DETERMINING ACCURATE CONTACT DEFINITIONS IN MULTI-BODY SIMULATIONS FOR DOE-TYPE RECONSTRUCTION OF HEAD IMPACTS IN PEDESTRIAN ACCIDENTS

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ABSTRACT

Crash reconstruction is sometimes used to study injury mechanisms and thresholds, but is often difficult because crash and model parameters are not known precisely. If simulation is used as part of the reconstruction process, then various Design-of-Experiment (DOE) tools may be easily applied to estimate response surfaces of the dependent variable (e.g. head acceleration), to a range of possible crash factors, subject to the validity of the model. This approach relies on the validity of the model's characteristics over the range of likely crash conditions, meaning that non-linear aspects of the system will often need to be included. The contact between the head of a pedestrian and the hood of a car is an example of a non-linear contact that is critical to the estimation of the variable of interest: the head impact severity (as measured by linear and angular acceleration or HIC, for example). This paper describes the reconstruction of four pedestrian collisions in which the effects of uncertainties in posture and impact speed on the estimation of a head impact severity were quantified. For each case, physical tests were conducted at lower, middle and upper estimates of head impact speed on a vehicle of the same make and model as the striking vehicle in the collision. The results of these tests were used to define a single non-linear contact characteristic in MADYMO that could reproduce the results of all three impact tests. This contact characteristic was then used in the simulation of the collision to estimate a likely range for the head impact severity.

INTRODUCTION

The reconstruction of crashes is one method that has been used to investigate the tolerance of the body to impact and the biomechanics of injury. Anderson et al. (2003) used the reconstruction of pedestrian crashes in the laboratory to test whether headform impact tests could discriminate the injury potential of vehicle structures in pedestrian crashes. We have also previously presented attempts to examine the ability of a finite element model of the head to predict axonal injury in fatal pedestrian collisions (Dokko et al., 2003). There are also other examples in the crash injury literature.

A shortcoming of using reconstructions to study the biomechanics of head injury is that many input parameters used in the reconstruction process are estimates. Uncertainties arising from the investigation process (for example the impact speed of the vehicle) may lead to point estimates of head impact conditions that may be significantly in error. Ideally, any uncertainty should be taken into account.

If computer simulation is used to reconstruct the crash, it is relatively straightforward to create many simulations that encompass, for example, a range of impact speeds. There are tools available that can be used in conjunction with computer simulations to perform simulations according to design-of-experiment principles. The large number of simulations required using such a design mean that it is advantageous to retain as much numerical simplicity as possible: for example, multi-body simulations are more efficient than finite-element methods. However, maintaining the validity of a multi-body model over a range of different conditions is not guaranteed if a simple (linear) multi-body contact model is used, when in reality, contact interactions are non-linear. Ideally, the head-to-vehicle interaction (and other interactions as well) should be valid over the range of likely crash conditions, so that estimates of head impact severity can be made more accurately.

One obvious solution would be to replace critical parts of the multi-body model with finite element structures. However, this may take too long to do. The size of the computation may also limit the number of scenarios that can be simulated, and when several crashes are being analysed these limitations are multiplied.

This paper describes the use of multi-body techniques to reconstruct several fatal pedestrian crashes. In each case, uncertainties about the crash were incorporated by performing variants of the simulation according to what was known about the collision. Subsequently, a contact characteristic between the head and the vehicle has been devised to be valid over the range of head impact speeds predicted by the modelling, and this allowed estimates to be made of the range of the head impact severity to be made, rather than a point estimate of the severity.

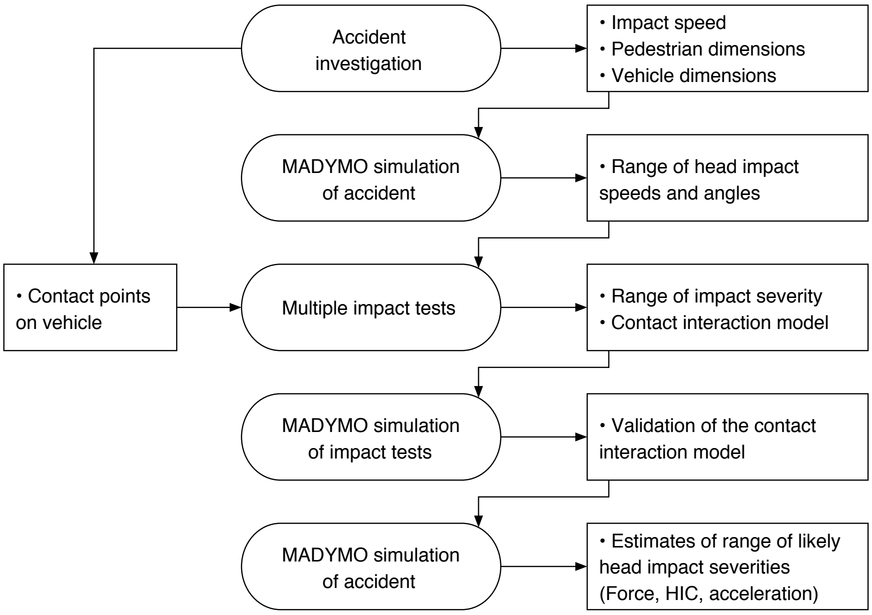

Figure 1. Methodology used in this study

METHOD

The methodology used for this study is illustrated in Figure 1. As explained in the introduction, the methods used in this study attempt to minimise the effects of uncertainties in the reconstruction process by estimating a range of the head impact condition that is likely to encompass that experienced in the actual collision. This means that many collision scenarios have been simulated, covering a range of plausible vehicle speeds and pedestrian postures. For each case, three speeds and six pedestrian postures are considered in 18 simulations. Note that the procedure would be equally applicable where there are other uncertainties in the reconstruction of a crash.

The simulations are analysed to choose three combinations of impact speed and angle (upper, middle and lower) that represent the range of the head impact velocity that was experienced in the accident (as predicted by the modelling). These three impact speeds and angles are used to do sub-system impact tests, on the same make and model of vehicle that was involved in the crash. These tests provide upper, middle and lower estimates of the head impact severity and, enable us to characterise the contact between the head and the car: the tests are used to generate a contact interaction model that can adequately describe the interaction of the headform and the vehicle over the range of test velocities.

The resulting contact interaction model is validated by reproducing the headform acceleration in a MADYMO model of each sub-system test. If the contact interaction model can reproduce the head impact acceleration over the range of impact speeds in the tests, by extension it can be considered suitable to describe the contact between the head and vehicle in the simulations of the pedestrian-vehicle collision. We then estimate a range of values for the head impact severity: the range should encompass that experienced in the crash. The impact severity is reported using HIC values, and linear and angular acceleration. Furthermore, the definition of this characteristic will make improvements in the estimate of head acceleration possible, should we improve the models.

