Road Safety Trust (RST 65-3-2017) “Reducing Road Traffic Casualties through Improved Forensic Techniques and Vehicle Design (“RoaD”)

FINAL REPORT

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Executive Summary

The “RoaD” (Reducing Road Traffic Casualties through Improved Forensic Techniques and Vehicle Design) pilot project overall aim was to improve understanding of pedestrian injury as a result of a vehicle collision. In particular, the project sought to understand whether it was possible to create a pedestrian trauma database (PTD). Such a database would contain vehicle profiles and would be capable of providing the injury severity from the impact speed, depending on vehicle and pedestrian stature. In order to create a PTD the project looked to solve the question of whether it is possible to develop a model and calculate trauma at organ level in a pedestrian collision.

More accurate and timely understanding of pedestrian injury severity has potential benefits including improved Accident and Emergency responses, less distressing Coronial process for families and new techniques to support law enforcement applications. This project was endorsed and supported by UK Police Force (UKPF), UK Coroners, EuroNCAP and the RoadPeace charity**.**

As part of the project methodology the requirement was for a large dataset of pedestrian fatalities, to be provided by the UKPF, for which vital organ injury severities would be extracted. These collisions would be reconstructed using computer modelling to ultimately generate a calibrated injury model, which would be then used to populate the PTD. As ageing was an important parameter, i.e. people become frailer when becoming older, it was necessary to access a large number of collision data samples to cover the widest range of ages, allowing the PTD to capture the trauma severity across the entire population. At the onset of “RoaD”, it was found in the scientific literature that organ stretch (using a ‘Maximum Principal Strain’ reading, or MPS) during an impact, which is a current standard method used in the scientific community to extract injury in computer models, was not adequate to extract all the levels of injury severity. Fortunately, a concept, named Peak Virtual Power (PVP), derived in 2001 by Prof Clive Neal-Sturgess, had the potential to solve this current deficiency and was selected for this project. This method uses the 2nd Law of Thermodynamics, stating that after an impact, Entropy (a measure of the molecular disorder) increases, hence suggesting organ degeneration and damage. This disorder is computed by extracting the maximum power experienced by each organ during the collision and linking it to the threat to life using the Ordinal abbreviated injury scale (AIS), which ranges from 1 (minor) to 5 (critical). This method had never been applied to human body computer models (HBM) and had never been used to capture differences in trauma severities as a function of ageing.

Unfortunately, due to an unexpected reduction of UKPF support staff, as well as a new procedure for the courts, it was not possible to approach this question as originally planned, which was through access to collision data as incidents occurred. Instead a mathematical approach was undertaken, which lead to the derivation of an innovative and unique Organ Trauma Model (OTM). The derived OTM model linked the impact energy (kinetic energy), deformation energy (strain energy) and the concept of power, which is represented by the product of pressure (stress) on the organ and its rate of deformation (strain rate). As the organ deformation for a given load is material dependant, it was possible to include the ageing material degradation, as well as the organ volume variation as a function of ageing, making the OTM a universal trauma model, able to capture trauma across the entire population.

The OTM model was tested against three pedestrian collisions provided by the UKPF and used the Total Human Model for Safety (THUMS) for trauma severity extraction, which had been adjusted to represent the height and weight of the deceased. Due to time constraints, the study only focused on brain white and grey matter injuries. The results confirmed that the OTM model projected accurate trauma brain injury severities when bleeding did not occur and under-predicted when bleeding was observed by the pathologist. The differences observed were an inherent limitation of the computation method which kept the volume of the organ constant. Conveniently, this computation limitation has also confirmed that the OTM mathematical model was physically representative to real world trauma responses, as OTM stipulates that injury severity is inversely proportional to the organ volume, i.e. a volume loss leads to a greater trauma. The results also confirmed that the OTM model trauma severity predictions were more accurate than the standard MPS method currently used in the scientific community, as all the MPS results were consistently over-predicting the injury outcomes. Furthermore, the OTM model had the capabilities to rate the injury severity level occurring under the critical trauma severity level, which is a breakthrough in its own right. This finding has been reported to JSOL, reseller of THUMS, which are in the process of including the OTM trauma model as part of their brain trauma indicators, which will be accessible by the scientific community worldwide.

The “RoaD” Pilot Study has therefore concluded that a PTD could be achieved with the improvement of blood loss modelling in HBM, hence requiring further work which would investigate whether it is possible to model ~~of~~ fluid inside the HBM, as well as haemorrhage. During this project, the “RoaD” team, has also gained a better understanding of the parameters influencing the trauma outcome of a pedestrian collisions, consequently, it is believed that the PTD could also be approached using data mining and machine learning techniques. This finding has led to the funding of two joint PhD’s between the University Hospital of Coventry and Warwickshire (UHCW) and West Midlands Ambulance Services (WMAS) to investigate these new challenges. It is believed that these two new research projects, generated from the “RoaD” grant award, will bridge the gaps to the generation of the PTD.

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1. Introduction

The "RoaD" pilot project (Reducing Road Traffic Casualties through Improved Forensic Techniques and Vehicle Design), was devised with the purpose of investigating whether it was possible to generate a pedestrian trauma database (PTD), with the aim of supporting in the first instance the forensic UK Police Force (UKPF). Current UKPF investigation court evidences use the pedestrian throw distance method as a mean of calculating the vehicle-to-pedestrian collision speed [1]. More complex cases, like hit-and-runs or events involving multiple impact, would benefit from a computer programme to calculate the vehicle impact speed from organ trauma severity; it would provide the UKPF with a unique and useful investigation tool. In order to generate this PTD, a collection of accident data containing collision information as well as anthropometric and Post Mortem (PM) information were initially required and would be based on current court case accident data.

Unfortunately, in November 2017, when the "RoaD" project was granted, some unforeseen obstacles were highlighted by the UK Police Force (UKPF), some were of political nature and some procedural. The first challenge the project "RoaD" faced was the significant reduction in the UKPF staffing in the last few years [19][20][21][22][23], limiting the support the UKPF could provide. The other challenge in performing such research was due to new court processes, as since 2018, as part of the English Law, the "Criminal Procedure and Investigations Act 1996", all the evidence considered must be made available to the defence [24]. **These two hurdles lead to a change of methodology, favouring a more mathematical approach to the research, using only three collisions provided in a pre-study for validation.**

As background, current safety tools to evaluate vehicle design use crash test dummies, or anthropometric Test Devices (ATD). These have contributed to improved transport safety since their first use in 1996 by EuroNCAP [1]. ATDs record displacements, accelerations and forces. During the vehicle design process, the ATD output information is cross-correlated to a probability of threat to life, based on injury severity, defined by medical professionals who have suggested a trauma injury scale or the Abbreviated Injury Scale (AIS) [1].

