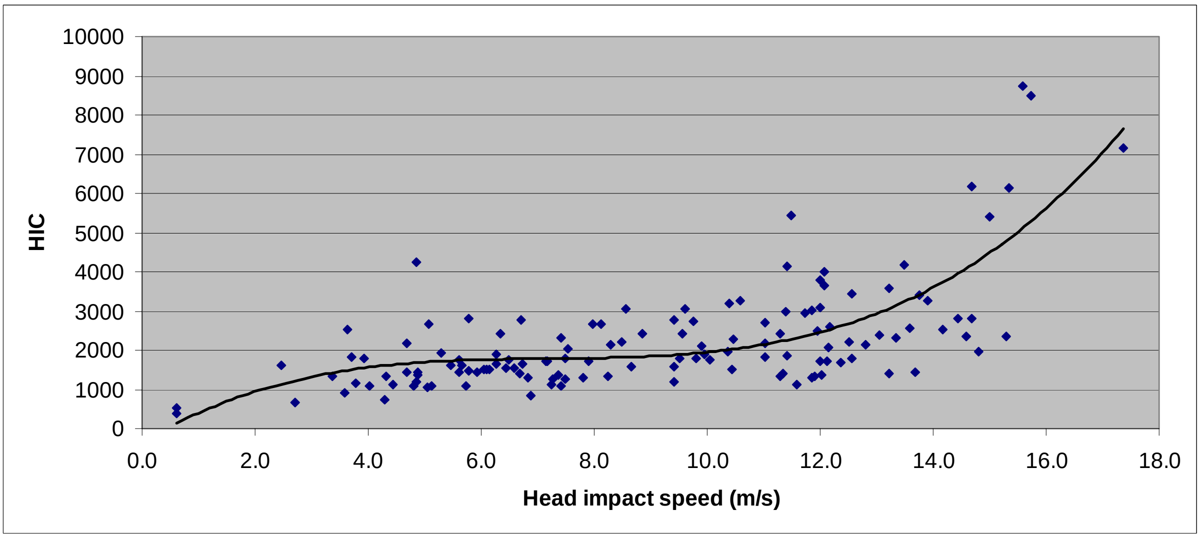

Figure 6 – Head impact speed vs. HIC

6.2.4 Head impact speed vs. vehicle impact speed

One phenomenon studied in the IHRA report was the ratio of head impact speed / vehicle impact speed (particularly relevant to a study on geometry as it is relatively independent of the vehicle's stiffness characteristics). The IHRA study found that different car shapes produced different ratios and also broke them down according to the head impact location on the vehicle. In the current study, these ratios were analysed for the first generation of 30 cars. Results are presented in Table 2 for each of the different test conditions. For both the male and more so for the female pedestrian models, this ratio was more often greater for the 'near leg forward position' (i.e. if struck while their near leg is forward, the pedestrian's head is more likely to strike the vehicle at a greater speed relative to the vehicle impact speed). This ratio also increased with the height of the pedestrian. Table 3 shows this ratio broken down according to the location of the head impact on the vehicle with the highest ratios being for impacts on the scuttle area.

Table 2 – Head impact speed / vehicle impact speed ratio by pedestrian size and gait

	6-year-old child (n=30)	5th % female: far leg f'ward (n=30)	5th % female: near leg f'ward (n=30)	50th % male: far leg f'ward (n=30)	50th % male: near leg f'ward (n=30)
Average	0.5	0.8	1.0	1.0	1.1
Range	0.1 – 0.9	0.1 – 1.3	0.5 – 1.7	0.4 – 1.5	0.4 – 1.4

Table 3 – Head impact speed / vehicle impact speed ratio by head impact location

	All impacts (n=150)	BLE (n=5)	Bonnet (n=72)	Scuttle (n=20)	W/screen (n=43)	Roof (n=10)
Average	0.9	0.4	0.9	1.1	0.9	0.7
Range	0.1 – 1.7	0.3 – 0.5	0.1 – 1.7	0.8 – 1.5	0.4 – 1.4	0.5 – 1.0

In some cases the head impact occurred at its peak velocity but in others, the head decelerated before hitting the vehicle. This was due to upper-body stiffness (most notably the shoulder) effectively slowing down the head before impact and varied greatly between different car shapes, different leg positions and different pedestrian models.

7. CONCLUSIONS & FUTURE WORK

The nature of evolutionary computation is such that a 'trial and error' approach is often required to find the ideal design of GA for a particular application. The solution for this optimization converged quite quickly suggesting that either the population size was too small, the original population's parameters did not cover enough of the design space (basing the original population on real cars may have been too limiting – most GA textbooks would endorse starting with random populations), or the design space itself was too constrained, or indeed a combination of all three. Another factor may have been the abortion both of 'clones' and of cars failing the constraints tests as opposed to slight mutation to make them unique or bring them into acceptable limits respectively. A significant increase in the number of simulations required would also necessitate better automation of the whole process to enable it to be carried out within a reasonable time frame. It is the intention of this paper to demonstrate the potential application of Genetic Algorithms for the optimization of vehicle design for the mitigation of pedestrian head injury and indeed for the broader field of automotive safety design, including the optimization of energy absorbent structures as their effectiveness can also be influenced by a large number of interacting parameters. The study also demonstrates the complex nature of pedestrian kinematics and reinforces the need for attention to be paid to the geometry of a car front when deciding test conditions for pedestrian sub-system impact tests.

8. ACKNOWLEDGEMENTS

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