Cases

The Centre for Automotive Safety Research has investigated over 200 fatal pedestrian crashes. Investigations include site surveys, vehicle examinations and photography, determining impact and travel speeds, and attending the autopsy of the victim. At the autopsy, injuries are noted with the aid of the forensic pathologist, and photographs and body dimensions are taken.

In South Australia, the Coroner investigates the cause of death of every road mortality, and as part of his investigation, he requires the examination of the brain by a neuropathologist. This examination has usually taken place at the Institute of Medical and Veterinary Science, located in Adelaide. The combination of this routinely collected neuropathological data, and the accident investigation, provides a rare source of data on human brain injury and the circumstances of its causation.

This study set out to find cases in which the brain injuries were suitable for further analysis by the finite element method. Some results from the FE analysis have been presented previously (Dokko et al., 2003).

The cases reconstructed for this study are summarised in Table 1.

Computer simulation

The model that was used for the simulation part of this study was developed specifically to simulate pedestrians in car-pedestrian collisions. The model has been presented previously (Garrett, 1996; Garrett, 1998) and used for accident simulation purposes (Anderson et al., 2002; Anderson et al., 2003). The model consists of 17 rigid segments linked by kinematic joints that are

Table 1.
Details of cases used for the reconstruction

Case	Pedestrian	Vehicle	Throw distance	Impact speed	Head contact structure	Head and C0 injuries (may not be the fatal injury)
H021-86	87 y.o. male, 66 kg, 186 cm	1976 Large 4-door sedan	22-25 m	50 - 64 km/h	bonnet	Fracture of right temporal base of skull and patchy subarachnoid haemorrhage
H032-86	81 y.o. male, 75 kg, 175 cm	1974 Small 4-door sedan	22-25 m	50 - 64 km/h	base of windscreen and dash	Subarachnoid haemorrhage
H029-89	87 y.o. male, 44 kg, 158 cm	1976 Mid-size 4 door sedan	28-33 m	57 - 74 km/h	bonnet	Fracture/dislocation of the atlanto-occipital joint with spinal cord laceration and lacerations to the head
H070-85	14 y.o. female, 64 kg, 163 cm	1970 Small 4-door sedan	24 m	53 - 64 km/h	base of windscreen and dash	Fractured skull base, subdural haematoma, contusion to left frontal lobe, cerebral laceration cerebral oedema

largely based on the model proposed by Ishikawa et al. (1993) although some joints have been added while others have been modified (see Garrett, 1996).

Before the simulations could be made, the model was checked to see that it satisfied validation corridors that were constructed from post-mortem human subject (PMHS) tests, carried out in Hannover (Ishikawa et al., 1993). These corridors specify the trajectory of different body components as well as the time history of the head velocity. The biofidelity of the model was tested using two car profiles used in the PMHS experiments. ‘Car A’ was simulated with the pedestrian model at three speeds, while ‘Car B’ was simulated at two speeds. The initial stance of the model was chosen to match the general stance of the PMHS in the experiments.

The model’s behaviour is in generally in accordance with the corridors drawn from the PHMS tests. The results of the simulation of the collision between the PMHS and Car B are particularly close. The characteristics of the model in a collision with the profile of Car A still produce results that mostly fit the corridors of the tests, but the behaviour seems to diverge slightly from experimental results in some parts of the simulation. The profile of Car A has a higher leading edge than Car B. The results of pedestrian collision models appear to become more variable with higher leading edges (Anderson and McLean, 2001). However, we judged that these discrepancies were not important for the current study.

Implementation of the model in the simulation of the accidents

The cases that were modelled in this study involved pedestrians of varying ages and statures. The model was based on and validated against the behaviour of a fiftieth percentile adult male. Therefore, the model was scaled to the dimensions of each pedestrian in each case. The pedestrians’ weights and heights were used to generate anthropometric data (segment dimensions, masses and moments of inertia) using GEBOD (Baughman, 1983), a program which generates anthropometric segment data using regression equations derived from a database of human body measurements. The resulting dimensions were checked against the actual body dimensions of the pedestrians that were measured at autopsy. In cases where the dimensions could be cross referenced, the dimensions were adjusted as the opportunity arose and used to generate a revised GEBOD data-set.

The next step in the simulation process was to model the posture of the pedestrian prior to impact. Body postures representative of the human gait cycle were used to generate separate simulations. Six postures were used in all and represented evenly spaced positions in one gait cycle. Combined with the three speeds, these postures meant 18 simulations were carried out in each case. The gait positions are illustrated in Figure 2.

Vehicle modelling

Vehicles that corresponded to the make, model and series of those involved in the cases were obtained for the physical reconstruction process. We also measured the geometry of the cars for the simulation. A Geodimeter (usually used in surveying) was used to measure the main geometrical features of the car. A prism was held at various points and the Geodimeter was used to record the position of the prism in Cartesian coordinates. These were used as a basis of the geometry created in MADYMO. The geometry was imported into Easi-CrashMAD (a MADYMO pre-processor) in IGES format. The vehicle geometry was then approximated by defining planes, elliptical cylinders and ellipsoids. An example is shown in Figure 3. Where the vehicle in the case braked heavily, the front of the vehicle was lowered by 100 mm and then rotated by 3˚, to take account of the dip in cars produced by braking (Figure 4). Sections of the vehicle were assigned contact characteristics based on published values.

Because the speeds of the vehicle were only estimated as a range, three sets of simulations were made to cover the range of possible vehicle velocities. These were at the upper and lower limits of the estimate of impact speed, and the third at the median speed of the range.

RESULTS

Each simulation provided estimates of the head impact velocity and impact angle. The head impact speed and angle were averaged over each gait position at each vehicle impact speed to provide test conditions for the impact reconstruction. The results of this are shown for each case in Figure 5 to Figure 16.