The AIS is internationally accepted and is the primary tool to conclude injury severity and is anatomically based. It is a, consensus derived, global severity scoring system that classifies each injury by body region according to its relative importance (threat to life) on a 6-point ordinal scale and provides a standardised terminology to describe injuries and ranks injuries by severity. The measurements from ATDs can only be used to speculate on the probability of death and have no internal organs, consequently they are not useful in predicting soft tissue injuries in a deterministic manner.

Human computer models, like THUMS [4][5], have modelled the soft organ tissues (heart, kidneys, liver, spleen, liver, grey and white matter) and can output soft tissue Maximum Principal Strains (MPS), which unfortunately only have a bearing with AIS4 [6][7][8]. MPS relates to the percentage the organ can be stretched before failing mechanically, i.e. tear (see Table 3). This percentage is obtained by performing organ tissue pull tests, hence is not fully representative, as in real life the deformation can occur in different directions and sometimes in combined directions. Furthermore, the MPS values recorded in literature do not take into account ageing effects as well as deformation speeds which tend to weaken the organ structure.

This research proposes a new Organ Trauma Model (OTM), as the foundation of the PTD, to compute soft tissue trauma in pedestrian collisions. Because of the complexity of the problem, it was decided to focus initially on the brain white and grey matter injuries.

The mathematical model was tested against three accidents provided by the UKPF (Table 1) by comparing the predicted trauma of a pedestrian collision (Figure 1) against the real world Post Mortem (PM).

Case Id	Vehicle	Pedestrian Mass (kg)	Pedestrian height (m)	Age (year)	Impact direction	Vehicle Impact Speed (m/s)
1	Toyota Corolla	58.6	1.65	34	Right side impact (right leg forward)	11.2
2	Renault Clio	79.2	1.73	79	Side (left leg forward)	12.5
3	Benz B180	56.4	1.65	25	from driver's near to far side	12.5

Table 1: UKPF Cases studied

Figure 1: Typical pedestrian kinematics during collision

At the end of this report recommendations of whether a PTD could be generated with the OTM model are discussed.

2. Relevance of the Research

Various stakeholders were approached (EuroNCAP, RoadPeace, the UKPF and Coroners) who all endorsed the relevance of this work, which could have major engineering and societal impacts:

- It could influence vehicle manufacturers in their choice of vehicle frontend design. This is the first step towards engineering safer vehicles for the entire population in vehicle - pedestrian accidents (EuroNCAP).
- It could help to support grieving families and particularly those with the need for immediate burial due to religious beliefs will see a direct benefit from the research, as the Post Mortems of their loved

ones can be replaced by a non-destructive CT-Scan, which will remove unnecessary distress and in specific cases can reduce the length of the coronial process (UHCW/ RoadPeace/ UK Coroner).

- It could support the UKPF by linking vehicle speed, vehicle shape and pedestrian anthropometry. This PTD will be used manually as a lookup table, when used in their investigation processes, to determine vehicle impact speeds based on the organ trauma AIS to assert the burden of proof.
- NHS A&E departments could benefit by using the PTD as a lookup table to assess organ trauma of a crash victim if a vehicle model (shape), speed and victim anthropometry are known to the response team at the site of the accident.

In 2018, 456 pedestrians died (25% of all UK road user types) with an economic loss of £1.7m per pedestrian [15]. There were 5,063 seriously injured pedestrians each costing £220,000 to the NHS [16]. In the longer term, the project aimed at reducing loss of life if the results of the research lead to the design of safer vehicles. In the medium term, this research will enable better public services for the UKPF hit and run accident investigations, in improving A&E triage responses, as well as using Coroners PM examination in courts.

The Road Safety Trust charity awarded a research grant of £37,412 (project RST 65 -3-2017) for this 2-year pilot study.

3. Methodology

3.1 Theoretical Derivation of Trauma

Injury severity can be computed from a concept called Peak Virtual Power (PVP). Peak Virtual Power is based on the general principle of the 2nd law of thermodynamics, stating that entropy (state of disorder) increases after each mechanical process [6][7][8]. When a collision takes place, the entropy (represented by PVP) always increases, never to return. A typical pattern of this behaviour is illustrated in Figure 2, where power goes up and down, while PVP keeps always to the maximum value at all time.

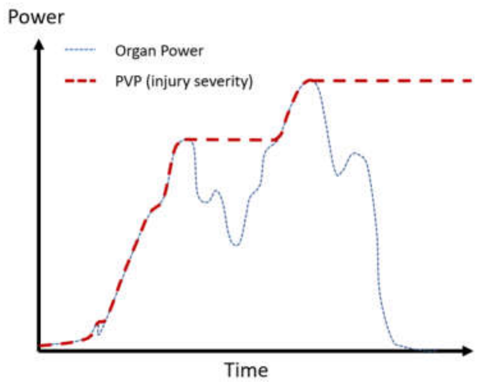


Figure 2: Power goes up and down, while trauma (represented by PVP) keeps on increasing [9]

PVP in a finite volume of the body (at organ level for example) is calculated by multiplying the localised "pressure" in that volume, or stress (σ), by its speed of deformation (or strain rate ($\dot{\varepsilon}$)). As the load varies during the impact, PVP will vary but will always take the maximum value (Figure 2).

It is demonstrated that the injury severity is a consequence of this increase of entropy and is proportional to the PVP generated by this collision (Equation 1). If PVP increased, then the trauma increases.

$$PVP \propto max(\sigma \cdot \dot{\varepsilon}) \propto AIS$$

Equation 1: Generic relationship between Peak Virtual Power and threat to life

The injury severity is coded via an Abbreviated Injury Scale (AIS), which has been medically derived and listed in Table 2; AIS is an "ordinal" measure.

AIS Level	Injury	Risk of death %
1	Minor	0.0
2	Moderate	0.1 -0.4
3	Serious	0.8 – 2.1
4	Severe	7.9 – 10.6
5	Critical	53.1 – 58.4
6	Un-survivable	100

Table 2: Abbreviate Injury Scale linking AIS level and threat to life [14]

When using human computer models in accident reconstruction, it is possible to relate the threat to life to human organ tissue deformations observed during real human organ tests. This information comes from literature and was performed by scientists (not part of this project). If the stretch is exceeded then severe injuries will occur (usually an AIS 4 outcome). Let's say that if some zones in the liver stretch by 30% (computed), then it will tear and cause a severe injury (AIS 4), as seen in Table 2. The organ cut-off trauma levels are challenging to obtain, however indicative values have been obtained from literature (Table 3). These values are based on Maximum Principal Strains (MPS), which is the principal direction of the stretch performed in the tissue tests.

