

CRANFIELD UNIVERSITY

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**INVESTIGATION OF TWO-WHEELED ROAD TRAFFIC ACCIDENTS
USING EXPLICIT FE TECHNIQUES.**

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**Investigation of Two-Wheeled Road Traffic Accidents using Explicit FE
Techniques.**

**Supervisor: J.C. Brown
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of Doctor of Philosophy.**

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Abstract

With the increase of road traffic accidents increasing due to motorised traffic in the developing world growing alongside the more traditional bicycles and light motorcycles there is good reason to re-examine the two-wheeler case. In addition, if you include the large congestion charge scheme now underway in London and similar projects being considered in other cities globally, there is an even stronger case. These schemes encourage commuters to get back onto two wheels but with a potential increase in road traffic accidents.

The development of Explicit Finite Element Analysis (FEA) over the last 15 years, and large improvements in solver times has made examination of complex impact events achievable. As an extension of this knowledge it is now beginning to be feasible to consider the complex case of injury to vulnerable road users (VRU's).

This thesis describes why two-wheeler accidents are increasingly relevant, and the details of which injuries are most common in each particular case. From physical testing, bicycle models for adult and child cases were created and the most relevant car to cyclist accident scenarios re-constructed. Existing humanoid models and vehicle models were adapted to understand biomechanical effects in the collision.

The results show that although there is great variation due to this complex event in terms of biomechanical and frictional effects and therefore the resulting kinematics, as a mathematical method of investigating future

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protection devices it should be possible to gain a greater understanding of their effects in the real world. To this end a final section detailing the development of active and passive technologies (including structural optimisation techniques) has been included.

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Abbreviations

ACEA	Association Constructeurs d'Europeen Automobiles
ACL	Anterior Cruciate Ligament
AIS	Abbreviated Injury Scale
ATD	Anthropomorphic Test Dummy
BMJ	British Medical Journal
CIC	Cranfield Impact Centre Ltd.
DTi	Dept for Trade and Industry (UK Government)
DfT	Dept for Transport (UK Government)
EEVC	European Experimental Vehicle Committee
ESV	Experimental Safety of Vehicles (conference)
ENCAP	European New Car Assessment Protocol
FMVSS	Federal Motor Vehicle Safety Standard
GSI	Gadd Severity Index
GCS	Glasgow Coma Scale
HIC	Head Impact Criterion
IHRA	International Harmonised Research Activity
IMechE	Institution of Mechanical Engineers
IRCOBI	International Research Conference of Biomechanical Impact
IRTAD	International Road Traffic Accident Database
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JARI	Japanese Automotive Research Institute
KBE	Knowledge Based Engineering
LCL	Lateral Collateral Ligament
MCL	Medial Collateral Ligament
NHTSA	National Highway Traffic Safety Administration
PCL	Posterior Cruciate Ligament
PT	Patellar Tendon
RTA	Road Traffic Accident
SDI	Stochastic Design Improvement
TfL	Transport for London (part of the Mayor of London's office).
TRL	Transport Research Laboratory (UK)
TWMV	Two Wheeled Motor Vehicle
UN	United Nations

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1 Introduction

1.1 Background

The cost to society of traffic accidents is significant. Within Europe alone 43,000 deaths and 3.5million injuries are attributable to road traffic accidents annually. In global terms the total figure is hard to calculate reliably, however, one estimate suggests that road traffic incidents now kills approximately 1 million people and injures 30 million (Trinca et al., 1988). With motorised vehicles now mixing with the traditional forms of transportation in developing countries, it is estimated that motor-traffic related accidents will move from 9th in the global table of disease to 3rd within the next 20 years (Murray et al., 2006). The World Bank estimates that 70% of these casualties occur in developing countries, and according to data from TRL (Jacobs et al., 2000), the trends of fatalities are improving in highly motorised countries, whereas those in the developing world are worsening (particularly Asia). It is suggested that at least 6 million more will die and 60 million will be injured in the next ten years, unless urgent action is taken. The majority of victims are pedestrians, and two-wheeled riders. Clearly this sets difficult challenges for all those involved in vehicle safety and associated disciplines. Figure 1 shows the trend in global fatalities and the difference between the developed world and the developing world.

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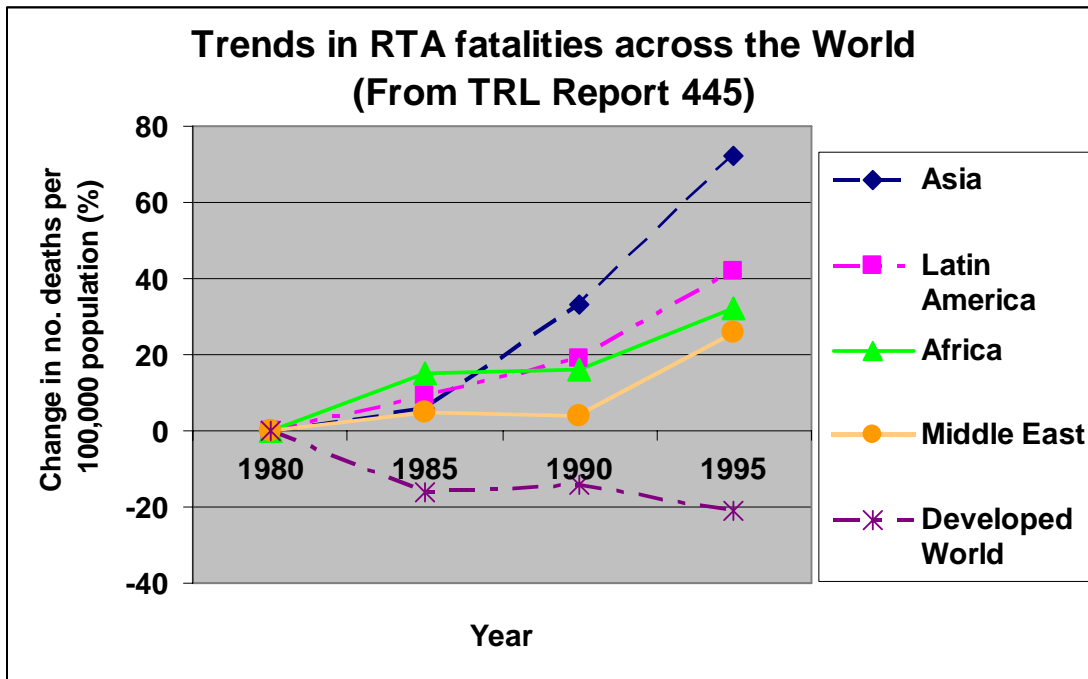


Figure 1 - Trends in RTA (Road Traffic Fatalities) across the Globe

With the advance of computer simulation and computer-aided engineering (CAE) the ability to model accurately both the vehicle's, and the occupants' crash response has developed greatly in the last 15 years. The use of dummies, or anthropomorphic test devices, (ATD's) for occupant crash correlation purposes has made this task easier to achieve, by having a specific 'performance envelope' to aim for. Obviously it is impossible to predict the response of every different human being; however, these devices when used in their most complex form give an acceptable parametric response to an agreed international standard for a specific test (e.g. side impact).

In the case of pedestrian and other "vulnerable road user" (VRU) tests, a variety of different dummies have been used, with differing results. Many have

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used HYBRID II or III dummies (normally used as an occupant device for frontal impact) as a basis and then heavily modified the pelvis, and legs in order to try and get a more representative kinematic response. A new-generation dummy used in pedestrian applications has been developed by Honda and GESAC (Akiyama et al., 2001). Called 'POLAR' it has a detailed knee structure and an on-board data acquisition system (allowing the dummy to be used in a test and the result not be affected by cables attached to transducers). As for motorcyclists, some work in the UK at TRL has used the OPAT dummy. However in order to achieve a much better biofidelic correlation, compared to existing occupant devices, the IMMA (International Motorcycle Manufacturers Association) funded a research programme (Newman et al., 1991) that has produced the Motorcyclist Anthropomorphic Test Dummy (MATD). This is based on a HYBRID III dummy, but has some important adaptations including handlebar-grasping hands, a curved lumbar spine section (in order to get a realistic rider position) and an on-board data acquisition system (similar to the POLAR dummy).

Work has been undertaken by TNO to look specifically at cyclist injuries using HYBRID II 50%-ile dummies, which showed that when compared to tests on cadavers, the dummies showed significantly less flexibility in the lateral plane (Janssen and Wismans, 1987).

Underlying the use of all present dummies for modelling VRU's is their inability to give an accurately repeatable result in a given vehicle impact test regime. For this reason the decision was made to move to a series of independent impactors for pedestrian safety. In the WG10 and WG17 reports produced by EEVC, full details are given of these impactors and the parameters that

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vehicles should achieve to mitigate injury at head and leg speeds of 40 kph. Cyclists were also included as a target group of vulnerable road users, in this new set of standards aimed at improving pedestrian safety, but only now with improved computer simulation is it possible to revisit the two-wheeler case in more detail, and analyse what is a very complex collision process.

To this end various detailed explicit Finite element models have been produced mainly for occupant injury (e.g. Toyota THUMS model) to re-examine biomechanical injury in more detail. This is a very difficult objective to achieve, as tissue injury mechanisms are not totally understood, however as further studies improve the overall knowledge base, these models can be updated and sub-models can be used to investigate specific issues in more detail (such as brain injury mechanisms). To this end Howard et al developed a humanoid model with Cranfield Impact Centre under a Ford contract to specifically examine pedestrian injuries. This model was a combination of the most representative ATD models (e.g. HYBRID III and EuroSID) and in turn each part was updated into to a more biofidelic representation, using correlation from cadaver testing. This model was successfully used to assess new designs and improvements to a vehicle in order to reduce injury for pedestrians.

With successful results is then possible to ascertain more accurately whether any new active or passive injury-mitigating technologies (either for rider or on the vehicle) will be appropriate, and what risk they may carry for the remainder of the time.

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This thesis will show how this model can be applied to two-wheeler accident scenarios and what options may be available to improve the topic in future iterations.

1.2 Problem Statement

Research into reducing vulnerable road user fatalities and injuries is almost as old as the motorcar, however in the 1970's more co-ordinated attempts to improve vehicle safety for pedestrians, cyclists and motorcyclists started in Europe. In 1984 the EEVC (European Experimental Vehicles Committee) had separate work streams investigating the detailed effects of RTA's on two-wheelers and pedestrians. All work undertaken in this field was merged into one single protocol that used a series of impactors (lower leg, upper leg and head impactors). This was aimed at covering mainly pedestrians but was meant to include cyclists as well. This initial work leading to the EEVC Working Group 17 legform has now been further adapted and is now embodied into the EU legislation for new vehicles (from Oct 2005).

Going back to the work in 1984 that led to cyclists being integrated into the pedestrian protocol, it can be seen from EEVC papers (ESV conferences from 1982 onwards) that although the methods used were state of the art, the research was empirical and based on rudimentary computer simulations and physical tests using ATD's that represented injury in a limited parametric manner.

In addition, until recently (Osendorfer and Rauscher, 2001) little work has been successfully carried out on reducing injuries for motorcyclists by the

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manufacturers, in spite of this form of transport having proportionately the highest level of deaths and injury per passenger mile compared to other forms of transport (UK Fatals database).

The challenges in terms of examining these forms of transport is to try and establish the most frequent types of incident, and understand if current pedestrian methods and tests are representative for two-wheelers, or establish other parameters that need to be considered. What differences are there in the most common RTA's between cyclists and vehicles and motorised two-wheelers and vehicles?

Additionally, from previous studies and papers it would be beneficial to understand the most common injuries for cyclists and motorcycle riders involved in RTA's and understand the differences compared to pedestrians, and examine why they are different.

Replicating a representative RTA means that there must be an accurate model for the humanoid, vehicle and two-wheeler, otherwise the kinematics of the incident will not be valid.

The challenge of having a representative device or humanoid FE model is that it is very difficult to replicate accurate tissue damage. Attempts to produce a pedestrian dummy (e.g. POLAR II) have gone some way to improve the ATD method for pedestrians; however it has many limitations (e.g. shoulder construction and performance which can affect the whiplash and head contact conditions). FE model development has improved dramatically due to

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increased IT solver capabilities, allowing more detailed models running in increasingly smaller timescales.

The challenge is to take a current correlated FE pedestrian model and adapt it for the two-wheeler case, without compromising the correlation previously achieved on injury parameterisation. As will be seen in later sections this work builds on the research conducted at Cranfield Impact Centre Ltd under a Ford contract for FFA Aachen and Jaguar Cars Ltd., and the PhD study of Mark Howard investigating pedestrian accident scenarios and associated safety technologies (Howard, 2002)

Additionally if an FE method is being used, it is equally important that both the vehicle model and the two-wheeler model are properly correlated to a series of tests to ensure that the deformation is consistent with the energies applied during a typical incident.

Finally, once these issues have been successfully overcome, it would be logical to examine how vehicles can be made less injurious, and understand what technologies and methods can be applied and how.

1.3 PhD General Aims

The PhD aims are as follows:

- Understand the real-world numbers and trends in accident data for two-wheeled accidents compared to other Road Traffic Accidents (RTA) incidents.
- Find detailed conditions and orientations for cyclist-to-car and Two-Wheeled Motor Vehicle-to-car accidents.
- Understand critical influences of bicycle and light motorcycle structures via impact testing, and create correlated LS-DYNA™ Finite Element models.
- Create accident simulation models for each of the most statistically relevant two-wheeler cases.
- Apply learning from clinical studies to improve the accuracy of the simulations to real-world cases.
- Discuss influences and effects of new passive and active safety systems on rider injury.
- Investigate new-generation non-linear optimisation techniques to allow improved methods of generation of injury reduction (component optimisation).

2 Literature Survey

2.1 Scope

The literature survey will start with some background examining the development of two-wheelers in terms of their history in society, their means of construction, and their growth as a means of transport across the world.

Following on from this, a study is shown of how road traffic injuries relate to two-wheelers on the road today and compares the most common vehicle to two-wheeler scenarios, injuries and how this compares to other road users, based on available data from various studies.

Other issues are included that are relevant to this topic in terms of epidemiology – what variation there is across the world / how congestion charging is affecting two-wheeler usage rates / developing world vs. developed world and so on.

The current pedestrian test methodologies are included, and how vehicles are currently assessed for injury, plus further detail is then shown on the steps taken after an actual RTA and some common injuries, typical for vulnerable road users. From relevant sources and previous studies, a table is drawn up to give injury thresholds for the two-wheeler cases.

2.2 Historical background

In the late 18th century, as the industrial revolution led to the rise of the middle classes (who in turn had more time and money able to be spent on leisure pursuits), early cycles appeared. Initially these were without pedals and were propelled using a walking action, whilst steering the front wheel. In 1818 a public demonstration was held in Paris by a German Baron Karl von Drais of his 'Draisine'. Other designs appeared at the same time using the same ideas from De Sivrac and Kessler. It wasn't long before these so-called 'Hobby-Horses' were adapted to include a set of pedals at the front wheel – nicknamed the 'Boneshaker' due to its rigid wood and iron wheels, and lack of suspension, as seen in Figure 2.

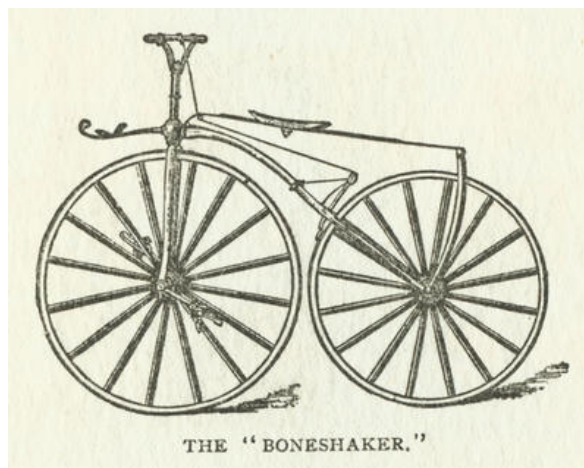


Figure 2 - A typical early bicycle (courtesy Mitchell Library – Glasgow)

Although there were other claims to the first true bicycle across Europe (including a Leonardo Da Vinci concept from the mid-15th century), a Scot -

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Kirkpatrick MacMillan from Keir in Dumfriesshire is recognised as being the first inventor of a machine that embodied most of the principles of today's bicycle. He was a blacksmith's son, and legend contends that a customer needed a repair to his hobby-horse. MacMillan set about the repair but also produced a copy. This copy was eventually modified with a crank at the rear wheel in 1839 – the first true bicycle. Unlike modern machines MacMillan's bicycle used a reciprocating action from the rider to rotate the rear wheel. Despite its heavy mass, Macmillan created a stir when in 1842 he rode his machine from Dumfries to Glasgow – a distance of 68 miles in 2 days. The only problem he encountered on this trip was being fined 5 shillings for knocking down a young girl whilst speeding through the Gorbals in the south of Glasgow.



Figure 3 - The Penny Farthing (Goodwood Collection).

In the 1850's Ernest Michaux and Pierre Lallement produced a boneshaker with an enlarged front wheel. By circa 1880, this format was commonplace and known in Victorian-era as the "Penny-Farthing" (Figure 3) due to the large and small wheel being in scale similar to the relative sizes of the coinage of the time. These were inherently dangerous (particularly when mounting and

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dismounting), so the "safety bicycle" was conceived in 1874 by Lawson. This had front and rear wheels of equal diameter with a chain driving the rear wheel (Figure 4).

In the early 1880's Starley, Lawson and Shergold introduced the chain drive. Following this, John Kemp Starley created the Rover Safety Bicycle in 1885, and the current form of bicycle was born. Starley perfected the pre-stressed spoked wheel, and shortly afterwards in 1888 another Scot - John Boyd Dunlop patented the pneumatic tyre. Welch and Bartlett (Burgoyne and Dilmaghanian, 1993) further improved the pneumatic tyre to allow use of the sidewalls in compression.

The evolution of the wheel – particularly the contributions made by Starley, and Dunlop could be said to have had the greatest significant changes to the bicycle in its early days, and possibly one of the most-overlooked major contributions to road transport.



Figure 4 - J.K. Starley riding his Rover "Safety Bicycle" (courtesy British Cycle Industry Association / Goodwood collection)

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Starley's bicycles went on to win every race in the 1908 Paris Olympics, and from these early days, the geometry of the standard bicycle in mass-production has changed little in 120 years of production, with the exception of different materials and joining techniques, the overall riding position and layout are basically the same as Lawson & Starley's early safety bicycles.

These meagre beginnings formed the genesis of the motorcycle industry, soon followed by the infant car industry. The Midlands, and Coventry in particular, was seen as the cradle of these new industries – at one time with 70% of the bicycle industry in the Midlands, closely followed in time by the motorcycle industry (with such names as Triumph, Bayliss, and Rudge-Whitworth). From the mid-1920's car and motorcycle production took over from cycle manufacture and companies like Rover, Singer, Riley and Triumph wound down their bicycle operations.

Today, only specialist manufacturers still assemble bicycles in the UK. Raleigh still has a design centre in the UK, but manufacture has now been sent overseas. With the advent of congestion charges and the emphasis on improving personal carbon footprints the bicycle is enjoying a small resurgence in urban areas and new ideas are being developed (such as low-power electric bike and new 'commutable' lightweight folding bikes).

New layouts such as so-called 'recumbent' bikes are available, and indeed may be more efficient, but they are not widespread, and so will not be dealt with in this course of research.

2.2.1 Bicycle Frames

Mass-produced bicycle frames are generally of two constructions – either braised steel tube or welded aluminium. Both were tested and this will be dealt with in a later Section.

It should be noted that areas such as the bottom bracket and the top of the seat stay can be particularly weak structurally and can be reinforced on some designs (especially if designed as an off-road 'mountain' bike).

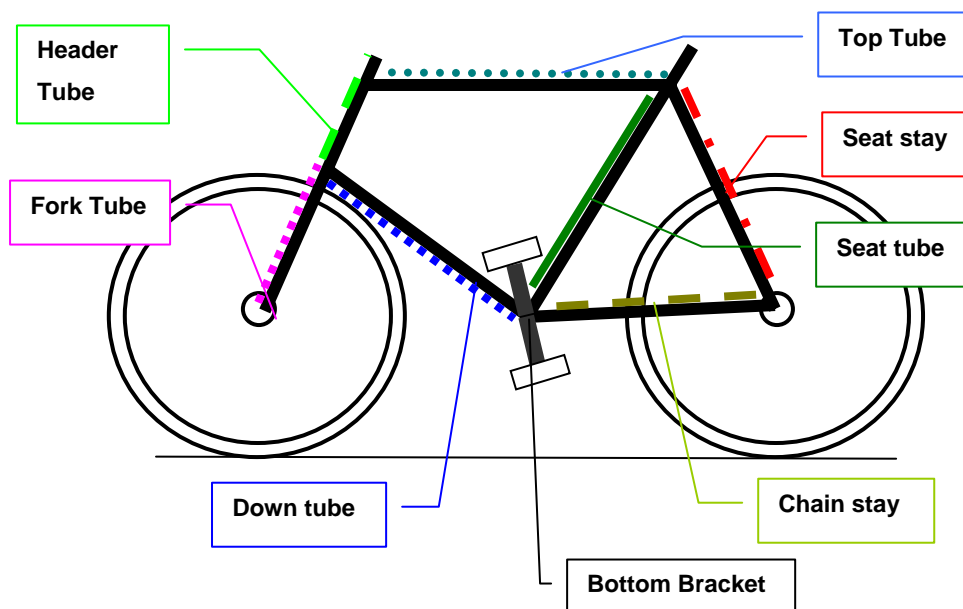


Figure 5 - Bicycle nomenclature

Figure 5 shows the main parts of the bicycle and frame.

2.3 The Motorcycle

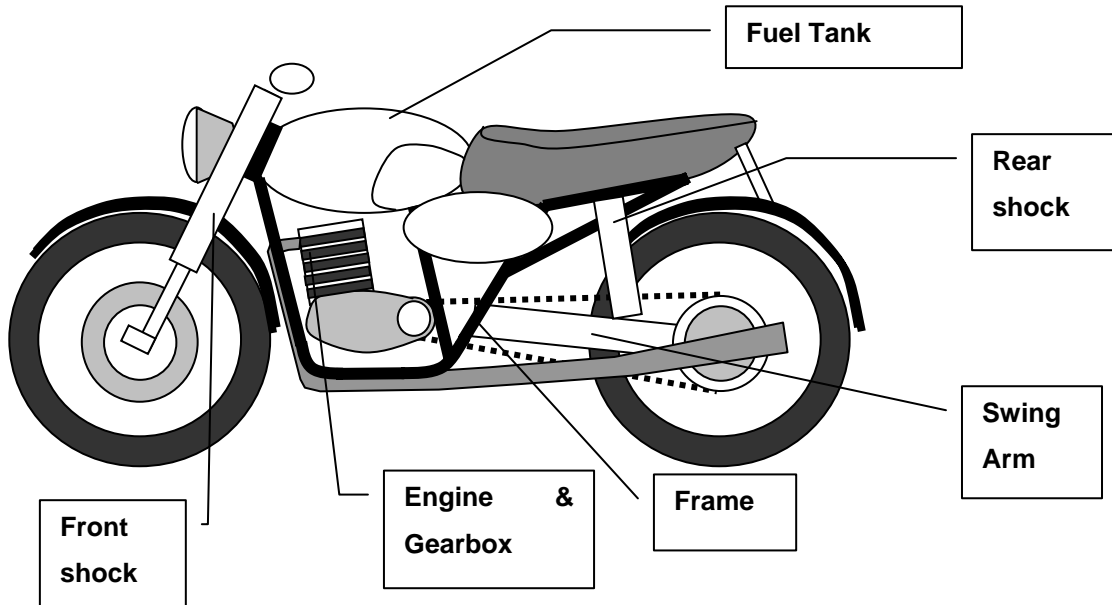


Figure 6 - A typical Modern Light Motorcycle.

The motorcycle was a logical extension of the safety bicycle and indeed the early motorcycles were simply based on a motorised version of the cycle frame with suitable re-inforcements. Over time the motorcycle has evolved into an array of different classes and power levels with the addition of more complex suspension systems. The advancement of improved materials has made a major difference to powertrains in term of reliability and the power to weight ratio however essentially the principles underpinning this type of vehicle have changed little.

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For the purposes of this research topic, a light motorcycle is considered, for the main reason that the majority of the world motorcycle population consists of this type of motorcycle and in particular is the most common in the developing world. As a basis for evaluation, the Yamaha RXS100 and the Honda CG125 are taken as this type of 'generic' light motorcycle, and are used as a basis for analysis.

On this basis the assumption for the motorcycle is as follows:

Wheelbase	1840mm
Height	1025mm
Length	1840mm
Width	750mm
Seat Height	755mm
Ground Clearance	135mm
Dry mass	95kg

2.4 Road Traffic Accident Data and Analysis

2.4.1 Accident and Injury trends

Vehicle occupant statistics, particularly in the Western world, are increasingly more reliable year on year, with better detail to an agreed international standard. For instance, a road traffic accident fatality in the EU varied depending on the home country's definition of how long the injured party survived the accident.

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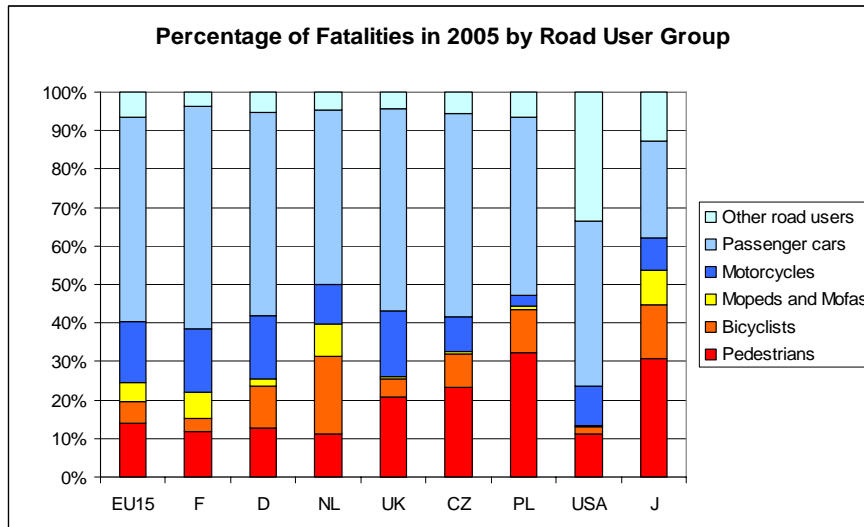


Figure 7 - Road Traffic Fatalities in 2005 (OECD - IRTAD)

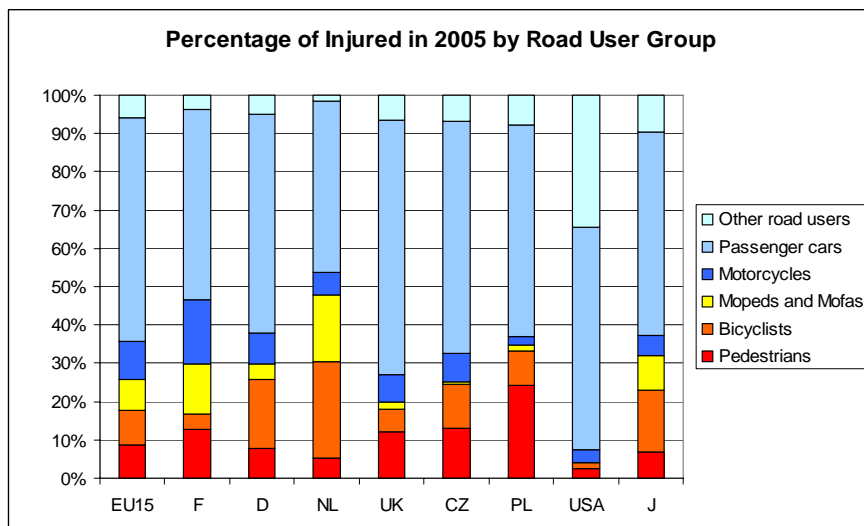


Figure 8 - Road Traffic Injuries in 2005 (OECD – IRTAD)

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As can be seen in Figures 7 and 8, the proportion of 2-wheeler injuries varies greatly between countries. As far as two-wheelers as a total group are concerned, the proportion of fatal and injurious accidents is similar to the European average when compared to pedestrians. It is possible in the future that there will be a greater mix of traffic in inner-city urban areas, as motorists are charged or limited from entering city centres. There is some evidence that this is happening (Devenport, 2007), as London is now successfully operating such a scheme, and Edinburgh, Manchester, Paris Rome and other major European cities are now giving serious thought to this measure.

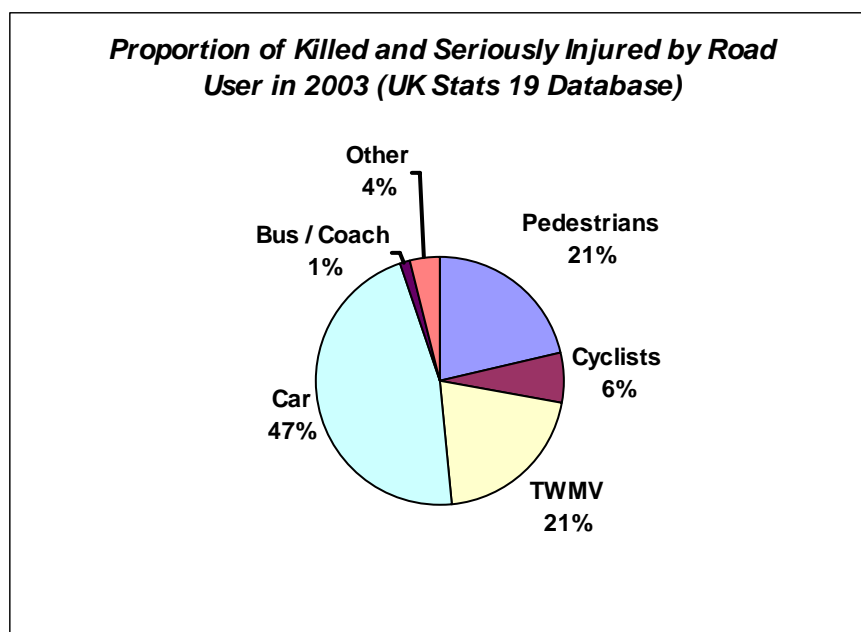


Figure 9 - Proportion of Killed and seriously Injured in 2003 in the UK

Figure 9 shows the proportion of killed and seriously injured in 2003 in the UK and figures 11 and 12 show the fatality trends and fatality rate per passenger kilometre respectively. It is worth noting that although there is a general

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downward trend, two wheelers have the flattest curve and along with pedestrians the greatest possibility of fatality on a given journey.

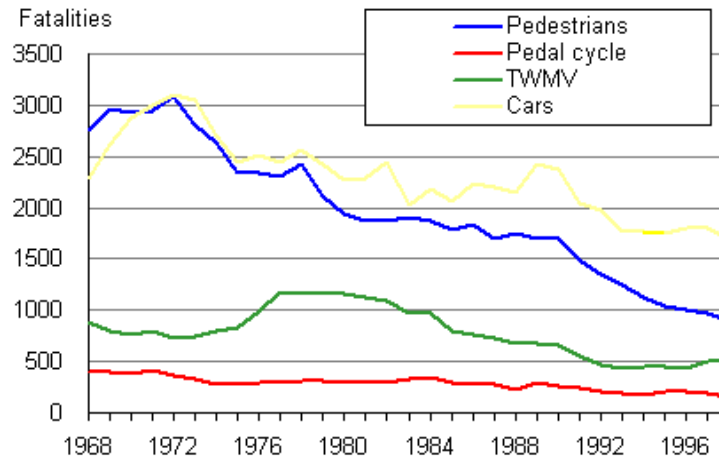


Figure 10 - Trends in Fatalities according to Road User Types in the UK (UK Fatals Database)

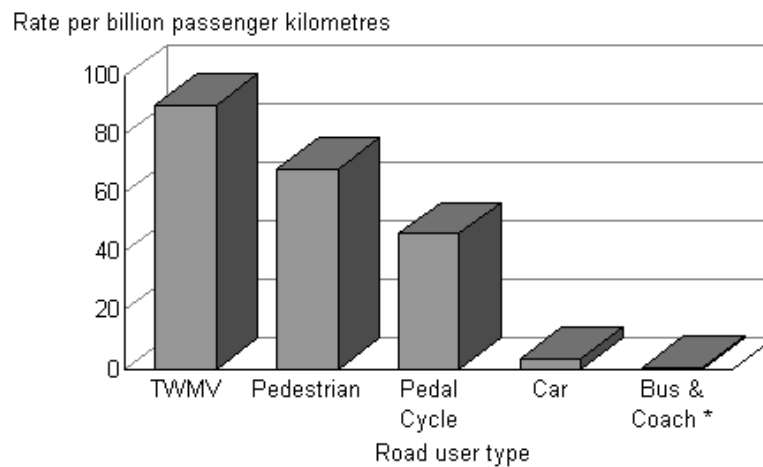


Figure 11 - Fatality Rate per Billion Passenger Kilometres for different Road User Types (UK Fatals Database 1998).

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Data for two-wheeled riders is variable depending on the country and due to the nature of the vehicle. For instance in some countries, cyclist accident data is included with that of pedestrian. Additionally, because the accident scene is generally easier to clear than that of the likes of a car to car accident, a great deal of information can be lost from the accident location. Measures have been taken by industry to improve the understanding of these events, such as IMPAIR / GIDAS in Germany (Otte, 2006), or 'On The Spot' Investigations sponsored by the UK Department of Transport, Local Government and the Regions (DTLR). However, the best way in the future for mapping the exact causation and effect of such crashes may be through the use of inner-city CCTV cameras, suitably de-sensitised by government authorities, for research purposes.

For powered two-wheelers, there is even more attention to address the lack of data, such that a European project called MAIDS (Motorcycle Accident In-Depth Study) is currently underway, and is already yielding some very useful data (Otte et al).

Although the lack of substantial information for two-wheeled accidents is a recognised problem that is being addressed in the west, the problem is more acute in developing countries. In particular, most developing countries use a large proportion of powered two-wheelers (motorbikes and mopeds) as well as bicycles as a major means of mass transportation. As their economies expand, and personal incomes increase, more of the population will move towards improved individual transport methods. By the time this occurs in large volumes, it is likely that traditional fossil-fuel driven vehicles may be superseded with new more environmentally-friendly powerplants. The future

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mix of vehicles will still have a high percentage of two-wheelers in the developing world, as Figure 12 suggests (e.g. in China there is an estimated 450 million bicycles in use).

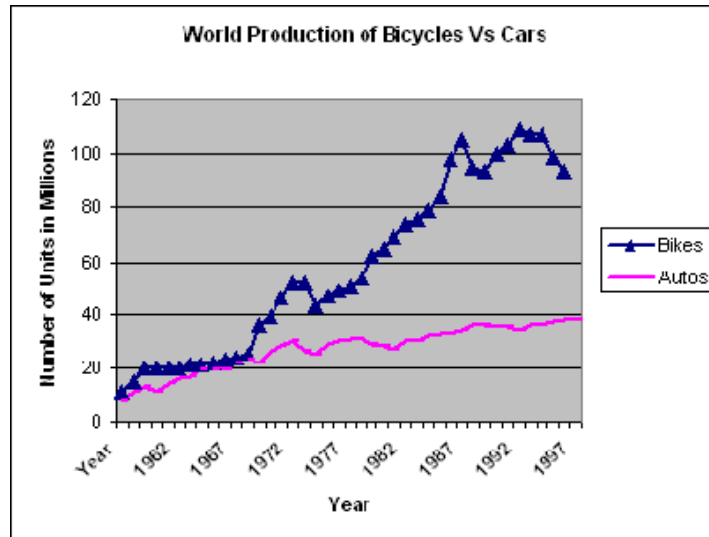


Figure 12 - Global Production of Bicycles vs. Cars

(Source: *Bicycling Life* – www.bicyclinginfo.org).

2.4.2 Pedestrian Safety – Consumer testing and Legislation

From early research, EEVC working groups from 8 on to 17 created the basis of understanding for what is a highly complex event. These groups also led a set of repeatable tests to understand how to apply these to different vehicles.

The following section will describe the current legal situation in Europe and the proposed GTR (Global Technical Regulation). Note this is a brief overview and does not attempt to describe the legislation in complete detail, nor legislation of countries outside the EU, or consumer tests (e.g. EuroNCAP – European New Car Assessment Protocol).

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2.4.2.1 Vehicle - Pedestrian Terminology and Mark-Up

Figure 13 shows the mark-up of a vehicle for testing. The following terms are used in determining which tests are required, depending on geometry:

Wrap-around distance (WAD) is the geometric trace on the hood surface created as if one end of a flexible tape (held in a vertical fore/aft plane) is traversed across the front of the hood and bumper, when the vehicle is in 'normal ride attitude'.

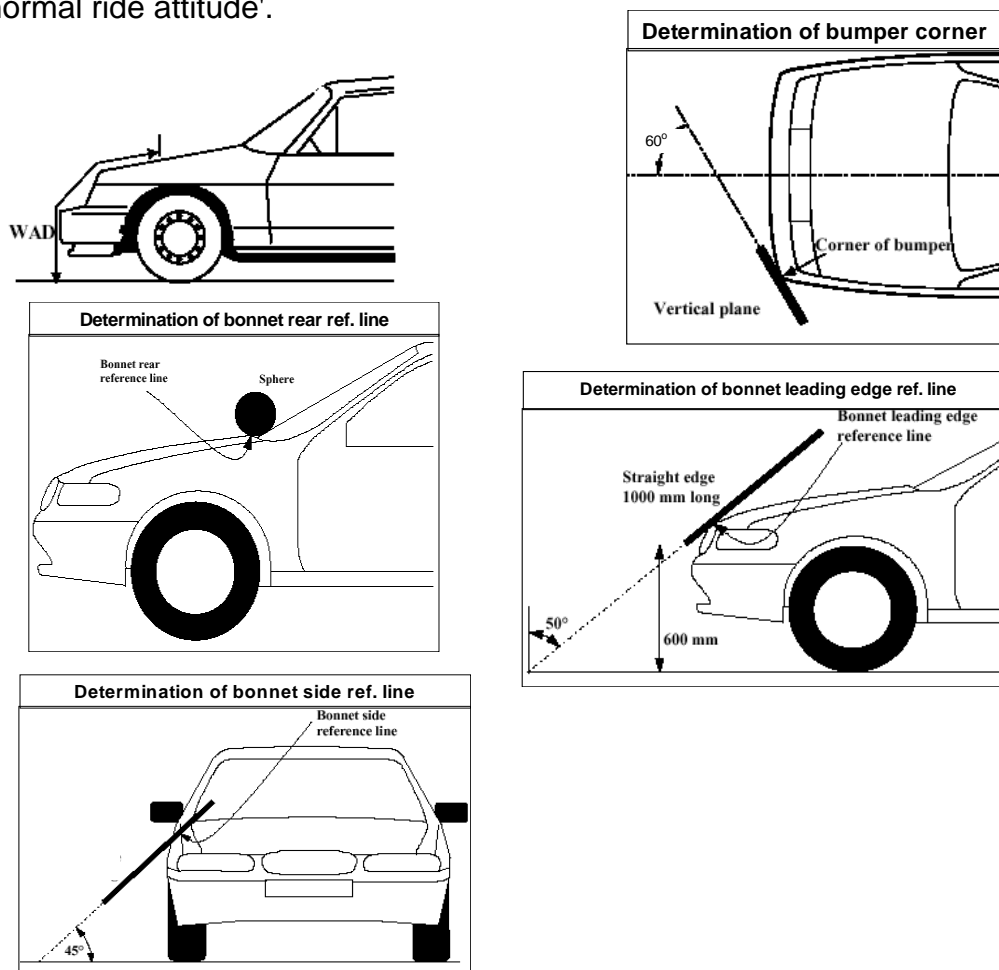


Figure 13 - Pedestrian Mark-Up Definitions

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Ground lines for Pedestrian testing (both EU, GTR and EuroNCAP) should be based on 'Normal Ride Attitude' This is the normal on-road set up with recommended tyre pressures, max fuel / fluids plus standard equipment and two 75kg adults in the front seats, as would be experienced at 40kph in normal conditions as specified by the manufacturer (especially for vehicles with an active suspension).