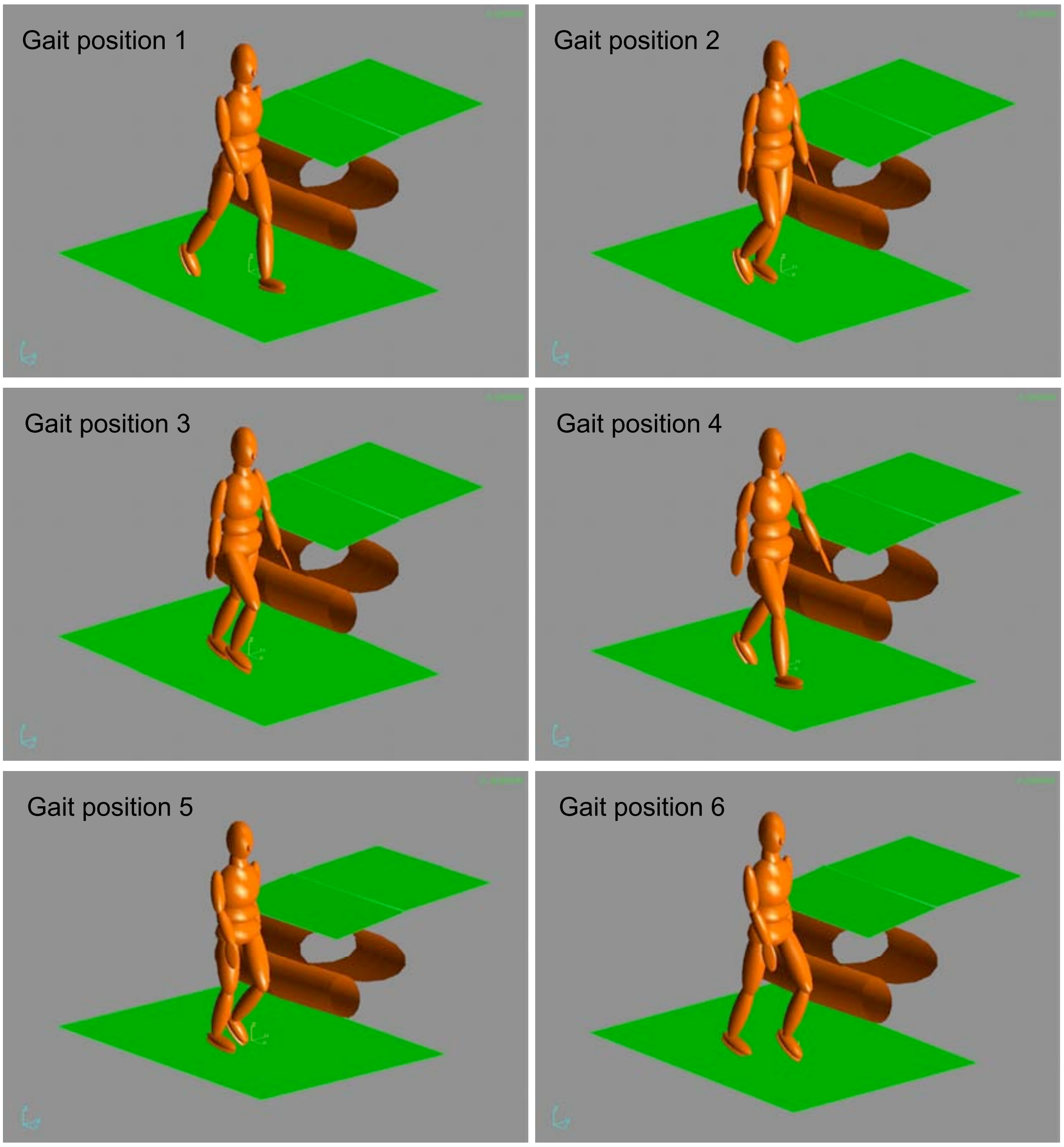

Figure 2. Gait positions used in the simulation.

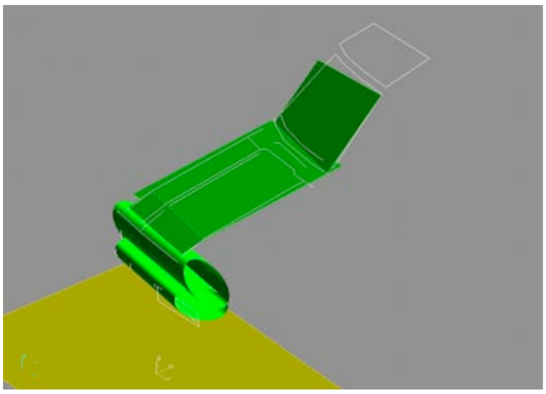

Figure 3. Geometry of one of the vehicles, and the entities used to approximate its shape in MADYMO.

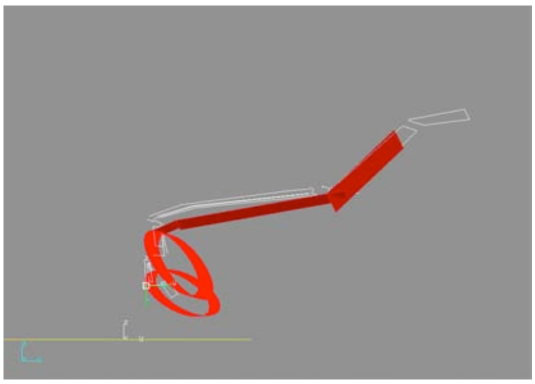

Figure 4. Dip introduced for vehicles that were braking.