Body Part	**Load**	**Threshold**	**AIS level**
Brain contusion	Maximum principal strain	26% [10]	3
Diffuse Axonal Injury (DAI)	Maximum principal strain	21% [11]	4
Heart	Maximum principal strain	30% [12]	4
Liver	Maximum principal strain	30% [13]	4
Spleen	Maximum principal strain	30% [12]	4
Kidney	Maximum principal strain	30% [13]	4

Table 3: Injury trauma values used in THUMS ***Error! Reference source not found.***

By considering further scientific literature [6][7][8], it was observed that the threat to life increases cubically when AIS is increased (Figure 3).

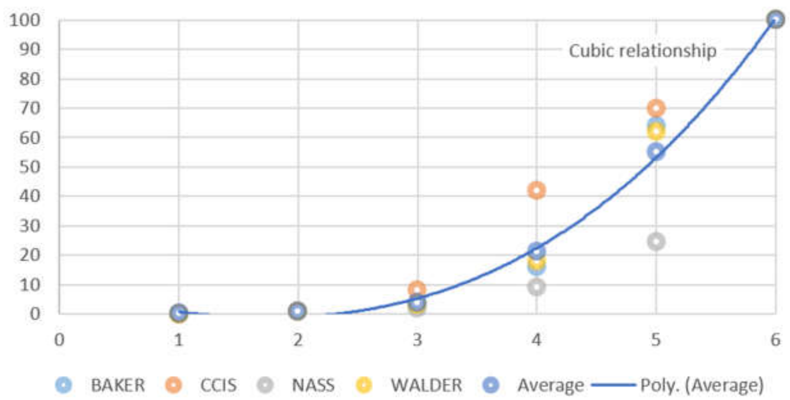


Figure 3: Relationship between Risk to Life and AIS [9]

This is a very important observation, as if the PVP necessary to cause a severe injury is known (AIS 4) then it is possible to extract how much PVP the organ can withstand to reach AIS 1, 2, 3 and 5. The PVP values can be scaled from AIS 4 by the ratios 1/64 ($\underline{1}^3/4^3$), 8/64 ($\underline{2}^3/4^3$), 27/64 ($\underline{3}^3/4^3$) and 125/64 ($\underline{5}^3/4^3$) respectively to create the full map of trauma injuries for that organ, creating an "Organ Trauma Model" (OTM). It should be noted that AIS is ordinal, and so the interpolation model is only interrogated at ordinal values.

As an illustration, any OTM, will be therefore represented by a graph containing the relationship between PVP, impact velocity and AIS, as illustrated in Figure 4. It has been possible to include error corridors (upper and lower) for each AIS value by considering the spread of data from Figure 3.

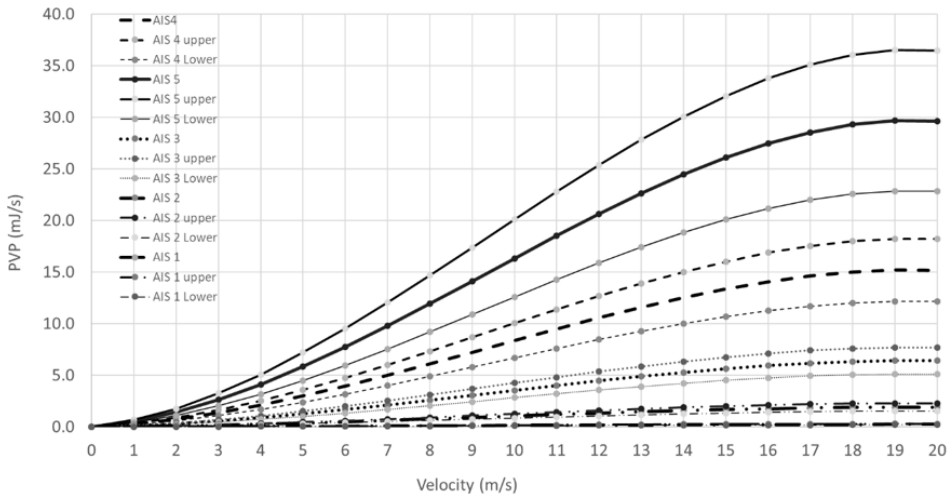


Figure 4: Typical Organ Trauma Model (OTM) starting from AIS4 and then deriving the other levels [14]

As an example, looking at Figure 4, the following arbitrary scenarios can be concluded (Table 4):

Impact speed (m/s)	PVP (mJ/s or mW)	AIS extracted from Figure 4
9	7.5	4
14	25	5
19	10	3 or 4 (depending on how close the PVP value is from the upper AIS3 and lower AIS4 corridors

Table 4: Hypothetical scenarios extracted from Figure 6

The theoretical derivation of trauma is complete, however it requires an algebraic definition in order to extract the PVP value from accident reconstruction. This phase is explained in the next section.

3.2 Theoretical Derivation of Trauma

By equating the organ kinetic energy and its deformation energy during the impact, it can be proven that AIS depends on the geometry of the organ at the time of impact, its material properties, the stiffness of the impacted surface and the velocity cubed (Equation 2):

$$PVP \propto \mathrm{AIS} \propto \frac{\mathrm{A}}{V_0}\sqrt{\rho E}.Kv^3$$

Equation 2: Algebraic derivation of PVP

Where:

- 'A' represents the contact of the Area of the organ which is impacting the vehicle. This Area will change according to the kinematics of the pedestrian while wrapping around the vehicle profile
- 'V_0' is the volume of the organ (constant)
- 'ρ' is the density of the organ
- 'E' represents the Modulus of Elasticity of the organ (Young's Modulus)
- 'K' is the contact stiffness between the impacting surface and the pedestrian
- 'v' is the organ impact speed, which is not necessary the vehicle impact speed. For an upright vehicle, i.e. bus, the organ impact speed is the bus impact speed, while in a low fronted vehicle, the speed of every part of the body do not impact the vehicle at the vehicle impact speed. These can be lower or higher. Such velocities can be computed during the accident reconstruction phase.

The outcomes of Equation 2 are sensible, such as:

- The higher 'K', i.e. rigidity of the impacted surface, the higher the injury
- The higher the impact speed 'v', the higher the injury.

An important fact is that, because the phenomenon is related to impact mechanics, the stress wave travels through tissues differently according to the human is impacted. Consequently, PVP, and therefore AIS, is impact direction dependant. As an example if a head is dropped on a rigid surface, the trauma will be different depending on the contact point (forehead, temple or occipital).

Another important point to notice that, in equations Equation 2, V_0 (organ volume) is constant. The method used to reconstruct the accidents is using finite elements. As a general principle, finite elements discretise the problem in small elements which are connected to each other, so the sum of these elements represent the whole problem. By cutting the problem in small parts, it is possible to investigate what can happen locally: this method is used to analyse complex shapes which differ greatly from say simple beams or plates which have been solved by engineers. Usually, organs which have a three dimensional aspect are represented by connected cubes (hexahedrons) or triangular based pyramids (tetrahedrons). This is the case with the computer model used in this study (THUMS 4.01). During the impact, these elements deform, stretch and change shape, however their volume remains constant. It is called a "Lagrangian" representation of the problem. The consequence, is that, should bleeding occur in the real-world accident, i.e. loss of volume due to the blood escaping the organ, then the finite elements will NOT be able to capture this. This is an inherent limitation which became apparent upon the derivation of Equation 2. On the other hand, should bleeding not been observed, then Equation 2 should provide the correct answer. This potential limitation will be re-visited in the discussion section of this report.