2.5 EU Phase 1 & 2


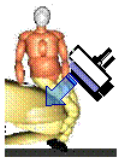


				
	Lower Leg:	Upper Leg:	Child Head:	Adult Head:
Europe Phase 1 New models 2005	<u>Mandatory</u> – Impact speed 40km/h Bending, 21 degree Shearing, 6mm Acceleration, 200g	<u>Monitor</u> – Impact speed 20-40km/h (Based on vehicle shape) Femur Force – 5kN Bending Mom. – 300Nm Energy Cap – 700J	<u>Mandatory to Hood Area</u> – Impact speed 35km/h Impactor mass 3.5kg Impact Angle 50deg. Hic Value 1000 2/3 total area / 2000 1/3 total area	<u>Monitor to Windshield area only</u> Impact speed 35km/h Impactor mass 4.8kg Impact Angle 35deg. Hic Value 1000 2/3 total area / 2000 1/3 total area
ACEA Proposal for Phase 2 New models 2010	<u>Mandatory</u> – Impact speed 40km/h Bending, 19 degree Shearing, 6mm Acceleration, 170g	<u>Monitoring</u> – No Values	<u>Mandatory</u> – Impact speed 35km/h Impactor mass 3.5kg Impact Angle 50deg. Hic Value 1000 2/3 total area / 1700 1/3 total area	<u>Mandatory</u> – Impact speed 35km/h Impactor mass 4.5kg Impact Angle 65deg. Hic Value 1000 2/3 total area / 1700 1/3 total area

Figure 14 - EU Phase 1 & 2 Impact Requirements

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HIC is described as:

$$HIC_{15} = (t_2 - t_1) \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a.dt \right]^{2.5}$$

Equation 1- Calculation of Head Impact Criterion.

HIC – Head Impact Criterion is a linear-acceleration based measurement taking account of the energy of head deceleration over a particular time period (in this case 15ms). This was originally derived for use in occupant interior head impact injury assessment – FMVSS 201. It is now an industry standard and although has recognised limitations (e.g. impact from to the side of the head is clinically more injurious than from the front, plus it takes no account of brain rotation) it is used as the basis of most head impact testing. Alternatives to this criterion (such as the Wayne State Tolerance Curve, Gadd Severity Index or the Japan Head Tolerance Curve) have been proposed as more accurate injury criteria, but are not in general usage at present.

Whilst it is currently still under discussion within the EU parliament, it is expected that the timing would be approx 2012 for new vehicle registrations and 2015 for all new homologations.

Current scope for both Phase 1 and Phase 2 is M1 up to 2.5t GVM (Gross Vehicle Mass) and N1 derived from M1 up to 2.5t.

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2.5.1.1 Global Technical Regulation (GTR)

There is also a Pedestrian Protection GTR in development. This GTR would be able to be applied in all signatory markets such as Japan, USA and Canada.

The GTR has as much as possible aligned with the EU Phase 2 (and vice versa). The notable acceptations are the lack of monitoring tests for Upper Legform to BLE and Adult Headform to windscreen monitoring tests.

The issue of scope is the same as in EU Phase 2.

Note that the GTR supersedes the Phase 2 standard as a global requirement. For further details see the EC website:

http://europa.eu.int/comm/enterprise/automotive/pagesbackground/pedestrian_protection/index.htm

2.5.2 Typical crash types for Two Wheelers

The basis for simulation has to be based on real-world accident scenarios. Some studies have been undertaken in some detail from Western countries to understand which orientations (in terms of cyclist to passenger car or truck), are the most common. The results of these are shown in Table 1:

Investigation of 2-Wheeled Road Traffic Accident Scenarios using Explicit FE Techniques.



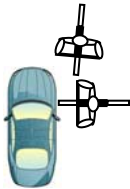

Source	Front Collision	Side Collision	Side /Swipe Collision	Rear Collision	Falling Down	Others
						
For Motorcycles						
BMW	42%	4%	18%	2%	10%	24%
Otte (SAE 2006-01-1562)	12.9%	3.4%	31%	5.3%		
For Cyclists						
DEKRA	20%	59%	-	21%	-	-
NHTSA	Included in "others"	62.3%	7.3%	8.6%	-	21.8%
EEVC (ESV 1984)	25.6%	R=21.2% L=49.6%	-	3.6%		

Table 1- Rider impact orientation

As can be seen junction-type crashes are the most common, according to these studies, however it can be noticed that there is a significant difference in the types of crashes experienced between motorcyclists and cyclists. In addition the data from DEKRA suggests that greater than or equal to 57% of all accidents take place at speeds up to 40kph. On this basis it would seem reasonable to concentrate initially on CAE simulation of side collisions for cyclists.

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A great deal more understanding has been gained from investigation of motorcycle crashes. This culminated in the ISO standard ISO13232 (Berg et al., 1998) Although this is relevant for all two-wheelers, as can be seen from above, the reality for cyclists is different from those of mopeds and motorcycles. Many of the methods developed within the standard are still applicable to cyclists and will be adapted for their most common RTA scenarios and investigated accordingly.

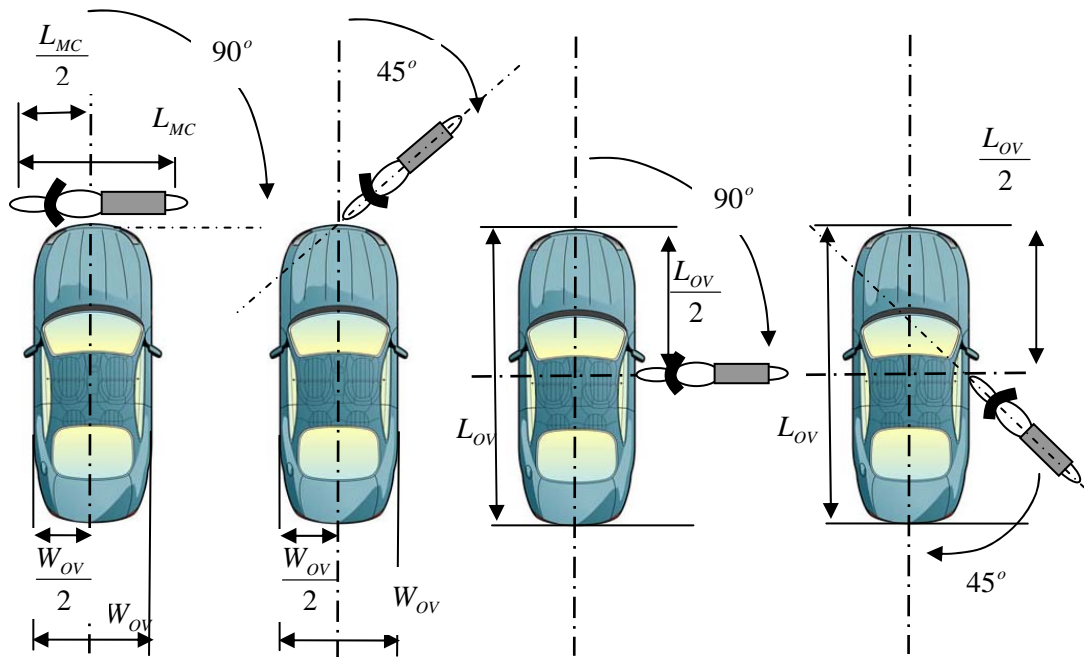
2.6 Studying TWMV Cases

2.6.1 Vehicle to Motorcycle / Moped Orientations – ISO 13232

Previous work on motorcycle safety devices resulted in differing methodologies developed by various safety organizations. This resulted in some cases in having differing results in performance from the same device depending on which impact evaluation was used (Berg et al). In an effort to harmonize these attempts, an agreed geometrical impact standard ISO 13232 was formulated in December 1996.

This standard recommends 200 configurations of motorcycle – car impact, at least 7 of which should be examined by full-scale vehicle tests (as shown in Figure 15), the remainder with computer simulation. This standard has now been universally been accepted as the main method of proving PTW safety devices.

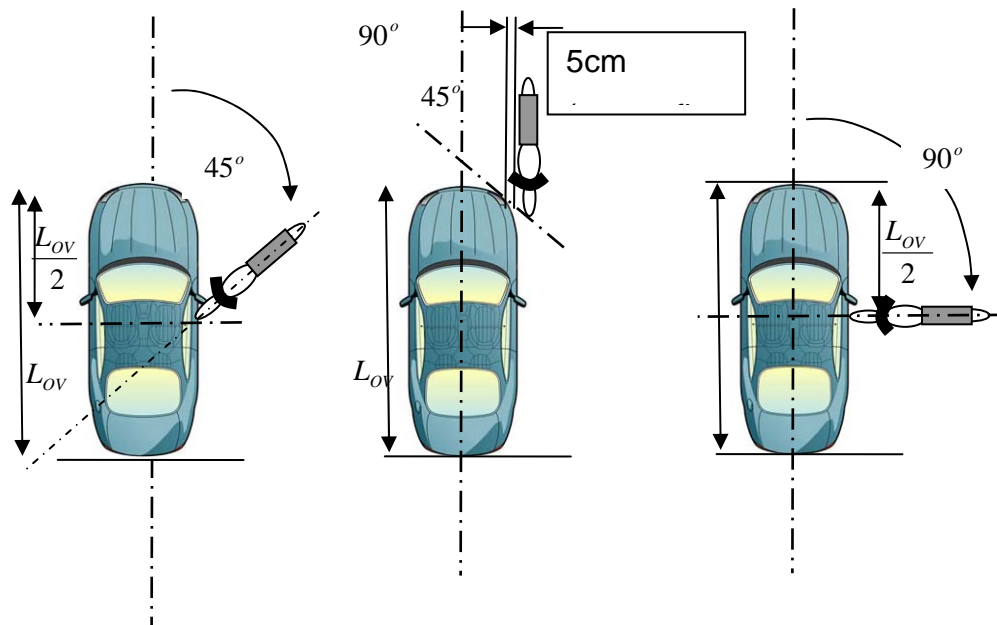
Investigation of 2-Wheeled Road Traffic Accident Scenarios using Explicit FE Techniques.



Note the subscripts OV=opposing vehicle and MC=motorcycle

Config	143-9.8/0	114-6.7/13.4	413-6.7/13.4	412-6.7
V_{ov}	35kph	24kph	24kph	24kph
V_{mc}	0kph	48kph	48kph	48kph

Investigation of 2-Wheeled Road Traffic Accident Scenarios using Explicit FE Techniques.



Note the subscripts OV=opposing vehicle and MC=motorcycle

Config	414-6.7/13.4	115-0/13.4	413-13.4
V_{ov}	24kph	0kph	0kph
V_{MC}	48kph	48kph	48kph

Figure 15 - The 7 main orientations of ISO 13232.

2.7 Developed World versus Developing World

The developing world is bearing a large cost for advancement into an industrialised economy. Factors such as lack of experience in road infrastructure management, a rudimentary health system and lack of enforced traffic laws, cause an increasing burden for the populations of these countries in terms of injury and death.

In 1980 pedestrians accounted for 33% and 21% of all RTA casualties in New Delhi, India (Mohan, 1984). In China approx 170 million bicycles were registered in 1987 – cyclists being involved in approx 30% of the total no of fatal accidents (Lianrong and Ze, 1991) and it is estimated there are approx 450 million bicycles in China.

Of course it is very difficult to accurately estimate casualties in these countries, but TRL 445 (Jacobs et al) gives methods which can be used.

The Middle East is another area in which RTA casualties are increasing (approx 20% increase between 1990 and 1995 according to TRL), as is Africa and increasingly Latin America, but it is in the so-called 'Tiger' economies of Asia that the biggest burden is to be found – an estimated increase of 40% between 1990 and 1995, and the trend looks set to become worse (as previously seen in Figure 1).

2.8 The effect of congestion charging in urban areas on RTA statistics

On 17th February 2003, Transport for London introduced the congestion charge for motor vehicles in central London. This is not the first such system in the UK (cities such as Durham pre-empted this scheme in a small way prior to this), but is certainly the largest implementation to date in Europe.

The need to change the way traffic was allowed into the city centre at peak times was clear – urban congestion was turning the road network into a 'log jam' (with average road speeds down to 9.6mph in the evening rush-hour by 2000), and the side-effects were having a major impact on a spectrum of issues ranging from environmental through to emergency services and the local economy.

In order to get a change in what was, and still is, a sensitive political subject there needed to be some major changes in the way the city was run. London was chosen to be the first example in the UK where a US-style mayor who had overall political control over traditionally centrally-run institutions. Ken Livingstone who went on to win the election established "Transport for London" or TfL as an administration department that runs the day-to-day transport system and provides a strategic view of how the expanding city should address its future needs. The congestion charging scheme was part of the Livingstone campaign, and after a period of hotly-debated public consultation through the 'Review of Charging Options for London' (ROCOL), the scheme was implemented. One of the election promises was that the

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revenue created would be driven directly into improving London's public transport system.

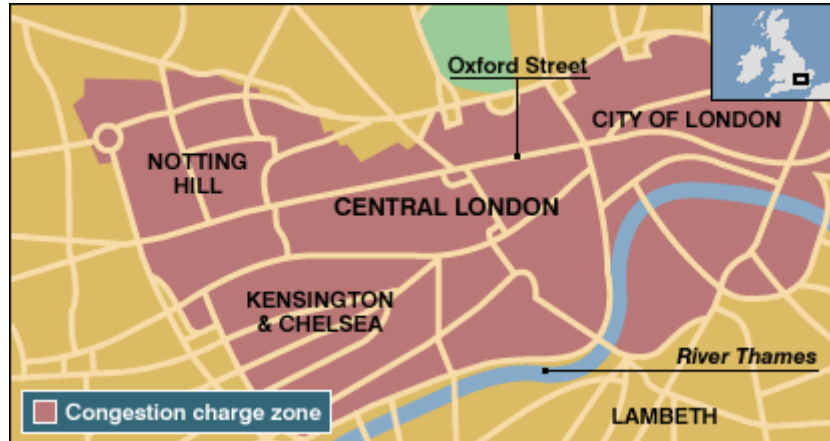


Figure 16 - Boundary of London Congestion Zone (courtesy BBC News Website)

Figure 16 shows the initial boundaries for the scheme. This is essentially the area within the inner ring road and covers 8 square miles (21 square km). Vehicles (with the current exceptions of public transport, London taxis, emergency services, motorcycles, minibuses and 'green' vehicles such as hybrids, and alternative fuelled-vehicles etc.) have to pay the charge during weekdays. Each vehicle is charged £5 for entering the congestion zone during weekdays (not including bank holidays) between 7:00am-6:30pm. A 90% reduction is available for residents but this is only levied when the vehicle is seen to be moving in the zone. The ticket can be purchased by 10pm on the same day after using the zone, but in this case the charge increases to £10. Fines start at £40 and escalate to £120 and potentially eventual seizure of the vehicle.

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The method of monitoring was also novel. ANPR (automatic number-plate recognition) is used – every time a vehicle passes through a congestion zone checkpoint, cameras interrogate the number and check the database of vehicles that are allowed travel for that day. This has led to some use of licence-plate piracy (theft or copying of other licence plates) and attempts to disguise licence plates but this is in contravention of the road traffic act and can result in its own set of penalties.

"Approved" forms of transport such as cycling were encouraged through pressure groups such as the Cycling Campaign for London, and these groups actively engaged by TfL in consultation to encourage more riders, improve rider training, aide communication, improve routing and road infrastructure for cyclists.

Mode	Modal Share
Cycling	1.3%
London Underground	9.9%
Buses	17.5%
National Rail	5.4%
Docklands Light Rail	0.5%
Car / Motorcycle	43.0%
Taxi	0.9%
Pedestrian	21.4%

Table 2 - Modal share of Transport in London in 2001 (LATS 2001)

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The Mayor of London established a Cycling Centre of Excellence (CCE) at Transport for London in 2004 to engage with all the major stakeholders (e.g. Local boroughs and the London Cycling Campaign) and plans to increase cycling in the city by 80% by 2010. As part of the London Cycling Action Plan (LCAP), there is a comprehensive cycling routemap for London – the London Cycle Network, LCN (www.londoncyclenetwork.org.uk). This is backed up with the London Cycle Guide (LCG). These have 4 categories:

Blue – signed routes

Brown – Off-carriageway routes

Green – Green Cycle Corridor (GCC) routes in areas such as parks.

Yellow – Unsigned, and are via lower traffic density routes.

The work on the cycle routing within London was also included in the 'Sustrans' National Cycle Network (NCN). Sustrans is an environmental transport charity which aims to increase the amount of sustainable transport infrastructure in the UK (www.sustrans.org.uk).

There is also a set of design standards for implementation of cycle lanes called the 'London Cycling Design Standards' (LCDS) setting out standards for implementation of cycling schemes.

In addition, encouragement has been given to parents and schools to get children back onto two wheels to commute to school and reduce the number of vehicles on the 'school run'. This has been backed not only for environmental reasons but also to try and arrest some of the trend in childhood obesity that has developed over the last few years as a result of poor diet and lack of exercise in childhood.

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Current statistics show a dramatic improvement in road congestion (e.g. the average speed in central London has improved greatly – it was only 9.9mph in some areas before the scheme). It was thought that the increased speed of inner-city travel and the increased mix of transport (plus the additional concern of commuters learning to ride on two wheels either motor or pedal-driven) may have had a detrimental effect on VRU road accidents. London has a marginally higher proportion of cyclist casualties compared with the rest of the country (7.7% killed or seriously injured compared to 6.9% for the rest of the UK in 2001-2003).

Interestingly, TfL's statistics show an approximately 20% reduction of casualties for PTW's and cyclists when the scheme was introduced. This is with the backdrop of a 23% increase in cycling (recorded between May 2003 and May 2004), however according to the safety statistics for 2005 there has been an increase in cyclists killed or seriously injured (from 340 in 2004 to 372 in 2005). Reasons for this trend have not been identified as yet, but it may be due to commuters either returning to cycling after many years, or learning from 'scratch'. Other factors such as low rider visibility and an incomplete cycle network may be further reasons.

Clearly the benefits of the congestion scheme have been shown to outweigh any inconveniences and other major cities (such as Manchester, Paris and Rome) are seriously considering implementing congestion charging schemes of their own, and other cities worldwide are monitoring the progress. In addition it is possible that the London scheme may be extended to a wider area (possibly to the orbital ring road), but this is not firm policy as yet. This

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may result in a much larger two-wheeled population in these cities, and therefore these populations will be monitored closely.

2.9 Conclusions from accident analysis and resultant analysis strategy

Clearly there are two sides to this increasing mix of vehicles on the road in different parts of the world, and for different reasons. In the Western world – there is the pressure to increase cyclist km's per person as a serious commuter tool instead of purely a form of exercise / leisure. Increasing fuel prices and 'green' concerns are an increasing significant factor.

In the developing world with the new economies becoming increasingly motorised, car bus and truck populations are mixing with more traditional forms of traffic. In some Asian countries there is a clear move along the following lines - cities grow, forcing the less affluent to move further out from the city centre on longer commutes, therefore bicycles are replaced by mofa's / light motorcycles and in some cases eventually cars. This appears to be happening in China and India in particular.

2.10 Clinical Studies and Biomechanical issues

2.10.1 Overview

Injuries as a result of Road Traffic Accidents have been occurring since the first machines were invented. An 'acceptable' level of road accident injury was generally endured by society until it was studied in some detail in the 1950's by scientists like John Paul Stapp (www.stapp.org). He was a flight surgeon for the United States Air Force investigating the tolerance of the human body to transient and sustained high 'G' situations – mainly for application to fighter training, early ejection seats and the space programme. On further investigation of the personnel records he realised that many of the USAF's young service personnel were being killed in road traffic accidents rather than on active duty. He set about trying to understand the reasons for the low survival rates of these car crashes. At that time (in the 1950's) little thought had been placed on occupant safety and only rudimentary safety was included in how the vehicle structure performed in collisions. Stapp began testing human volunteers (mainly himself!) in tightly controlled conditions to provide a template of fundamentals on human around which interiors and future safety systems could be designed.

Occupant injury grew in understanding over the years with seatbelts, airbags and other restrain systems being integrated within a vehicle structure of understood performance. In developed countries, as occupant survival improved (with the allied improvements in road infrastructure, emergency services and reporting) more attention was drawn to vulnerable road users (VRU's) – i.e. pedestrians, mopeds / mopeds / motorcyclists, and cyclists.

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Although some vehicle manufacturers investigated some research devices, only relatively recently have studies been performed into pedestrian and other vulnerable road users in a co-ordinated way (WG 7 / 8 /9 /10 / 12 / 17, MAIDS et al).

As a result of this initial work EuroNCAP launched their own targets for Pedestrian safety. Following this approach and on engagement with the European industry body (ACEA), pedestrian safety is now a legal requirement for all new vehicle designs in Europe. Japan, due to its particular problems with VRU's also has legislation, and further harmonised global standards are being examined.

To understand some of the fundamentals in common injury mechanisms in major trauma caused by cyclist / motorcyclist RTA's it is worth examining the basis behind trauma management in patient care of each body segment.

It is worth briefly examining the process by which patients are treated in terms of initial trauma care, and the major injuries which are experienced in road traffic accidents for vulnerable road users.

For the purposes of this study we will break down the injuries into three categories –

- cranial & neurological
- thoracic & abdominal
- limbic (with emphasis on lower limbs).

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The following figure gives the a comparison between pedestrian and cyclist RTA's

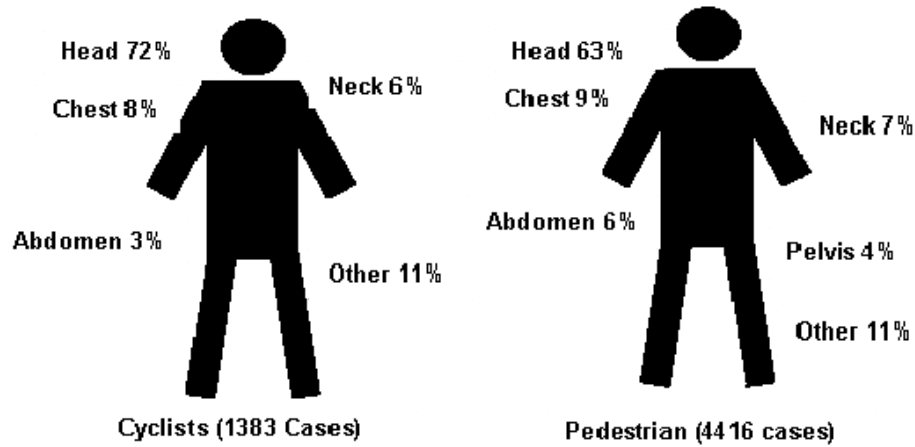


Figure 17- Proportion of fatal injuries received by cyclists (left) and pedestrians (right)(Maki et al., 2000)

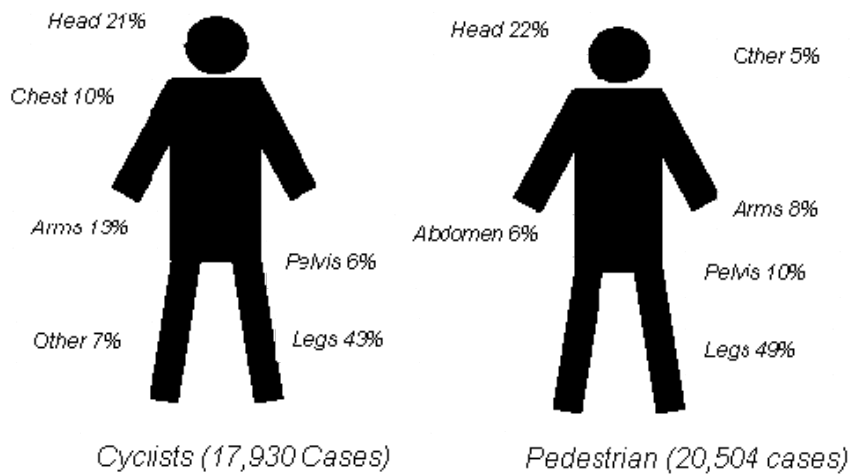


Figure 18 - Proportion of serious injuries received by cyclists (left) and pedestrians (right) – (Maki et al)

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As can be seen from the study shown in Figures 17 & 18, head injuries are by far the biggest cause of death, whereas the largest reason for serious injury (and hence the biggest cost to society in terms of burden) is damage to the lower legs. It is also worth noting that in terms of serious injuries for cyclists, chest and upper extremities appear to be more prevalent than for pedestrians.

In another recent study in the US, the proportion of injury to children in pedestrian RTA's can be seen. According to Woods (Woods et al., 2001), pedestrian injuries account for 61% of all paediatric trauma admissions. This may well be due in a major part to the reliance on the car / truck in the US, the greater mix of large truck / SuV's and the lack of pedestrian infrastructure on many roads / interchanges.

It is a reasonable assumption to take the trends of paediatric pedestrians to be that of paediatric cyclists, as the difference in ride height (as compared to adult pedestrian versus adult cyclists) is not as marked as the difference between adult cyclists and pedestrians.

Investigation of 2-Wheeled Road Traffic Accident Scenarios using Explicit FE Techniques.

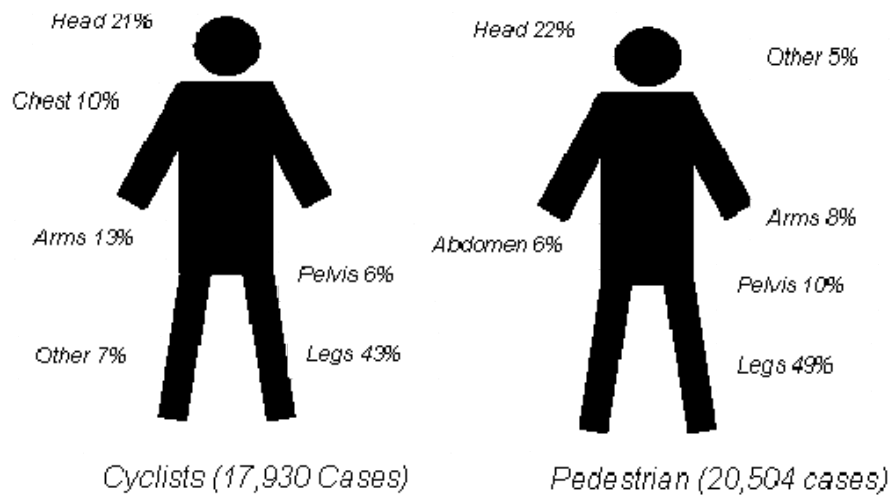


Figure 19 - Frequency of injuries (all types) experienced by paediatric pedestrians aged 5-9 (study = 2,426 injuries in 776 patients).

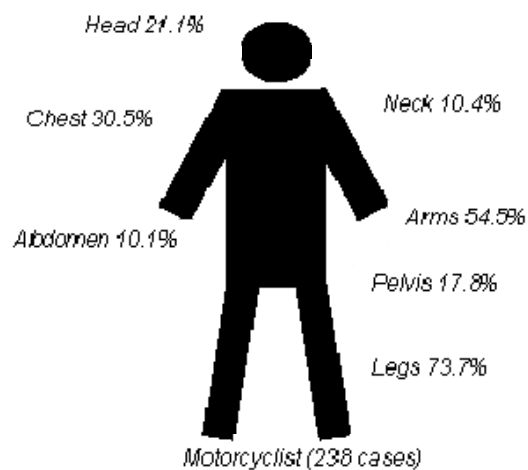


Figure 20 - Frequency of injuries (all types) experienced by motorcyclists (note in these cases all were helmeted). (Otte, 2006)

The data from a recent motorcyclist injury study is shown above. In this case all riders were helmeted (clearly without a helmet the rates of brain injury

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increase dramatically – as can be seen in the US States that have repealed their helmet laws). The lower extremities are particularly vulnerable in this type of vehicle.

Due to the higher energies involved and the larger mass of the vehicle they are riding, the injuries to the chest and pelvis are much greater than was seen in the studies for cyclists and pedestrians, and crush injuries to the legs are also a result of the higher mass of the motorcycle (compared to a bicycle).

2.10.2 Trauma Management

Figure 17 shows the trimodal pattern of morbidity following trauma (Solomon et al., 2005) pp 257.

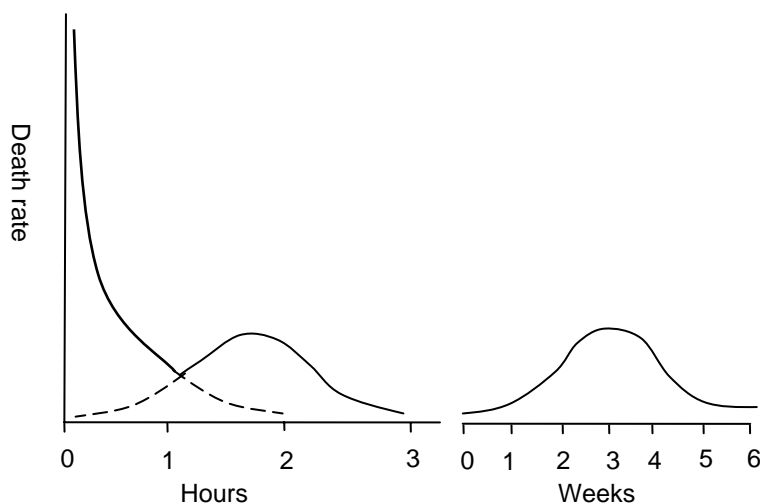


Figure 21 - The Trimodal pattern of post-trauma mortality (Solomon et al).

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As can be seen, the 'Golden Hour' is well-named – being the critical period to treat major trauma successfully. Normally, there are several well-followed stages:

- Movement away from any obvious danger (if appropriate).
- Initial emergency care – immediate first aid (airway / breathing / circulation and consequently immobilise fractures / control pain) on the scene.
- Gather any information from patient / first aiders on health background.
- Transport to hospital (normally ambulance / paramedic).
- Admission to the Accident & Emergency unit

Primary survey followed by secondary survey and regular re-evaluation examining Airway / breathing / circulation & level of consciousness (measured via Glasgow Coma Scale – GCS). Treatment normally then is as follows:

- Treatment of any cardio respiratory issues
- Management of bleeding major vessels
- Assessment and treatment of musculoskeletal injuries (normally in a 'fracture clinic' run by the orthopaedic surgeons).
- General ward rest & recuperation followed by physiotherapy and long-term care.

2.10.2.1 The Glasgow Coma Scale

This is a metric used by clinicians to determine consciousness and is used as a monitoring method during the initial critical care period, examining the patients responses to various stimuli. It is so-called since the method was created by emergency specialists in Glasgow, Scotland.

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A score of 15 is the 'normal' level of consciousness, and a score of less than 8 means there is the potential of severe neurological damage (normally close to or in coma). A change in score during monitoring can then give clinicians warning of any changes in the patients' neurological state and hasten any action needing to be taken.

Glasgow Coma Scale (GCS)	
Score	
Eye Opening	
Spontaneous	4
On Comand	3
On Pain	2
Nil	1
Best Motor Response	
Obeys	6
Localises Pain	5
Normal Flexor	4
Abnormal Flexor	3
Extensor	2
Nil	1
Verbal Response	
Orientated	5
Confused	4
Words	3
Sounds	2
Nil	1

Table 3- Glasgow Coma Scale

2.10.3 Cranial & Neurological Trauma

The Figure 22 gives the basic anatomy of the brain, its major functions and its connected and supporting tissues.

Investigation of 2-Wheeled Road Traffic Accident Scenarios using Explicit FE Techniques.

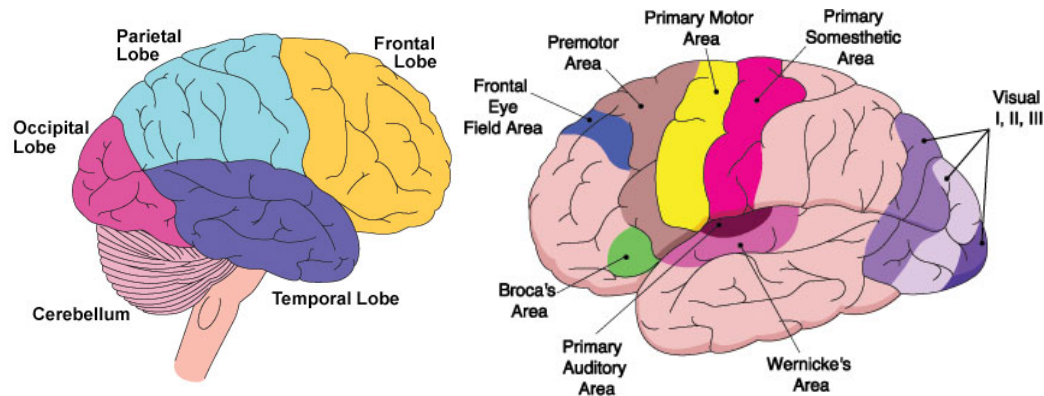


Figure 22 - The human brain (courtesy of www.braininjury.com)

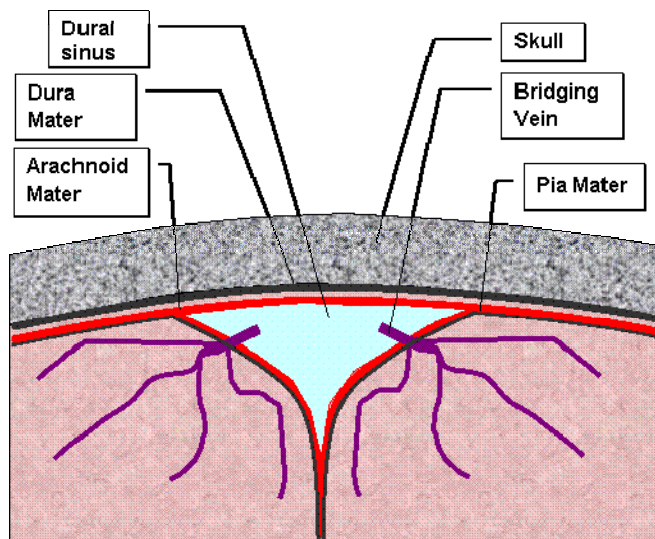


Figure 23 - Lateral cross-section of the top of the skull

The brain rests in a suspension of fluid (cerebrospinal fluid or CSF), and this provides a level of damping isolation when the cranium is struck by blunt trauma. Figure 23 shows the brain has several membranes surrounding it – the outer membrane (dura mater), the mid-membrane (arachnoid) and the inner Pia Mater (collectively known as the meninges).

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The brain is a particularly delicate organ, with several methods of protection against damage being incorporated as part of evolution. In terms of impact trauma, the brain itself can basically suffer from 3 types of direct injury – direct damage from a blunt impact, intracerebral movement as a result of rapid acceleration or deceleration, or a penetrative injury.

In addition there are serious secondary injury mechanisms due to trauma. Due to brain tissues having a low shear modulus, during trauma if shear waves propagate, high strains can result. The end result of this is diffuse axonal injury – damage of the individual axons in a large scale due to tissue shear strain (Ommaya, 1984).

If the trauma is serious enough or due to direct damage from a penetrative skull fracture, haemorrhaging can be another serious brain injury mechanism. Intracranial pressure due to blood loss and oedema can be a serious side-effect (Lawson, 1997), resulting in intracranial pressure which can lead to ischaemic brain damage (loss of oxygen and glucose). One serious closed head injury mode is for the sagittal bridging veins to rupture. Dorsal bridging veins are particularly prone to injury from experiments (Lindenberg, 1971).

Depreitere (Depreitere et al., 2003) studied 86 cyclist patients involved in accidents whom had suffered head injuries and underwent neurosurgery. 42 of this number had been involved in an impact with another motor vehicle. Of those admitted the initial Glasgow Coma Score varied from 3 to 15 (mean 9.9). Of those involved in an RTA 80% had skull fractures with 90% suffering brain swelling.

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The brain is particularly susceptible to side accelerations - any rotation or translation of the cerebrum in relation to the brain stem at the base of the brain can cause major neurological damage. It has been recently understood that the scalp 'slipping' over the cranium can lead to a de-coupling effect to reduce this effect. This principle is being applied to a novel type of motorcycle helmet developed by Dr Ken Phillips which tries to increase this decoupling effect using a lubricant between outer shell and inner core (www.netcomposites.com, 2003).

Proportionately Huijbers (Netherlands) (Huijbers and Janssen, 1988) and Nicholl (UK) have shown that head contact with the vehicle is the most common cause of fatal and serious injury for pedestrians, cyclists and PTW's.

In the case of cyclists and PTW's, helmets are a significant area of interest and controversy. Cyclist helmets are designed to protect the user from a fall from a height of approx 1-2m, and are not specifically designed to reduce injury in high-speed impacts. This will be investigated later in the thesis.

In terms of measurable injury parameters, a HIC value of 1000 for adults and 850 for children has been taken as a target. This is based on work on interior head contact and work derived from the EEVC WG10-17 (EEVC, 1985). In addition, maximum linear acceleration (80g) and rotational acceleration (3000 rads/s²) have been examined as secondary areas of interest.