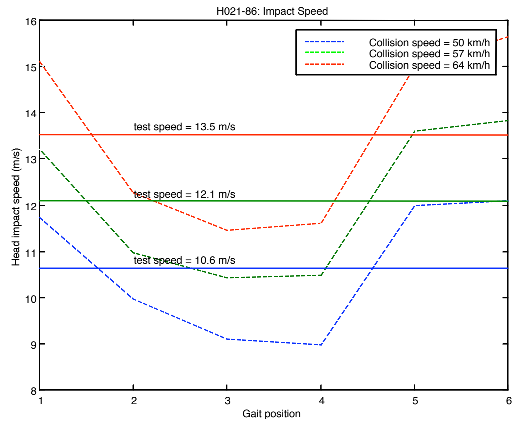

Figure 5. Head impact speed in the simulations of Case H021-86

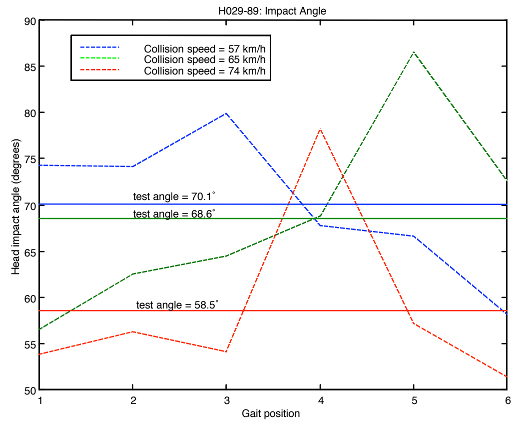

Figure 8. Head impact angle in the simulations of Case H029-89

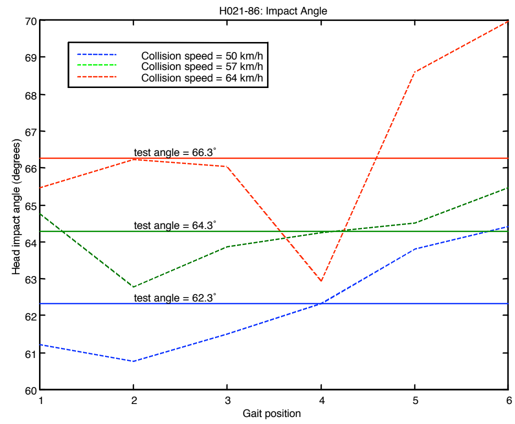

Figure 6. Head impact angle in the simulations of Case H021-86

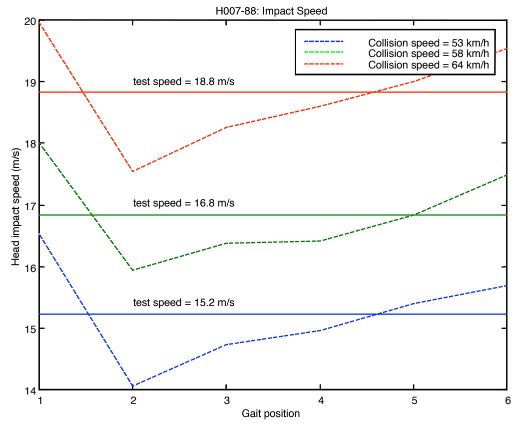

Figure 9. Head impact speed in the simulations of Case H0007-88

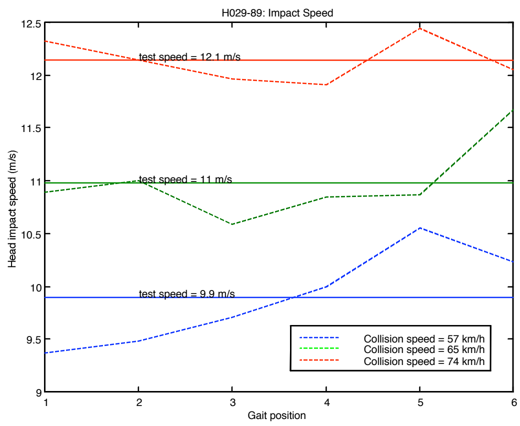

Figure 7. Head impact speed in the simulations of Case H029-89

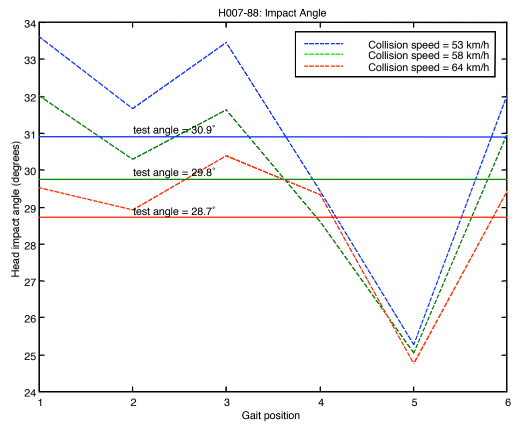

Figure 10. Head impact angle in the simulations of Case H007-88

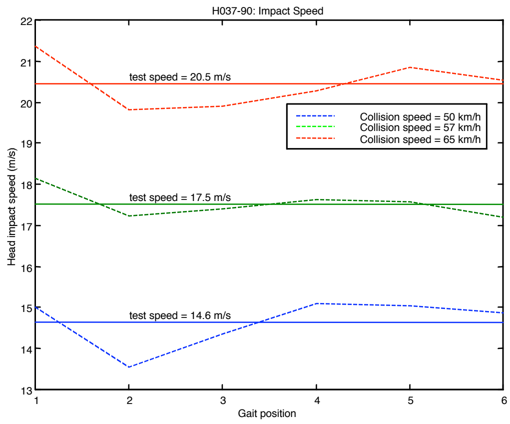

Figure 11. Head impact speed in the simulations of Case H037-90

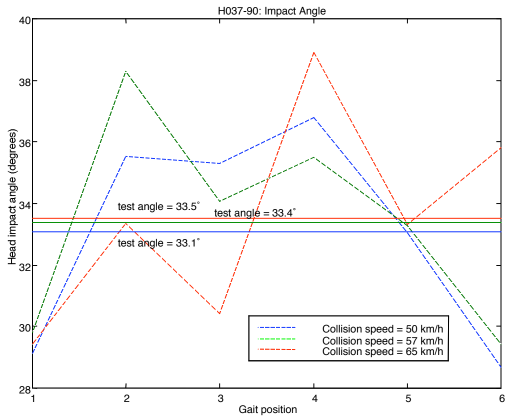

Figure 12. Head impact angle in the simulations of Case H037-90

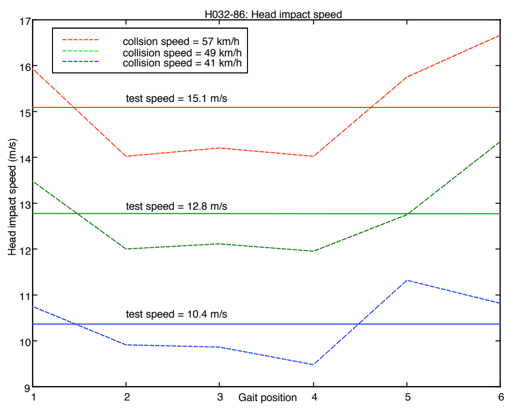

Figure 13. Head impact speeds in the simulations of Case H032-86

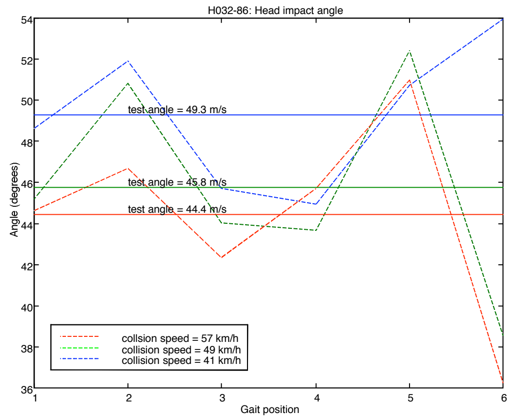

Figure 14. Head impact angles in the simulations of Case H032-86

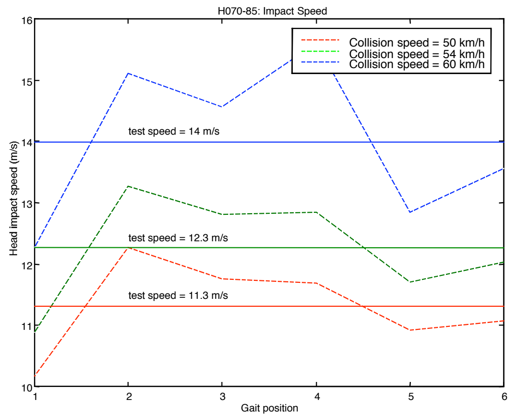

Figure 15. Head impact speeds in the simulations of Case H070-85

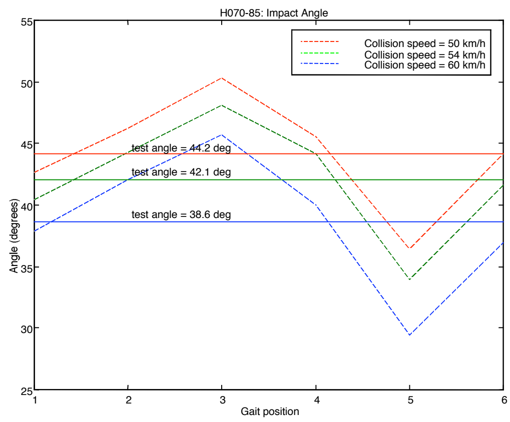

Figure 16. Head impact angles in the simulations of Case H070-85

HEADFORM IMPACT TESTS

The aim of the headform impact tests was to characterise the contact interaction between the head and the vehicle. The impact was reconstructed using a free flight headform, using the angle and speed estimated from the MADYMO simulations of the accident.