4.3 Including the Ageing Effect in OTM

It has been observed that as people become older, they become frailer [25]. It can be therefore assumed that material properties are decreasing as a function of ageing. It was found that loss of bone thickness, material elasticity and density were key outcomes of ageing (Figure 5). It can be observed that the mechanical properties of a human have indeed reduced by 20% when the pedestrian is 80 years old, compared to a 20 year old pedestrian.

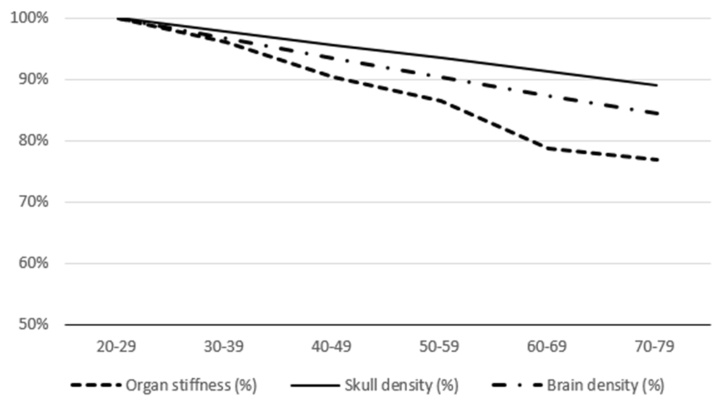


Figure 5: Bone and Organ Performence as function of ageing [32][33]

The human brain is the central organ of the human nervous system and consists of the white matter and the grey matter, the brain stem and the cerebellum, is also subject to shrinking with age [32]. Previous work has generated a regression relationship linking brain volume and age (V_{age}) [33], which is illustrated in Equation 3.

$$V_{age} = -0.0037 * age + 1.808$$

Equation 3: Relationship between age and volume loss

In the model used in this study, the brain white and grey matter were scaled about the brain centre of gravity to adjust for ageing.

Equation 2 can be therefore modified (including the effect of Equation 3) to highlight which terms are age dependant (Equation 4).

$$PVP \propto \mathrm{AIS} \propto \frac{\mathrm{A}}{V_{Age}} \sqrt{\rho_{age} E_{age}} . Kv^3$$

Equation 4: Relationship between Trauma and ageing

Consequently, for each accident that will be studied, the modulus of elasticity and density of each organ and bones will be adjusted to reflect the age of the pedestrian at the time of collision.

In order to illustrate the outcomes of Equation 4, when a human head computer model was impacted by an impactor on the forehead, it can be noticed that it takes less power for an older person to experience a head injury (Figure 6), at a set impact speed, to be injured, which is consistent with what is observed in real life.

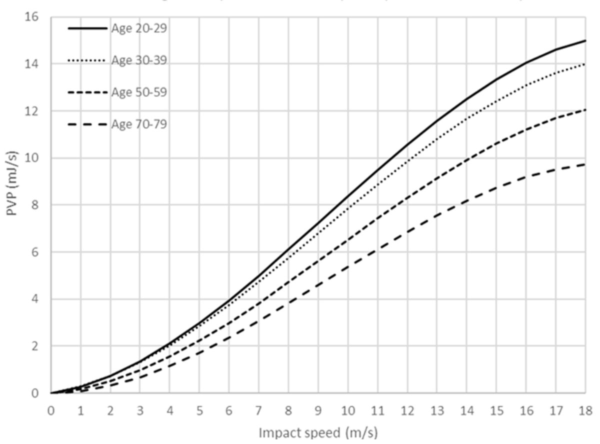


Figure 6: Illustration of a typical brain white matter AIS 4 trauma response as a function of age [14].

The mathematical model is consistent with the trends observed in real-life trends. It will be now tested against the three accident scenarios provided in Table 1.

4.4 Methodology Framework to test Mathematical Trauma Model

Once the OTM model theory defined, it can be implemented and tested in the framework in Figure 7:

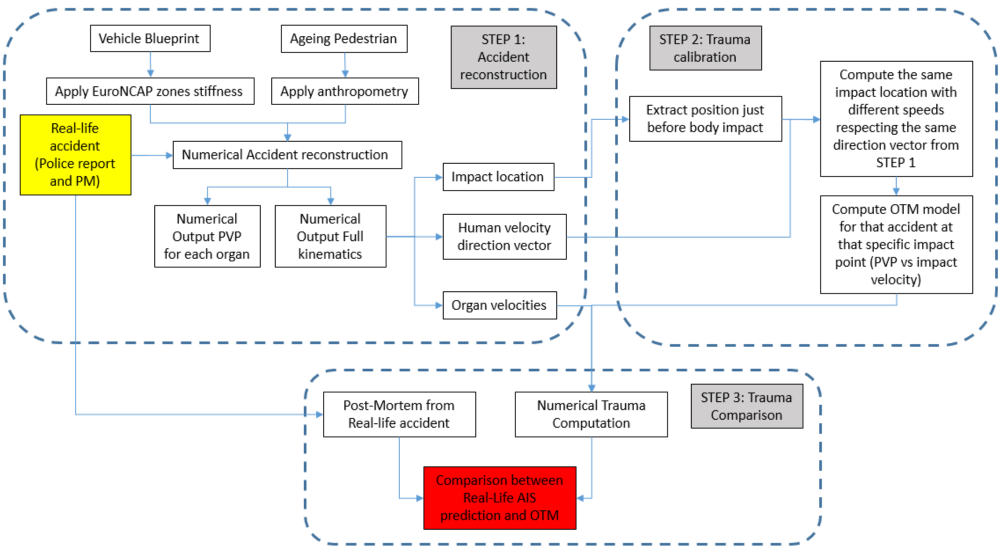


Figure 7: Methodology to test the OTM Model

i. The first step of this method is the accident reconstruction phase, whereby three accidents provided by the UK Police Force (UKPF) were investigated. This accident reconstruction phase recaptured the collision event, by creating vehicles from their blueprints. These vehicles were split as per their EuroNCAP pedestrian zoning [26][27][28], which was represented by stiffness characteristics matching their real world test performance [29]. The pedestrians were aged sized and massed to their exact anthropometry. Once the accidents were computed, the full kinematics were extracted and compared to the damage observed (denting or smudge) on the vehicles to ensure that that the reconstruction was plausible. Following this verification, the PVP values per organ for each collision as well as well as each organ velocity just before the impact were extracted.
ii. The second step was the trauma calibration phase, which will be explained in detail in the next section of the report, which is vehicle and impact point specific. The full pedestrian kinematics from step one were 'rewound' and the pedestrian was positioned a few millimetres from the bonnet (usually 3.0 mm). The direction velocity impact vector from Step 1 was then used to impact the pedestrian at various velocities to construct an OTM model. It was checked that the head impact location was virtually constant as it was observed that the variation in head impact location only varied by 4 mm, which is negligible when compared to the size of the impact area. Consequently, the approach undertaken is compatible with keeping the impact location constant. The velocity of interest is the impact velocity perpendicular to the windscreen, which is the main contributor to the blunt trauma impact.
iii. Finally, step three used the PVP and true brain impact velocity (perpendicular to the windscreen) responses from the first step and the OTM model built in the second step to propose a predicted AIS value. This AIS value was compared to the value obtained in the real-life scenario. It was proposed that the OTM model was valid if both values have the same AIS ordinal value.