2.10.4 Thoracic and Abdominal Injury

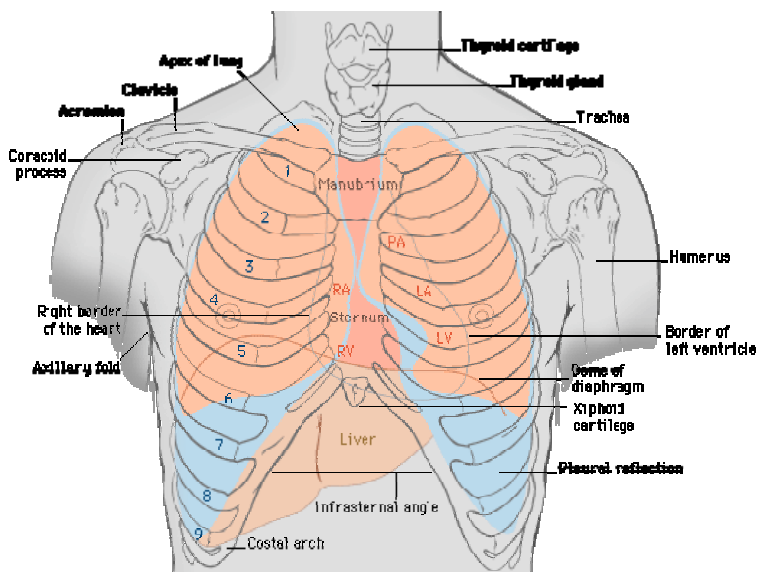


Figure 24- Skeletal Structure of the Human Thorax (courtesy Yale Medical School).

As has been shown in the previous sections on thoracic, abdominal and pelvic trauma is a major concern particularly for PTW's but is also of interest for cyclist RTA's. Clearly the geometry of the vehicle involved will influence the effect of this and trucks may have a greater effect than a more conventional passenger car on this particular injury mechanism. According to Nusholtz (Nusholtz et al., 1982) one of the most common physiological responses to blunt abdominal impact is hypovolemic shock (blood loss), and subsequent intra-peritoneal bleeding (this is the membrane surrounding the vessels and organs within the abdomen and pelvic cavity). Major injury to the main organs and in particular the major blood vessels can lead to death very rapidly. This is very difficult to model as it would involve modelling the entities within the body cavity – a major task.

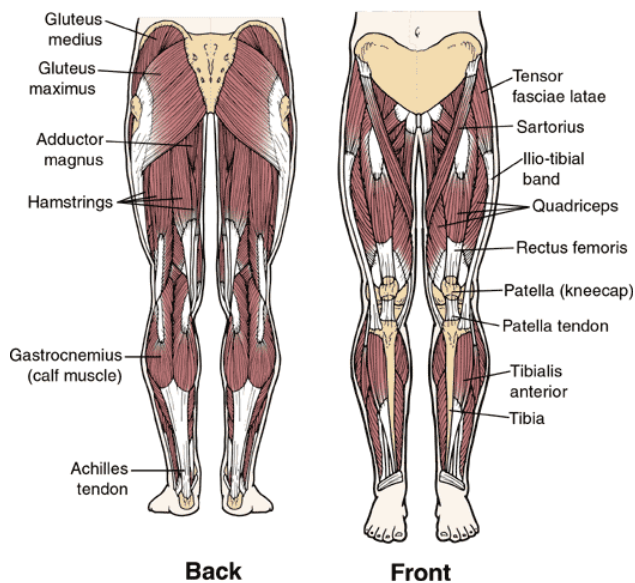
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Aortic trauma is a major issue for occupant injuries, but is less of an issue in VRU injuries (Franklyn et al., 2003).

For the purposes of this study, according to Yang et al (Yang, 2000), an acceptable limit for pelvic peak force is 4kN for Women and 10kN for Men. In addition a maximum linear acceleration of 60g is taken as the upper limit for the thorax.

2.10.5 Limbic Injury

Leg Anatomy



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Figure 25- Leg anatomy (courtesy McKesson Health Solutions LLC).

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Details of the lower body are shown in Figure 25.

Injuries to the hip and upper femur are relatively uncommon for pedestrian / cyclists unless there is another underlying cause (for instance osteoporosis, most commonly seen in the elderly).

Common types of lower leg fracture are as follows:

- Greenstick (an incomplete fracture, but with lateral displacement – common in children).
- Displaced transverse fracture (a complete fracture with dislocation).
- Oblique fracture (fracture at an angle)
- Spiral fracture (when the bone fails under torsion)
- Segmental fracture (usually a high-energy impact)
- Compression fracture (usually seen in vertebrae)
- Avulsion fracture (when a segment of bone is torn away by a ligament).

By means of an example, a Figure 26 shows a displaced transverse fracture of the tibia and a 'greenstick' fracture of the fibula is seen below from a 10-year old boy who was knocked down in a pedestrian RTA. This is a typical bumper injury from a vehicle which has not been designed to the latest pedestrian standards.

In particular for children, a common form of injury can be an epiphyseal fracture. This is where the bone is still growing, and the growth plates (physis) have a weakness at their join. This type of fracture breaks into 5 basic types originally defined by Salter and Harris (Solomon et al., 2005).



Figure 26 - 'Greenstick' Fracture of the Tibia and Fibula.

From Yang et al, for the purposes of this study, the Injury criteria will be as follows:

- 150g max for Tibia / Fibula;
- Maximum bend of 200Nm for the Tibia / Fibula
- 220Nm for the Femur
- 4kN force for the Tibia / Fibula and Femur.

2.10.5.1 Injuries of the Knee

The knee can suffer similar injuries to any joint. In basic terms, the ligaments, soft tissues, the bones themselves, or any combination of these can suffer injury. Valgus (distorted outwards) injury can result in damage to the medial tibial condyle (the protrusion at the top of the bone) or varus (distortion inwards) can result in damage to the medial tibial condyle.

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Examination of the knee joint in great detail would result in a complex model, so again, a simplified holistic approach is taken.

Knee injury will be determined via knee translocation (6mm max), and a force of 2.5kN, as proposed by Yang.

2.10.5.2 Injuries to the Arm

Although statistically of interest particularly to PTW's currently there are no major biomechanical methods or targets for arms. This is mainly due to the fact that a repeatable test is very difficult to achieve, to the nature of arms flailing during impact. So long as competent trauma management is administered quickly, and major blood loss is stemmed early (i.e. the brachial artery), loss of life is unlikely due to arm injury.

It is worth noting that the patients' quality of life and ability to continue a professional career are major concerns for arm and particularly hand injury, and is therefore one of the areas of interest in terms of cost to society and insurance considerations.

This area would be a suitable area of study for future research, but as described will not be directly measured in terms of injury criteria.

3 Methodology

3.1 Approach

Based on the previous data and from methods used in crash analysis in the car industry, the approach taken by the author was as follows:

- Purchase 'typical' mass produced bicycles and construct an FE model with material cards based on testing the frame and wheel.
- Construct sub-models (i.e. frame / wheel) to correlate.
- From most common accident scenarios, adapt ISO 13232 for the cyclist case, and examine with a total FE model.
- Understand difference cyclist helmets can make.
- Examine motorcyclist case using an empirical motorcycle created from known material data and apply to selected ISO 13232 cases.

3.2 Cyclists (and associated pedestrian studies)

As part of the original EEVC investigation into pedestrian and cyclist accidents, WG 8 and 9 respectively conducted experiments into how injury could be reduced using basic ATD's and early analysis (EEVC, 1984). These studies were limited in applicability to the real world due to limitations with the then available dummies plus limited computing, CAE toolsets and methods. Much work was undertaken to understand the real-world cases and this forms a good foundation for the assumptions for biomechanical modelling.

The challenge of this course of work is to understand real-world situation in accident situations. This means accurate analysis of a combination of some or all of the following:

Investigation of 2-Wheeled Road Traffic Accident Scenarios using Explicit FE Techniques.

- accurately model cycle and rider interaction
- wheel collapse and tyre interaction
- frame failure & distortion
- vehicle impact and effects
- Helmet effects.

A systematic has been approach adopted to achieve this end, as shown in Figure 27.

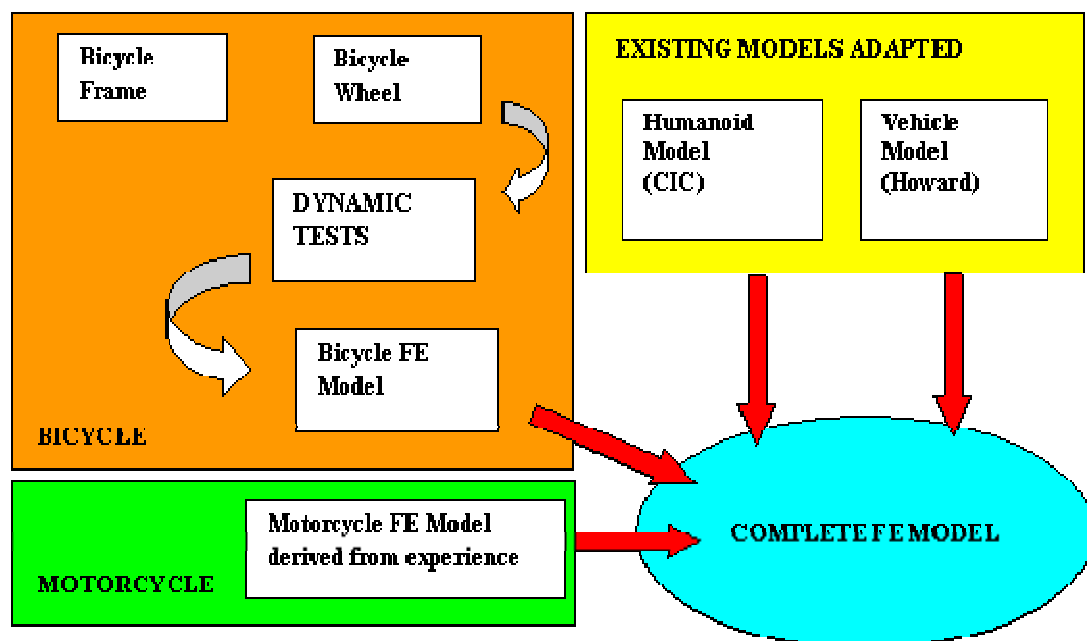


Figure 27 - Outline of modelling approach to PhD study.

The approach above shows how the author has broken down the problem into its constituent parts – taking each in turn:

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3.2.1.1 Bicycle Method

The Bicycle model is constructed for 50%-ile adult male and 6-year old child cases. Existing literature was sourced to understand the current simulation work in this area within industry and academia and whether there is any consensus on direction. With the noted exception of a few institutions (Bellogi, Carter, Chawla, McLundie et al) it appears that there is little work being conducted in this area with the main emphasis being pedestrian studies.

The author procured existing production bicycles and these were tested in terms of material stress-strain and individual impact / quasi-static experiments (as detailed in Section 8).

Where it was not possible to test, material cards were substituted from known sources.

3.2.1.2 Humanoid Model

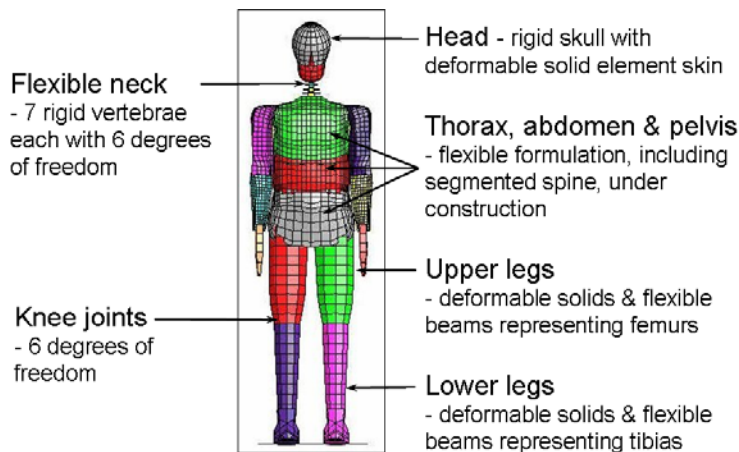


Figure 28 - Ford / CIC Humanoid Model Details

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The humanoid model created by Cranfield Impact Centre under a contract from Ford was at the time of writing the most biofidelic available to the author. To create something equivalent from scratch would have been a huge task and counter-productive to the main aims of this PhD.

The humanoid model was adapted to suit the riding position of the bicycle. A CAD model was supplied to Cranfield Impact Centre and the humanoid supplied in the correct orientation. It was not possible for the author to adapt this model himself due to contractual issues.

The formulation of the model was not altered considerably, as the joint stiffnesses were created from a function for each of the 6 degrees of freedom. Once complete an initial model was constructed and refined once physical test results were secured. For further details see Howard (Howard et al., 2000)

3.2.1.3 Light motorcycle / scooter

The light motorcycle case was included as a counterfoil to the main cyclist study. From an early stage it was apparent that testing would not be a possibility due to budgetary and time restrictions, and would have to rely on previously published data. Fortunately this was available, and material was gained from papers by the likes of Fuji (Fujii, 2003) et al.

3.2.1.4 Vehicle

The vehicle is the same as that created by Howard (Howard, 2002), and has not been significantly altered. It should be noted that this vehicle represents

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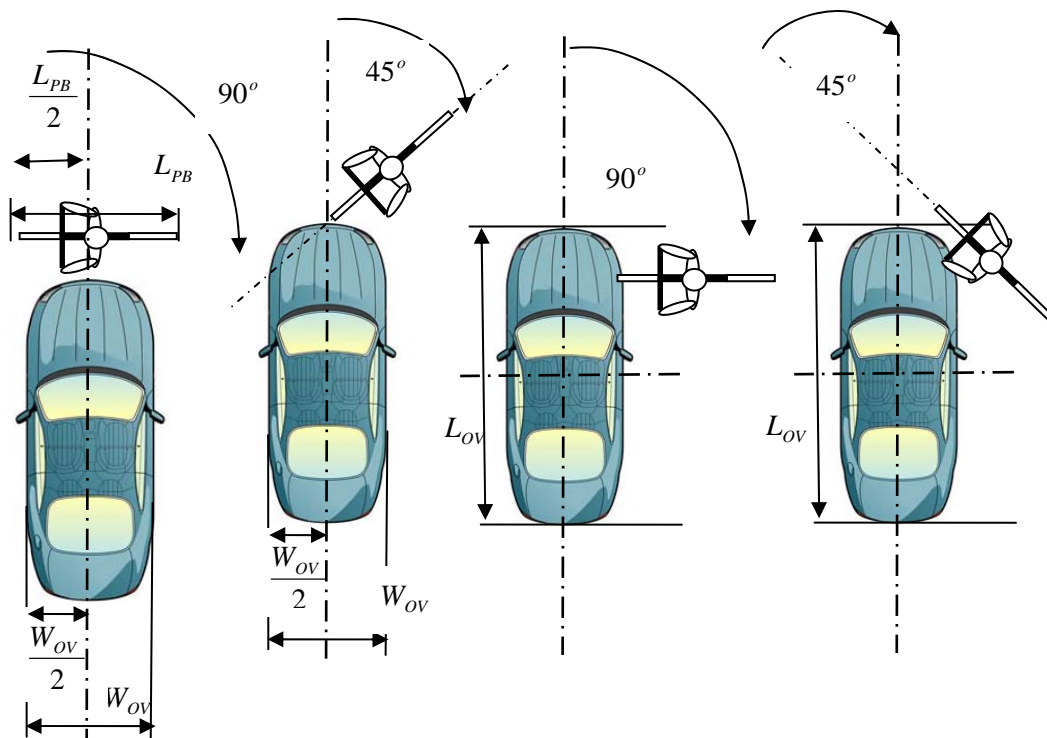
an older production vehicle that is not specifically designed for pedestrian safety. The rationale for using this model was that it was fully correlated by taking each individual component and performing impact tests at representative energies for pedestrian safety. This method was used at the component, sub-system and system level. The FE model was correlated at each of these levels. The author used this model as it was the most accurate available at the start of the course of work. Other models are available on-line but the pedigree and accuracy of these models is at best variable.

In addition that due to the vehicle having been in production for some time, it was likely this vehicle could be involved in a cyclist incident. This did indeed occur and details are shown in Appendix A. For further details see Howard (Howard, 2002).

3.3 Studying Cyclist Cases

3.3.1 Orientations – modified ISO 13232

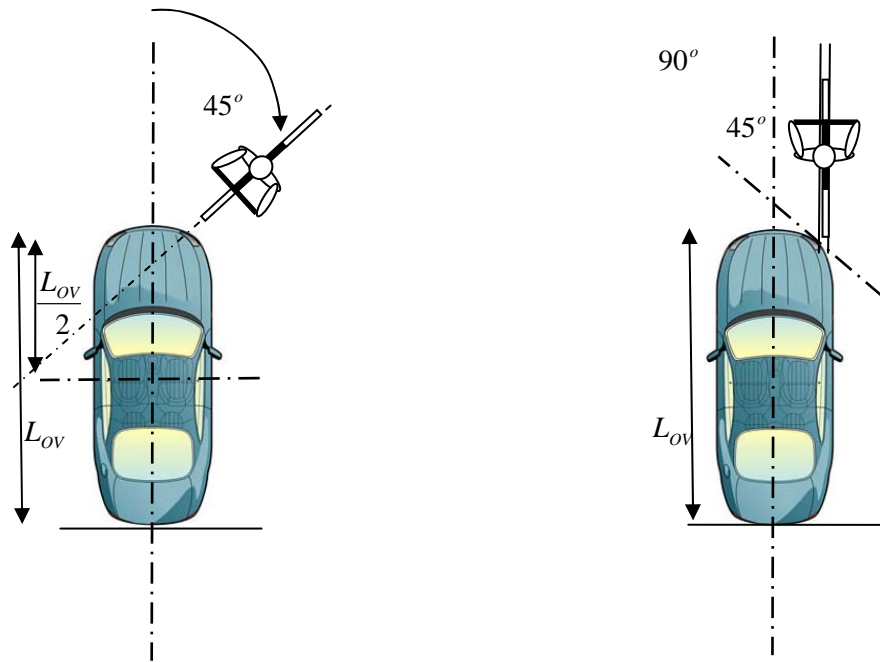
The following diagrams use the same methodology of the ISO 13232 standard, but are adjusted according to the accident variation seen in the real world statistics seen to date (see previous chapter comparing collision orientations).



Note the subscripts OV=opposing vehicle and PB=pedal cycle

Configuration	1	2	3	4
V_{OV}	40kph	40kph	40kph	40kph
V_{PB}	0kph	20kph	30kph	20kph

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Note the subscripts OV=opposing vehicle and PB=pedal cycle

Config	5	6
V_{OV}	40kph	40kph
V_{PB}	20kph	5kph

Figure 29- Main Modified ISO13232 Orientations for cyclist case.

3.3.2 Conclusions and application to Biomechanical Modelling

As with all analytical approaches there are limitations – for instance it is problematic to know how the rider will respond to external stimuli and how this will be manifested physiologically. For instance if a rider sees and can react to a potential collision it seems conceivable that his arms will lock out and use maximum muscle tension to grip on the handlebars. It seems reasonable to assume that this can give a significant effect on kinematics (as shown by Soni, Chawla et al – SAE2006-01-0460 for lower limbs in pedestrian RTA's), and may have a significant impact on injuries. For example - referred injuries such as patients when they collapse who tension an out-stretched arm to arrest their fall may break their clavicle (collarbone) when the load passes through their arm. Clearly muscle tension / relaxation may have a significant effect, but for the purposes of this study due to the complexity in understanding the variations, it has been overlooked as a secondary noise factor.

In summary the following targets are taken, based on previous work by Yang et al.

Investigation of 2-Wheeled Road Traffic Accident Scenarios using Explicit FE Techniques.

Parameter	Body Segment	Tolerance Level
Force	Tibia	4kN
	Knee	2.5kN (Shear)
	Femur	4kN
	Pelvis (Male)	4kN
	Pelvis (Female)	10kN
HIC	Adult	1000
	Child	850
Linear Acc.	Head	80g
	Thorax	60g
	Tibia	150g
Angular Acc	Head	3000 rad/s ²
Rotation Angle	Knee	15 degrees
	Neck	60 degrees (approx)
Bending Moment	Knee	350Nm
	Tibia	200Nm
	Femur	220Nm
Translocation	Knee	6mm

Table 4 - Summary of targets from clinical studies (Yang et al)

3.4 Numerical Method and Its Application

The mathematical principles for the F.E. method were put forward by R.L. Courant (Courant, 1943) for vibration problems in structures. With subsequent researchers realising its potential for use in computer routines, due to its use of matrix methods, it has now been applied from problems as diverse as fluid flow to electromagnetic simulation, but it is in structural analysis that it has had the biggest impact.

This technique is an extremely powerful method of breaking down a structure into discretized elements with their own particular properties. Each element has a number of nodes (2 for a beam, 3 for a triangle, and 4 for a quad element etc). The nodes act as the mathematical means by which the

Investigation of 2-Wheeled Road Traffic Accident Scenarios using Explicit FE Techniques.

computer works out the loading and direction on the adjoining set of nodes. The elements themselves are given the particular properties of the working material (stiffness, density etc) and from this the desired results can be processed

These nodes and elements make up a grid known as a mesh. Within limits, the more dense the mesh, the more accurate the answer will be, however this has an impact on computer time and thus only areas of special interest are refined to supply the most accurate answer.

Initial FE techniques concentrated on linear problems, that is constant material properties during the event under investigation. This does not happen during high-speed impacts. For instance the stiffness of a material can become non-linear at high strain rates. For this reason Dr J. Hallquist created an explicit non-linear code in 1976 called DYNA-3D. A commercial version of this code (LS-DYNA™) is being used by the author.

Rigid multibody techniques (e.g. TNO's MADYMO™) are another method of emulating real-life problems. A series of rigid parts are joined using pre-defined constraints and boundaries (e.g. a knee joint). This can be used to give a good representation of a highly complex system and give a fast turn-around of results. It enables particular areas of interest to be highlighted quickly and in-depth FE techniques to be applied as appropriate.

As computing power has increased, it has become more practicable to produce a car to VRU (vulnerable road user) crash model. Even as recently as 1994 it was suggested that the application of FE methods were too slow

Investigation of 2-Wheeled Road Traffic Accident Scenarios using Explicit FE Techniques.

compared to that of multibody rigid analysis (Wismans and Janssen, 1994). Although the rigid body technique is a very powerful tool (still used in occupancy modelling very effectively) this may not be true in the future. With VRU modeling, FE models have the ability to give much more intrinsic detail at a more fundamental level (e.g. MADYMO uses a simple linear material model for foams, whereas LS-DYNA can use a full hydrostatic model), and this level of detail may affect the overall results in the more complex analyses of the future (i.e. post-impact kinematics, accelerations, etc.)

4 Results from Physical Experimental Investigation

4.1 Overview

4.1.1 Objective

The purpose of the testing is to characterise the materials, the major sub-components and the complete bicycles themselves as accurately as possible, so that the deformations and crush mechanisms that may effect the overall kinematics of the humanoid in the final, detailed cyclist-to-vehicle model can be modelled accurately in a typical cyclist to vehicle impact.

4.1.2 Test Approach

Firstly bicycles are procured that are representative of the majority of commuter cycles on the roads in the EU. One frame of each type is sacrificed to be cut into material samples

The dynamic testing splits into two main activities:

- longitudinal impacts
- lateral impacts

This is in line with the evidence from real-world accident data and the proposed modified ISO 13232 method as put forward by the author in Figure 24. The longitudinal impacts are mainly investigating wheel collapse / buckling, as this will be the major deformation mechanism (particularly when impacted from the rear – the front less so, due to the forks rotating the wheel away from impact when placed under load). The lateral impacts mainly

Investigation of 2-Wheeled Road Traffic Accident Scenarios using Explicit FE Techniques.

investigate the integrity of the frame and any failure modes that are not immediately obvious (e.g. the bottom bracket is a structural weak point).

4.1.3 Bicycle Characterisation & Materials Analysis

Tests were carried out on representative mass-produced modern bicycles – these are mass-produced in China (as are the majority of modern cycles in the EU and beyond) and were chosen as being available in superstores throughout Europe. Figure 30 shows the type of bicycles used in the testing. The adult bicycle is constructed of welded aluminium 7000-series tube. The wheel construction uses formed aluminium extruded rims which use steel self-tapping fixings at the join and are also conventionally-spoked.



Figure 30 - Adult aluminium bicycle and steel child's bicycle used in testing.

The child's bicycle is of steel tube brazed construction with wheels constructed in a similar way to the adult cycle. 10 sets of each type are procured for testing as described in the following text.

Investigation of 2-Wheeled Road Traffic Accident Scenarios using Explicit FE Techniques.

The frames were cut up and examined for the relative gauges, as shown in Table 5.

	Mens Bike		Child's Bike	
	Thickness	Diameter	Thickness	Diameter
Top Tube	1.80mm	31.80mm	1.20mm	35.00mm
Seat Tube	2.30mm	35.00mm	1.50mm	29.00mm
Down Tube	2.00mm	35.00mm	1.20mm	38.10mm

Table 5- Bicycle material gauges.

Material tests were conducted on the constituent materials from the frames by Cranfield Impact Centre under instruction from the author, and the following material definitions were chosen, as shown in Table 6.

Model Material No.	Dyna Material	Material	Density (tonnes / cubic metre)	Young's Modulus E (MPa)	Poisson's ratio	Yield Stress (MPa)
Al Frame	*MAT_PIECEWISE_LINEAR_PLASTICITY	7000 Series Aluminium Tube	5.66E-09	70000	0.33	460
Steel Frame	*MAT_PLASTIC_KINEMATIC	Chrome-Molybdenum-Steel	9.00E-09	208000	0.3	240
Pedals, Cranks, Seat	*MAT_RIGID	Properties Based on Chrome-Moly-Steel				
Handlebars	*MAT_PLASTIC_KINEMATIC	Steel	7.89E-09	207000	0.33	200
Wheel Rim	*MAT_PIECEWISE_LINEAR_PLASTICITY	Aluminium 6061-T6	5.66E-09	70000	0.33	259
Wheel Spokes	*MAT_PIECEWISE_LINEAR_PLASTICITY	Steel	7.89E-09	207000	0.33	210

Table 6 - Material Data used in Bicycle / Motorcycle Model.

4.2 Initial Tests

4.2.1 Scope

The author proposed the following test series (Table 6) be carried out at the Jaguar Engineering Centre using a dynamic rig sled. The principle of operation is that smaller vehicle sub-system tests can be performed on

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vehicle programmes quickly and at moderate cost in-house. An energy-balance can be calculated for a given impact, and using a determined dropped mass connected by hawser to the sled, it can be accelerated to a given speed at impact. The author could not conduct the test directly due to health and safety implications, and instructed a qualified test engineer to carry out the investigation according to the following description.

4.2.2 Testing

Initial tests were carried out on an adult steel frame and an adult aluminium frame to understand how the structure would withstand a known impact and to investigate any strain-rate dependencies (particularly for the aluminium welds). The initial test series culminated in a single longitudinal wheel impact, again using a trolley method, and attempting to constrain the wheel using the forks as shown in Figure 33. This was attempting to understand how the wheel buckling would occur in a realistic dynamic impact. This was latterly discounted and abandoned, due to lack of control of the trolley / wheel combination and deciding that although the most effective way of mounting the forks to the trolley, this was not representative of real-world as discussed later in section 4.3.2.

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Table 7 below shows the tests that were carried out:

Test Number	Velocity	Set – up	Bike Frame Type.
1	11.97m/s	Bike frame free flight into vertical rigid impactor	Alum frame
2	No trig	Bike frame free flight into vertical rigid impactor	Alum frame
3	6.95m/s	Bike frame strapped to sled. Vertical rigid impactor	Alum frame
4	6.95m/s	Bike frame strapped to sled. Vertical rigid impactor	Steel frame
5	6.95m/s	Bike frame strapped to sled. Horizontal rigid impactor	Alum frame
6	6.95m/s	Bike frame strapped to sled. Horizontal rigid impactor	Alum frame
7	6.95m/s	Bike frame strapped to sled. Horizontal rigid impactor	Steel frame
8	6.95m/s	Longitudinal wheel impact	-

Table 7 - Format of initial testing.

These initial tests looked at examining the dynamic lateral impact of frames vertically and horizontally using a distributed-mass system as shown in Figure 31 below. The impactor used was an FMVSS 214 cylinder used in side intrusion tests.

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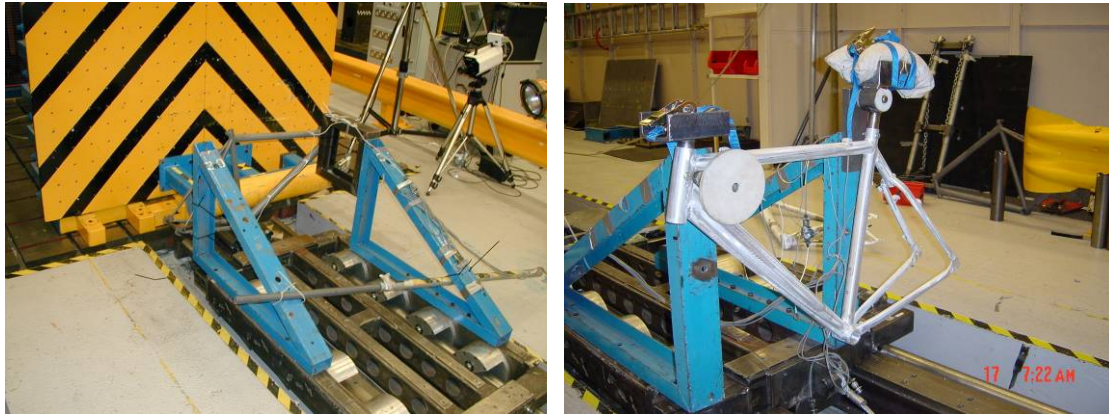


Figure 31 - Format of initial testing.

The drop-rig shown above at the Jaguar Engineering Centre was initially configured to create a transverse throw for a weighted bicycle frame (mass at the seat approx 20kg) at a 40kph impact speed. This was conducted for the first two impacts, but the instrumentation (reference accelerometers) was damaged in the test, so a simpler method with the frames constrained was used latterly.

As can be seen in Figure 32 the steel frame's joints withstood the impact, but the aluminium frame's joints failed at the join between the seat stay and the seat tube. From previous experience on aluminium vehicles a strain-to-failure of approx 15% was chosen as a failure criterion for welded joints in an LS-DYNA™ model for this material.



Figure 32 - Comparison of performance between steel and aluminium frames.

4.3 Wheel Collapse Tests

4.3.1 Scope

Most mass-manufactured bicycle wheels are still of rim and spoke construction, however, rather than a steel rim, most now use extruded aluminium alloy formed into a C-section shape and fixed together with a self-tapping steel insert.

If the cyclist is involved in a frontal or rear impact (accounting for approx 40% of all incidents) the first structure involved in the impact is the wheel. For this reason a relatively detailed model was attempted, and therefore understanding of how the collapse mechanism takes place was required.

Rim-spoke buckling and collapse is a particularly difficult problem, as it is highly non-linear. The wheel is a stressed structure since each of the spokes exerts a tensioned force between rim and hub. The tension and layout of

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these spokes can have a significant effect on the collapse characteristics, so it was decided to take the available mass-produced wheels as being representative of those in mainstream use.

There is little work attempted in this field – Fuji created an explicit motorcycle wheel which including modelling the nylon bands within tyre construction. This complex model shows good correlation to simple drop-tests, but there is no attempt to explain how this micro-level model can be adapted to a vehicle-level version.

The motorcycle wheel, however, is structurally different to the bicycle wheel with a much larger and more robust rim section, resulting in less buckling in dynamic crush. No testing was conducted on motorcycle wheels, but work derived from Fuji et al was used in the construction of a rudimentary wheel model.

4.3.2 Test Method

Initial tests attempted to perform a dynamic impact in representative circumstances, however this was found to be unsatisfactory in the initial attempt due to the test set-up (the small sled on which the wheel was mounted was unstable and could not be constrained in the test configuration), and this method was abandoned.

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Figure 33 - Initial attempt to replicate rim-spoke dynamic collapse.

Instead of this approach a second method was created at Cranfield Impact Centre using the 233kg pendulum rig.

4.4 Follow-On Testing

4.4.1 Scope

As a result of this initial series of tests it was decided to try and complete a more comprehensive series of tests to characterise the wheel crush in particular. The author specified the following tests to be performed at Cranfield Impact Centre for an adult aluminium bicycle and a steel child's bicycle:

- Longitudinal quasi-static crush from front and rear using a hydraulic ram rig, measuring force-deflection of the wheel / frame.
- Longitudinal dynamic crush using CIC's 233kg pendulum rig from rear to examine wheel buckling.

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In both cases the frame was constrained at the saddle post and the header post.

The objectives were:

- characterise frames in longitudinal axis
- understand wheel collapse
- understand wheel / frame interaction

Each relevant test is now described (note additional testing was carried out that is not directly relevant, so the test numbering is not sequential).

4.4.2 Test 5

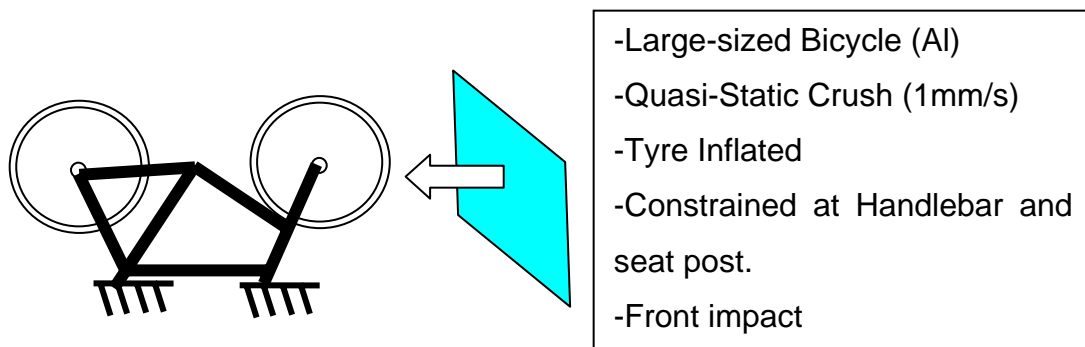


Figure 34 - Test 5 scenario

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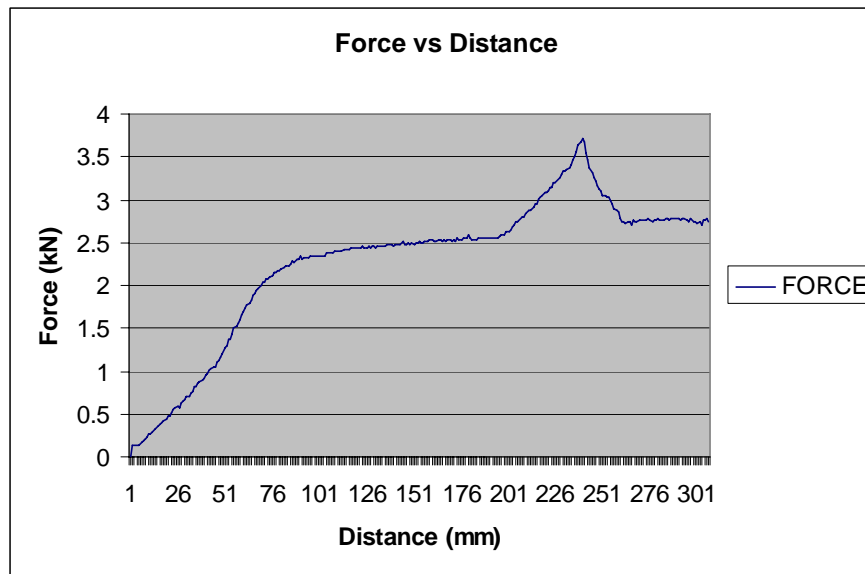


Figure 35 - Force vs Crush for Test 5

4.4.2.1 Analysis of Test 5

The initial part of the graph shows the load increasing until the junction of the header tube / forks starts to deform plastically (at approx 2.5kN). The load plateaus at this point until the forks bottom out and the wheel collapse mechanism takes over. The wheel fails at approx 3.5kN, and the fork assembly rotates away from the impact wall.

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4.4.3 Test 6

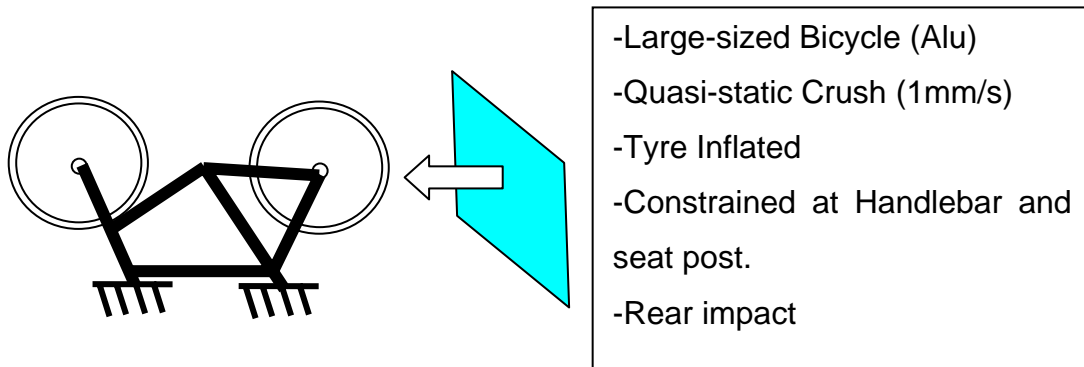


Figure 36 - Test 6 Scenario

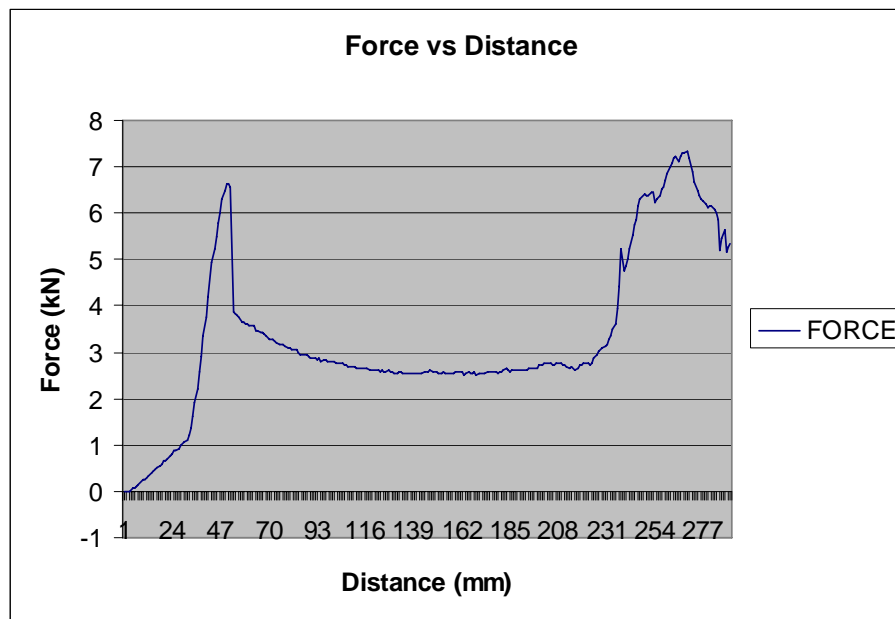


Figure 37 - Results from test 6.