Methods

The impact tests were undertaken at the Pedestrian Impact Laboratory at the Centre for Automotive Safety Research. The laboratory includes a free-flight headform launcher that is capable of propelling a headform of 4.8 kg at speeds up to 70 km/h.

The headform used for this study was one conforming to the specifications of EEVC WG10. The head impact speed and angle were set according to the results of the simulations (discussed previously). Three tests were conducted for each case. Where necessary, a separate vehicle was obtained for each test. This was necessary where the structure of the car was altered by the impact.

The results of the impact tests were used to derive contact interaction models that were valid over the range of speeds used in the impact tests. This is discussed in the next section of the paper.

SIMULATION OF HEADFORM IMPACT TESTS

The aim of this part of the study was to determine a suitable contact characteristic that could be used to describe and reproduce the impact of the headform and the vehicle in MADYMO, over the range of velocities used in the testing. The derived contact characteristic should reproduce, in a simulation of the impact test, the acceleration history of the headform test at each test speed. Such a contact characteristic was then considered a valid approximation of the contact characteristic over the range of estimates that the modelling predicts for the head impact speed in the collision. Therefore, the contact characteristic enabled further simulation of the accident to provide justifiable estimates of HIC, and the linear and angular acceleration experienced by the head of the pedestrian.

The contact between headform and vehicle is non-linear. There are rate effects, as well as the presence of other non-linearities in the structure, which means that simple linear stiffness is rarely a satisfactory description of contact over any range of impact speeds. An approximation of the non-linearities arising from rate-effects (such as damping), can be made using a dynamic amplification factor. In MADYMO, dynamic amplification applies a scaling factor that depends on the rate of penetration, to a “base” stiffness. This factor may include stiffening or softening effects.

The use of dynamic amplification factors is not new, and has been used to estimate the dynamic response of structures from quasi-static tests (Prasad and Padgaonkar, 1981).

Determination of contact interaction parameters from test results

The procedure used to determine the contact interaction between headform and vehicle will be explained by way of an example. Figure 17 shows the acceleration time histories from three impact tests. These tests were conducted at upper, lower, and middle estimates of the head impact speed, as determined from the initial simulations of the pedestrian-car collision in Case H021-86. These results can be used to approximate the force-displacement characteristic of each impact by converting the acceleration to force (by multiplying by the mass of the headform) and by integrating the acceleration to derive the displacement of the headform throughout the impact. The three force-displacement characteristics that result from this process are shown in Figure 18.

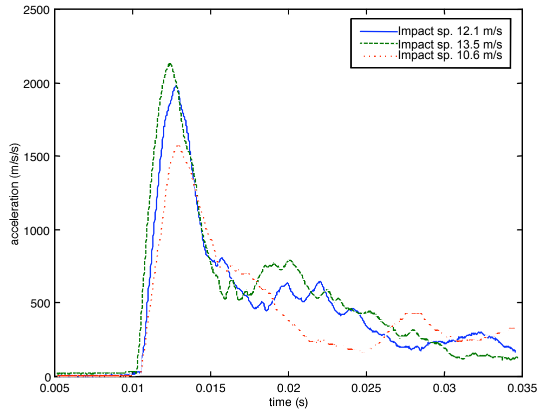

Figure 17. Head acceleration measurements made in the reconstruction of Case H021-86

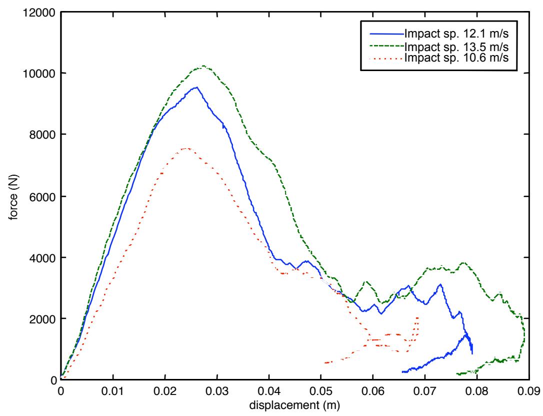

Figure 18. Dynamic force-displacement curves estimated from the impact tests for Case H021-86

What is notable here is that the three curves are essentially scaled versions of one another. (In other cases, the relationship between results and different speeds may be more complex.) In this example it would seem reasonable to try approximating the contact behaviour as a stiffness that is scaled linearly according to the impact velocity. For example, a dynamic amplification factor may be chosen that is of the following form:

$$c_1 + c_2|v|$$

where v is the rate of deformation and c_1 and c_2 are constants.

To get an idea of how well such a dynamic amplification factor could approximate the contact interaction, we can scale each of the force-displacement curves by the above factor, using the initial impact speed as a proxy for the rate of deformation. (In reality, the velocity of the headform will rapidly drop throughout the impact, but the assumption is that the velocity profiles of each test are roughly proportional to one another.) The result of this is shown in Figure 19. The similarity between the three resulting curves indicates that the contact interaction model that includes the dynamic amplification factor should be a reasonable description of the contact interaction over the speed range of the testing. To use the model in MADYMO, we defined a "base" stiffness. This base stiffness will be amplified according to the velocity of the headform. The base stiffness for the example is shown in Figure 20, for $c_1 = 1$ and $c_2 = 0.25$. The unloading is approximated by a null curve, and the hysteresis slope is set to 800000 N/m.