4. Results

4.1 Accident Reconstruction

Three accidents provided by the UKPF force were reconstructed. The details of each accidents pedestrian damage and kinematics are presented in Table 5.

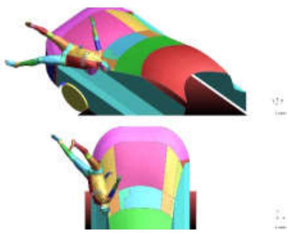
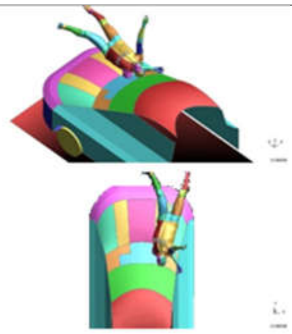
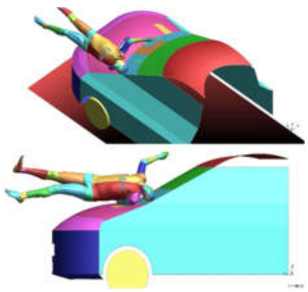
Case id	Pedestrian Kinematics	Vehicle Damage
1		
2		
3		

Table 5: Vehicle damage and Pedestrian Kinematics

The vehicle geometries were reconstructed from blueprints and their respective local stiffness calibrated against EuroNCAP pedestrian test results [26][27][28].

4.2 Trauma Computation and Results

Toyota Corolla Brain Trauma Results

<u>Step 1: Extraction of pedestrian kinematics and PVP during the accident</u>

The accident was initially reconstructed according to the accident report, ensuring that the vehicle damage was consistent with the pedestrian kinematics. During this step, the PVP was extracted, as well as the white and grey matter velocities at the time of impact (Table 5). It can be noticed, in this instance, that these velocities at the moment of impact are different from the vehicle impact speed, as illustrated in Figure 8 and Figure 9.

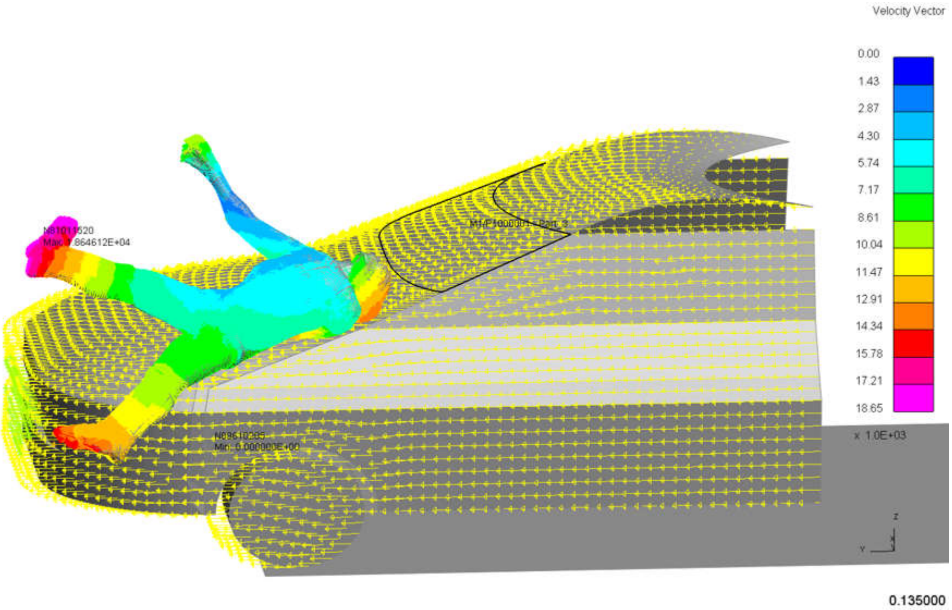


Figure 8: Toyota Corolla - Collision Velocity Profile – Units: mm/s

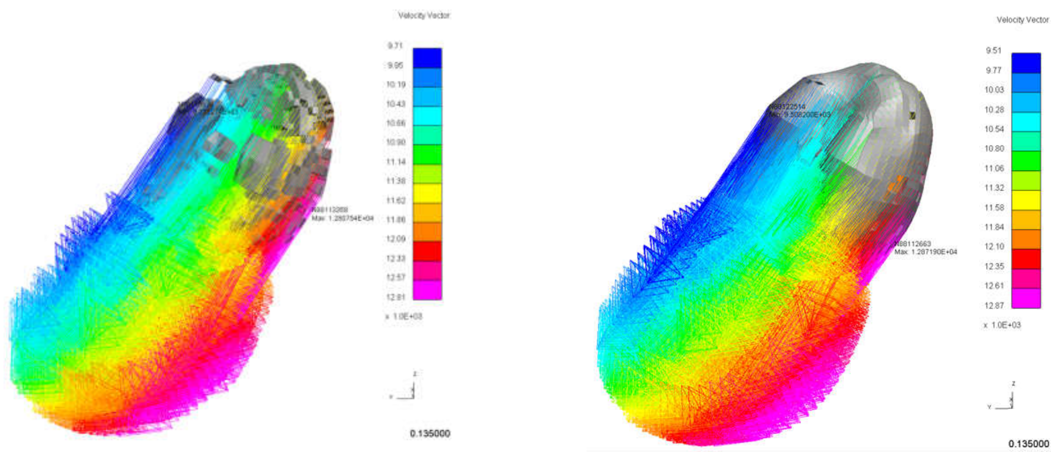


Figure 9: Toyota Corolla - Brain velocity plot (White Matter (right), Grey Matter (Left)) – Units: mm/s

Organ	Resultant Velocity in car line (m/s)	Resultant velocity perpendicular to the windscreen (m/s)
Grey Matter	12.87	7.53
White Matter	12.81	7.89

Table 6: Summary of Toyota Corolla brain velocities (at the time of impact)

Step 2: Creation of the OTM model for this specific accident

The pedestrian kinematics was 'rewound' back in time, and repositioned 5 mm from the bonnet surface, just prior to contact. This step was performed so that the pedestrian hit the same location of the vehicle (as the collision is unique). The pedestrian was then impacted at different speeds, respecting the direction vector of the pedestrian kinematics and impact location from Step 1, to construct an OTM model for each organ, comparable to Figure 4.