In this test the load increases to an initial peak at just under 7kN. This is the initial failure of the wheel rim. The load drops to a steady 2.5kN and then

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rapidly increases as the influence of the frame takes effect, until the wheel pops from the frame attachment at a peak load of 7.3kN.

4.4.4 Test 7

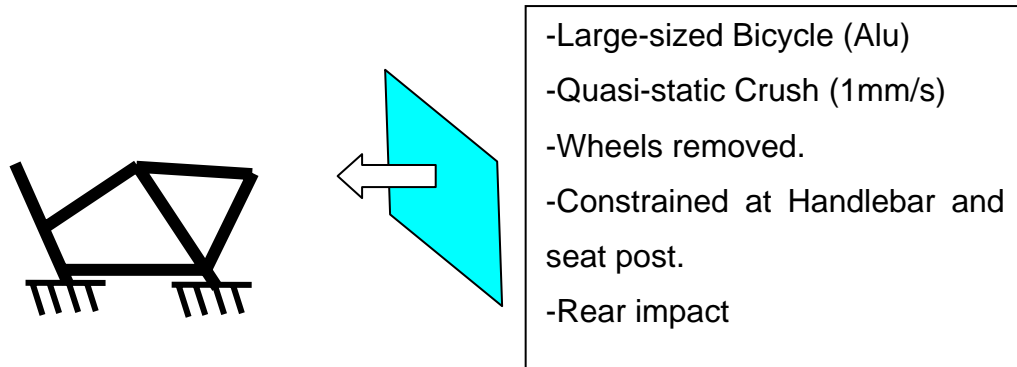


Figure 38 - Test scenario 7.

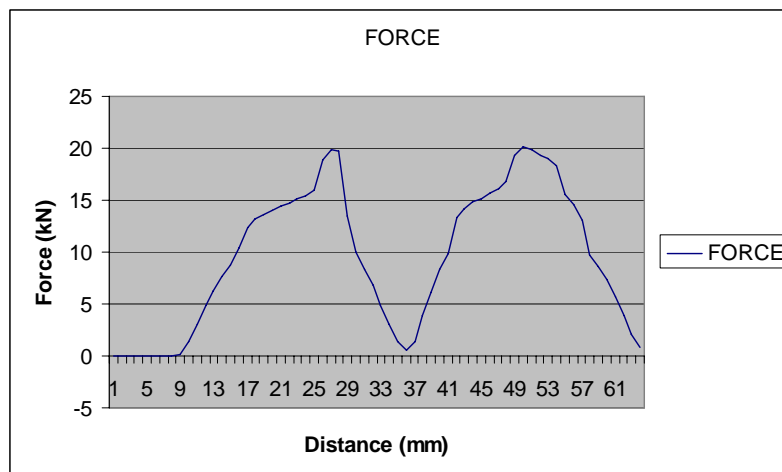


Figure 39 - Results from Test 7

This figure shows the failure profile of an aluminium bicycle frame. The initial peak force of 20kN is the point at which the wheel fittings buckle; this is then followed by failure of the chain stay / seat stay at approx 53mm.

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4.4.5 Test 11

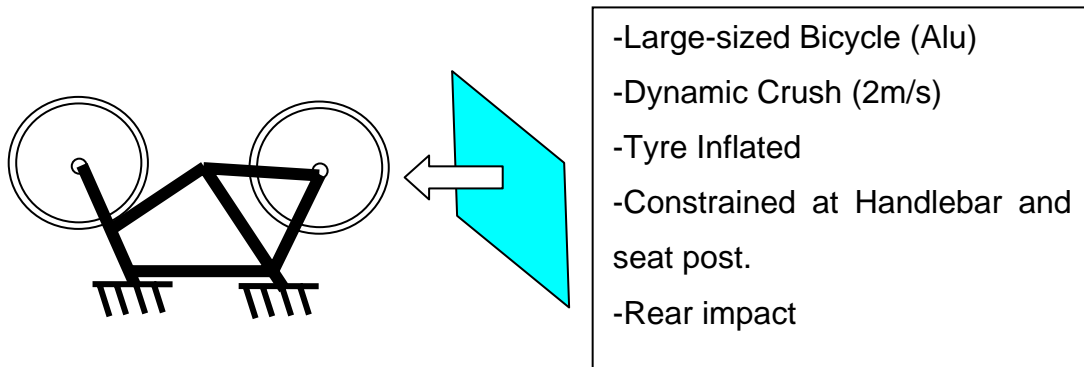
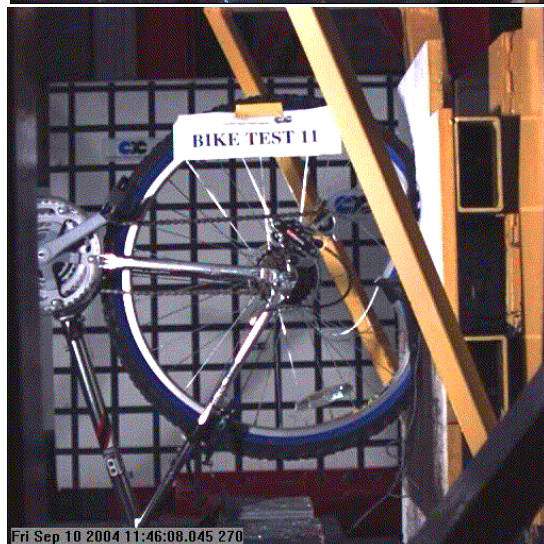
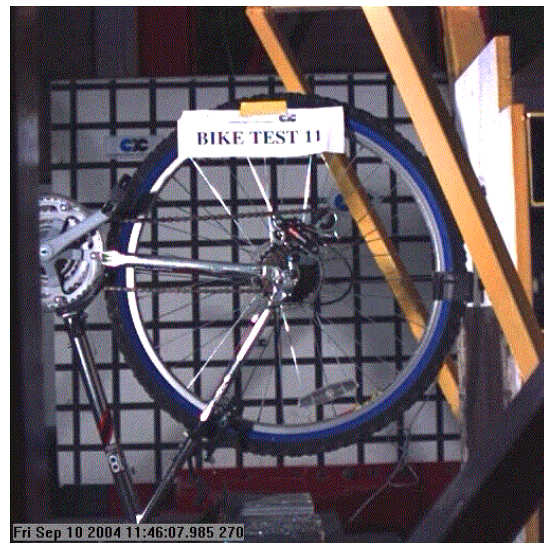
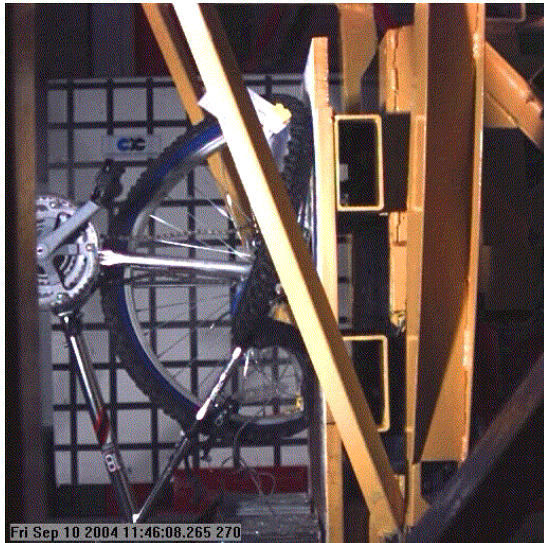


Figure 40 - Test 11 Scenario

There is no load data from the dynamic collapse, but knowing the mass, and speed of the pendulum, visual analysis for the model can be useful.

The following set of pictures from the animation show the dynamic collapse of the spoked wheel. Note the tyre bursting on the last frame.

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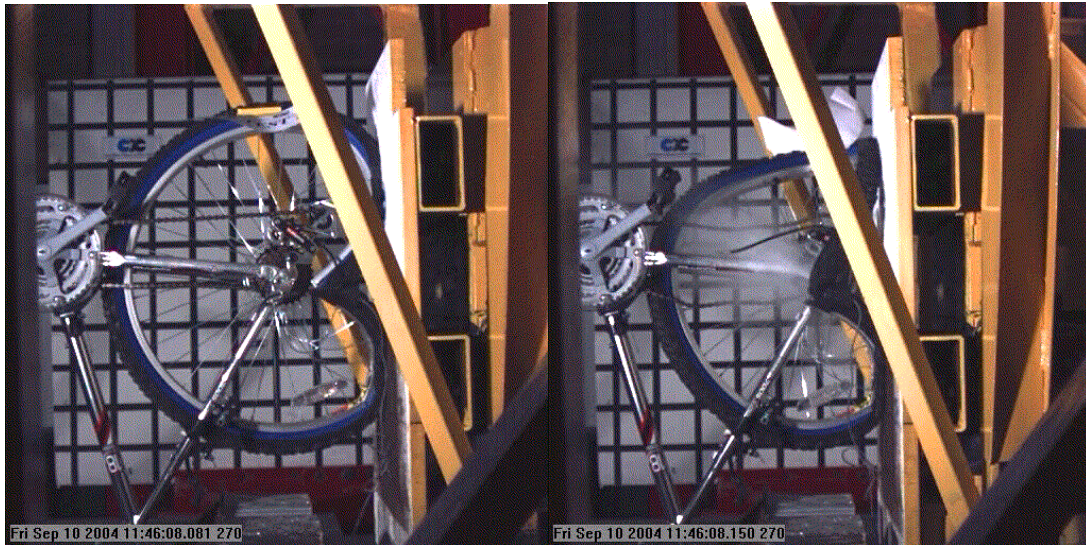
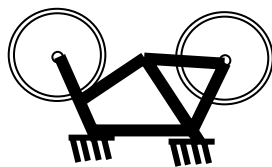


Figure 41 - Dynamic collapse of a wheel (test 11).

Test 14



- Child-sized Bicycle (Steel)
- Quasi-static Crush (1mm/s)
- Tyre Inflated
- Constrained at Handlebar and seat post.
- Rear impact

Figure 42 - Test 14 Scenario

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Figure 43 - Quasi-static Test Pre-Impact

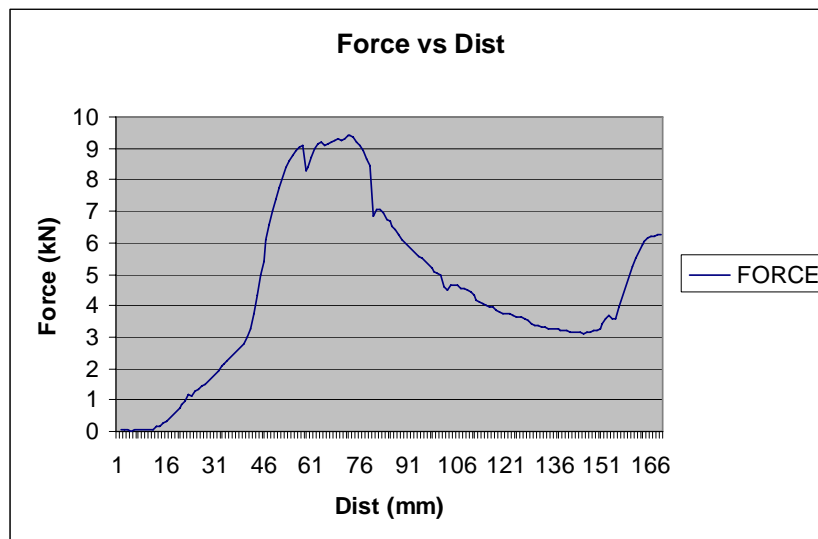


Figure 44 - Test 14 Results

Again there is a peak load of just over 9kN as the wheel buckles, before the effect of the frame picks up at 150mm intrusion.

4.4.6 Test 15

Test 15 is a repeat of test 14

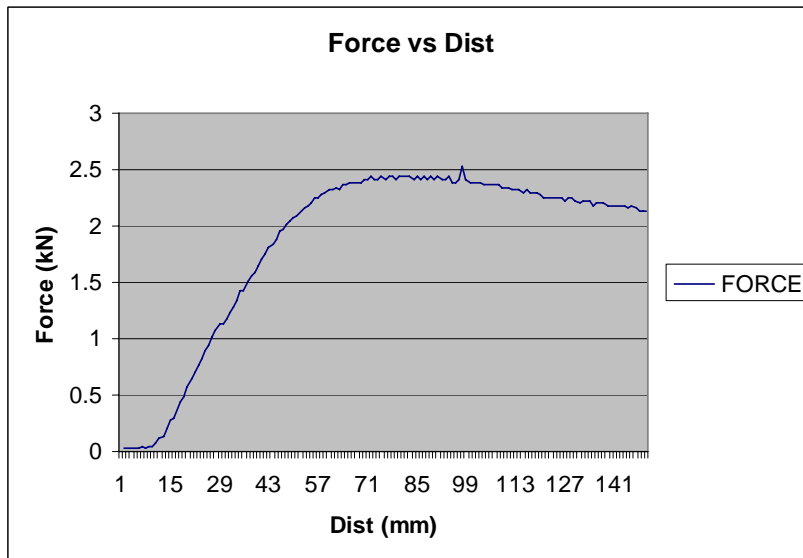


Figure 45 - Test 15 Results

The reason for the difference in values between this test and test 14 is that the wheel buckled laterally early on in the experiment, resulting in a much lower load response.

4.4.7 Test 16

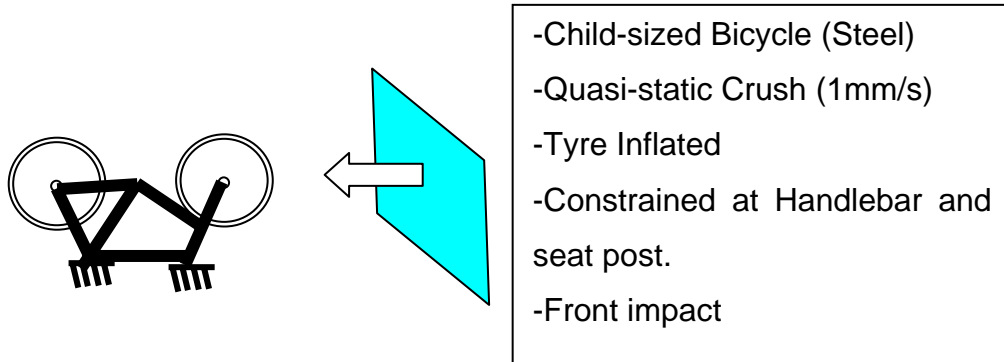


Figure 46 - Test 16 Scenario



Figure 47- Test 16 Results

In this test, the forks distort initially and the wheel rotates away from the wall as it intrudes, resulting in a modest load response.

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4.4.8 Test 17

Repeat of test 16



Figure 48 - Test 17 Results.

Similarly to Test 16 the forks buckle and there is less wheel rotation away from the impact wall as it intrudes. Peak load is just under 2.5kN

4.4.9 Summary

A repeatable sequence of testing on the bicycle frame / wheel combination was difficult to achieve. As can be seen from these results the performance in quasi-static and dynamic tests is highly non-linear. The most 'reliable' results come from rear impacts into the rear wheel (i.e. tests 6, 11 and 14).

5 Mathematical Modelling and Analysis

5.1 Introduction

As stated in the literature survey, there has been very little detailed analysis of bicycle to vehicle accident reconstruction using finite element methods. To this end the author has had to create models and methods not tried before and as such have been a genuine case of learning in many areas as the investigation has progressed.

The main part of this work has been examining the cyclist case, however a section on how the motorcycle was constructed and cycle helmet model construction are also included. A summary is given for the adapted models to review some of their assumptions as well.

Details are presented of individual bicycle component tests, their results and comparison to the testing carried out as described in the previous section.

5.2 Geometry and pre-processing

All geometry generated or adapted in this study were created using SDRC's I-DEAS computer aided design (CAD) package at the Jaguar Engineering Centre. This forms one part of C3P – an integrated system allowing generation of geometry, pre-processing and a limited solving capability (for implicit problems only). The 3-D solid CAD was generated for each constituent part of the bicycle (and motorbike) and the surface extracted. From this a mesh could be created – either manually or by automesh (which usually

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required manual intervention to keep the mesh to a uniform consistency & quality). Hypermesh (another pre-processor) was available latterly, but the author had started his work using I-DEAS and wanted to continue with a consistent process.

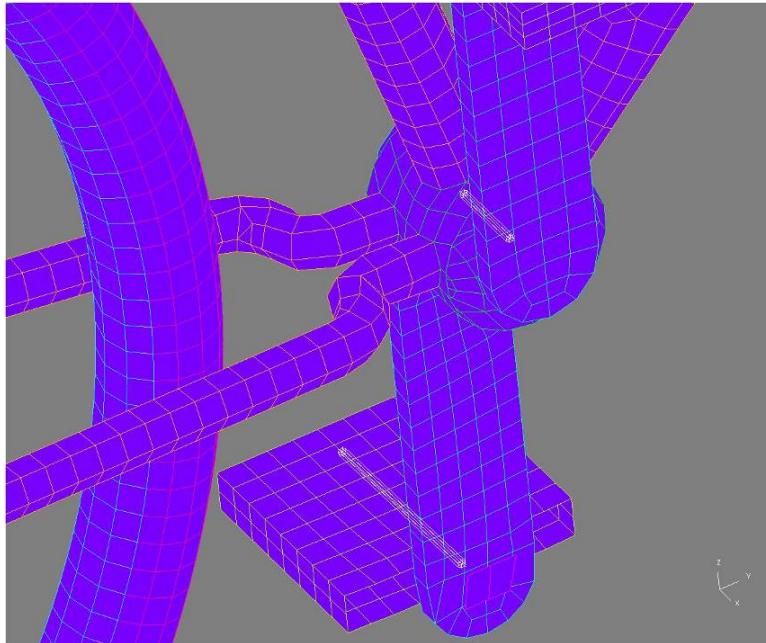


Figure 49- Mesh detail showing cylindrical joint on pedals

The explicit solver used was LSTC's (Livermore Software Technology Corporation) LS-DYNA. This is the most recent generation of the explicit method originally descended from the original DYNA code created by John Hallquist. Three versions were used in the analysis as time progressed. LS-DYNA 950e, 960 and 970-5434a. When a code change occurred, checks were made on a simple 'standard' model to ensure consistent results could be relied upon (within 5%).

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The mesh was mainly built of the Belytschko-Lin-Tsay element formulation – according to LSTC (LSTC, 1999) due to its computational efficiency, this element type has become the element formulation of choice. In addition it is relatively robust, even with relatively large warp angles it will not cause coredumps. In order to minimise any likelihood of hourglassing (or other reasons for runtime error) the author maintained quality checks on each model as follows:

Issue	Quality Check
Free Nodes	Delete free nodes
Free Edges	Use free edge check in meshing tool
Element Warping	15 degrees max. warping allowed (mesh check)
Small internal angles	45deg<Internal angle <120 degrees for quads >25 degrees for triangles.

Table 8 - Mesh quality criteria

Once a run was completed, any added mass greater than 3% of the original was scrutinised and any mesh formulation errors corrected. This is standard practise in industry and is based on the recommendations of DuBois et al.

The KEYWORD file is the input deck to the solver. Once the mesh has been created, with the required part, material and physical property naming it is possible to formulate the rest of the analysis using PRIMER to create the Keyword file. This includes Boundary Conditions, adding material properties, and the control cards for the run (e.g. termination details) and output data files (ptf / thf / xtf files). In addition the contact groups are also added at this stage, giving control on any physical interaction within the components within the model.

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One such example of a control input is the timestep – this is derived from the speed of sound through the densest material with the minimum element size.

The minimum shell size was kept to 5mm, as this was equivalent to a timestep of 9.22×10^{-7} , as shown in the following calculation:

$$\text{Stable Timestep} = \frac{\text{Characteristic Element Length}}{\text{Acoustic Wave Speed in Element Material}}$$

Where, for steel:

$$\text{Dilatational Wave Speed} = \sqrt{\frac{203000}{0.78 \times 10^{-8} [1 - (0.3^2)]}} = 5,420,000 \text{ mm/s}$$

For a maximum 4-node shell element length of 5mm:

$$\text{Element Length} = \frac{\text{Area}}{\text{Max}(L_1, L_2, L_3, L_4)} = \frac{25}{5} = 5, \text{ Hence:}$$

$$\text{Stable timestep} = \frac{5}{5,420,000} \approx 1 \times 10^{-6}$$

Equation 2- Calculation of minimum timestep for model stability.

All models were created in line with the standard LS-DYNA metric units (Newtons, tonnes, mm, seconds, Kg and MPa).

The following gives an overview of the construction and validation of each model.

5.3 Humanoid Simulation

5.3.1 Background

The humanoid model used in the simulation has been developed by Cranfield Impact Centre under a Ford contract (Howard et al., 2000) specifically for use

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in determining the real-world effects of devices developed to improve pedestrian safety. It is an LS-DYNA model using elements from HYBRID III and EuroSID crash dummies, and heavily modified to give the best possible biofidelic performance (within reasonable run-times). The material models were adapted to as real-world a response as possible by using cadaver data from published papers by Ishikawa (Ishikawa et al., 1992) et al.

In addition, the humanoid can be adapted into any size or ethnic group by manipulating the 50%-ile 'reference model' by changing the regression equations in the 'GEBOD' model. For the purposes of this initial study, a male 50%-ile humanoid will be used as standard.

Most simulation of cyclist and motorcyclist accident scenarios have been developed using rigid-body methods (TNO's MADYMO routine in particular). This is an effective method to give a parametric appraisal of the crash kinematics (particularly when dummies have been used in a physical crash test), however, when examining injury criteria, it has been shown that a more complex FE model will provide better biofidelic response in a complex crash case.

Results from the pedestrian use of the model have been very promising, and it is hoped that further development of this technique will yield a useful design tool for examining real-world crash scenarios when new deployable technologies become available. The next step on from this is to examine how two-wheeled crash events can be mitigated. It is hoped in both cases that suitable real-world accidents can be found that allow the model to be correlated. For further details see Howard (Howard, 2002).

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5.3.2 Head

The head is uses a rigid material for the skull (LS-DYNA MAT 20) and a deformable skin. A central accelerometer element is used to assess head deceleration, and it is from this that the HIC value is calculated. In addition it is also possible to examine head rotational acceleration / deceleration, which as previously stated in the literature survey, is another injury mechanism of interest.

In terms of detailed injury analysis it is possible to take the acceleration trace and apply this to a more complex sub-model (which can include analysis of brain stem rotation / shear, CSF fluid analysis and failure criteria for blood vessel haemorrhage). These areas are still under development, and so this study will only examine the acceleration trace and HIC.

5.3.3 Neck

The neck is a flexible formulation with seven rigid vertebrae and 6 degrees of freedom. This formulation builds on work derived to create the EuroSID side impact dummy. Clearly a representative biofidelic neck model has direct implications for HIC, as potential 'whiplash' effects can accelerate the head onto the stuck surface in an RTA.

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5.3.4 Thorax & Pelvis

As mentioned in the literature section, the thorax is a difficult body area to model due to the large volumes of soft tissue with complex interconnecting tissues. As a result a rigid material is used for the thorax, abdomen and pelvis.

Future work is examining a flexible formulation with a segmented spine, however this was not available. Peak chest force and acceleration will be monitored.

5.3.5 Legs & Knee Joint

The leg models use deformable solids for skin and surrounding tissues and a flexible beam formulation for the tibias. By using a segmented beam method and applying the appropriate constraints at each beam end, it is possible to gain good correlation to cadaveric test data.

The knee joint has 6 degrees of freedom, and the physical movement is constrained to achieve good biofidelic performance.

For more information see Howard et al (Howard et al., 2000).

5.3.6 Child Model limitations

The child model is created in the same methodology as above, however the data is scaled from adult data, which is a major limitation. Children's physiology is considerably different to adults and can suffer different injury mechanisms (e.g. Epiphiseal plate failure in long bones).

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This is and will remain a difficult area of research due to very little 'real-world' cadaveric data being available for researchers.

5.4 Vehicle Model

This is a mid-size family car model, as developed by Howard, as part of the on-going development work on pedestrian safety. Clearly the effect of geometry on the crash event is a major factor in the results obtained, however it was chosen to keep to this vehicle, as this is a fully validated model for pedestrian collisions at 40kph and is equally applicable to the two-wheeler scenarios examined.

Individual components on the front of the vehicle are modelled in detail and have been correlated to individual impact tests aimed at pedestrian speeds (40kph). It should be noted that the remainder of the vehicle is modelled as a rigid item to reduce processing time and model complexity.

An *INITIAL_VELOCITY card is used to provide the 40kph vehicle speed, however a *RIGID_BODY_MOTION card attached to the rigid part at the rear of the vehicle provides a 1G deceleration to simulate heavy braking.

One area of the model that could be improved is the windscreen. The loads received by the humanoid in pedestrian impact were acceptable in correlation with physical tests at the centre of the windscreen according to Howard; however this was not the case closer to the boundary conditions at the edges. It would be beneficial to have an improved model for glass breakage, however

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due to variability in the manufacturing processes for these items it is a difficult task to achieve. New methods are being developed at Jaguar; however these are at an early stage and have not been published.

The vehicle model used in the simulations will be the same as used in the pedestrian simulations, as the energies and impacts are approximately the same, so the author believes this to be representative. It is an FE mesh of a typical family hatchback, created by Mark S. Howard at FFA Aachen. This has been chosen, as the vehicle has been fully correlated, and response from the model has been proven to be representative in component tests. For further details see Howard (Howard, 2002).

5.5 Bicycle Model

Creation of the model began by creating the basic geometry of a using a bike that is generally representative of those seen on the roads in the UK. The geometry is based on a commercially-available mountain bike. Three bikes were chosen as a basis for testing and analysis, but two were only used in the event as previously described. This section will show how the major components were developed and correlated.

5.5.1 Frame model generation and correlation to test

The frame was modelled in I-DEAS as per the physical data shown in the physical testing section and meshed using 4-node quadrilateral elements.

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Beam elements were considered (particularly at the early stages) however this was rejected as it was thought that the multiple interactions in the various contact groups would be difficult to control / visualise.

Sub-models were created to test the modelling assumptions for the frames, according to the component tests completed previously.

5.5.1.1 Lateral Impact

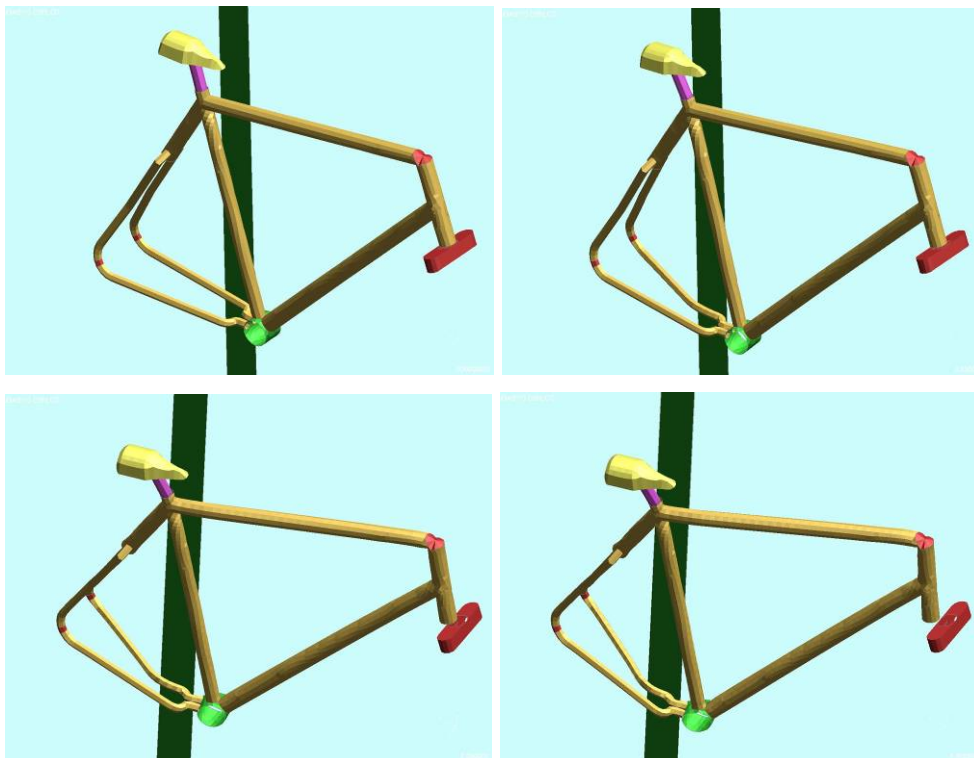


Figure 50- Lateral impact (233kg at 2.5m/s)

The frame was constrained at the wheel attachment and at the header tube and a simple rigidwall impactor using a Prescribed Boundary Motion card

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representing an impactor of 233kg at 2.5m/s struck the frame as shown in Figure 50.

Figure 51 shows the Force Displacement curve generated:



Figure 51 - Force displacement curve for Steel Frame (lateral impact).

From the graph it can be seen that there is an almost linear relationship. This seems reasonable as the steel framed bike is relatively homogeneous in terms of material and the joints performed without failure in the physical testing. Although there was no instrumentation on the frame, from the video analysis it is possible to conclude that, for the equivalent energy inputs, a

Investigation of 2-Wheeled Road Traffic Accident Scenarios using Explicit FE Techniques.

good correlation can be observed in the dynamic test (Figure 52). The final state of the steel frame post testing is shown previously and this deformation is in line with that of the final state shown above.



Figure 52 - Comparison of simulation to test.

It would be beneficial in any future work to perform more of this type of test to improve the sample size and therefore increase the known database of such tests.

The material card used was based on the chrome-molybdenum steel figures in and used a simple *MAT_PLASTIC_KINEMATIC card (LS-DYNA Material 3) without the Cowper Symonds strain rate model. This again was due to computational efficiency, however looking at a stress-strain model using a *MAT_PIECEWISE_LINEAR_PLASTICITY model may be worth examining in future.

5.5.1.2 Longitudinal Impact

A similar set of runs was performed to test the correlation of the longitudinal testing (again 233kg at 2.5m/s).

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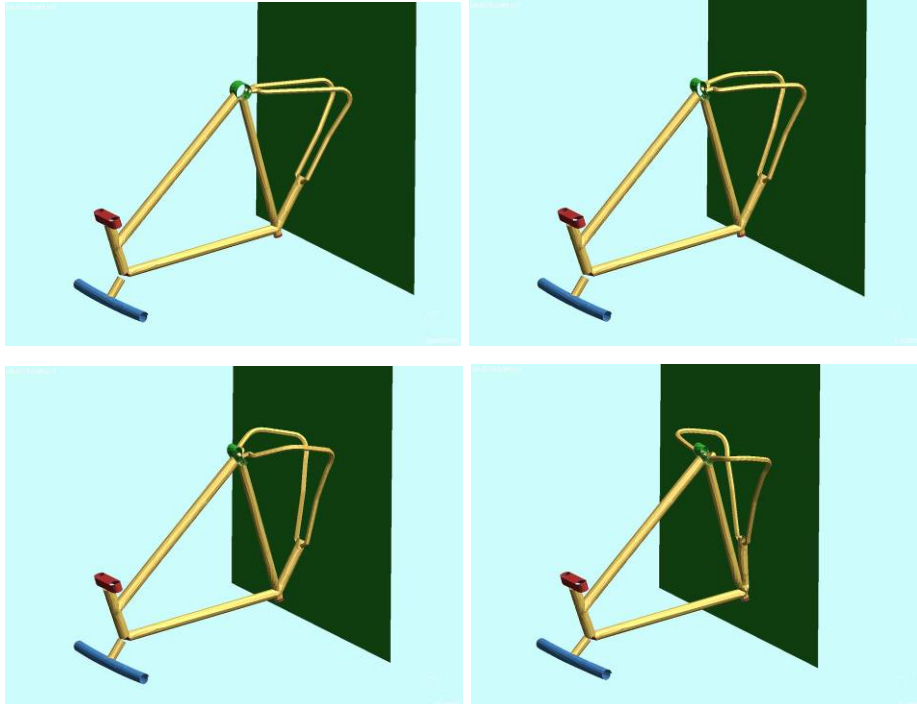


Figure 53 - Steel frame longitudinal simulation (2.5m/s 233kg)

Although tests on the frame were performed quasi-statically, the author decided it would be worthwhile understanding how the frame performed in this test, and allow data to be drawn from how the frame performed on its own without the wheel in situ. The impact was based on the same CIC impact (233kg impactor at 2.5m/s), and the frame was constrained using a constraint on the *MAT_RIGID material at the top of the header tube and the seat stock.

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Figure 54 - Force displacement graph (Longitudinal 2.5m/s, 233kg)

Figure 54 shows the force displacement for the longitudinal impact of the chrome-molybdenum-steel frame. Note that the graph should be read from right to left (the displacement was in a negative direction in the simulation). The initial loading peaks at around 14kN and as the chain and seat stays buckle the load drops to approx 6kN. After 220mm the simulation is no longer valid, as the rigid wall continued past the rigid seat stock and the noise observed is purely the deformable elements distorting.

This model contained 4124 elements and 4170 nodes and ran in 24mins on a single processor of a current workstation.

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From Figure 39 there is a difference in loading (the peak load is 20kN in the quasi-static physical test), however this test was performed on a 7000-series aluminium bike and only one test was performed. Again with more physical testing it should be possible to improve the fidelity of this model; however it is a reasonable assumption for the complete vehicle tests.

5.5.2 Wheel collapse simulation

The author wanted to successfully simulate the wheel structure collapse – this is a difficult task to achieve as the whole structure is pre-stressed due to the tension of the spokes. Initial attempts used springs to try and emulate this feature; however in the end a beam element method was used.

Taking the adult wheel initially, a model was created in I-DEAS and geometry was created of the rim and the tyre. The rim diameter (620mm) was meshed with a channel section (as per the physical rim) and the 40mm thick tyre was meshed as a toroid with a common node at the rim / tyre interface.

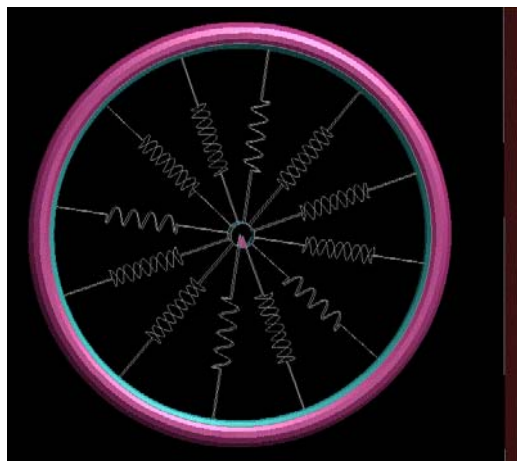


Figure 55 - Original Bicycle Wheel Construction

Investigation of 2-Wheeled Road Traffic Accident Scenarios using Explicit FE Techniques.

The original stressed spoke wheel model as used in main adult bicycle simulations is shown above in Figure 55. Discrete elements (*MAT_DISCRETE_NONLINEAR_ELASTIC) were used to create a pre-stressed spoke construction, and a *MAT_PIECEWISE_LINEAR_PLASTICITY model was used for the 6000-series aluminium rims. The tyre used a *MAT_PLASTIC_KINEMATIC steel model for speed (a foam model was examined, as was using an airbag model, but these were considered too complex for the contribution of the tyre to the wheel model).

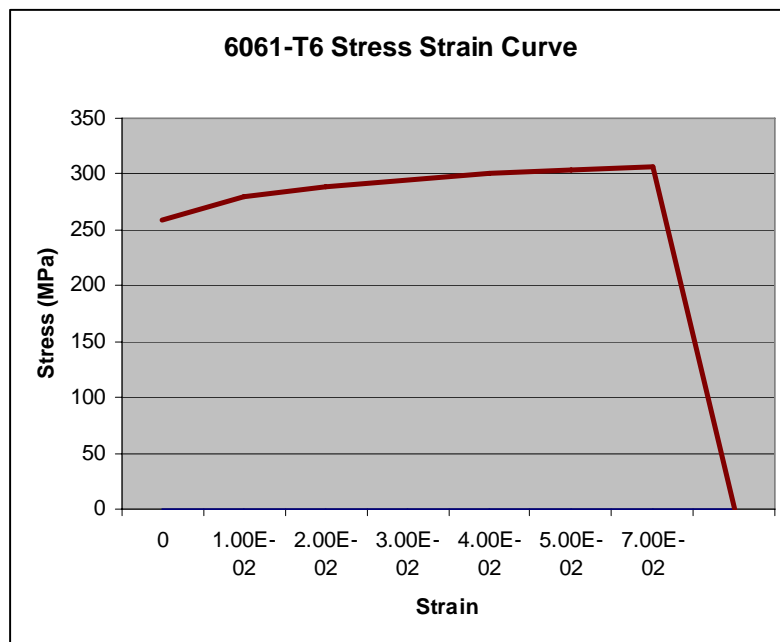


Figure 56 - 6061-T6 Aluminium Rim Stress Strain Data

No matter what was altered with regard to the spoke formulation the results were disappointing as seen below in Figure 57.

Investigation of 2-Wheeled Road Traffic Accident Scenarios using Explicit FE Techniques.

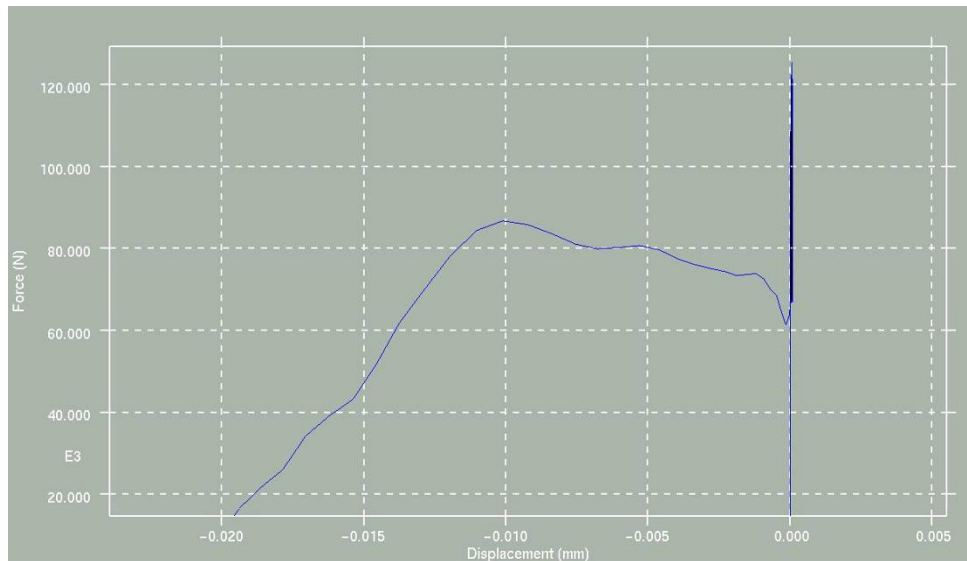
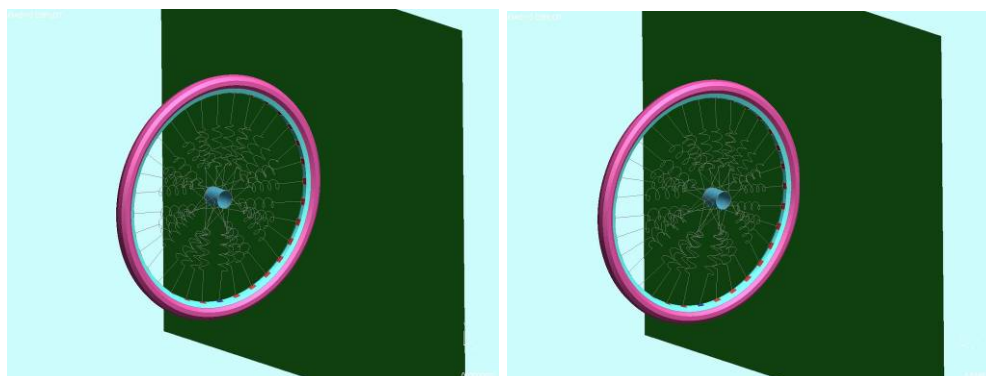


Figure 57- First wheel formulation - force vs dist.