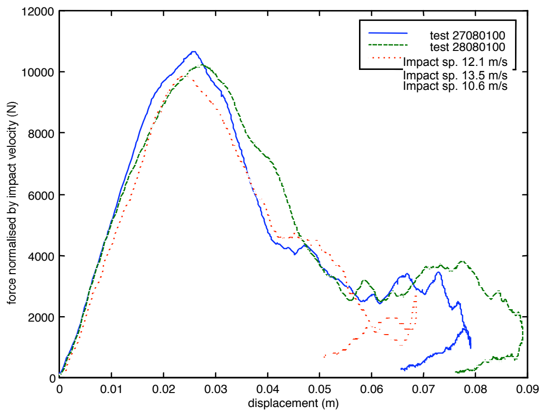

Figure 19. Force-deflection curves from impact tests associated with Case H021-86, normalised by the impact velocity

The next step is to model the three impact tests in MADYMO, to see how well the contact interaction model can reproduce the results of the impact tests. The model set-up is shown in Figure 21. The headform model is taken from the MADYMO dummy database. The bonnet of the car is modelled as a single plane, and the contact interaction with the headform is modelled with the base stiffness and the dynamic amplification model ABSEXP, with $c_1 = 1$ and $c_2 = 0.25$.

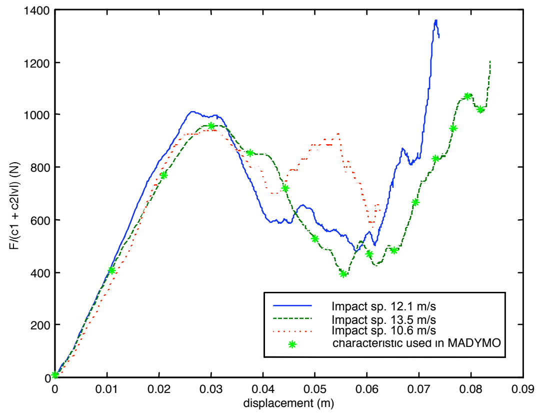

Figure 20. The force-displacement curves of each test, divided by the proposed dynamic amplification factor, and the discrete curve used in the MADYMO simulation of the impact tests.

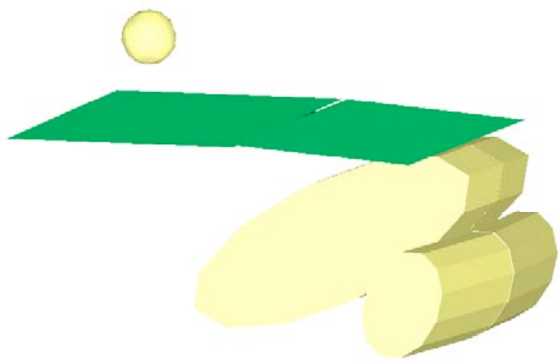

Figure 21. Illustration of the simulation of the headform test

The results of the simulations, and the results of the actual impact tests are shown in Figure 22 through Figure 24.

These figures show that the headform acceleration predicted by the simulation is very close to that measured experimentally. The important feature of this result is that the model can predict the acceleration of the headform over the range of velocities used in the testing. Therefore, collision scenarios with different velocities can be modelled, and over the range of resulting head impact velocities, better estimates of head impact severity can be made than had a simple linear contact characteristic been used. The accuracy of the acceleration measurement is now dependent on modelling parameters other than the contact characteristic, such as the behaviour of the neck and the geometrical and inertial properties of the head. Changes can be made to the model to improve biofidelity, and the definition of the contact interaction should remain valid (as long as the head velocity is not grossly affected by modelling changes).

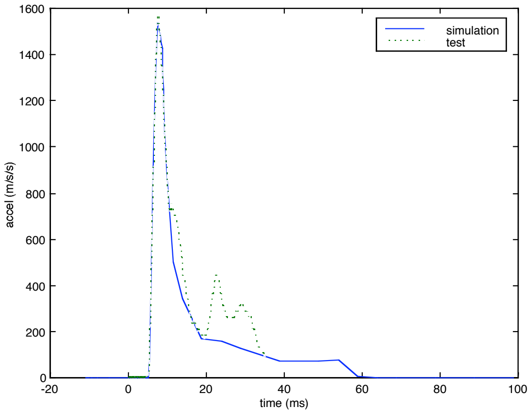

Figure 22. Headform acceleration estimated from the simulation, and the acceleration recorded in the impact test (Case H021-86, impact velocity = 10.6 m/s)

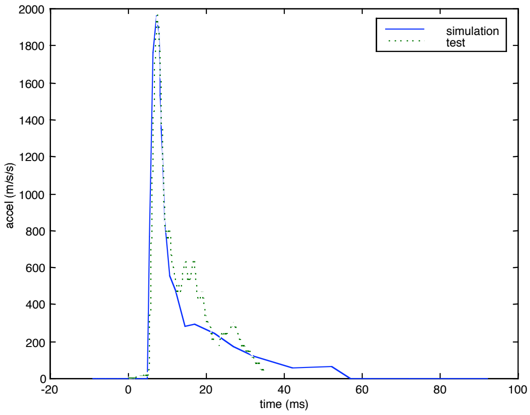

Figure 23. Headform acceleration estimated from the simulation, and the acceleration recorded in the impact test (Case H021-86, impact velocity = 12.2 m/s)

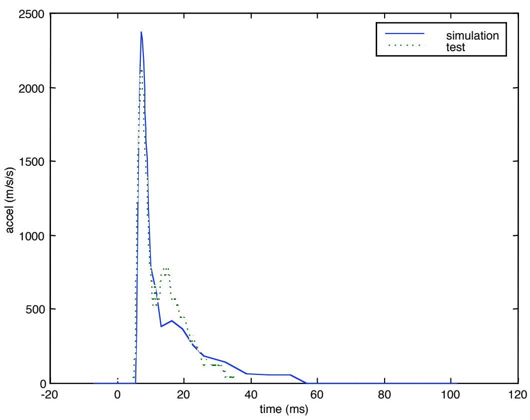

Figure 24. Headform acceleration estimated from the simulation, and the acceleration recorded in the impact test (Case H021-86, impact velocity = 13.7 m/s)

Results of headform impact simulations

The contact interactions resulting from testing of selected cases were analysed, and the resulting dynamic amplification models are summarised in Table 2. Note that the base stiffness functions are not presented here.

Table 2.
Dynamic amplification used to model the interaction in each case

Case	Dynamic amplification factor	Constants
H021-86	$c_1 + c_2\lvert v\rvert + c_3v^2 + c_4\lvert v\rvert^3 + c_5v^4$	$c_1 = 1.0$
		$c_2 = 0.25$
		$c_3 = 0$
		$c_4 = 0$
		$c_5 = 0$
H029-89	$c_1 + c_2\lvert v\rvert + c_3v^2 + c_4\lvert v\rvert^3 + c_5v^4$	$c_1 = 1.0$
		$c_2 = 0.25$
		$c_3 = 0$
		$c_4 = 0$
		$c_5 = 0$
H032-86	Windscreen: none	$c_1 = 1.0$
	Dash: $c_1 + c_2\lvert v\rvert + c_3v^2 + c_4\lvert v\rvert^3 + c_5v^4$	$c_2 = 1.0$
		$c_3 = 0$
		$c_4 = 0$
		$c_5 = 0$
H070-85	Windscreen: none	$c_1 = 0$
	Dash: $c_1 + c_2(v/c_3)^{c_4}$	$c_2 = 1$
		$c_3 = 3$
		$c_4 = 0.41$

A comparison between the headform acceleration predicted by each model, and its associated experimental result are shown in Figure 22 to Figure 33.