Step 3: Overlay step 1 and step 2 to extract trauma value

The white and grey matter brain velocities of the actual impact were remapped on the OTM trauma graphs, as shown in Figure 10 and Figure 11.

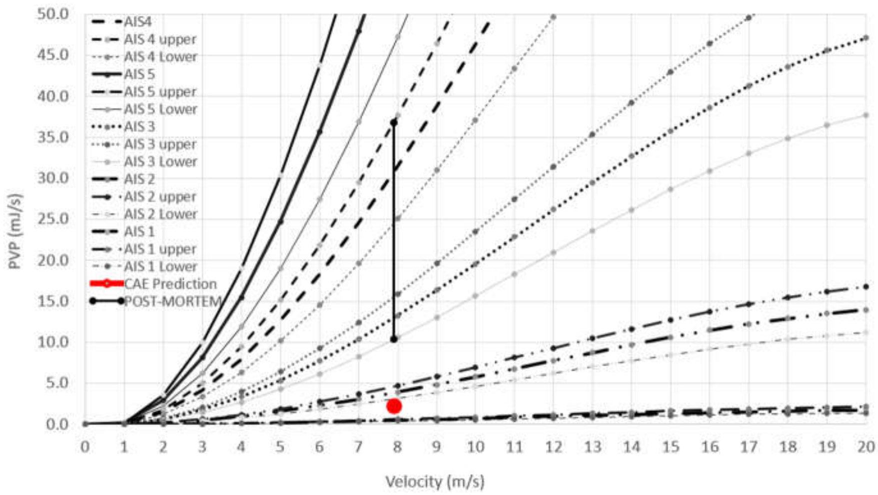


Figure 10: Toyota Corolla - White Matter Trauma

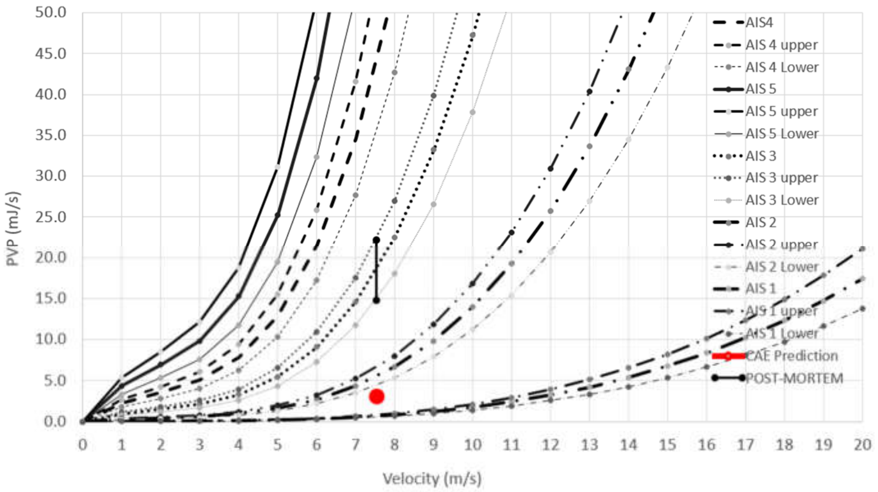


Figure 11: Toyota Corolla - Grey Matter Trauma

The collision impact speed was 11.2m/s, however the brain velocity was different at the time of impact. Consequently, the AIS values plotted (red dots) was adjusted to match the true organ speeds, Looking at Figure 10 and Figure 11, the AIS value for the white matter was 2 (at 7.89m/s) and the grey matter 1 (at 7.53m/s). The process was repeated for Case 2 and Case 3. Their kinematics and trauma plots can be found in Appendix 1 and Appendix 2. The mathematical parameter fits for the three collisions are provided in Appendix 4 and the trauma estimation using the current MPS method (recommended standard THUMS output) in Appendix 6.

In all the cases, the head injury predictions had some similarity with the Post Mortem results, as shown in Table 7. When no evidence was recorded in the PM, it did not necessarily mean that there was no injury, but that there was no observable injury. Consequently, no observation could mean that the AIS range could be from 0 to 2. This step has been taken, as it was found that, overall, the quality of autopsy reports (PM) is often questioned: just half of PM reports 52% (873/1,691) were considered satisfactory by experts, 19% (315/1,691) were good and only 4% (67/1,691) were excellent. Over a quarter were marked as poor or unacceptable. Proportionately, there were more reports rated 'unacceptable' for those cases that were performed in a local authority mortuary (21/214 for local authority mortuary cases versus 42/1,477 for hospital mortuary cases)" [34]. Consequently, for trauma injury severities cases not observed in the PM, a probable PM range has been included and is illustrated in Appendix 1 and Appendix 2. As an illustration, the PM range has been illustrated in Figure 10 and Figure 11 as the vertical 'bar', representing the most probable range of PM outcomes

All the study results are listed in Table 7. Diffuse axonal injury (DAI) occur when the long connecting fibres in the brain, called axons, are sheared as the brain rapidly accelerates and decelerates. Brain contusion is bruising of the brain tissue, which can be associated with multiple micro-haemorrhages, small blood vessel leaking into the brain tissue.

Vehicle (Case id)	PM report details	Organs/Tissue	Injury	AIS from PM	MPS THUMS (Appendix 6) (AIS estimation)	**OTM Prediction**
Toyota Corolla (1)	Subarachnoid haemorrhage. The brain appeared diffusely swollen to a mild degree. There were contusions on the inferior aspect of the right temporal lobe.	White Matter	Diffuse Axon Injury (just reached)	3 - 4	48% (AIS 4 > 21%)	**2**
		Grey Matter	Brain Contusion	3	32% (AIS 3 > 30%)	**2**
Renault Clio (2)	No evidence of skull fracture and brain showed no evidence of contusion	White Matter	No evidence	0-2	127% (AIS 4 > 21%)	**1**
		Grey Matter	No contusion	0-2	113% (AIS 3 > 30%)	**1**
Mercedes Benz (3)	Multiple area of cerebral contusion Rupture at right parietal lobe Cerebral oedema Subarachnoid haemorrhage Subdural haemorrhage	White Matter	Diffuse Axon Injury	3 – 4	72% (AIS 4 > 21%)	**2**
		Grey Matter	Brain Contusion	3	58% (AIS 3 > 30%)	**1**

Table 7: Study results for brain injuries

Due to time constraints it was not possible to study in detail the thorax and abdomen organs trauma injuries. Initial results did not correlate with the PM reports, which suggests that more research is necessary especially in the definition of the vehicle bonnet stiffness and geometry.