As can be seen for the given 2.5m/s impact of a 233kg mass, the response is poor – an initial large spike of approx 120kN (which is a result of the spring modelling method used). Even the 80kN load response is clearly wrong. This model was clearly not correct.

The author studied the spoke arrangement of the wheel and wondered if this would make a difference, again using a discrete method, as seen in Figure 58.



Investigation of 2-Wheeled Road Traffic Accident Scenarios using Explicit FE Techniques.

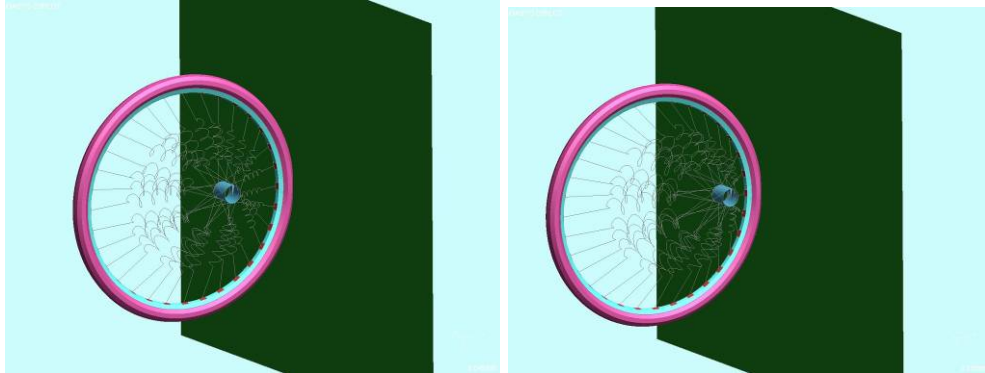


Figure 58 - Updated spoked wheel collapse.

Figure 58 shows a refinement of the original model using discrete elements in the same orientation as the physical spokes, with rigid patches on the rim to prevent local element distortion during crush. The results were similar to the original wheel and this method was abandoned for spokes.

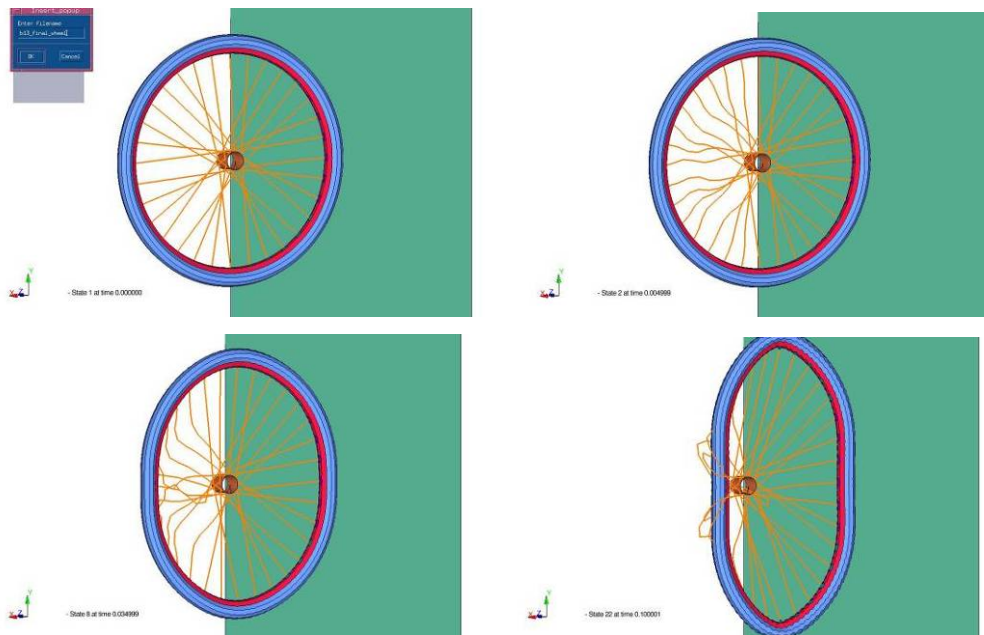


Figure 59 - Updated Wheel Model

Investigation of 2-Wheeled Road Traffic Accident Scenarios using Explicit FE Techniques.

Figure 59 shows the final version of the spoked wheel – this includes 'tunable' beam elements for the spokes and an airbag model for the tyre itself. In addition a *CONTACT_TIED_SURFACE_TO_SURFACE_FAILURE model was used between the rim and tyre to promote rim buckling.

The beam card is shown in Figure 60. By having two sets of beam material cards (one slightly less stiff on the left circumference than the right) it was possible to tune the buckling of the wheel in conjunction with the contact method mentioned above. A method using a strain-to-failure deletion formulation may have improved the collapse mechanism but this was not tried.

Investigation of 2-Wheeled Road Traffic Accident Scenarios using Explicit FE Techniques.

The screenshot shows a 'MODIFY MATERIAL M1/MAT306' dialog box. At the top, there are buttons for 'ABORT_MODIFY', 'RESTORE_ORIGINAL', 'HELP', 'UPDATE_MATERIAL', 'COPY_EXISTING', 'SKETCH', 'VIEW_XREFS', and 'CHECK_DEFN'. Below these are options for 'MAT_ADD_EROSION', 'MAT_NONLOCAL', and 'MAT_ADD_PERMEABILITY', each with an 'EDIT' button. The main area contains fields for 'Label: 306', 'Elem types: Solid, Shell, Beam, Tshell', 'Type: MAT_024: PIECEWISE_LINEAR_PLASTICITY', and 'Title: MATL24_304'. An 'IMPORT...' button is also present. At the bottom, there is a table with 8 columns and 4 rows of material properties.

Row\Col	1	2	3	4	5	6	7	8
1	<Label>	RO F	E F	PR F	SIGY F	ETAN F	FAIL F	TDEL F
	306	7.89E-9	207000.0	0.33	259.0	0.0	0.0	0.0
2	C F	P F	LCSS I	LCSR I	VP F			
	0.0	0.0	0	0	0.0			
3	EPS1 F	EPS2 F	EPS3 F	EPS4 F	EPS5 F	EPS6 F	EPS7 F	EPS8 F
	0.0	1.0E-2	2.0E-2	3.0E-2	4.0E-2	5.0E-2	7.0E-2	0.0
4	ES1 F	ES2 F	ES3 F	ES4 F	ES5 F	ES6 F	ES7 F	ES8 F
	259.0	279.0	289.0	295.0	300.0	303.0	306.0	0.0

Figure 60 - Material Card for Beam Elements

Investigation of 2-Wheeled Road Traffic Accident Scenarios using Explicit FE Techniques.

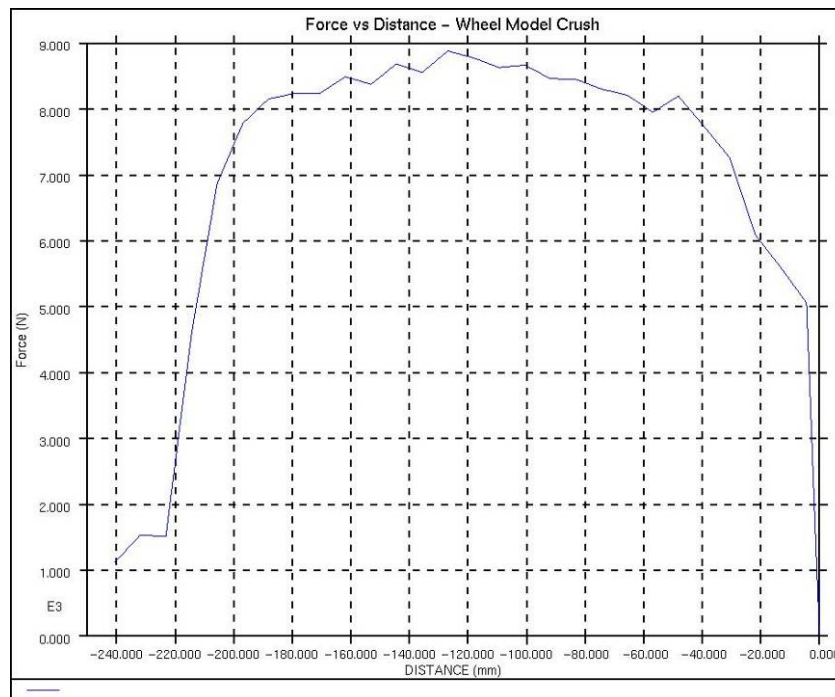


Figure 61 - Wheel Collapse (Updated Wheel Model).

Figure 61 shows the contact force for the updated wheel model and shows reasonable correlation with the physical testing in terms of initial buckling and peak load when compared to Tests 4 and 14 (note it should be read right to left as the impactor travelled in a negative X-direction). Post-buckling differences may be purely due to the Force-recording method used in the model – the wheel was impacted on one side, but a further rigidwall was on the opposite side to provide a reaction surface. In addition it must be remembered that this is a highly non-linear event and is extremely difficult to replicate reliably in physical tests, however with the given data this seems a good approximation at component level.

Investigation of 2-Wheeled Road Traffic Accident Scenarios using Explicit FE Techniques.

5.5.2.1 Child's Bicycle

A similar method was used for the child's wheel and frame. The Child's bicycle wheel was proportionately stiffer than the construction of the adult wheel and the rim has proportionately more effect compared to the stressed spokes of the adult wheel. Peak load was just under 8kN which again gives reasonable correlation to the physical testing. It should be noted that the frame is steel and was modelled using a *MAT_PLASTIC_KINEMATIC card for steel.

5.5.3 Helmet Material Model

Cyclist helmets have to meet a fairly rudimentary test (EN 1078). This is a simple test where the helmet is secured and a hemispherical impactor is dropped onto the helmet. As a result the construction is simple – the helmet is mainly compressed polystyrene foam (or polyurethane foam). The author used a material model as used in the car industry for crash analysis of a 30g/l polyurethane foam as a representative model.

Material Number	DYNA Material	Material Type	Density (tonnes / cubic metre)	Young's Modulus E	Tension Cut-off Stress (TC)	Hysteretic Unloading Factor (HU)	Viscous Damping Cut-off
2474	DYNA MAT 57 (Low Density Foam)	Polyurethane Foam	3.00E-11	3.2	9000	1.00E-02	0.1

Table 9 - Material Data used in Bicycle / Motorcycle Model.

Investigation of 2-Wheeled Road Traffic Accident Scenarios using Explicit FE Techniques.

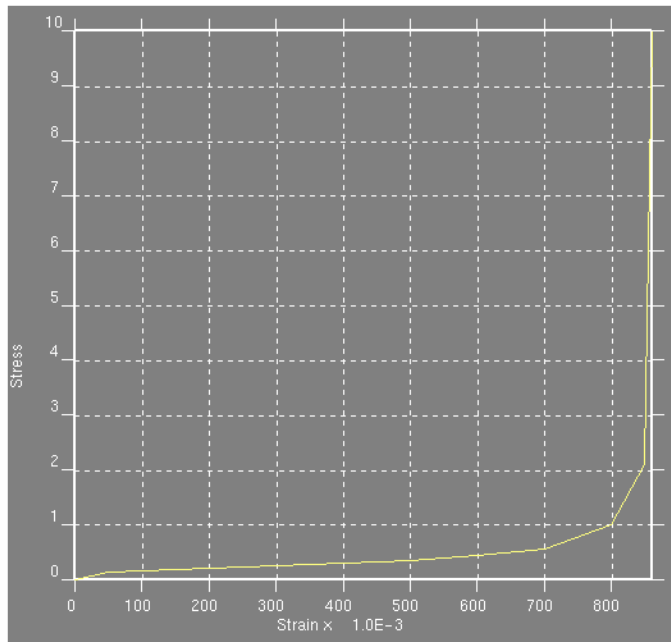


Figure 62 - Stress-Strain data for Helmet

5.6 Motorcycle Model

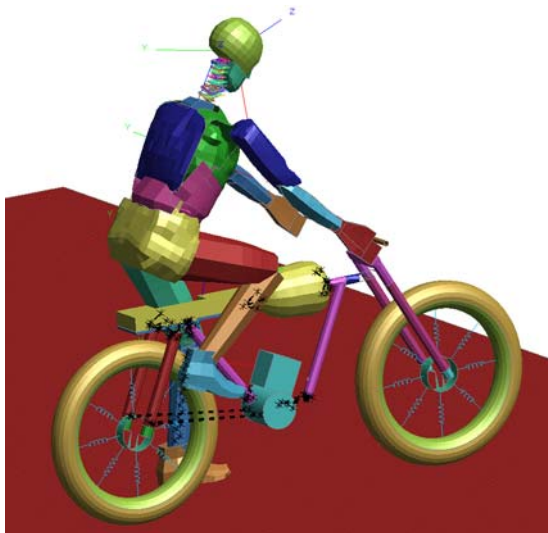


Figure 63 - Rudimentary Motorcycle Model.

Investigation of 2-Wheeled Road Traffic Accident Scenarios using Explicit FE Techniques.

The motorcycle model was created as a counterfoil to the bicycle simulations to illustrate the different potential injury mechanisms with a heavier two-wheeled vehicle.

A basic MAT_PLASTIC_KINEMATIC card was used (from the steel card in the vehicle model), and several parts of the model were rigidised (engine, wheel hub, seat support and rigid connectors). In addition NODAL RIGID BODIES were used to represent the swing arm as shown in Figure 63.

5.7 Assembling the Total Model

The bicycle model was assembled with cylindrical joints on the headstock, wheels and cranks. The humanoid was oriented with the left leg in the upper crank position and the right leg on the lower crank position.

From the above results it is the authors belief that a sufficiently robust model can be constructed for the final total simulations – based on the authors modified ISO 13232 methodology (see Figure 29).

Once the bicycle was complete and ready to use, the model assembly could continue. The humanoid was called in first, then the vehicle and finally the bicycle. Once the orientations were completed, the model could be merged

Investigation of 2-Wheeled Road Traffic Accident Scenarios using Explicit FE Techniques.

(with the humanoid as master in order to avoid any errors especially with the contact groups).

For full details of the model assembly process see Howard (Howard, 2002). The author added contact groups for the bicycle to the humanoid, ground and vehicle, and assumed a frictional coefficient of 0.2.

6 Results

6.1 Introduction

As explained in the problem statement, it was vital to determine the most statistically relevant real-world accident cases for investigation with regard to two-wheelers. For motorcyclists this has already been established in the form of ISO 13232. To that end, as a result of the available data from published accident sources this standard was modified by the author to examine cyclist incidents.

Further to this, the author in Table 4 has shown the biomechanical limits typical of the human body derived from a literature study. The results will show the main results for each of these criteria in graphical format.

The model size was approx 90000 elements and 95000 nodes and ran on 4 processors of a Hewlett-Packard workstation in approx 8 hours.

The following matrix explains the series of simulations run with a complete model in a full RTA scenario.

Investigation of 2-Wheeled Road Traffic Accident Scenarios using Explicit FE Techniques.

Run	Model No.	Scenario	Bike Speed Km/h	Vehicle Speed Km/h	Bicycle Contact Point
1	000450/b13	Adult Male	5	40	Lateral (100% side on)
2	000450/b24	Adult Male	20	40	Lateral (100% side on)
3	000450/b21	Adult Male	30	40	Cyclist front wheel impacts vehicle corner
4	000450/b17	Adult Male	20	40	Cyclist front wheel impacts vehicle corner
5	000450/b16	Adult Male	20	24	Cyclist front wheel impacts vehicle corner
6	000450/b27	Adult Male	45	5	Cyclist front wheel impacts vehicle corner
7	000450/b30	Adult Male	5	40	Repeat of Run 1 with Helmet
8	000450/b19	Child	5	45	Struck from Rear
9	000450/b22	Child	4	40	Lateral (100% side on)
10	000450/b32	Adult Male	5	40	Lateral (100% side on) - Motorbike

Figure 64 - Matrix of Complete Vehicle RTA Simulations

6.2 Adult Male - Case 1 (000450/b13)

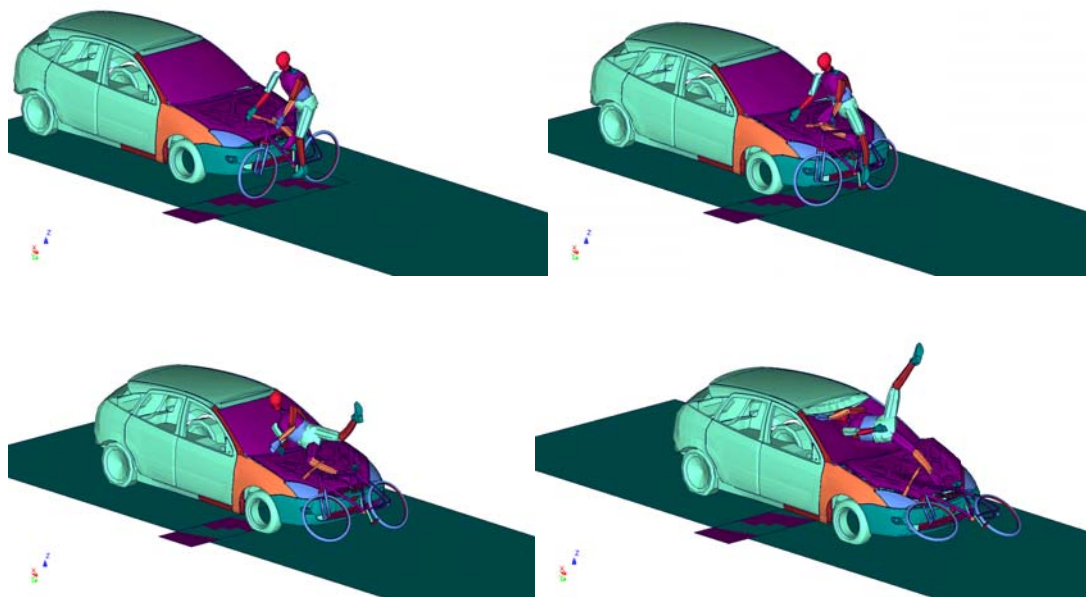


Figure 65 - Total vehicle model showing adult male in a Case 1 accident.

Figure 65 shows the complete vehicle model for a 'Case 1' incident (vehicle 40kph /cyclist 5kph).

Investigation of 2-Wheeled Road Traffic Accident Scenarios using Explicit FE Techniques.

The plots Figure 66 to Figure 69 show injury criteria from the model. Due to the impact occurring at the centre of the windshield the HIC value should be survivable (approx 800), however the figure recorded is far below what is expected. There may be limitations on the windscreen model (glass fracture being an extremely difficult issue to overcome and is beyond the scope of this PhD), but with this proviso in mind, previous physical tests using headform impactors in the centre of a windscreen for this class of vehicle have resulted in HIC values in the region of 800 which should be survivable in most cases according to previous work (EEVC, 1985). The simulation in this instance is a reasonable representation of a real-world event and if the EEVC impactor test is taken as a worst-case this is a reasonable assumption for this scenario.

Chest and pelvis accelerations are within injurious levels. There appears to be a possibility of a tibia / fibula fracture as the peak (7kN) is above the critical level (4kN).

Investigation of 2-Wheeled Road Traffic Accident Scenarios using Explicit FE Techniques.

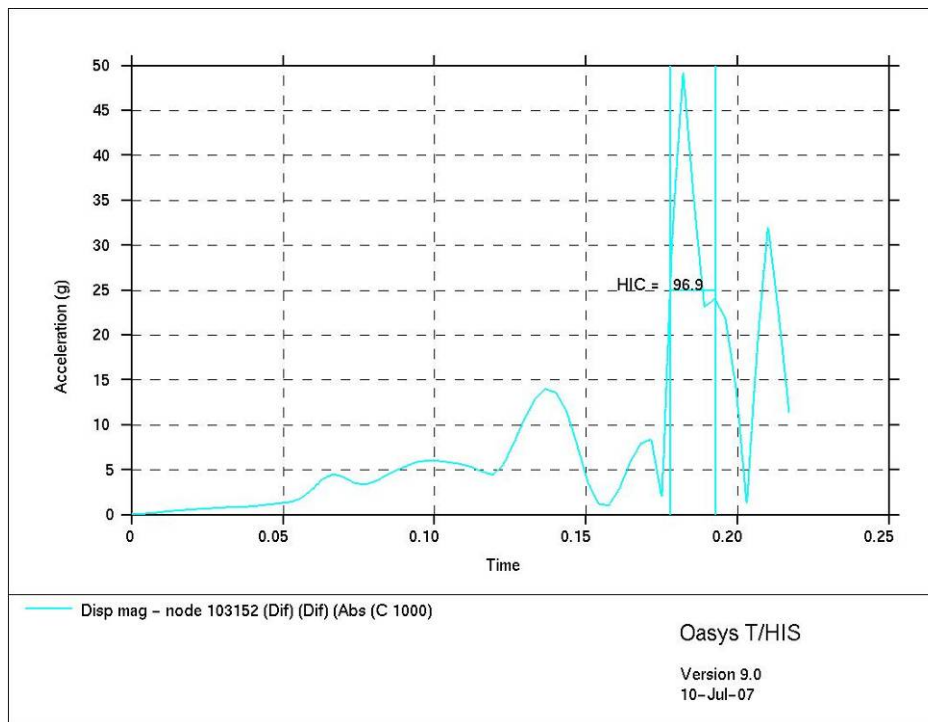


Figure 66 - Head acceleration and HIC (97).

As can be seen a HIC value of 97 is recorded – this may be a limitation caused by the windscreen model. The initial spike at 0.12 seconds is probably caused by the initial shoulder contact.

Investigation of 2-Wheeled Road Traffic Accident Scenarios using Explicit FE Techniques.

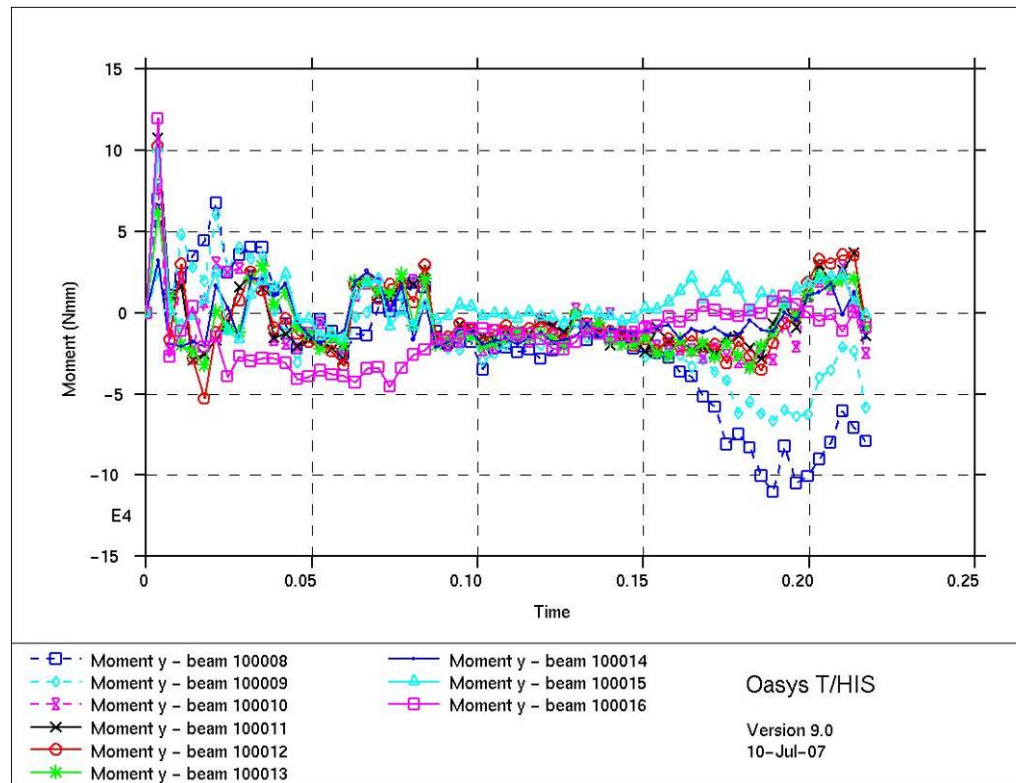


Figure 67 - Bending Moment on Tibia and Fibula beam elements.

This diagram shows the bending moment on tibia and fibula. The limit for injurious level is 200Nm and as can be seen the peak is approx 120Nm – well within the target. This level may still cause an issue for elderly cyclists who may be suffering from conditions like osteoporosis. It is interesting to note that the levels seen here are much lower than the pedestrian case (from the authors' own experience). This may be due to the higher centre of gravity of the rider, the higher location of the leg and the lower friction from a small tyre contact area versus a human foot and shoe.

Investigation of 2-Wheeled Road Traffic Accident Scenarios using Explicit FE Techniques.

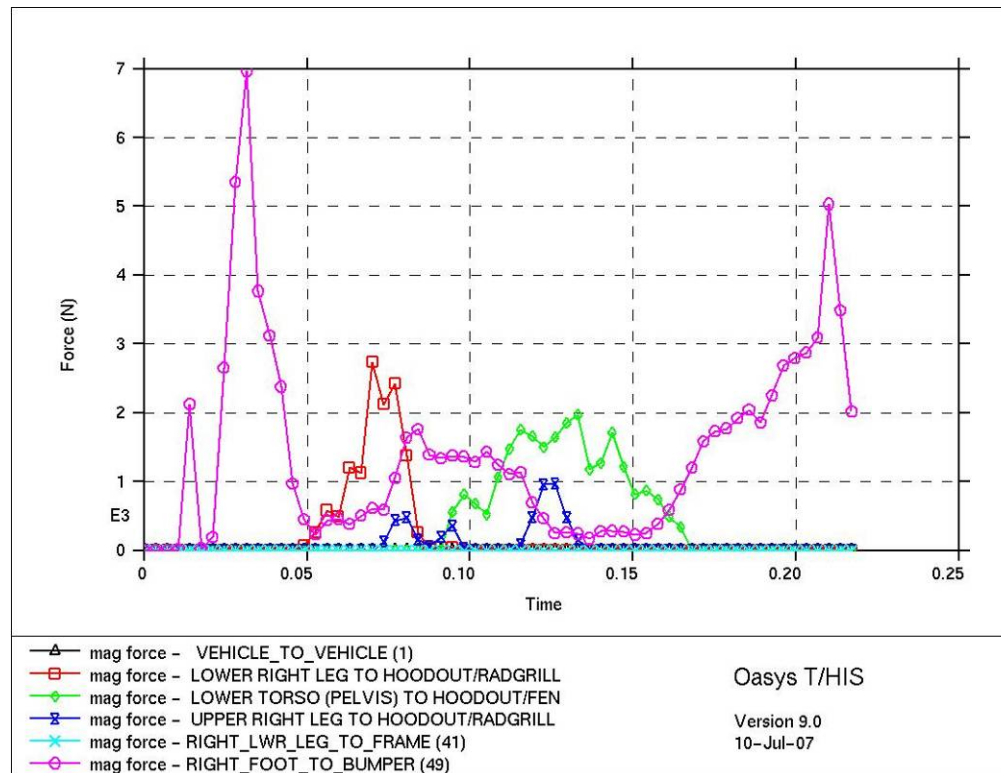


Figure 68 - Tibia and Fibula beam element forces.

The peak figure of 7kN is beyond the injurious target of 4kN. This certainly may cause severe soft tissue damage such as haematoma; however the duration is relatively short, so the overall energy the tissue receives is quite low.

Investigation of 2-Wheeled Road Traffic Accident Scenarios using Explicit FE Techniques.

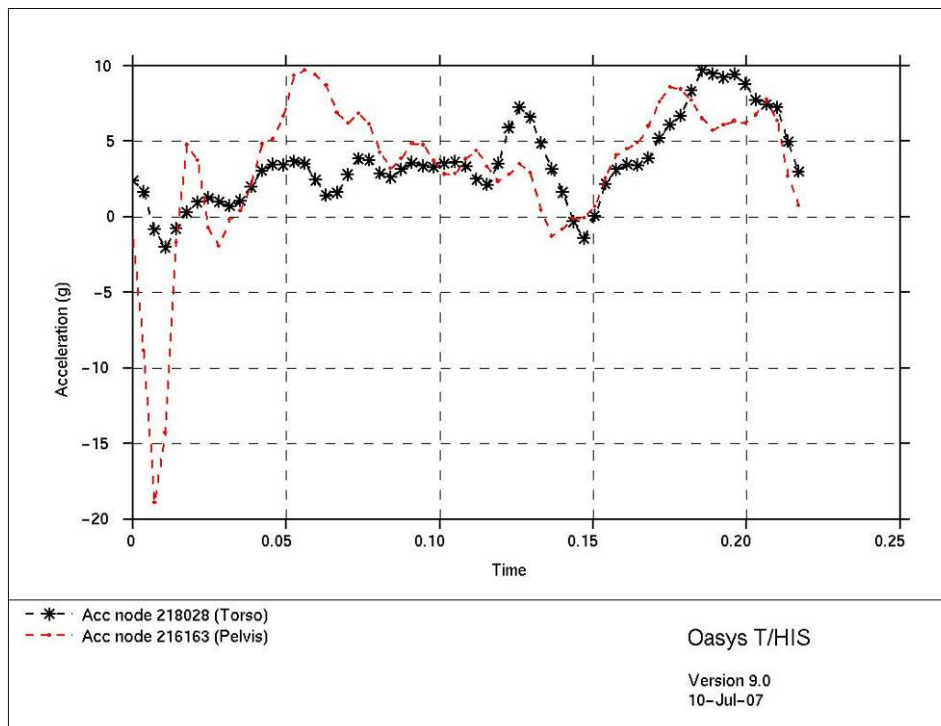


Figure 69 - Acceleration for Torso and Pelvis

The acceleration pulses for the Torso and pelvis are well below the 60g threshold. The initial spike on the pelvic trace is the initial impact onto the bonnet, and this may be exacerbated by the intrusion onto a relatively hard contact point. Again this is different to the pedestrian case in as much as the pelvis is possibly slightly higher than a normal 'walking stance' human.

6.3 Adult Male – Case 2 (000450/b24)

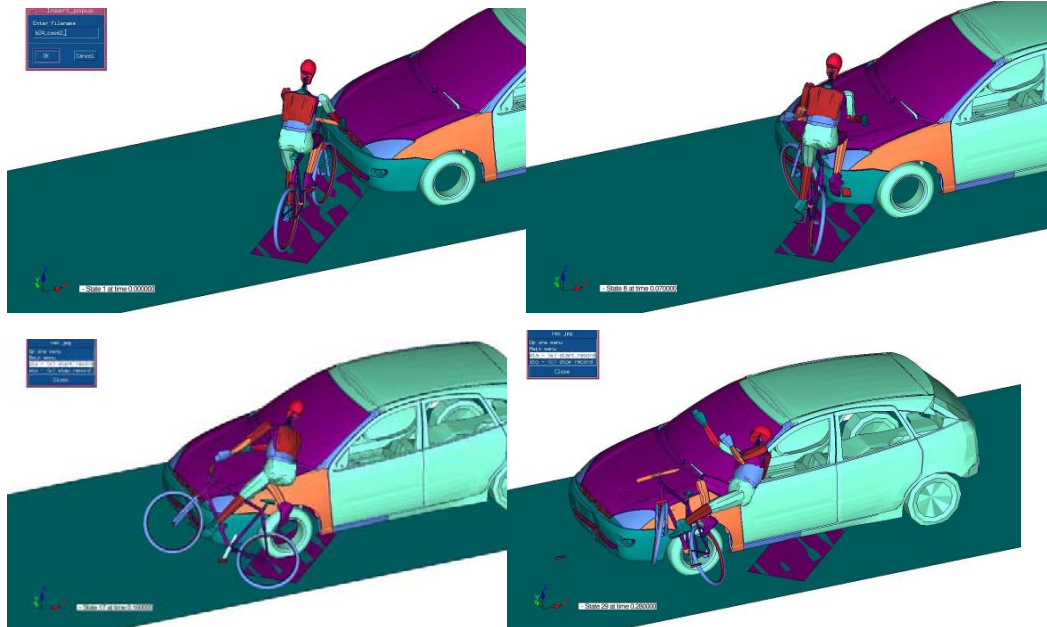


Figure 70 - Total Vehicle model showing the Adult Male 'Case 2'

Figure 70 shows 'case 2' the adult male cyclist to car accident. The vehicle speed is 40kph and the cyclist speed is 20kph. Highly apparent is the rotation of the upper body due to the knee striking the bonnet and the consequent head impact at the top of the A-pillar.

Figure 71 to Figure 75 show the biomechanical results. Note that although the HIC value is high (as expected) this is below the 1000 HIC threshold. The torso acceleration is just above the 60g injury level, and the Knee Translocation is very close to injury at 5mm. Other levels are within their limits of injury.

Investigation of 2-Wheeled Road Traffic Accident Scenarios using Explicit FE Techniques.

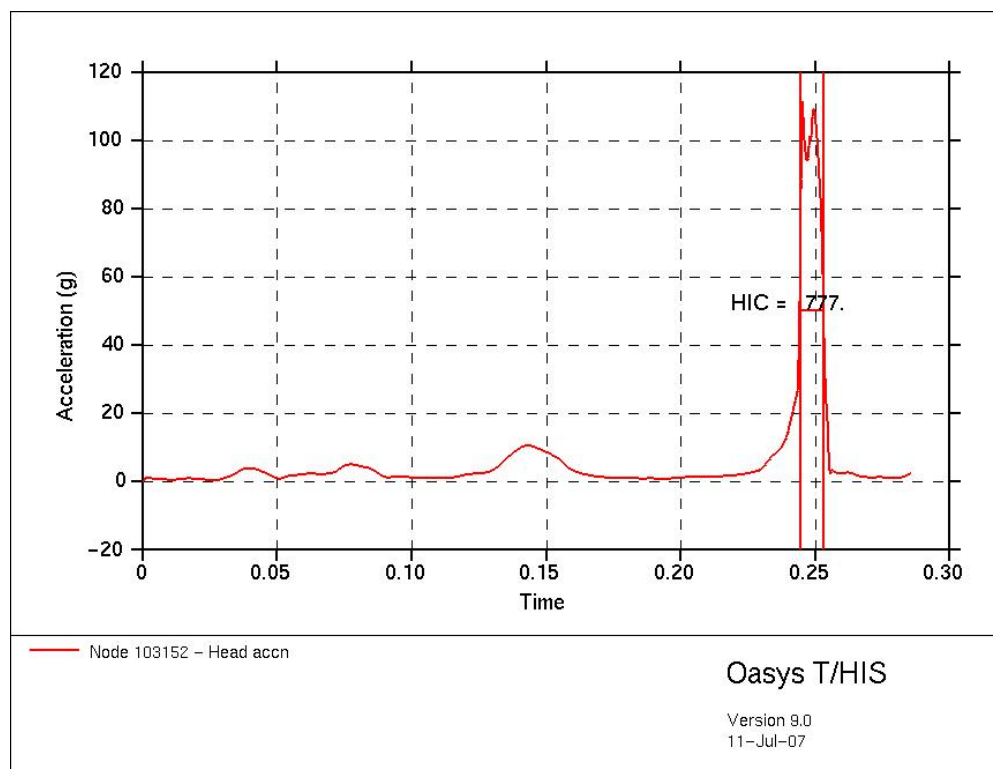


Figure 71 - Head acceleration curve (HIC = 777)

With a contact close to the stiff boron-steel structure of the A-pillar this HIC value seems low. It may be that the shoulder takes much of the impact (as seen in the high torso pulse in the next diagram). Alternatively it may be due to the windscreen model limitations.

Investigation of 2-Wheeled Road Traffic Accident Scenarios using Explicit FE Techniques.

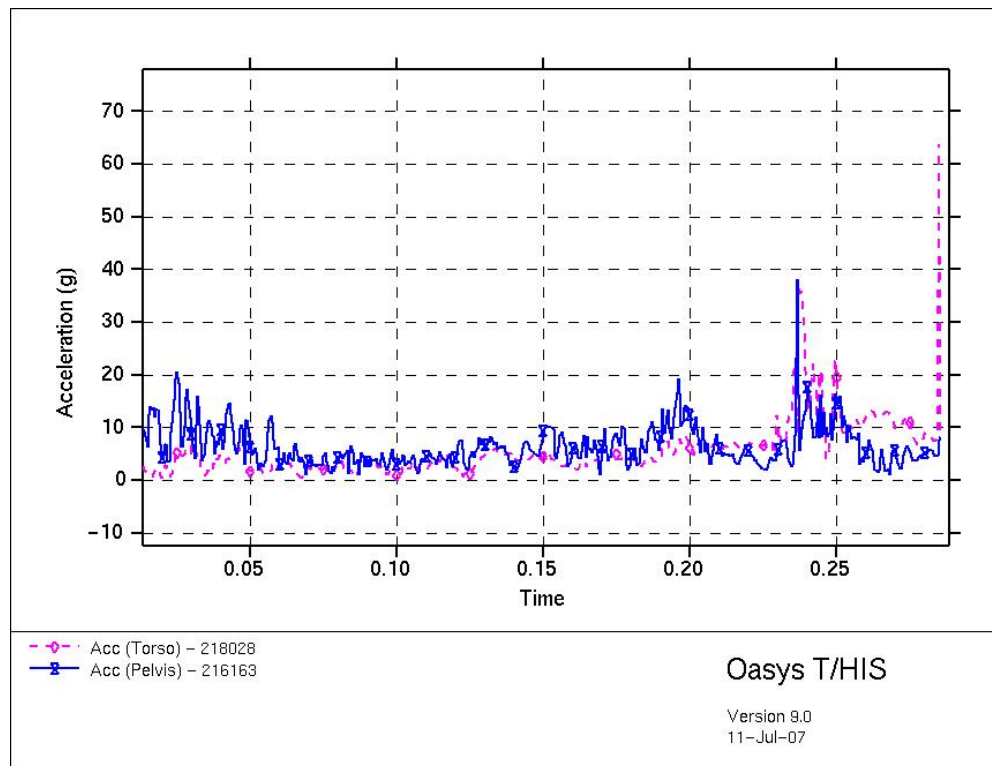


Figure 72- Acceleration pulse for Torso and Pelvis

The strong pulse for the torso would result in probable injury to the clavicle (collarbone) and the acromioclavicular joint. Complications of these are serious and lead to a long period of recuperation.