The magnitude and shape of the acceleration curves are similar in each case showing that the selection of a dynamic amplification model can adequately describe the contact of the headform and bonnet over the velocity range of the impact tests. The second part of the impact in the simulation of the headform tests for Case H070-85 shows that some refinement of the dynamic amplification model may be required. However, the principle of using such a model is demonstrated by the satisfactory simulation of the 12 impact tests performed for this study.

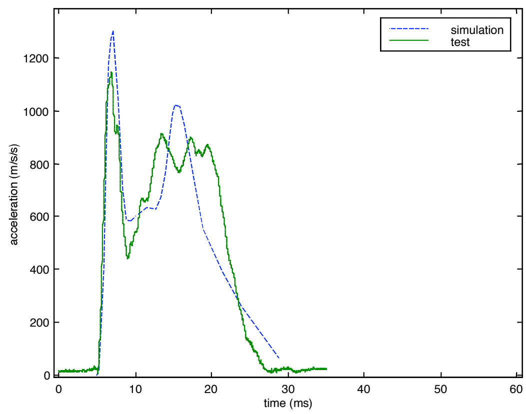

Figure 25. Headform acceleration estimated from the simulation, and the acceleration recorded in the impact test (Case H029-89, impact velocity = 11.14 m/s)

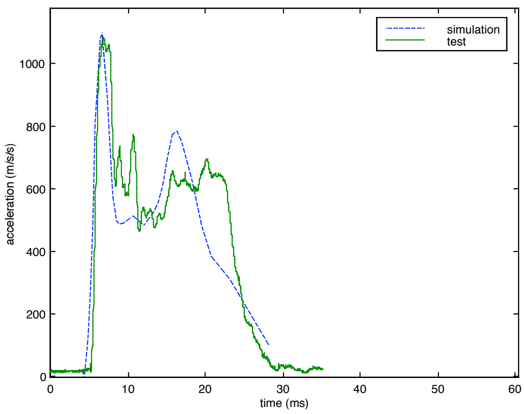

Figure 26. Headform acceleration estimated from the simulation, and the acceleration recorded in the impact test (Case H029-89, impact velocity = 9.97 m/s)

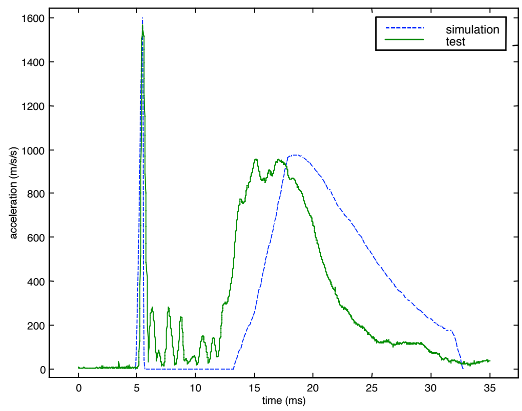

Figure 29. Headform acceleration estimated from the simulation, and the acceleration recorded in the impact test (Case H032-86 impact velocity = 11.71 m/s)

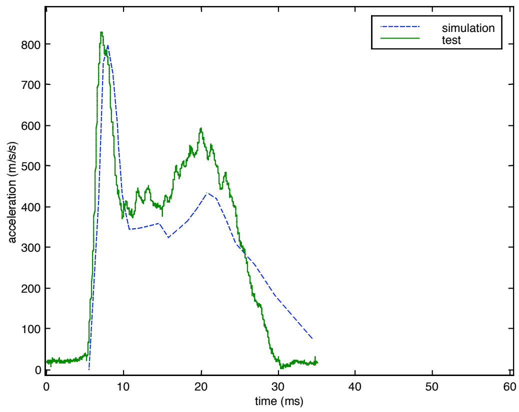

Figure 27. Headform acceleration estimated from the simulation, and the acceleration recorded in the impact test (Case H029-89, impact velocity = 8.08 m/s)

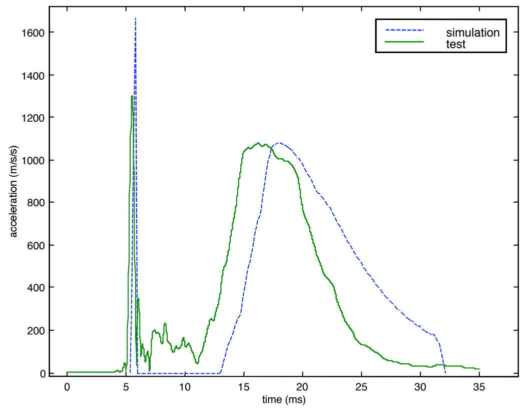

Figure 30. Headform acceleration estimated from the simulation, and the acceleration recorded in the impact test (Case H032-86, impact velocity = 12.46 m/s)

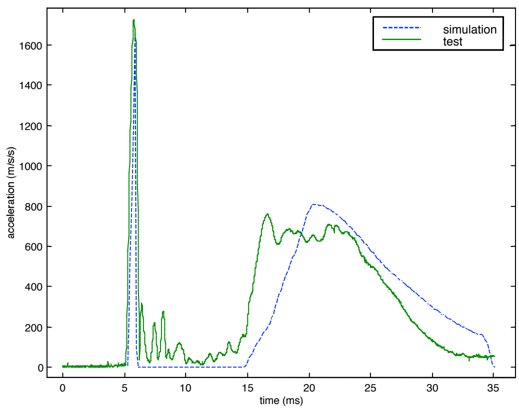

Figure 28. Headform acceleration estimated from the simulation, and the acceleration recorded in the impact test (Case H032-86, impact velocity = 10.24 m/s)

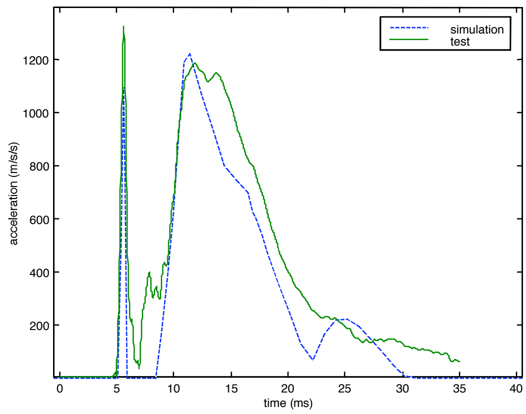

Figure 31. Headform acceleration estimated from the simulation, and the acceleration recorded in the impact test (Case H070-85, impact velocity = 11.1 m/s)