5. Discussion

The aim of this section is to compare the OTM trauma injury severity predictions against the real-world PM outcomes.

- In Case 1 (Table 7), the PM states that bleeding was observed in the white matter and the brain "appeared diffusely swollen to a mild degree". This would suggest that the DAI has just been reached and hence the white matter PM AIS has to be 3 or 4 – the reason for a range to the AIS is that blood loss volume is a subjective matter and a higher blood loss can increase AIS from 3 to 4. The OTM model predicted AIS 2. At this point in time it is important to remember that the THUMS model is using a Lagrangian method, which implied that the volume of each element remains constant during the impact. This method cannot cater for bleeding. Including bleeding would involve a reformulation of the THUMS' brain model and include Smooth Particle Hydrodynamic (SPH) or Arbitrary Lagrangian and Eulerian (ALE) formulations. Consequently, the AIS under-prediction using PVP is a logical numerical outcome in the case of blood loss. In Case 1, the standard MPS method over predicts the real-world PM outcomes.

- In Case 2 (Table 7), it can be observed that the brain injury values (ASI 1) are an exact match with the PM (AIS 0 – 2). In this case no bleeding was evidenced. This has been well captured by the OTM method, while the MPS method gave injury severity predictions much higher than the PM (suggested AIS 3 for grey matter and AIS 4 for white matter). As no bleeding was present, the OTM's model outcome, based on a constant organ volume, is as mathematically expected (Equation 2), as discussed in the "Theoretical Derivation of Trauma" section 3.2 of this report. Case 2 has validated Equation 2.

- Case 3 has a similar PM (AIS 3 - 4) outcome as in Case 1, however it has to be noted that the MPS method suggests a higher prediction compared to the PM (AIS 1). Again, when the critical MPS is reached for AIS 3 and AIS 4, it is not possible to estimate when the next AIS levels are reached. The PVP method under-predicts the PM, which states that bleeding occurred, consequently not possible to capture with a Lagrangian solver.

Looking at all these results, it can be observed that the MPS method does not allow the grading of AIS as a function of MPS level. Only one level is provided, i.e. the critical one, which is a serious limitation when trying to match PM to computations. The MPS overall over-estimates the injury, while PVP under-predicts should bleeding occur. This study is suggesting that a new brain model would be necessary to capture the bleeding effect which is recorded in the PMs.

These results may also be sensitive to the geometry of the vehicle model. Indeed, the vehicle model shape was extracted from blueprints. In the future, it would be maybe necessary to obtain a scanned surface of the vehicle so that the exact curvature and the local geometry are accurately captured. Also, the vehicle stiffness was based on calibrating the head impact zone using a head impactor HIC panel thickness calibration to match the local pedestrian EuroNCAP performance rating. It is suggested that maybe another method of vehicle modelling, for example using the APROSYS bonnet stiffness corridors, would be another venue of investigation. An important parameter, is that it is not known whether each of these accidents involved a head impact to the ground, which would increase the head AIS level. In all cases, the trauma caused by the primary impact is always the same or lower than the trauma at the end of the collisions. Consequently, if the PVP method is under-predicting in the primary impact, the trauma severity outcome discrepancy could have come from the pedestrian's head landing on the ground.

6. Conclusions

Project "RoaD" experienced at the onset substantial challenges due to understaffing of the UKPF, who did their best to support the project, as well as new changes of court proceedings. As such, a new research method was devised to study the feasibility of a Pedestrian Trauma Database (PTD).

During the project, the "RoaD" pilot study developed a new method (OTM) to extract brain trauma and early results indicate it could be capable of greater accuracy that the current MPS model, used against real worlds accident cases. This computer approach is HBM independent and has the capability to be transferred to any organ in the human body. Time restriction have sadly not allowed to test in detail the OTM on the thorax and abdominal organs. The initial findings are very promising however more cases are required to ascertain the OTM methodology robustness.

The authors have already presented the OTM at a safety conference in September 2019. The detailed method will be presented at the SIMBIO-M conference (June 2020) and the CARHS international conference (November 2020): this conference is tailored to a worldwide transport OEM safety audience, including EuroNCAP. It is also planned to submit a detailed journal article for peer review before December 2020.

Thanks to the mathematical derivation, it was evident that state of the art human body models (HBM) have some fundamental deficiencies when modelling the exact trauma outcome during a pedestrian collision, due to the fact that bleeding could not be represented. This discovery is important and leads to necessary HBM improvements should a PTD be solely created using such models. The next stage is to include means of representing fluid loss, not possible with constant volume elements as currently provided in the current HBM models. Once these limitations a have been lifted, still using the OTM methodology, it is believed that it will be possible to create a virtual tool to support A&E, UKPF as well as the coronial process.

In the OTM a mathematical approach was applied to a limited number of accident case and took a lot longer than was initially available in the project timeline. From the work undertaken, using computation on its own, it is believed that it is not possible to generate a PTD within the scope and timeframe of the project, simply because of the computation runtime, the time necessary to build the computer models, positioning the pedestrian, calculating its gait and walking speed etc. Even when some trauma extraction routines were programmed as part of "RoaD", allowing the visualisation of injury severity at organ level, the trauma extraction could take in order of eight hours per accident.

As a conclusion to the "RoaD" pilot study, the research team believes that creating this PTD is possible, however it requires a blend of improved computer models (including to take account of fluid) as well as real world accident trauma data which could be made available from the NHS, West Midland Ambulance Services (WMAS) as well as the Road Accident In Depth Studies (RAIDS) from the Department for Transports (DfT). Such data was investigated however it became apparent in the project that, to date, NHS and WMAS information are not compatible and that RAIDS data required specific authorisation to release age, gender and anthropometric information. Once the machine learning relationship is created, real-time trauma estimation will be then possible. The improved computer model would be needed to populate the design space to add to the Machine learning dataset. Some artificial intelligence methods have already been selected as best candidates for this PTD. The neural networks method has been identified as a good candidate to learn from discrete responses, while time dependant events, for the real-time accident reconstruction vehicle and pedestrian kinematics, could be computed real-time using Proper Orthogonal Decomposition.

7. Further Work

The "RoaD" Pilot study has concluded that a PTD was feasible and would require more research activities:

1. **Improving the integration of NHS – WMAS pedestrian accident data for PTD – RAIDS machine learning.**
   Merging Trauma Accident Research Network (TARN) data with West Midlands Ambulance Service University NHS Foundation Trust (WMAS) will provide unique data which, coupled with machine learning methods, will help to generate the PTD from existing data.
2. **Organ bleeding modelling.**
   The research from "RoaD" has shown that fluid needed to be included in the current HBM to replicate bleeding, hence improving the AIS predictions. Modelling bleeding will allow the creation of accident scenario which will feed into a machine learning tool to create the PTD.