The peak acceleration of nearly 40g for the pelvis is also serious and may result in a fracture (which can be potentially life threatening if any major blood vessels are ruptured). At the least there would be severe bruising and soft tissue damage.

Investigation of 2-Wheeled Road Traffic Accident Scenarios using Explicit FE Techniques.

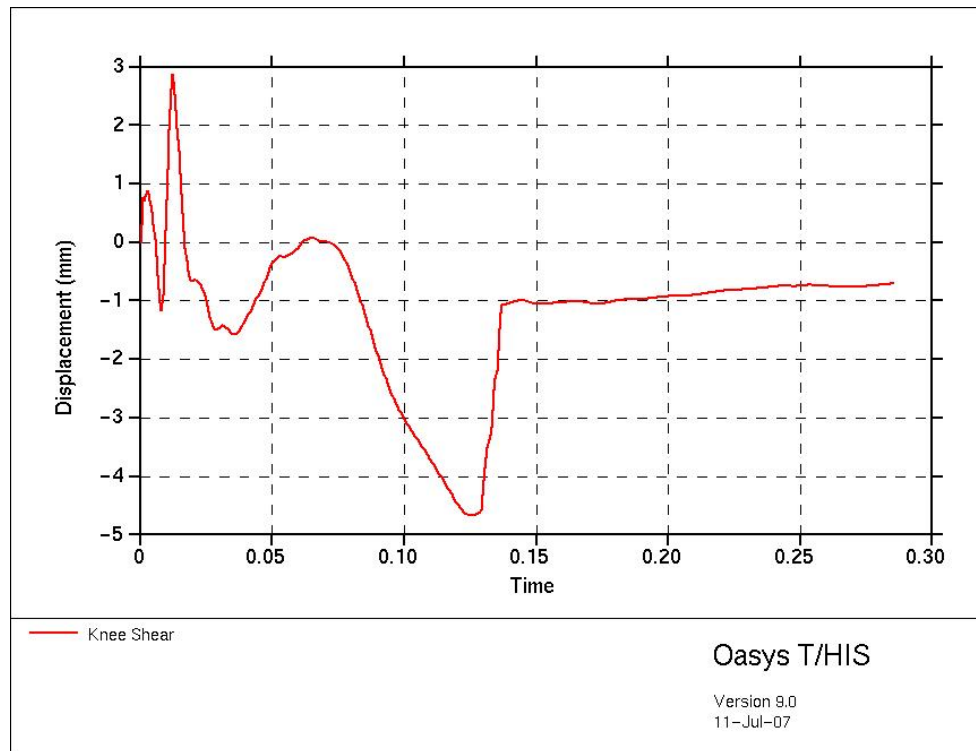


Figure 73 - Knee Translocation

The knee translocation shown is within the injurious target of 6mm. At this level though, it is possible to have serious ligament strain and if any of these tissues had been previously injured then they may indeed rupture.

Investigation of 2-Wheeled Road Traffic Accident Scenarios using Explicit FE Techniques.

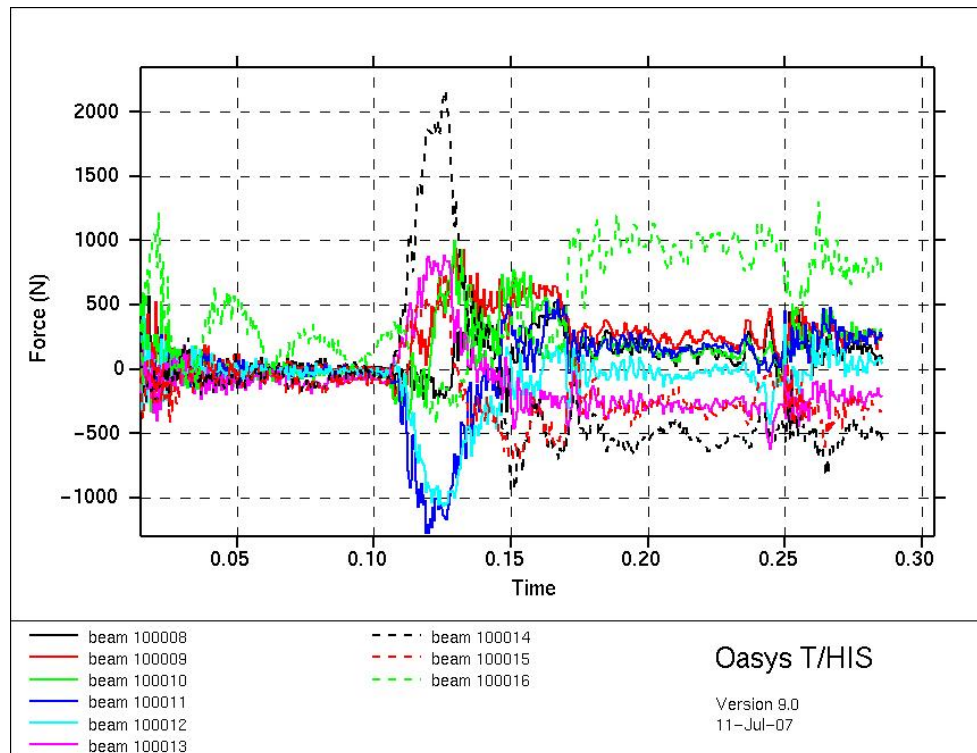


Figure 74 - Tibia and Fibula Force

The peak force on the Tibia is within the 4kN injurious level at 2.2kN. Again this may lead to soft tissue damage. The peak occurs as the knee impacts on top of the bonnet.

Investigation of 2-Wheeled Road Traffic Accident Scenarios using Explicit FE Techniques.

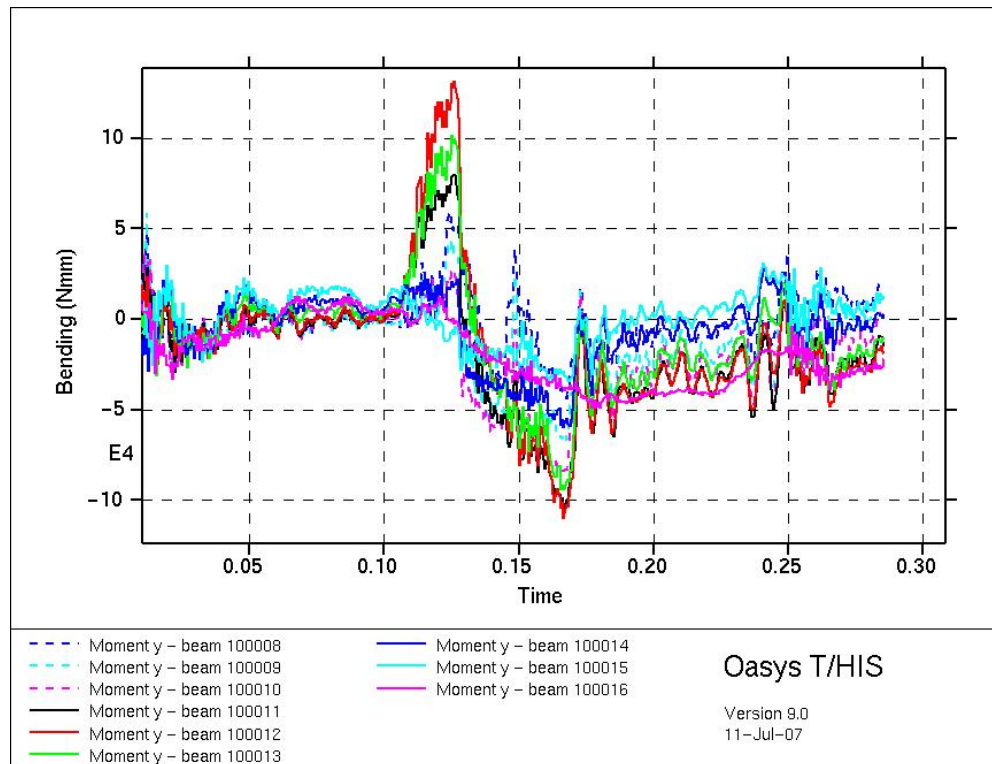


Figure 75 - Tibia and Fibula Bending Moment

The peak bending moment of 140Nm is below the injury criterion of 200Nm. Again although this load is below the threshold it is very conceivable that at least soft tissue injury will occur. The peak figure is generated when the leg is hit by the vehicle bumper.

6.4 Adult Male – Case3 (000450/b21)

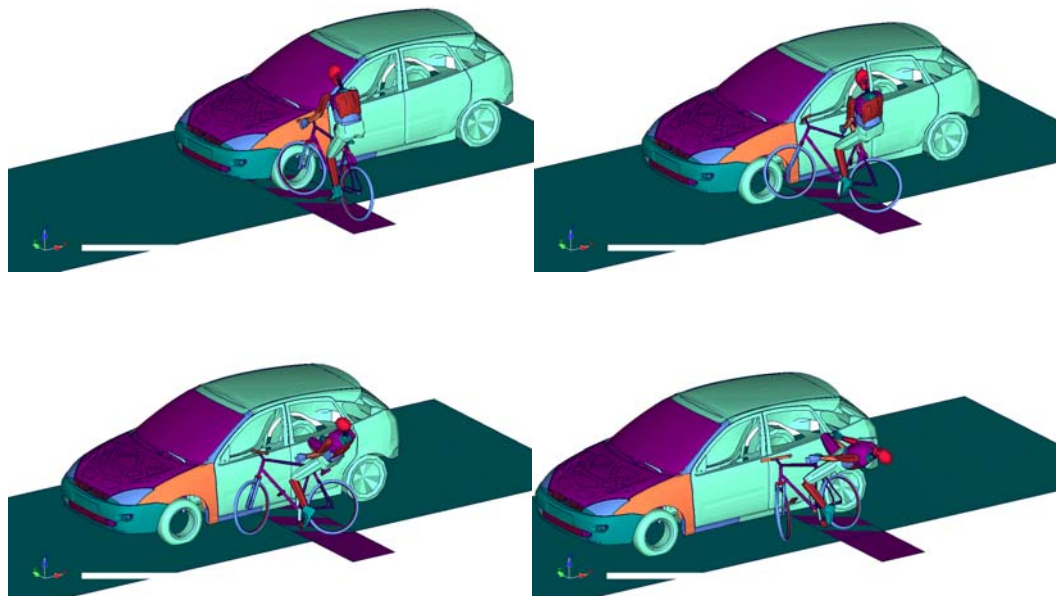


Figure 76 - Adult Male cyclist to car – 'Case 3'.

Figure 76 shows 'Case 3' of the cyclist to car accident scenario (vehicle speed = 40kph, cyclist = 30kph).

It should be noted in this case that there was no contact by the humanoid to the vehicle, and the recorded biofidelic data was well below injury criteria – for this reason it is not shown here in this instance.

From this data it is clear that the author's suggestion of the variation to the ISO 13232 standard in this particular case is not beneficial. A better scenario may be a higher bicycle speed, or constraining the hands to the handlebars with a strain to failure method to allow for disengagement.

6.5 Adult male – Case 4 (000450/b17)

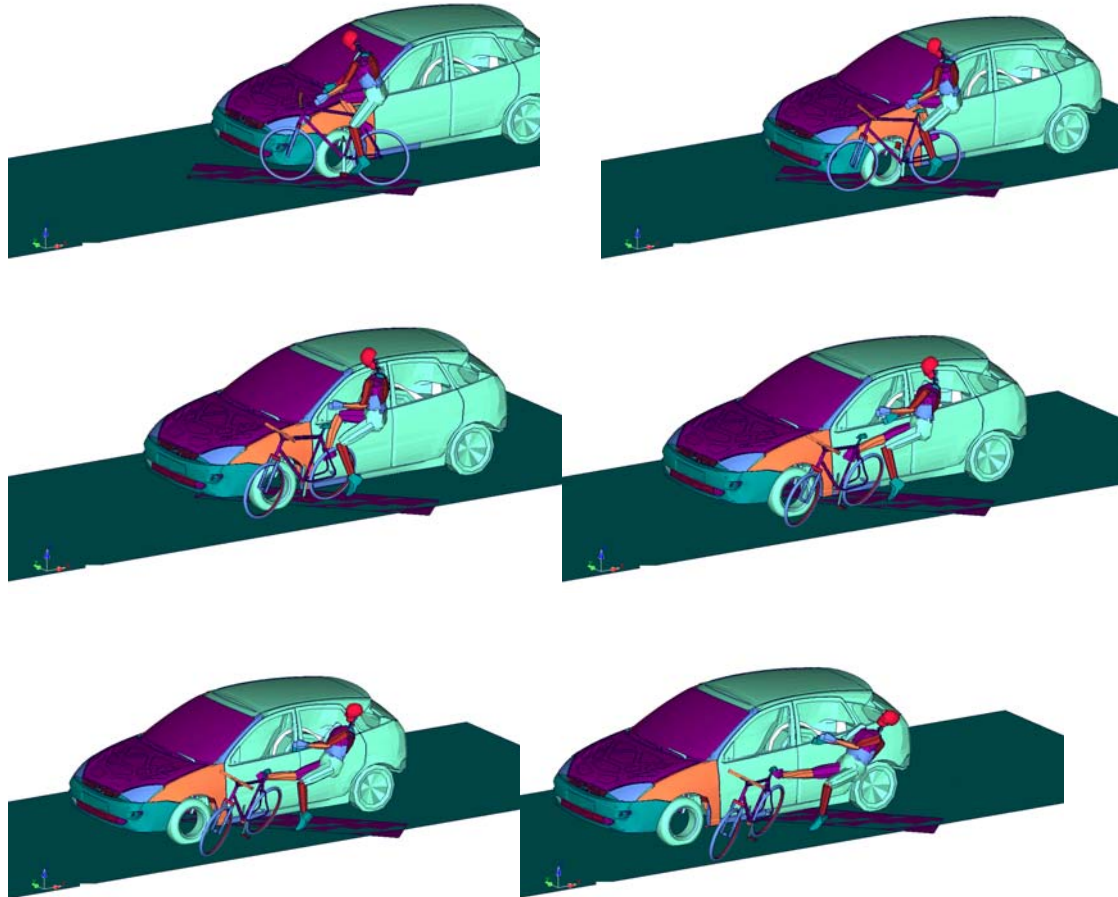


Figure 77 - Adult male full model – Case 4

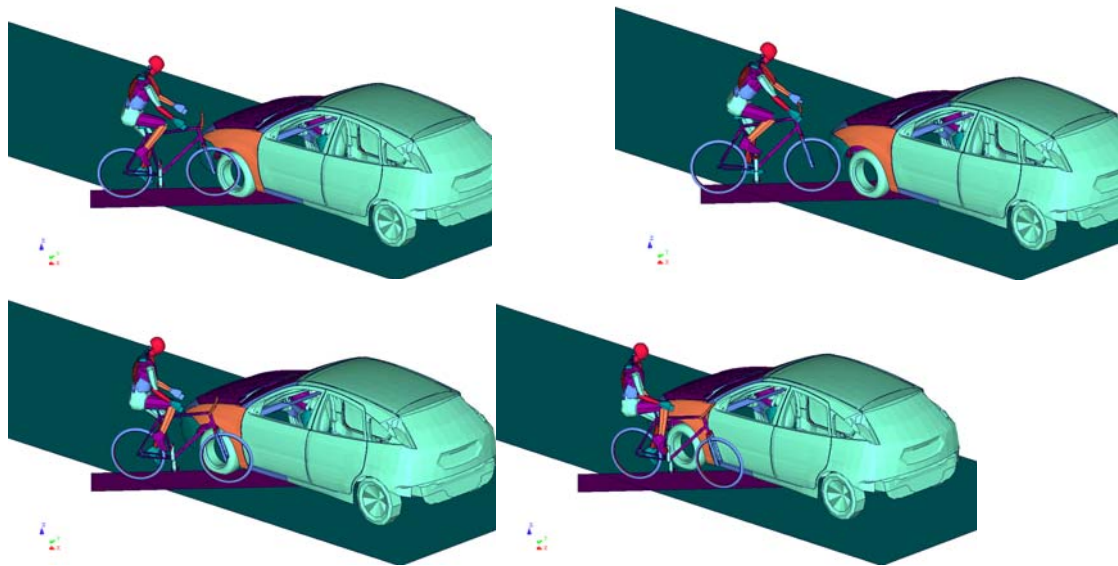
The adult cyclist to car accident scenario is shown in case 4 (Figure 77) – vehicle speed is 40kph, cyclist is 20kph.

Investigation of 2-Wheeled Road Traffic Accident Scenarios using Explicit FE Techniques.

Again, similar to the previous case, there is no contact between the humanoid and the vehicle – injury figures are well below the threshold for injury and therefore not shown.

Again, as per the previous case, a higher bicycle speed would be more accurate in terms of the humanoid having enough momentum to impact the vehicle.

6.6 Adult male – Case 5 (000450/b16)



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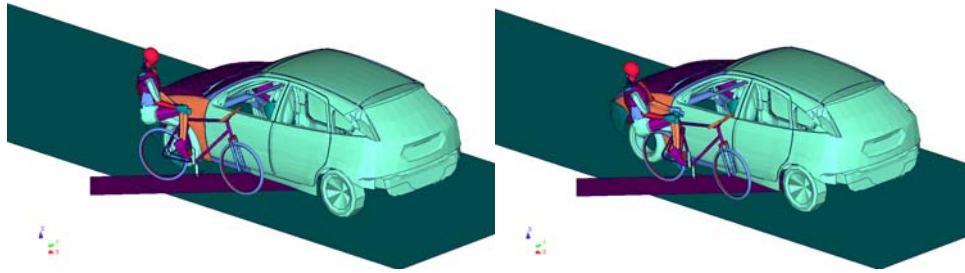
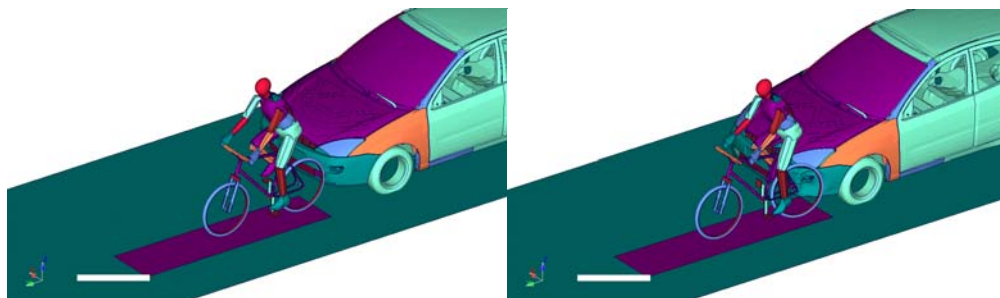


Figure 78 - Adult male to vehicle impact – Case 5

Figure 78 shows the sequence for the adult male cyclist to vehicle case 5 – vehicle speed is 24kph and the cyclist speed is 20kph. Once again there is no humanoid – vehicle contact, and with injury criteria well below their injurious thresholds, they are not shown.

As per the two previous cases it would be beneficial to alter this case, so that the cyclist has higher speed and imparts more momentum to the rider, or move the position of the cyclist closer to the front of the vehicle. It is also possible that this scenario may be accurate and that head to ground impacts are the injury mechanism in which case little can be done.

6.7 Adult male case 6 – (000450/b27)



Investigation of 2-Wheeled Road Traffic Accident Scenarios using Explicit FE Techniques.

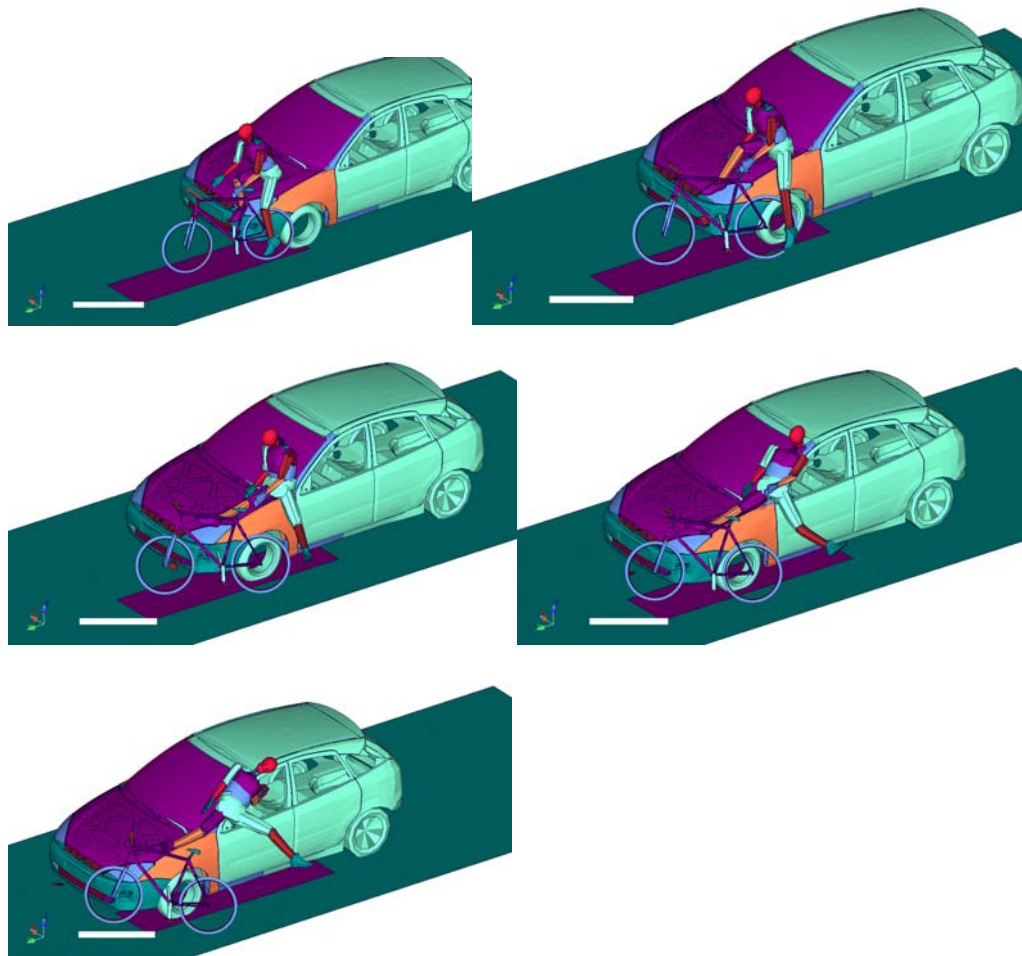


Figure 79 - Adult male cyclist to car – Case 6.

Figure 79 shows the adult male to car accident reconstruction (case 6). The vehicle speed is 45kph and the cyclist speed is 5kph. The whiplash on the humanoid should be noted and the impact at the top of the A pillar. This is an accurate 'severe' case and shows the benefit of the modified ISO 13232 method.

Investigation of 2-Wheeled Road Traffic Accident Scenarios using Explicit FE Techniques.

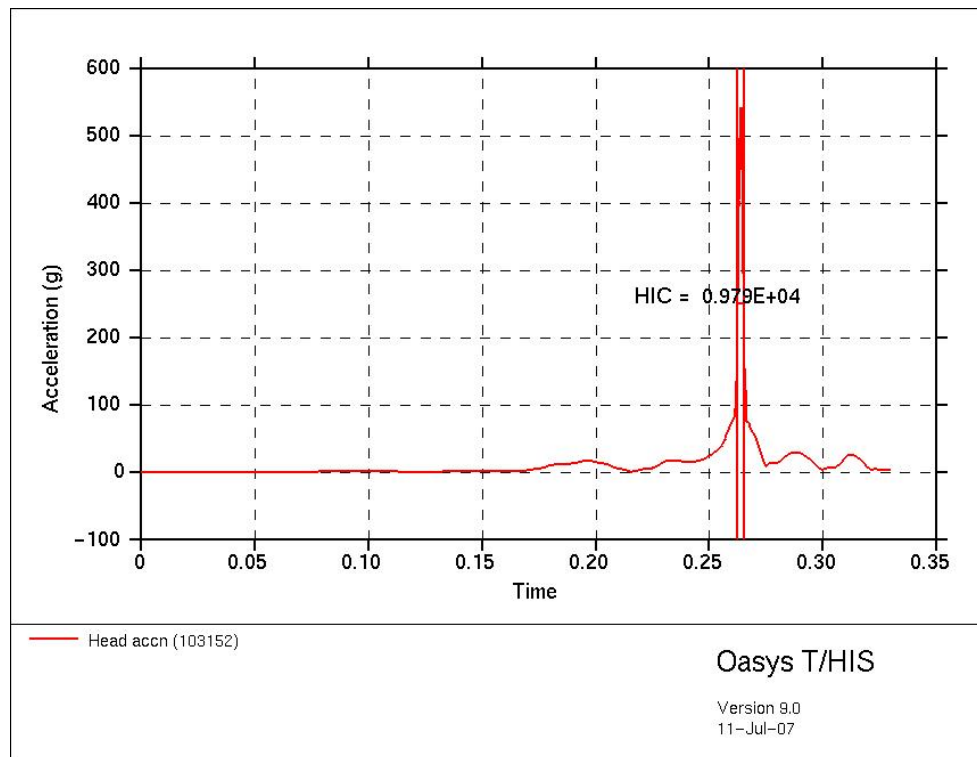


Figure 80 - Head acceleration curve (HIC 9790)

The HIC level is huge and the contact is the back of the skull – instantly fatal. The author is aware of a similar real-world case to this (but with a much higher vehicle speed – approx 100kph) where the cyclist was virtually decapitated (Report, 2001).

It could be argued that the model may be exacerbating this result, but this is a particularly stiff part of the vehicle. There is a clear whiplash effect seen in the animation, accelerating the head into the A-pillar. This may also contribute to the high pulse.

Investigation of 2-Wheeled Road Traffic Accident Scenarios using Explicit FE Techniques.

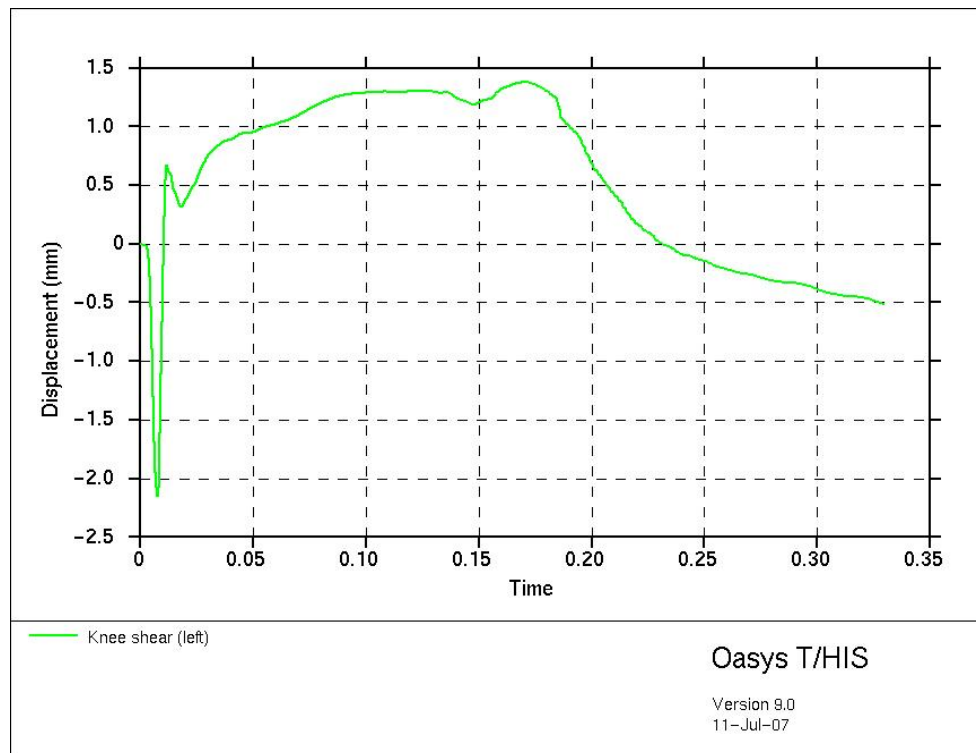


Figure 81 - Knee Translocation

The knee translocation is well below the injury threshold. 2mm is small and is unlikely to cause damage. This occurs at the initial impact with the bumper.

Investigation of 2-Wheeled Road Traffic Accident Scenarios using Explicit FE Techniques.

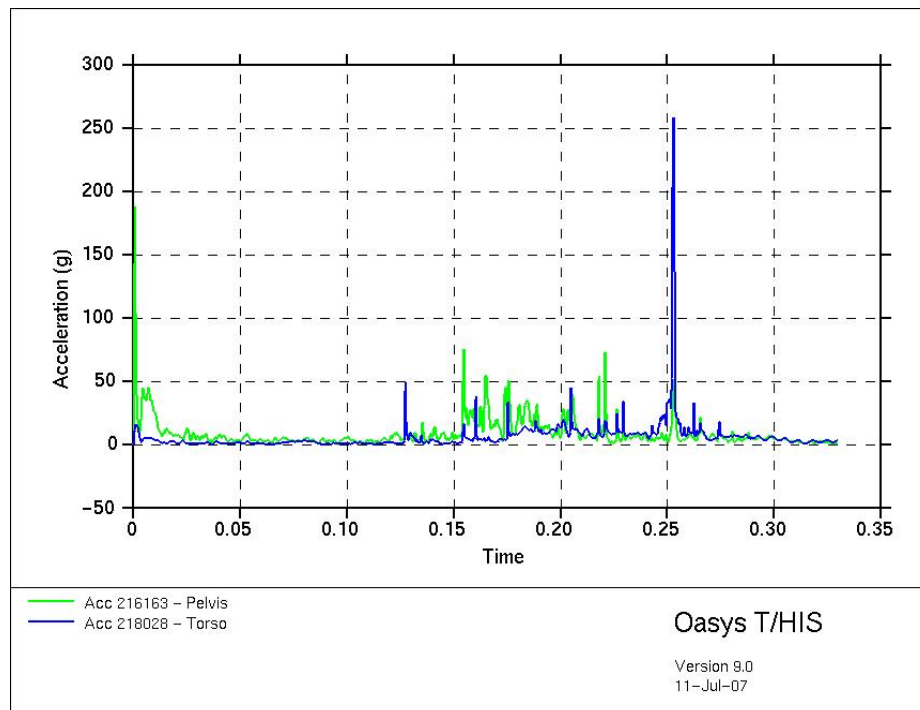


Figure 82 - Pelvis and Torso Acceleration

Just prior to the fatal head contact the chest receives a huge pulse from the rear as the humanoid falls back onto the windscreen / pillar junction. This is way beyond the 60g threshold and would lead to serious injury and possibly aortic rupture, since it is so severe.

Investigation of 2-Wheeled Road Traffic Accident Scenarios using Explicit FE Techniques.

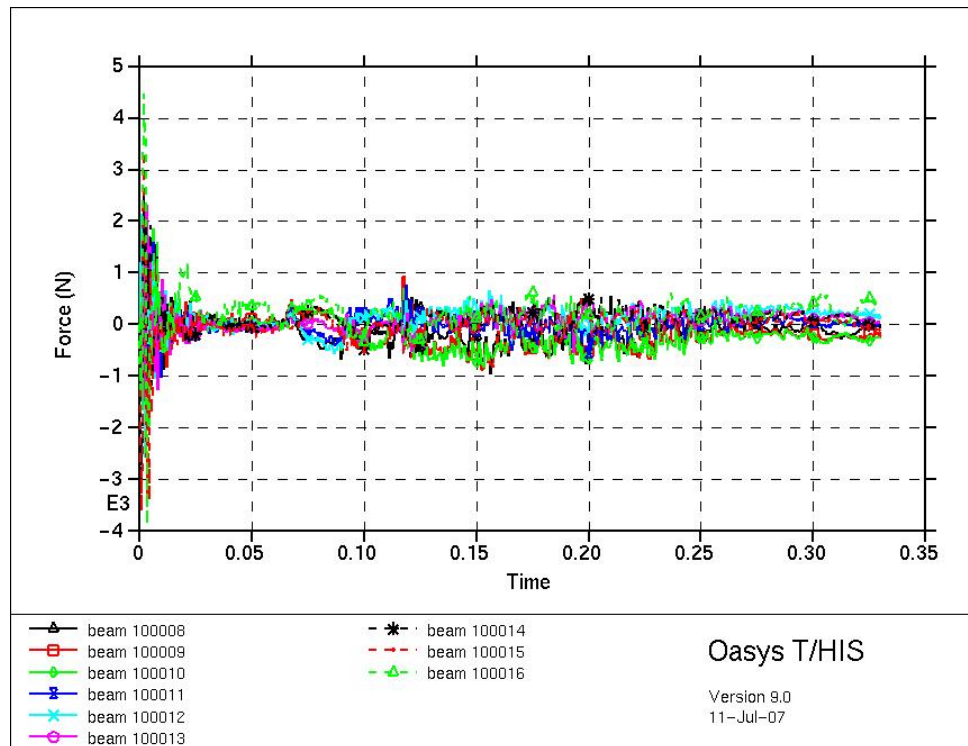


Figure 83 - Tibia and Fibula Force

The force of 4kN is on the injury limit and is generated on initial impact with the bumper. This seems like a reasonable level considering the type of impact. The interesting point about this is that the impact is from the rear. There is no reliable data available for rear impacts for pedestrian studies, as the usual assumption is that the impact is from the side. This criterion may have to be re-examined in the light of this impact case.

Investigation of 2-Wheeled Road Traffic Accident Scenarios using Explicit FE Techniques.

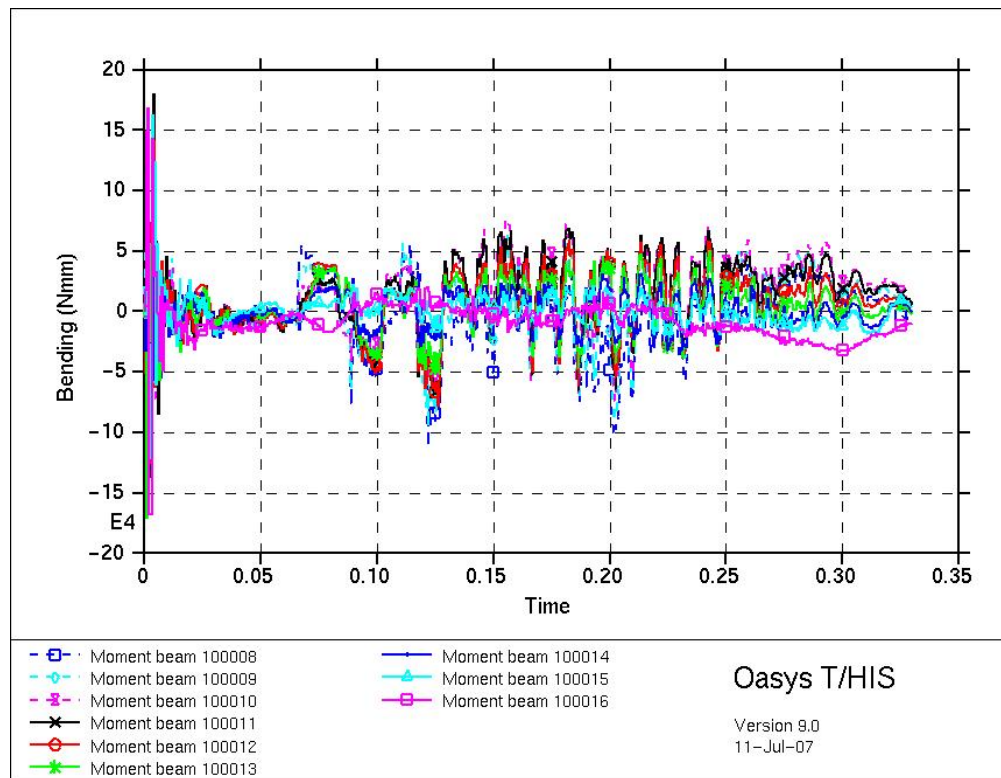


Figure 84 - Tibia and Fibula bending Moment

Figure 84 shows the tibia and fibula bending moment. The peak of 170Nm is just below the threshold for injury (200Nm). The direction of impact may be a factor (again being a rear impact) and further research may be needed into this orientation to gain reliable target data.

6.8 Re-run of Adult Male Case 1 with a cycle helmet – 000450/b30.

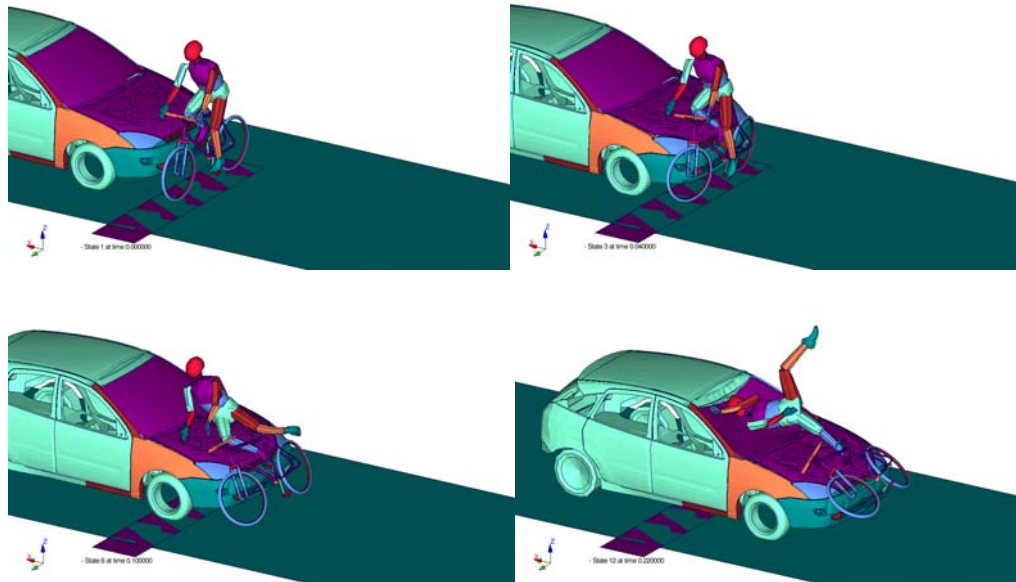


Figure 85 - Adult male to car (case 1) with helmet.