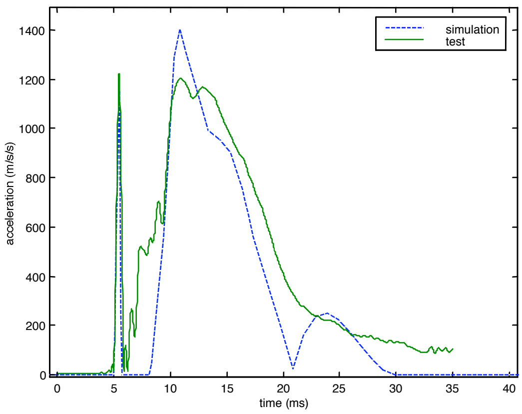

Figure 32. Headform acceleration estimated from the simulation, and the acceleration recorded in the impact test (Case H070-85, impact velocity = 12.56 m/s)

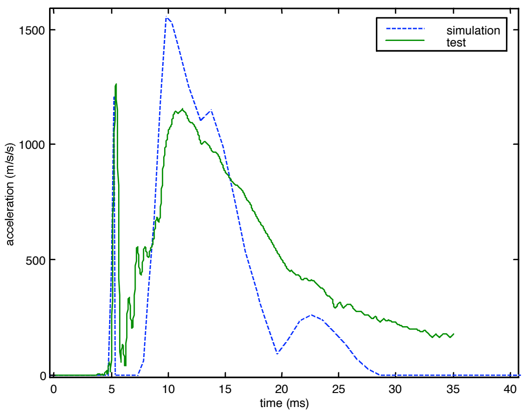

Figure 33. Headform acceleration estimated from the simulation, and the acceleration recorded in the impact test (Case H070-85, impact velocity = 14.37 m/s)

HEAD IMPACT SEVERITY ESTIMATES FROM REVISED MADYMO MODELS

The previous section of this paper described the derivation of contact characteristics for each case. The contact characteristics appear to be valid over the range of head impact speeds used in the associated impact tests. By extension, we will assume that the contact characteristics are also a valid representation of the stiffness of the head impact over the range of likely head impact velocities in the crashes themselves. The simulations of the crashes can be used to estimate head impact severity by applying the derived contact characteristic to the head-vehicle contact in the MADYMO model of the crash.

Each variant of the case simulation was rerun with the new contact characteristic. The peak linear acceleration, the angular acceleration and the HIC value were estimated in each simulation. The results of these simulations are given in Table 3. The head injuries noted in each case are also given in this table.

Further analysis of the solution space is possible: Figure 34 shows a contour plot of peak linear acceleration values, estimated for Case H021-86. This plot shows the variation in head impact severity over the solution space defined by the range of the dependent variables Gait Position and Vehicle Speed. Gait positions around position 3 (also refer to Figure 2) produce the lowest head impact severity, whereas higher severity estimates are found about gait position 6. As might be expected, higher impact speeds lead to higher estimates of impact severity. Table 3 and Figure 34 show that the variation in the estimate of head impact severity may be considerable.

DISCUSSION

In previous reconstruction studies using our MADYMO pedestrian model, we have limited the use of the model to estimating the impact velocity of the head. We have preferred to estimate impact severity by a physical test using a free flight headform on a vehicle of the same make and model as the vehicle involved in the accident. This is because the use of arbitrary values for - or point-estimates of - the impact stiffness will lead to unreliable estimates of head impact severity. For our purposes, the use of complex and valid finite element models (which might overcome some of the objections to using simulation for estimating head impact severity) is not practicable.

Table 3.
Mean values and standard deviations for head impact severity estimated from the 18 variants of the MADYMO model of each crash, using the experimentally derived stiffness values

Case	Mean estimated HIC (std dev. in parenthesis)	Mean estimated peak acceleration (g) (std dev. in parenthesis)	Mean estimated peak angular acceleration (krad/s^2) (std dev. in parenthesis)	Head and C0 injuries (may not be the fatal injury)
H021-86	1141 (793)	213 (80)	40.8 (8.9)	Fracture of right temporal base of skull and patchy subarachnoid haemorrhage
H032-86	612 (344)	108 (41)	22.9 (6.5)	Subarachnoid haemorrhage
H029-89	1175 (486)	176 (45)	27.2 (9.2)	Fracture/dislocation of the atlanto-occipital joint with spinal cord laceration and lacerations to the head
H070-85	1121 (840)	205 (46)	27.0 (6.0)	Fractured skull base, subdural haematoma, contusion to left frontal lobe, cerebral laceration.

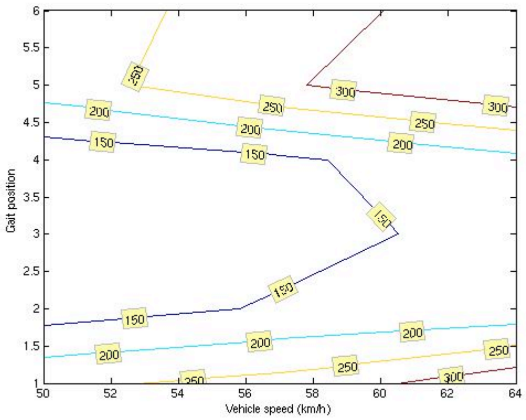

Figure 34. Contour plot of peak acceleration (g) by gait position and impact speed, Case H021-86.

We have developed a multi-body modelling technique that can use a range of estimates for input parameters that are not known precisely, without compromising the validity of the head-vehicle contact interaction model. If the contact interaction model is valid over the range of one or several simulation parameters (such as impact speed of the vehicle or pedestrian posture), then the model may be used to explore the solution space that is bounded by the limits of the simulation parameters over their range.

The mean estimated HIC values and acceleration values reflect not only the choice of the range of each parameter, but also all model parameters. Therefore, the estimates of head injury severity would be likely to change if other aspects of the model were altered.

Figure 34 is an example of the distribution of estimates that this kind of analysis can produce. By checking the kinematics of the simulation and comparing these to the physical evidence left after the collision, the range of each of the dependent variables may be reduced further by, for example, ruling out certain postures as being unlikely in the collision. This may reduce the variance in the estimates of the head impact severity.

CONCLUSIONS

This paper has demonstrated that multi-body techniques can be successfully used to reconstruct and simulate crashes where certain dependent variables are not known precisely. Design-of-experiment type analyses may be applied readily and efficiently to multi-body techniques, and non-linearities in contact interactions may be empirically derived using a combination of simulation and impact testing.

This technique was applied in the reconstruction of four car-to-pedestrian collisions. The results showed that the use of a dynamic amplification model within model could adequately describe the non-linearity in the head impact. The range in the estimate of the head impact severity provides both bounds on the impact dynamics in the actual crash, and demonstrates the sensitivity of the estimate to chosen initial conditions.

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