Figure 85 repeats case 1 with the addition of a helmet. The helmet uses the material 57 (low density foam) formulation to represent a 30 g/l polyurethane foam which the author believed to be similar in performance to commercially available cycle helmets.

The HIC value in Figure 86 below is more representative in a real world event. More study needs to be performed on helmet design and modelling to come to any statistically relevant conclusion, but this model was run to prove the feasibility of this activity.

Investigation of 2-Wheeled Road Traffic Accident Scenarios using Explicit FE Techniques.

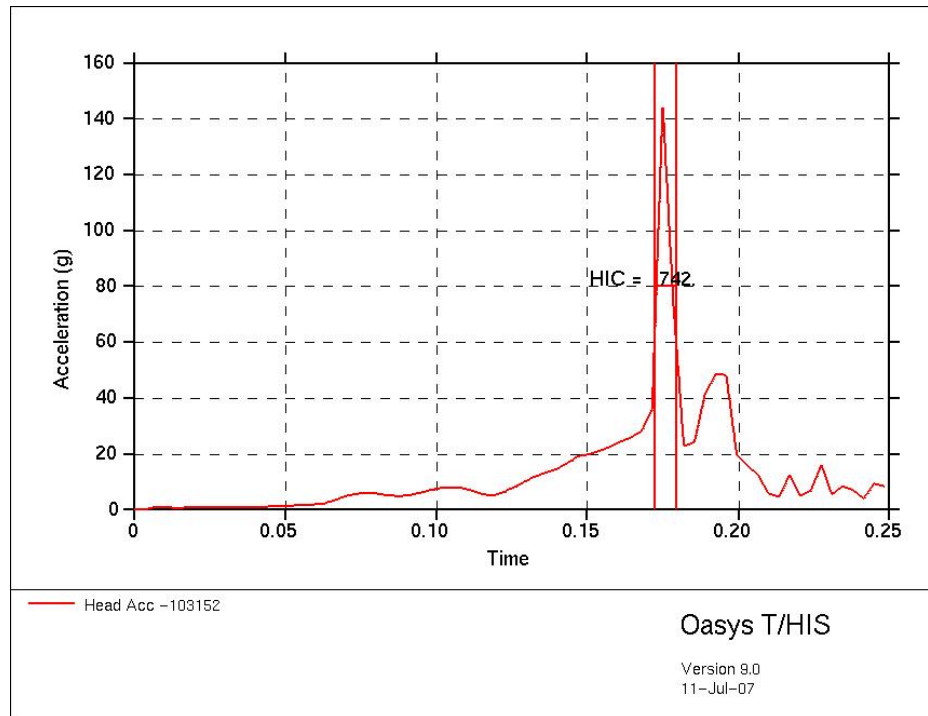


Figure 86- Head acceleration curve (HIC = 742).

It can be seen that the figure is reduced compared to the 777HIC figure generated previously; however with the windscreen model is a limitation of this approach. A previously stated the current helmet designs are to prevent injury from a fall – not in high speed accidents.

6.9 6 Year old Child to car – Case 6 (000450/b19)

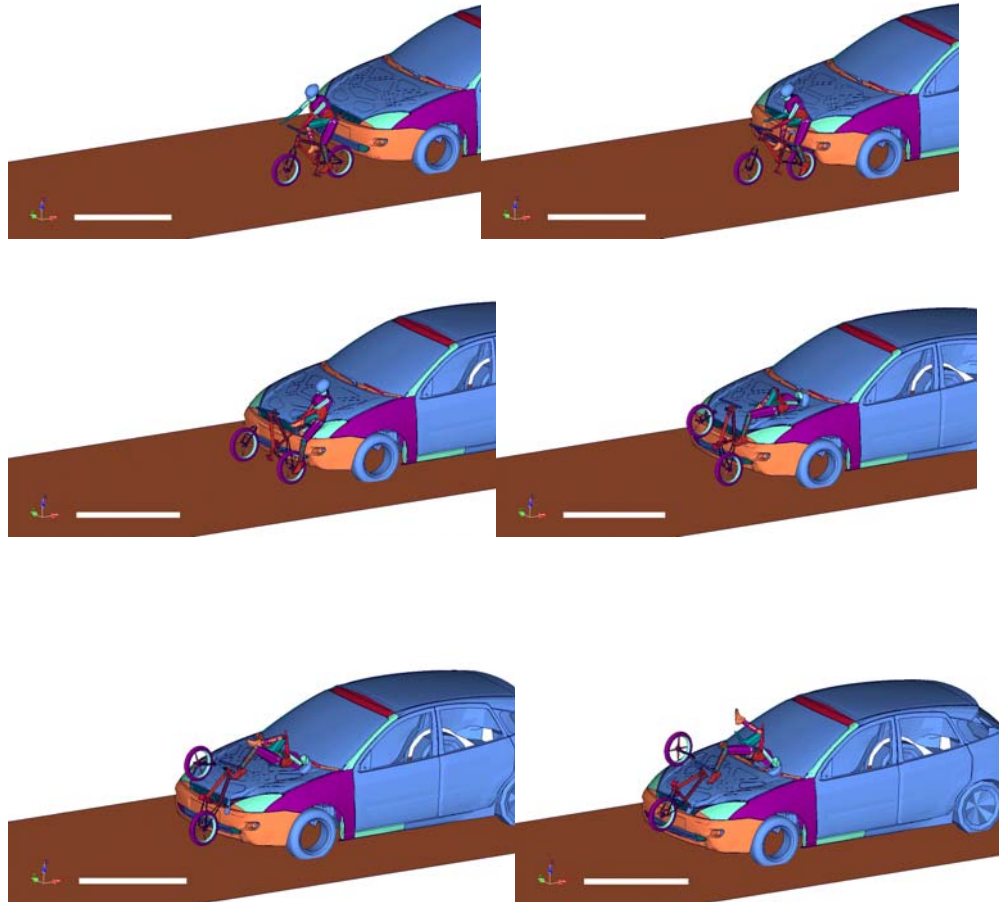


Figure 87 - Child to vehicle Case 6

Figure 87 shows a 6 year old child cyclist being struck from the rear (vehicle speed = 45kph, cyclist speed = 5kph).

Investigation of 2-Wheeled Road Traffic Accident Scenarios using Explicit FE Techniques.

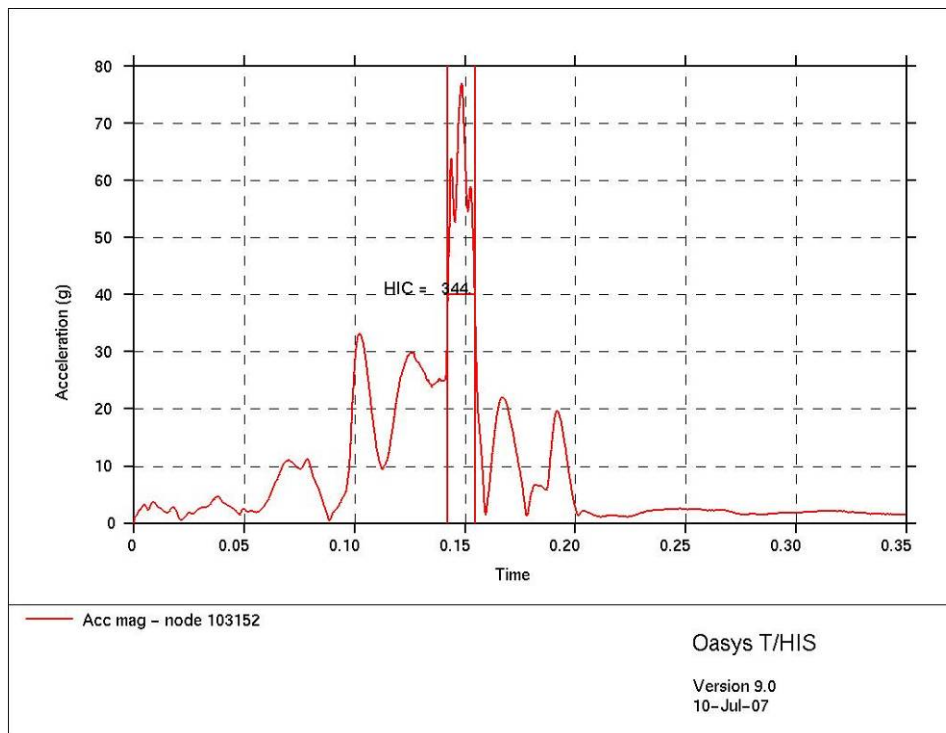


Figure 88 - Head acceleration (HIC = 344).

The impact from the rear may be more injurious to the child than the impact to the side or front – this is a particularly 'weak' mode for the brain. It is interesting to note that the head impacts the bonnet and does not reach the screen, although it is maybe slightly further along the bonnet than in a pedestrian 'standing' position.

Investigation of 2-Wheeled Road Traffic Accident Scenarios using Explicit FE Techniques.

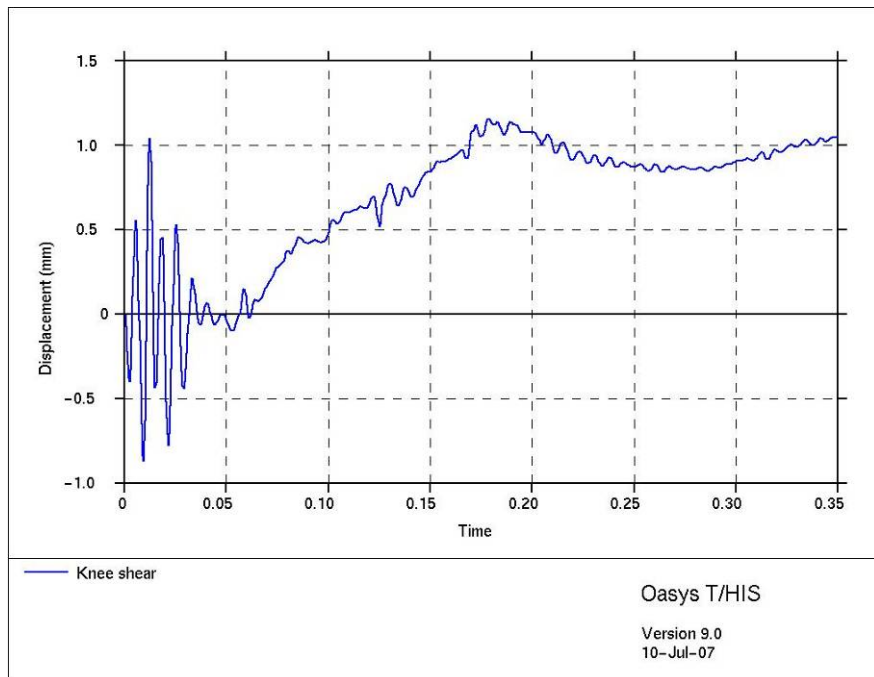


Figure 89 - Knee Translocation.

The knee translocation is within injurious limits for an adult. In the case of a child whose bones are not yet developed and tend to be more elastic this should be non-injurious.

Investigation of 2-Wheeled Road Traffic Accident Scenarios using Explicit FE Techniques.

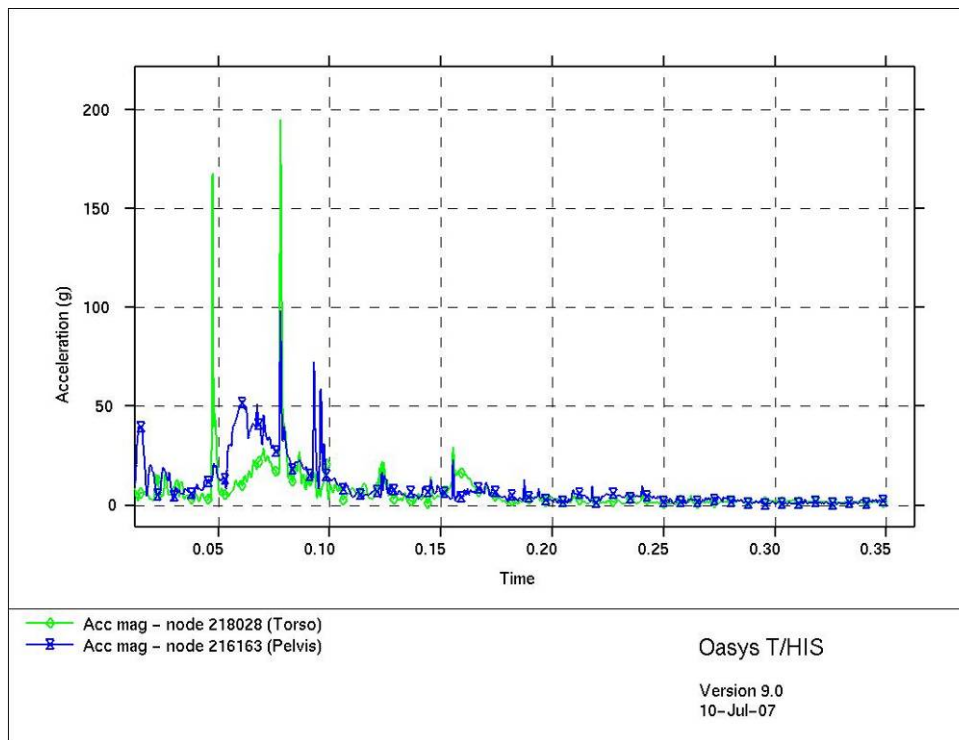


Figure 90 - Torso and Pelvis acceleration.

The high peaks shown in both Torso and pelvis are significant. This may lead to serious internal injuries and serious haemorrhaging.

Investigation of 2-Wheeled Road Traffic Accident Scenarios using Explicit FE Techniques.

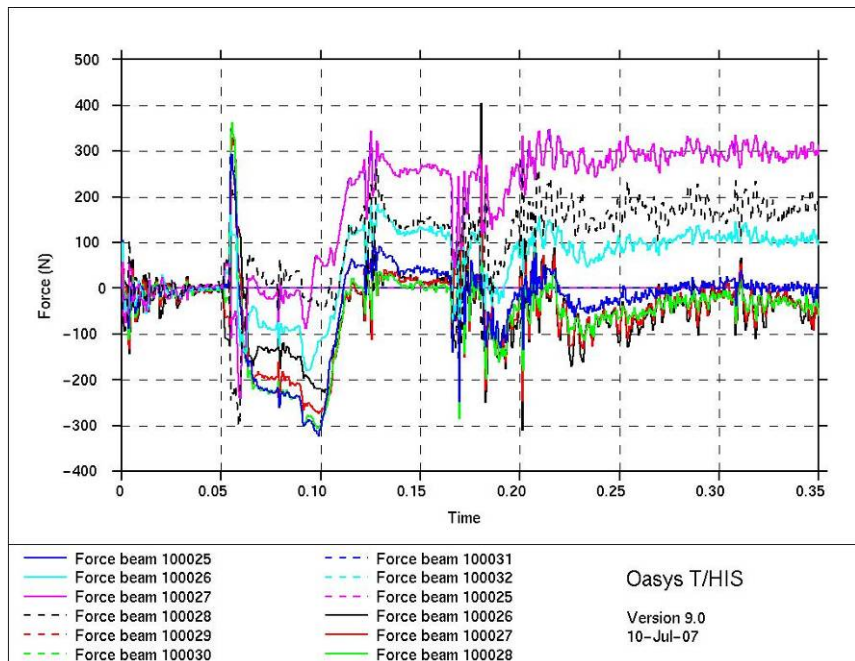


Figure 91 - Tibia and Fibula Beam element forces.

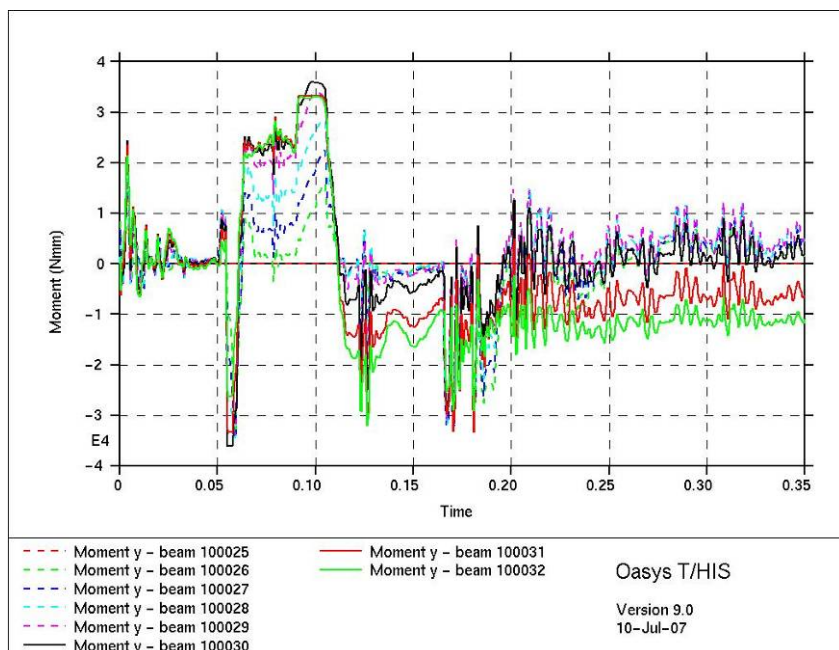


Figure 92 - Tibia and Fibula bending.

Investigation of 2-Wheeled Road Traffic Accident Scenarios using Explicit FE Techniques.

The tibia forces and the bending are difficult injury criteria to assess for a child as there is very little data for paediatric injury. Epiphyseal plate injuries may well occur as the forces are high.

6.10 Child to Vehicle – Case 1

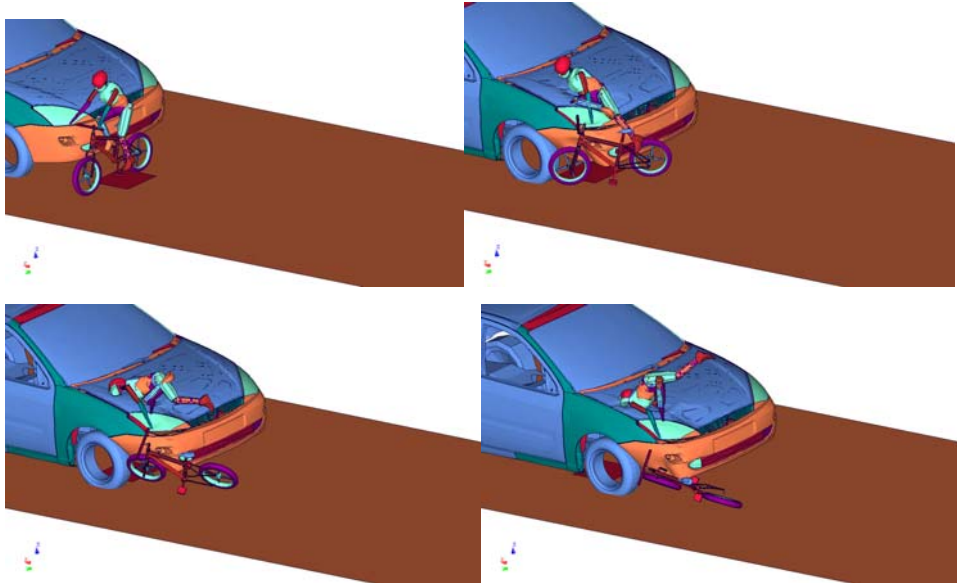


Figure 93- Child to vehicle impact (Case 1)

Figure 93 shows case 1 – vehicle speed is 40kph, cyclist speed is 5kph.

Figure 94 to Figure 98 show the injury results. The HIC level appears within limits of injury thresholds, but the chest and pelvis acceleration appear to be severe. There would be strong potential for internal trauma and potentially lower leg injury.

Investigation of 2-Wheeled Road Traffic Accident Scenarios using Explicit FE Techniques.

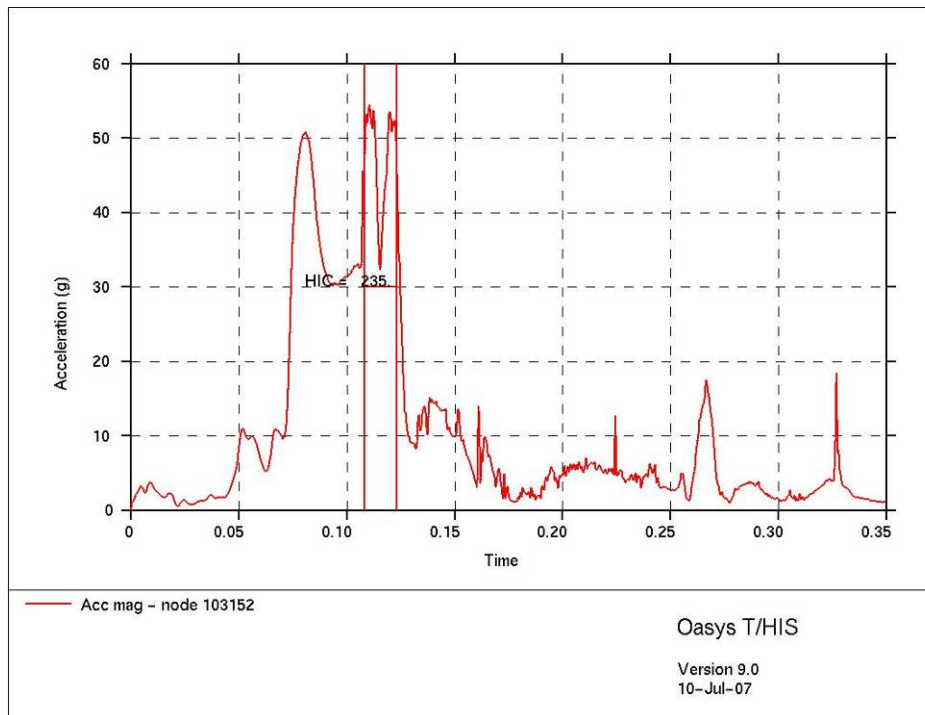


Figure 94 - Head acceleration (HIC = 235)

The head acceleration gives a HIC of 235. This is a survivable level, for a healthy child. It is worth noting that the bonnet is decelerating the head successfully and managing the energy in the event.

Investigation of 2-Wheeled Road Traffic Accident Scenarios using Explicit FE Techniques.

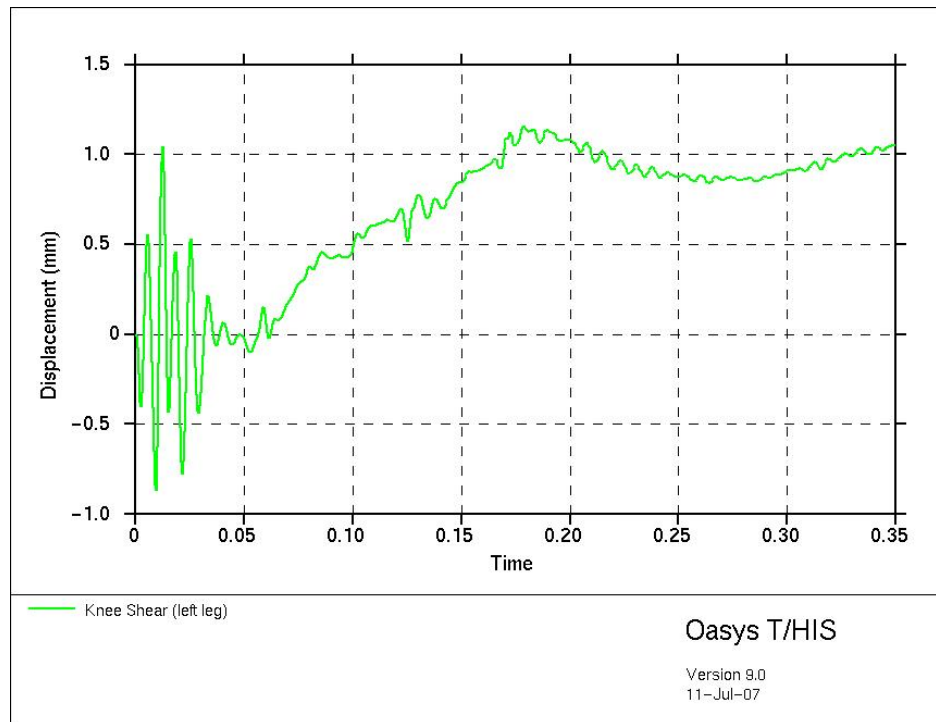


Figure 95 - Knee Translocation

The knee translocation is well within injurious levels and should not cause severe injury. It is possible that the leg flailing action midway through the event is responsible for the secondary peak.

Investigation of 2-Wheeled Road Traffic Accident Scenarios using Explicit FE Techniques.

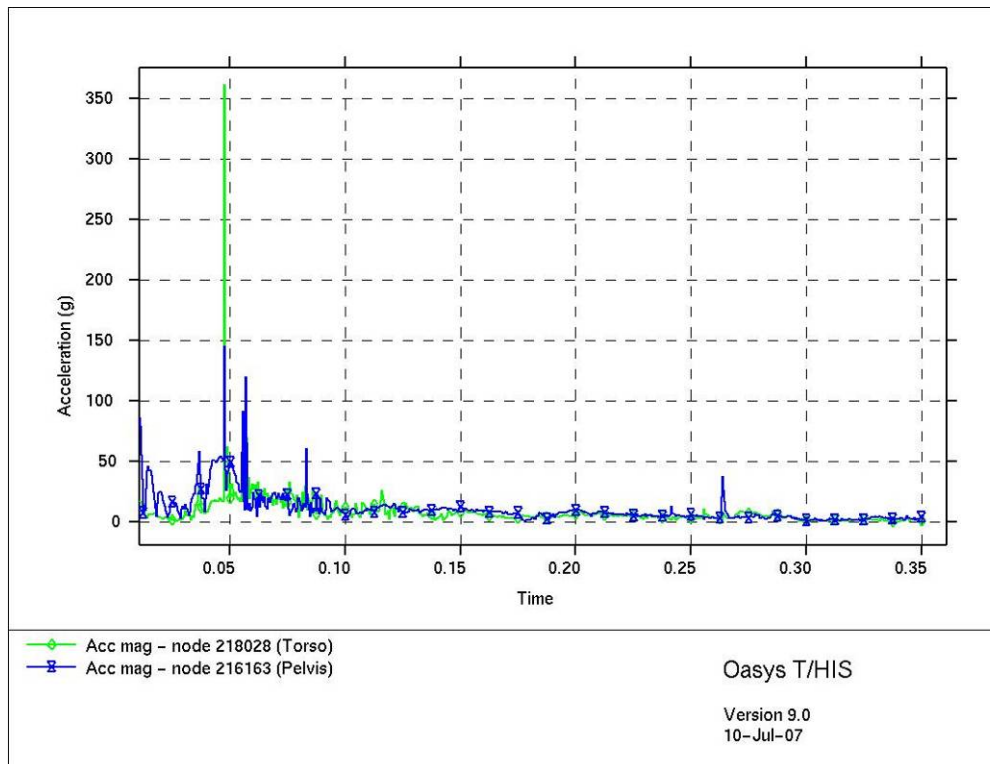


Figure 96 - Torso and Pelvis Acceleration

The torso and pelvis acceleration are particularly interesting. Unlike the adult whose torso is well above the bumper, the child is subject to a high acceleration as the vehicle front end impacts the chest. This would be an injurious impact and would possibly lead to organ injury and blood loss.

Investigation of 2-Wheeled Road Traffic Accident Scenarios using Explicit FE Techniques.

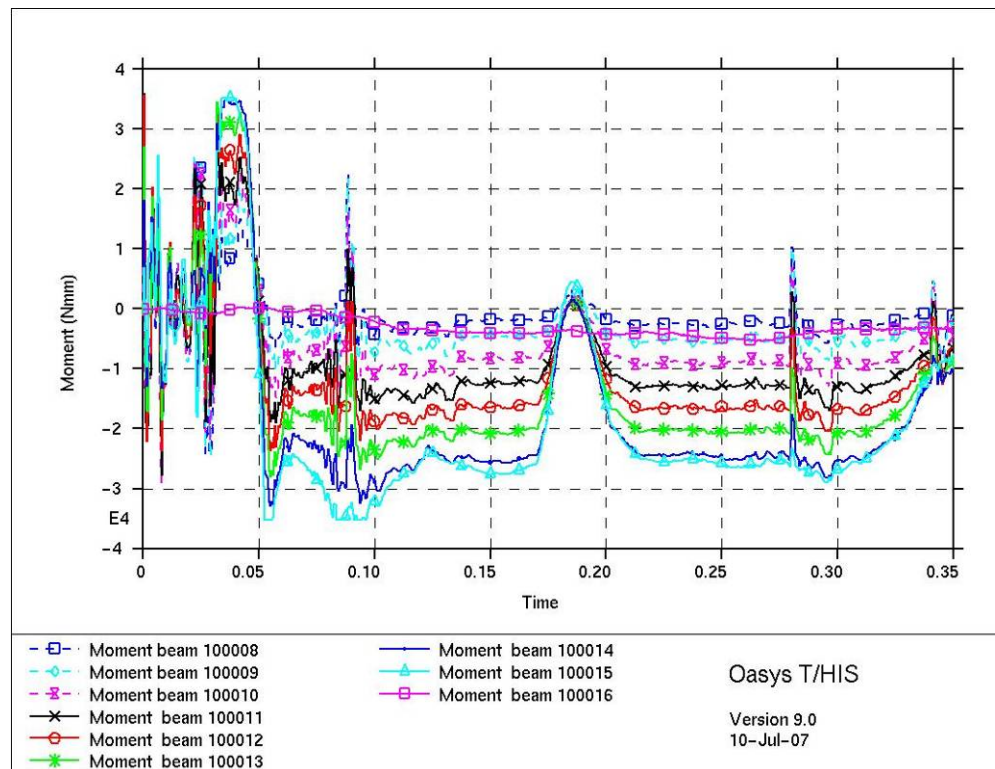


Figure 97 - Tibia and Fibula beam element bending moment

The level of 35Nm is a relatively low bending moment and unlikely to cause injury through this mechanism.

Investigation of 2-Wheeled Road Traffic Accident Scenarios using Explicit FE Techniques.

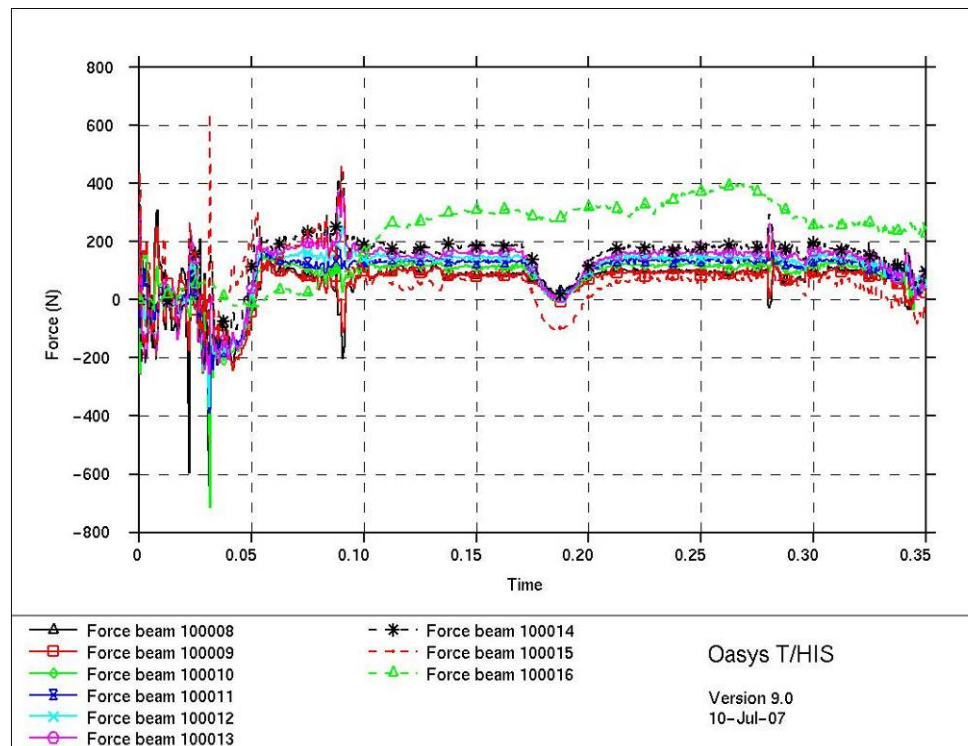


Figure 98 - Tibia and Fibula beam element forces.

This graph shows a maximum force of 650N. This would be injurious and occurs just after the initial impact. It may be due to the upper leg being trapped between the bonnet and the torso on impact. This would not occur in a pedestrian incident, and is due to the leg being raised in the cycling position.

6.11 Motorcyclist to Vehicle Collision (Case 1 Comparison)

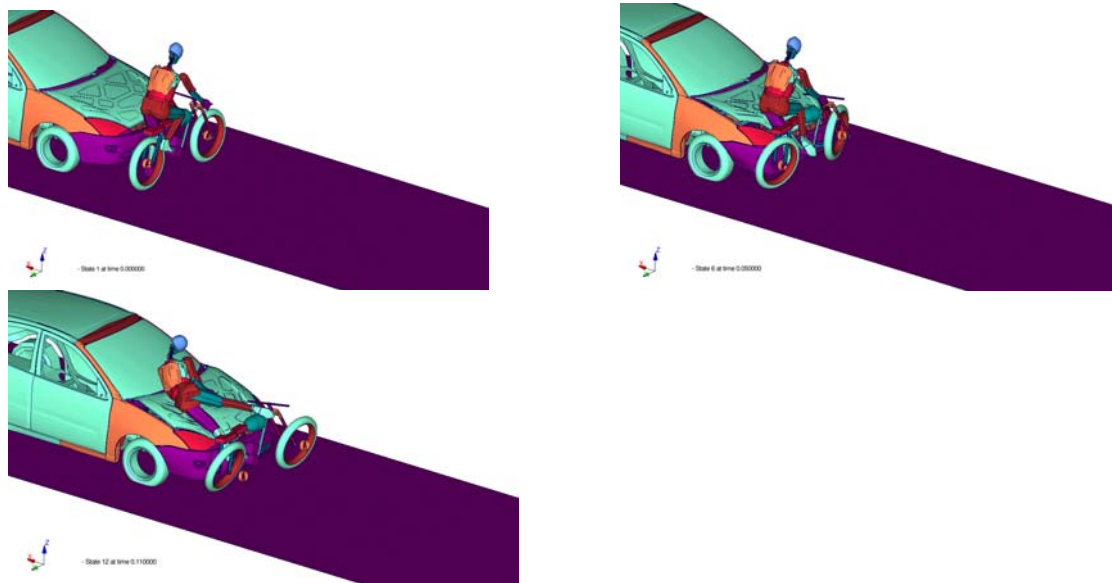


Figure 99- Motorcyclist to vehicle impact (Case 1)

Figure 99 shows the motorcyclist to vehicle accident scenario for case 1. This is an elementary motorcycle formed as a comparison to the cyclist case. Immediately apparent is the joint / spoke formulation needs improvement. The spokes were again using a discrete element formulation, as per the original bicycle wheel formulation.

The figures below show very high head acceleration with a high HIC value – clearly this would be reduced with the addition of a representative helmet. Also of note are the proportionately higher loads on the lower leg. The higher inertia of the motorcycle means that leg appears to be trapped and crushed during the impact, as borne out by accident statistics.

6.12 Conclusions and the Effect of Experimental Analysis on the FE Analysis Model.

The approach shown even 5 years ago would not be possible due to limitations in solving time; however it is possible to see that complex analyses such as this can now be used to examine large real-world incidents.

The modified ISO 13232 standard appears to be a valid argument for examining cyclist impacts, with the exception of cases 3,4 and 5 where a higher cyclist speed could be used to give the humanoid enough inertia to impact the vehicle. Another improvement may be moving the cyclist nearer the front of the vehicle to improve contact. Attaching the hands to the handlebar may be a simple method to overcome this issue, and possibly use a strain-to-failure method to release the grip from the handlebar.

Alternatively the scenario itself is perhaps correct and the injury mechanisms are due to impact with the ground in which case little can be done in terms of improving vehicle design. Only further real-world data assembled in a consistent manner from sources such as CCTV will allow these incidents to be statistically proven.

Other factors need to be examined in more detail - for instance the effect of muscle tensioning pre-impact is an interesting issue and others have considered this (Soni et al). In addition the effect of the rider impacting the ground is a notable area that could be analysed. The issue with this particular FE approach is that the run-time becomes excessive and so this was not attempted in this study.

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It is seen that the helmet case did indeed result in a lower HIC value but as stated previously cycle helmets are not specifically designed for high-speed impacts – only for protecting the head in a fall. Could a specifically-designed item improve accident statistics? The Snell Foundation and similar institutions are examining ways to improve head protection for cyclists without compromising the ability to ride.

This approach shows the detail possible in terms of holistic injury replication, and what can be achieved in a structured approach.

7 Vehicle Safety Developments

7.1 Introduction

Studies investigating reduction of injury to VRU's have been underway for decades. It is only relatively recently that manufacturers have been able to apply agreed test methods that allow repeatable results to what is a highly chaotic event. One of the aims of this study is to examine how new ideas can be applied to improve safety for riders.

Emerging technologies break into two categories – **Passive** and **Active**. The following section gives details on how some of these methods operate and how their application may affect cyclists and PTW riders.

7.2 Passive Technology

Vehicle manufacturers have invested large amounts of time and money to ensure the front end components perform their inherent functional tasks (i.e. low speed bumper tests such as ECE 42) as well as performing well in pedestrian safety tests. In particular the bonnet structure and bumper system are of particular note, but other components also include items such as headlamps (depending on design). The following section describes the project that was the idea of the author to create an autonomous pedestrian-friendly hood generator, optimised for the safety case, but mindful of the basic criteria a bonnet must perform (e.g. good torsional stiffness, etc).

Investigation of 2-Wheeled Road Traffic Accident Scenarios using Explicit FE Techniques.

The project specification was written by the author and delivered to Corus Automotive to utilise their KBE expertise to create a knowledge-based routine that would create an optimised bonnet structure for pedestrian safety.

7.2.1 KBE Bonnet Safety Optimisation - Overview

Knowledge Based Engineering has been used with great effect in both Automotive and Aerospace to automate design tasks, greatly reducing design lead times whilst at the same time improving design quality. An excellent example of the benefits to be gained by the use of this technology was reported by Airbus UK Ltd (Soumilas and Bobrowski, 2000) in a press release in January 2000:

“The use of KBE is revolutionising the design of Airbus wing components at British Aerospace Airbus. It vastly reduced the time taken to complete some of the lengthy repetitive design and development processes on the A340-500/600 wings.(...)For example, design of a set of wing ribs for this aircraft took two people just six weeks, previously such a task would have taken twenty people six months.”

Jaguar is an established user of KBE technology (Birch, 1996), with a number of specific applications providing support to its vehicle design and packaging teams. One of the most successful applications has been the hood designer. This tool operated by taking in a styled surface and, by applying the basic structural and manufacturing rules, delivers a fully surfaced hood inner panel design together with the necessary attachment flanges for the style surfaces. By providing the capability to suppress features such as small fillets, the resulting hood assembly can be passed to the CAE teams to assess structural

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and durability performance prior to passing to the design teams for final detailing.

The introduction of Pedestrian Safety legislation (e.g. EC Agreement Phase 1 in Oct 2005) places significant demands on the design and engineering of hood structures, needing to balance the needs of pedestrian safety with structural and durability requirements. Various methods have been studied as to how an impactor can be decelerated in the shortest amount of space without exceeding the HIC values given as criteria for the test procedures (Westwood et al., 2000, Ikeda and Ishitobi, 2003, Schwarz et al., 2004). The Mazda RX-8 hood and the new Jaguar XK hood (Fig. 79) are examples of creating a homogeneous hood – i.e. a regularized structure that will exhibit a uniform energy response no matter where impacted.

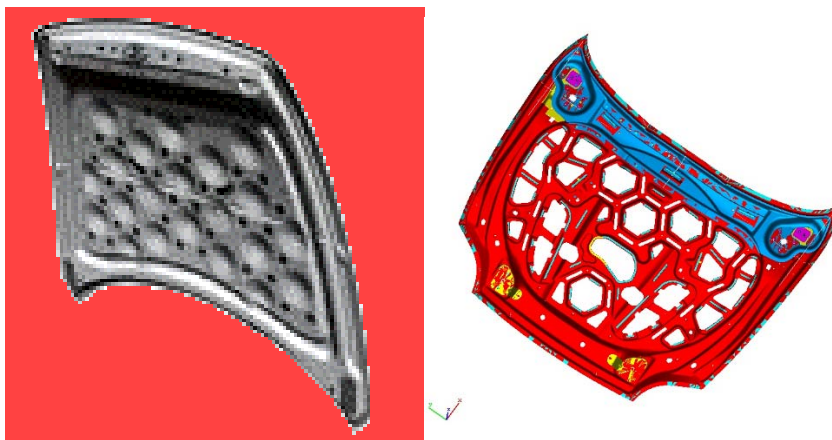


Figure 100 - Mazda RX-8 Hood (left) & Jaguar XK Hood (right)

A significant issue, however, is in determining the geometry parameters for the inner structure. Changing parameters, such as the size of the repeating

Investigation of 2-Wheeled Road Traffic Accident Scenarios using Explicit FE Techniques.

pattern or the depth of the structure will clearly require the whole structure to be redesigned prior to any analysis being performed.

The prospect of optimizing a structure (which needs to be redesigned on each design iteration) led the author to consider coupling a KBE design module to an automated analysis back end with the whole of the process driven by an optimizer.

The point to be made about this method is that it is the first time that any automotive company has used ICAD beyond purely geometric generation and may allow any future standards to be taken into account. For instance, should the head impactor standard be changed, this method should ensure a fast method to develop a hood that will provide a passive safety benefit within the already existing constraints.

The base concept was to develop a fully automated geometric optimizer delivering a hood structure conforming to pedestrian safety requirements, subject to manufacturing constraints, and respecting design best practice. This concept is shown schematically in Figure 101.

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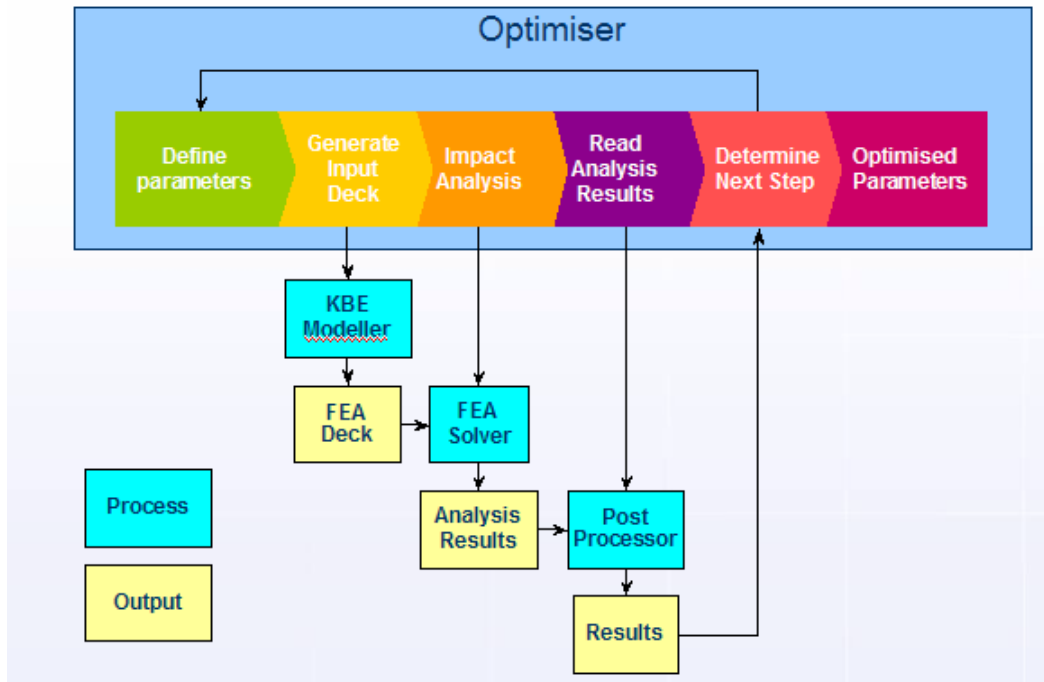


Figure 101 - Overview of the KBE Pedestrian hood process

A number of fundamental decisions were taken at an early stage relating to the tools and techniques to be used for the different stages in the process, although the overall architecture was designed such that each tool could be replaced with another one with minimum development effort.

When considering the optimization technique, a non-linear optimiser was felt to give the best chance of success since the design envelope for hood performance was expected to be highly non-linear. In particular, it was felt that there was a significant risk of bi-Modal behaviour and that outliers may be possible with potential for best solution to be next to worst.

It was also recognized that an optimum solution was not necessarily required, but simply a solution, or a number of alternative solutions, which conformed to pedestrian safety requirements. It was also felt that tools which would provide

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a greater insight into the dynamic response of the system would be invaluable in gaining a greater understanding of the options available and recognized that there could potentially be a large number of input variables. With these objectives in mind, the stochastic design improvement (SDI) methodology was considered to be most appropriate. SDI is a variant of the general optimisation process that establishes relationships between input variables and output results leading to a clearer understanding of the problem. Using Monte-Carlo algorithms, SDI is largely insensitive to the number of design variables and the random nature of variable selection handles non-linear behaviour.

Simple mathematics, however, demonstrated the magnitude of the problem to be solved. SDI needs, as a minimum 4 runs of 16 shots to converge to a reasonable certainty. To satisfy pedestrian safety requirements, a minimum of 50 separate impacts would be required for each design iteration. The size of the problem was therefore:

64 unique, fully surfaced, inner panel designs

64 fully meshed unique models

50 impactor models at desired position and orientation

64x50=3200 non-linear analyses plus 3200 master control include files

—
Clearly without full automation the use of SDI does not present a feasible engineering solution.

Using Knowledge Based Engineering to generate the hood inner structure geometry only represents a small element of the full automation required. The KBE application, based on the ICAD system, was therefore extended to

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deliver a full 'ready-to-run' LS-DYNA keyword deck, including all outer panel clinch flanges, inner structure, hinge and latch reinforcements and gutters.

The KBE application (shown in Figure 102) contains a number of unique features.

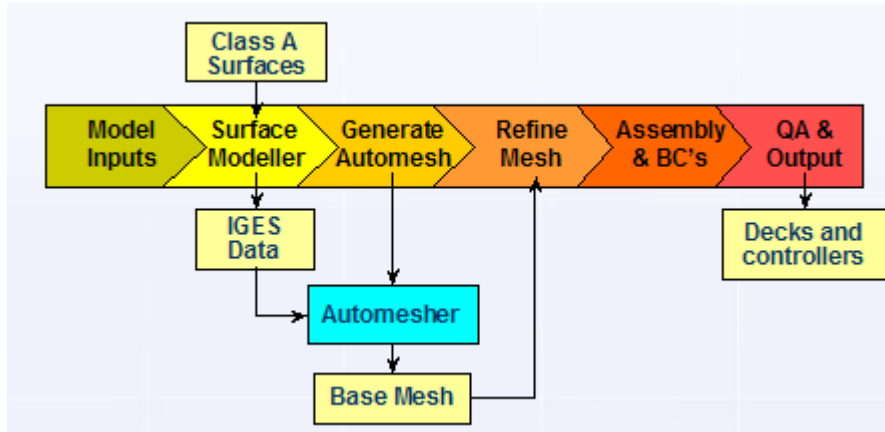


Figure 102 - KBE Application schematic

The inner structure geometry, based off the class A surface (the A-surface is the visible outer surface from the design clay), is generated completely automatically. Whilst speed was considered to be important, the need for a successful completion was paramount. To achieve this, speed was sacrificed for to use of more rigorous surfacing techniques, capable of coping with some of the extreme geometry conditions seen during testing. Following generation of the inner structure, hinge and latch reinforcers, gutters and clinch flanges are also generated and exported as separate models for automeshing. The KBE application invokes an external automesher and on completion of this process reads back in the individual meshes.

These meshes are then refined (for example 2 elements deep along all flanges) and assembled into a single model, applying connections to the

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Jaguar modelling standards. Finally QA is run on the mesh and corrections made to elements of poor quality.

Table 10 shows a comparison of the results from automeshing alone, KBE generated mesh and a professionally prepared manual mesh. It can be seen that the KBE approach offers a number of enhancements over normal automeshing and can approach the quality of a manually prepared mesh. Bear in mind, however, that the KBE mesh takes just 12 minutes to prepare, compared to typically several days required for the same manual process.

Criteria	Automeshing	KBE	Manual Deck *
No. of elements	35460	35737	-
Minimum Angle	97 non-conform	28 non-conform	7 non-conform
Maximum Angle	303 non-conform	18 non-conform	6 non-conform
Warp	160 non-conform	140 non-conform	174 non-conform
Skew	2 non-conform	2 non-conform	1 non-conform

Table 10 - Comparison of mesh quality from automeshing and manual deck preparation with deck prepared automatically using KBE

* Values normalised to KBE Mesh size

As part of the initial preparation, an input deck is created from a library which includes material details, standard head impactors, a rigid engine under-hood reaction surface etc.

The head impactor is called from this library and its location and orientation modified to enable it to be used at a specific location, and the impact is run

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with the generated LS-DYNA hood encompassing the other library details (e.g. materials etc).

Finally all controls, material properties and master include files are output, and the simulation is run. The post-processing of results is controlled by ST-ORM (the Stochastic Design Iteration software), and are mainly based on the HIC (head impact criterion) calculated from the acceleration output of the head impactor. These results are used in the optimisation process, and fed into the SDI method. This continues until a solution converges for an acceptable hood, or if no solution is possible, the process stops after a number of cycles.

The details of creating a batch method, within the constraints of a large OEM's CAE suite was a challenge, however after some dedicated work, it was possible to show the KBE/ST-ORM routine running as an entire continuous process. The CAE hardware at Jaguar forms part of a dedicated grid of computing power on different platforms, and in addition ST-ORM also had to interact with the JLR queuing and submission architecture. As substantial amounts of data were being transferred around the JLR network, data routing was crucial to the success of this project and had to be optimized. As with all 'bespoke' architectures, this set-up had to be maintained within the changing demands of the mainstream CAE community.

Using Stochastic Design Improvement, there is potential for a number of design solutions to be delivered which conform to the goals. Given that all of these solutions meet the requirements, it is necessary to determine which the 'best' solution is. At the outset it was decided that this would be based on other performance requirements (such as stiffness, normal modes etc) and

Investigation of 2-Wheeled Road Traffic Accident Scenarios using Explicit FE Techniques.

mass. By evaluating each option against these criteria and applying engineering judgment a 'best fit' solution (one which meets legislative performance and best satisfies product requirements) can be delivered.

To carry out this assessment, the KBE application is re-run, but this time in standalone, rather than optimizer, mode to generate the decks suitable for the performance analysis.

This is an important feature of the whole process; automation has been used to significantly reduce lead times and indeed make a process feasible to use, but the end results require skilled interpretation and engineering judgment applied to locate that design which best fulfils all requirements.

The adoption of KBE techniques is the key element in being able to use SDI to determine a design solution that meets challenging requirements. Tables 8 and 9 show process and model dimensions and total estimated runtime for a SDI scheme based on 4 runs and 16 shots

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Number of configurable inputs	280
Number of potentially variable geometric inputs	21
Geometric model size (IGES)	25-35Mb
Analysis model size	~40000 elements
Outer panel, flanges & BIW surface generation run-time	3 minutes
Outer panel mesh & Impactor translation run-time	4 minutes
Inner structure surface generation run-time	7 minutes
Inner structure deck generation run-time	13 minutes

Table 11 - Process and Model dimensions

Model	Time (mins)	Runs	Total time (mins)
Outer deck generation	7	1	7
Inner deck generation	20	64	1280
Total for optimization			1287

Table 12 - Solution time based on and SDI scheme of 4 shots x 16 runs

As can be seen, a total time of just under 22 hours for all model preparation required for an SDI project can be delivered using automation, compared to 3-4 days for geometry generation and 4-5 days for deck preparation (3360-4320 minutes) for one manual iteration. In summary, 64 iterations can be carried out in less than 40% the time for a single manual iteration. Obviously this does not take into account the solver time, which for an SDI run of this magnitude will be extensive.

7.2.2 Summary

This is the first time to the author's knowledge that anyone has successfully driven the fundamental geometry of a component using explicit FE controlled by an SDI optimisation package. This section has shown how a complex (yet contained) repeatable CAE task can be broken down and addressed using a high-level language KBE routine, coupled to existing off-the-shelf analysis software. The same approach could be used for other applications, and further research is on-going.

Care must be taken at all times to ensure that any automation empowers the user. The definition being that a repetitive task can be undertaken by a KBE routine, allowing the analyst more time to examine the wider problem than spend time carrying out on laborious tasks. Additionally it is important to maintain the balance of providing the analyst with enough information on how a solution is developing, but not over-burden him/her with redundant data.

Knowledge Based Engineering has already been shown to be the key enabler in achieving large-scale geometric optimization; however when analysis is included in the routine, a significant reduction in time, plus a consistent and repeatable improvement in quality can be derived.

This section has shown how a number of other standard tools have been used within their basic functionality, and combined into something that is much more powerful than the sum of its parts. It is hoped that this approach can be further developed by the analysis vendors and in future a 'modular' approach to analysis and pre-processing tools may be developed to allow easy implementation.

7.3 Active Systems

7.3.1 Deployable Bonnet

In addition to the passive route some vehicle manufacturers are examining alternative methods of mitigating pedestrian and cyclist injuries. 2005 Jaguar Cars Ltd was the first vehicle manufacturer to produce a deployable bonnet system, and the author was part of this team.

A pedestrian event is a chaotic, uncontrolled scenario, and therefore it is extremely difficult to produce repeatability in the same way that is now a standard procedure for occupant testing. With the advent of standardised tests and advanced finite element methods, it is now possible to achieve repeatable robustness for this difficult event. The author considers that this method also has benefits for cyclists and indeed the system has indeed been fired in such an incident.

Legislation in the European market requires manufacturers to commit to a two-phase introduction of a range of active and passive safety improvements on all new cars to improve the protection of pedestrians in the case of an accident. The XK combines passive and active features that can not only mitigate pedestrian injury, but also maintain the unique design language of the Jaguar brand. This is crucial to Jaguar's business improvement.

Using the principles behind this system it is possible to see what benefits there are for cyclists as well as pedestrians.

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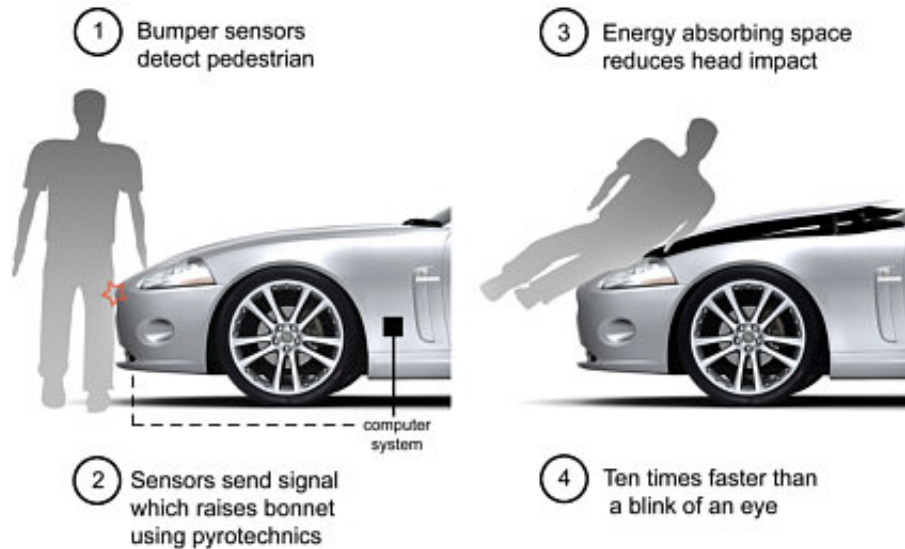


Figure 103 - Deployed bonnet on Jaguar XK (courtesy Jaguar Cars).

7.3.2 Pre-Impact Sensing Systems

This section investigates the design and analysis of a complete pedestrian airbag system, based on a staged bumper and scuttle airbag system. The major reasons behind the configuration of the system, the parameters chosen and why Finite Element (FE) analysis was used as a method to test the applicability of such a system are discussed. A vital part of the project was to understand the implications in terms of range and speed of response for the sensing system, driven from the time it would take for the airbags to deploy and stabilise. In addition it was important to understand the injury sensitivity to the human body if the airbag was to deploy too close to the body. This section also includes benefits and limitations of the approach taken, culminating in

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conclusions that can be drawn from the analysis and recommendations for which areas of the project would benefit from further studies.

The main aims of the APVRU project, from which this section was derived, were:

- Investigate the human factors, accident statistics and causes of VRU accidents and quantify potential risks and benefits.
- Specify the hardware and software components and develop a “proof of concept” pedestrian sensing system.
- Demonstrate technology capable of detecting a pedestrian prior to an accident and predict the point of impact.
- Demonstrate the technology to detect, accurately and reliably, the presence of pedestrians under representative environmental conditions.

As part of the original APVRU proposal, it was suggested that a vehicle or buck should be used with occupant airbags fixed to the exterior in order to test a pedestrian airbag system against an ATD (anthropometric test dummy) such as the O-PAT. This work was proposed to lead on from the work carried out in Active Adaptive Secondary Safety.

In light of more detailed project investigation, this approach was not feasible and was therefore modified in order to best meet the requirements of the project aims. The reasoning for this change is provided below.

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It was agreed within the project team to exclusively use explicit FE analysis (LS-DYNA), and attempt to create a complete airbag system and examine the risks and potential for this type of active safety system. Coupled with Jaguar's expertise in pedestrian analysis and using a previously developed correlated FE humanoid and vehicle, this would allow a cost-effective, detailed examination of several impact scenarios and a basic design of experiments to discover the risks and limitations of a proof-of-concept active airbag system.

This led to the following objectives for the airbag modelling work:

Create a realistic proof-of-concept pedestrian airbag system.

Determine the corresponding timing envelope for a pedestrian sensing system.

Investigate the consequences of the airbag firing early or late when the humanoid is in a non-optimum position.

Provide recommendations for further work.

7.3.2.1 Introduction

Explicit finite element analysis allows accurate reconstructions of dynamic impact events. It is widely used in the aerospace, automotive, military and nuclear industries using various modifications for the needs of each sector (for examples see www.lstc.com). With the increase in computational power and improvement in modelling techniques over the last decade, it is now possible to run very complex models within a relatively short timeframe with comparatively modest equipment. It is for this reason that more and more companies are following a 'virtual' product development route rather than the

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more traditional intensive experimental methods in the past. This is because it is possible to run a significantly greater number of situations and understand the variables of a dynamic event, in more detail, in a shorter space of time. This allows a smaller, targeted number of impact tests to correlate the CAE analysis.

Pedestrian impact analysis is a particularly complex event. Early experimental work used modified occupant ATD's (anthropometric test dummies) to represent the pedestrian, however this can lead to inaccurate results. Most ATD's were designed to act as a representation of a humanoid for a specific event – understanding the forces and accelerations experienced by the body parts of a 'standard' occupant. From details of real-world events it is clear that these occupant dummies are not well suited for analysing pedestrian events – for instance subtle differences in the dynamic behaviour of the lower leg may have dramatic differences at the later stages of the impact event (e.g. head whiplash or where the head finally impacts on the vehicle structure). Some work has been carried out in Japan to create a more representative dummy, POLAR (Akiyama et al). However, development work is still on-going, and at present this ATD is expensive and not widely available.

FE analysis allowed the project to investigate the already complex event in several scenarios with the addition of airbags. The analysis case is by no means trivial. If you consider the number of contact groups that need to be created which represent the objects that may touch at some point in the simulation (e.g. upper leg – rest of body / upper leg – bumper airbag / upper leg – vehicle front / etc.). and the effects that each of these may have on each other plus all the assumptions that have to be taken into account such as

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material values and frictional effects, it leads to a large FE model that takes several days to solve, even on a large dedicated solver with several processors being used in parallel. All assumptions in terms of the interaction of parts were based on experience and preliminary real-world analysis. The following sections provide details of the FE approach and how this has can lead to reasonable assumptions when applied to a real-life case.

7.3.2.2 Finite Element Model Details

The FE model consists of three distinct entities: the humanoid, the vehicle and the airbag system. It was developed and run using LS-DYNA version 950e, and each run was solved on a Compaq ES 45 in approximately 80 hours total CPU time (20hours on 4 heads).

Each model used the following assumptions:

- 1) Friction between foot and ground was 0.2
- 2) 40kph impact.
- 3) No braking used on the vehicle.
- 4) -9.81m/s^2 Global Body Z card to represent gravity.

7.3.2.3 Pedestrian Airbag System

The proposed airbag system was based on existing occupant airbag systems and underlying basic sensitivity studies carried out to develop each airbag.

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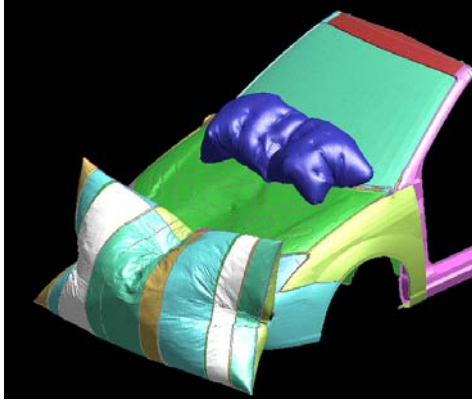


Figure 104 - Proof of concept pedestrian airbag system.

The system itself consists of a bumper airbag and a scuttle airbag. The concept being that the pre-impact sensing system will detect when an impact is unavoidable and will deploy the bumper airbag first, reducing initial impact, bending and shear on the ankle and knee. Following this the scuttle airbag will fire in sequence allowing reduction in head acceleration, and protecting the head and upper body from any hard points (e.g. the wiper mechanism).

Taking each of the airbags in turn:

7.3.2.4 Bumper Airbag

This airbag was based on an occupant airbag; however the final inflated volume is approximately 350 litres. It should be noted that since this is again an extrapolated version of the occupant bag, the stretch to this volume is the best estimate that could be applied, given the lack of detailed expertise from an airbag supplier.

The shape and form of this FE airbag was based on:

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Sufficient depth to reduce leg acceleration, bending and shear, plus spread the impact load over the entire leg.

Sufficient width & length to cover bumper area and hardpoints.

This airbag should be treated as an empirical estimate. However, the effect of the airbag (as discussed in the results section) gives an effective result in terms of the effect on the adult humanoid in perfect conditions. The total time to deploy & stabilise was approximately 95 ms.

7.3.2.5 Scuttle Airbag

The airbag was based on a 60 litre occupant airbag, in terms of materials and inflator profile, and uses internal springs as tethers. The shape and form of the FE airbag was based on the following criteria:

Sufficient depth to reduce head acceleration onto the scuttle, but not too great so as to obscure driver vision.

Sufficient width & length to cover scuttle area and hard points.

There was no venting specifically built into the model; however material leakage was used instead. The final volume is approximately 89 litres and the time to deploy and stabilise is approximately 50ms.

7.4 Situations Investigated

7.4.1 Introduction

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Table 10 below gives a summary of the scenarios investigated. In greater detail, the first column gives the directory in which the simulation run is held, the "Airbag" column indicates if an airbag has been run as part of the simulation or not, and Stance A is an upright, feet together stance, as shown in Figure 106. All simulations were conducted at Y=0, i.e. the centreline of the car.

Run AEG/001350	Humanoid	Airbag	Vehicle Speed (kph)	Location of impact on vehicle	Stance	Perfect Humanoid Positioning for airbag?
B103	50%-ile Adult Male	Yes	40	0	A	Yes
B104	50%-ile Adult Male	Yes	40	0	A	Too close
B105	6 Year old Child	Yes	40	0	A	Yes
B106	50%-ile Adult Male	No	40	0	A	N/A
B107	6 Year old Child	No	40	0	A	N/A

Figure 105 - shows the scenarios run in FE simulation.

This is shown in plan form in Figure below.

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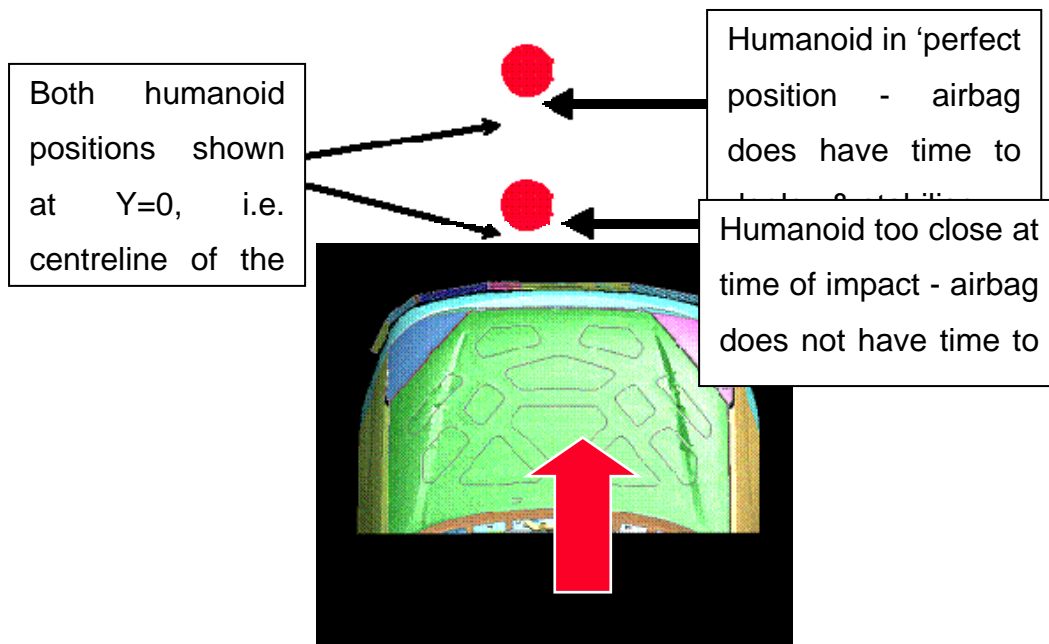


Figure 106 - Plan view of the pre-impact set-up.

Due to the effort required in developing the airbag systems and the integration of the sensing system on the vehicle, only the cases described were examined. However, useful conclusions can be drawn based on this system.

7.5 Results

7.5.1 Timing

From the airbag deployment times, the bumper airbag gives the overriding time for deployment; therefore 95ms before impact, the airbag must receive the signal to fire. The estimated timing envelope with the system developed for this project will have a small margin of error, probably in the order of +/- 5 to 10ms, particularly if the airbag is deployed late. If the airbag is deployed early there may be some possibility within the design to keep the bag inflated for a period of time. As a result, it is better to deploy the airbag too early rather than too late.

7.5.2 Kinematics and Humanoid Injury effects

The bumper airbag can prevent serious damage to the knee in terms of bending and shear. However, due to the compressibility of the gas in the airbag, the upper body acceleration is faster and the head impacts into the windscreen / scuttle area more quickly. Clearly the venting on the bumper airbag is critical, and if this is incorrect for a given event, the effect is to potentially add more energy into the event rather than dissipating it, leading to greater injury and throwing the pedestrian further.

As far as the child case is concerned the initial impact into the airbag looks effective in terms of spreading the load and reducing knee and chest injury, but once again the compressibility of the gas acts like a spring and adds more

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energy into the event. It is worth noting that the HIC for the non-airbag event is lower than that of the event with the airbag system. In this case the venting would have to adapt according to the impact event and therefore a complex adaptive venting system, would have to be designed to cope with the differing scenarios if such a system were to work effectively.

It is also worth noting that the child's head impacts onto the bonnet and therefore the scuttle airbag is rendered useless. It is conceivable that the bumper or scuttle airbags could be extended in some way, but this again leads to extra complexity beyond the scope of this project.

7.6 Discussion

Airbag development, particularly FE modelling of airbag systems is a complex area and the lack of a supplier in the project made this especially difficult. However there has been comparatively little published work in terms of simulating pedestrian airbag systems, and certainly not at this level of detail. How to vent the airbag, whether it should have different stages, tethering, and the size and numbers of pyrotechnic devices to fire the airbags are all areas of research which could be investigated more thoroughly with an airbag supplier.

It should be realised that the main aim of the project was to develop a pedestrian sensing system, and therefore that is where the majority of the effort was correctly applied. The basis of this work was to provide a foundation to this aim, and given time to investigate the effects of the airbag system in terms of risk and benefit.

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A system that uses a passive front on a vehicle and a scuttle airbag looks more promising than the total airbag system as described in this report. In particular if the scuttle bag could be designed such that the A-pillars and header was included this may be a potential solution, however this would need much more investigation, and again it would need a very reliable pre-impact sensing system.

It is worth re-enforcing this is a 'proof of concept' system – this is a purely an empirical attempt at an airbag-based active safety system. However, given the available time and resources it provided the vital input needed to bound the timing envelope required for the sensing system.

It should also be noted that an active system (airbag) is now in production for the Honda Goldwing, and other large motorcycle manufacturers are considering this move (Iijima et al., 2000).

8 Conclusions & Recommendations

8.1 Introduction

To re-iterate the original aims of the PhD study:

- Understand the real-world numbers and trends in accident data for two-wheeled accidents compared to other Road Traffic Accidents (RTA) incidents.
- Find detailed conditions and orientations for cyclist-to-car and Two-Wheeled Motor Vehicle-to-car accidents.
- Understand critical influences of bicycle and light motorcycle structures via impact testing, and create correlated LS-DYNA™ Finite Element models.
- Create accident simulation models for each of the most statistically relevant two-wheeler cases.
- Apply learning from clinical studies to improve the accuracy of the simulations to real-world cases.
- Discuss influences and effects of new passive and active safety systems on rider injury.
- Investigate new-generation non-linear optimisation techniques to allow improved methods of generation of injury reduction (component optimisation).

In the author's opinion, this research study achieved the objectives.

A structured methodology was incorporated at an early stage of study and applied through all events, culminating in a series of complex finite element

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simulations that show this is now a suitable method to examine injury mechanisms on a holistic level, and is a suitable foundation to build on and add in greater detail as required.

8.2 Conclusions

8.2.1 Examination of underlying accident statistics

The RTA accident statistics show clear implications for vulnerable road users on a global basis. Time will tell as to whether these trends suggested will occur, but with the increase in the price of fuel and 'green' issues strongly emerging during the course of this study, the trend for increasing vehicle mixes in urban environments means that two-wheelers as a form of transport are good subjects to be examined in more detail.

8.2.2 Injury criteria for cyclists

Using the existing criteria developed by Yang et al, it is clear that further refinement is required. Data is generally created for a lateral impact to the body as this is the most frequent scenario for a pedestrian event. With cyclists impacts can be from almost any angle and it may be necessary to re-visit some of these criteria.

The child case in particular is a real issue in terms of injury criteria and this will not be an easy issue to overcome.

8.2.3 Modified ISO 13232 standard

A methodical approach to impact testing and adaptation of an existing two-wheeler standard showed how the cyclist case can be tackled. This is the first time anyone had proposed such a methodology for cyclist cases. It should be

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noted that cases 3, 4, and 5 may require some adjustment (either higher speed or stronger attachment of the humanoid to the bicycle model) but nevertheless the approach is sound.

8.2.4 Bicycle Dynamic Impact Testing

There was no dynamic crush data available for cyclists before this course of work. By taking existing mass-produced bicycles and examining their constituent components performance longitudinally and laterally it was possible to gain an understanding of the failure modes and load values to build a suitable FE model.

8.2.5 Bicycle Model

Very little serious work had been created on cyclist reconstruction before this study and only one other paper had been seen by the author on this exact subject. The CAE models successfully showed how injury can be assessed for real-world incidents and potentially how they may be used in evaluating new protection systems. There are limitations in terms of all variables that can be examined (the physiological effect of a real rider on a bicycle will have differences – for instance in terms of muscle tensioning pre-impact), but the principle is sound.

8.2.6 Active and Passive Safety Solutions

With the FE model established it can then be used to analyse new passive and active safety concepts for pedestrians, cyclists and other vulnerable road users.

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The knowledge based engineering solution for the optimised pedestrian-friendly bonnet is the first time anyone has successfully driven total geometry generation at CAD level from an optimised explicit analysis. This is a major achievement and allows complex multi-variant problems to be tackled in a structured way.

With further safety systems now being actively pursued for both vehicles and motorcycles, the approach detailed in this thesis should provide a basis for at least some of the work to come.

8.3 Future Work

8.3.1 Accident Statistics

There is very little reliable data for the developing world – this would be very beneficial for growing economies to understand how to implement road infrastructure changes, as well as investigate how road user profiles are changing. In addition in the West continued monitoring of how congestion charging schemes are effecting the vehicle types being used would prove useful for similar reasons.

Improved detailed analysis of both cyclist and motorcyclist accident statistics would be useful in the West and indeed there is increasing interest in this area growing driven by funding from the EU.

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8.3.2 Physical Testing

Further impact testing to create a valid database of results would be very useful. The variability of results for the wheel and frame buckling means that a significant number of tests would need to be performed.

8.3.3 Mathematical Models

The bicycle models can be extended into a range of bicycles and could examine different frame materials. Different positions / riding styles, as well as the interaction between rider and cycle would be beneficial to observe and understand how this effects the kinematics in impact.

The motorcycle in this study was rudimentary, and was created to examine the difference with a cyclist RTA. This could be a very interesting field to examine properly, as the riding position and injury mechanisms (due to higher speeds and greater mass of the motorbike) would merit examination.

Later vehicles with pedestrian countermeasures could be included, as could other motorised vehicle types – namely trucks and buses.

The humanoid model has many areas that could be examined and improved for instance greater injury details for the thorax / abdomen. This could include major organs and a method to calculate haemorrhage from major blood vessels.

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Joints could also be examined – in particular the shoulder (a particularly difficult proposition due to the connections between muscle, bone and ligament).

Improved brain injury could be also included using methods such as proposed by Lawson (Lawson, 1997).

From these it should be possible to simulate and evaluate further safety features for vehicles of the future.

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Appendix A – Real World Cyclist to Car Accident

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A cyclist crossed at a staggered pedestrian junction across a busy A-road, where the speed limit is 40mph.

The cyclist is a 30 year old male commuting to work, with no reason for any impairment. The exact time and location is being withheld for confidentiality, however it was in Summer 2003 in the early morning, and lighting conditions were good.

From discussion with the cyclist, it was a clear day with good road conditions. The rider admitted that he did not think he had pressed the button on the staggered pedestrian junction, and had ridden into the road without seeing the vehicle coming towards him. Other witnesses claimed that the impact was at the front of the vehicle at the nearside headlamp, and although the car had braked, the vehicle was estimated to be travelling at around 30mph at impact. The bicycle was impacted first, followed by the right hip of the rider. This rotated the rider so that his back was thrown across the bonnet and he impacted near the center of the windscreen with his head. The windscreen was smashed and the vehicle came to a halt 50m within the junction.

Amazingly there was little damage to the rider – a small fracture of the sacral vertebra. He was kept in for observation and was given a thorough neurological examination, but this seemed to be the extent of his injuries.

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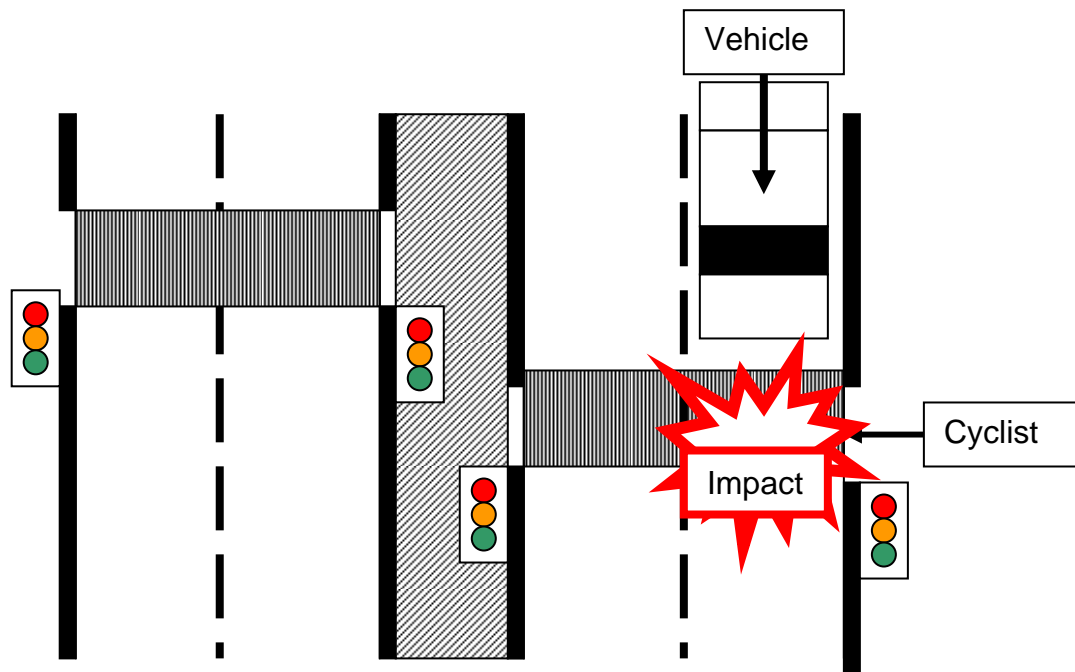


Figure A1 – Plan View of Cyclist-Car Accident