8. "RoaD" Project Output

Published article

- Rubrecht, B., Bastien, C., Davies, H., Wellings, R., & Burnett, B. (2019). Numerical Validation of the Pedestrian Crossing Speed Calculator (PCSC) using Finite Element Simulations. Global Journal of Forensic Science & Medicine forensic, 1(4), [GJFSM-19-RA-525].

Article in writing

- Bastien, C., Sturgess, C., Davies, H., Bonsor, J., Wellings, R., Cheng, X., (2020?) "Calculation of White and Grey Matter AIS Injuries in Pedestrian Collisions". Journal TBC. Submission July 2020

Presentations

- <u>Scheduled:</u> "The Computation Of Pedestrian Brain White And Grey Matter Trauma Severity Considering Mechanical Ageing Using The Finite Element Method". CARHS Human Body Symposium. November 2020 (Germany)
- "A Method to Calculate Brain AIS Trauma Score from a Finite Element Model". 6th Edition of SIMBIO-M 2020. Virtual Conference, 18th – 19th June 2020 (www.simbio-m.eu)
- "The Use of Peak Virtual Power to Model Human Organ Trauma in Automotive Accidents". 2nd Annual Automotive Safety Summit. Dusseldorf 18-19 September 2019
- "Ethical and Procedural challenges to study Pedestrian Trauma in UK Road Traffic Collisions". SIMBIO-M 2018. Stratford-Upon-Avon. 18-19 June 2018
- "Numerical Investigation into Pedestrian Crossing Collisions" SIMBIO-M 2018. Stratford-Upon-Avon. 18-19 June 2018
- "An indicator for Head Trauma Response under impact as a function of age". SIMBIO-M 2018. Stratford-Upon-Avon. 18-19 June 2018
- "An Engineering Indicator for Human Head Trauma Prediction". SIMBIO-M 2018. Stratford-Upon-Avon. 18-19 June 2018

PhD

- Mr Xiang Cheng (2020) "The Modelling of Ageing in Human Body Model and its Application in Trauma Prediction" – Self funded – Viva expected February 2021. The "RoaD" research project has indirectly benefitted this student with advice from the "RoaD" team.
- UHCW (Start January 2021) "Modelling of leg fracture in pedestrian accident". Funding: £150,000. Following a presentation using the "RoaD" findings, UHCW have sponsored a PhD
- CU (Start January 2021) "Modelling of thoracic and abdominal injuries in pedestrian accidents". £75,000. Coventry University have matched funded the PHD from UHCW (consequence of "RoaD" funding).

Student Projects:

- Ott Mannik (BEng Individual) “Development and Validation of an Automated Pedestrian Trauma Extraction Software for Oasys LS-DYNA Environment Using a Power Method” (May 2019)
- Stephanos Adamou (BEng Individual) “JavaScript scripting of CAE post processor for pedestrian trauma assessment OASYS “ – (May 2020)
- Joshua Bonsor (MEng Individual) “AIS Trauma in Pedestrian Accident Cases Finite Element Model” – (May 2020)

Research Proposals

- **“Automotive Body Structures Beyond Year 2030 (OBEY-2030)”.** EPSRC Proposal (£2.7m). Scientifically, realistically, holistically and accurately assess the severity of Road Traffic Victim Injuries (RTVI) beyond year 2030 as a function of predicted Connected Autonomous Vehicle (CAV) design and technology including active/passive safety subject to regulations and projected market penetration. Project narrowly not funded.

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- The UK Police force and the UK Coroners who have provided data without which this project would have never seen its existence,
- The RoadPeace charity and EuroNCAP for providing the letters of support to endorse this research and promoting its value.
- All the Coventry University students who have contributed to this project directly and indirectly as part of their thesis and individual Undergraduate projects.

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Appendix 1: Velocity Plots – Case 2 (Renault Clio)

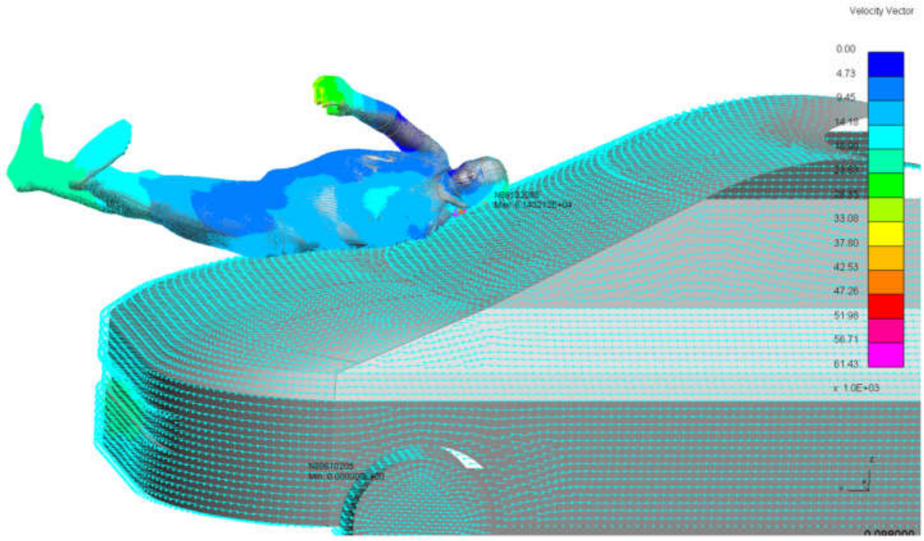

Figure 12: Renault Clio - Collision Velocity Pattern (mm/s)

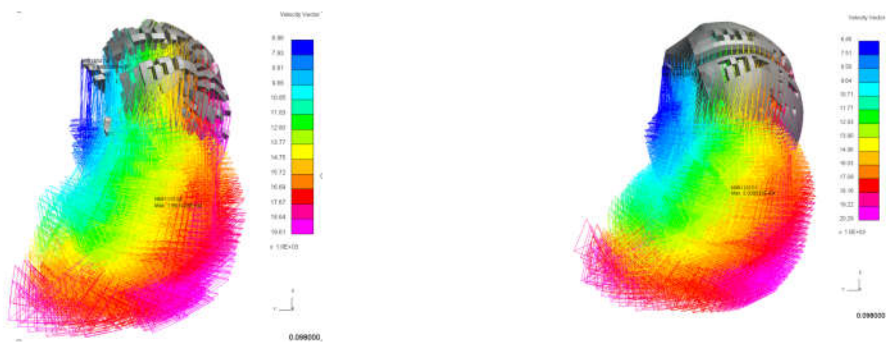

Figure 13: Clio - Brain velocity plot (White Matter (right), Grey Matter (Left)

Organ	Resultant Velocity in car line (m/s)	Resultant velocity perpendicular to the windscreen (m/s)	Time (s)
Grey Matter	20.29	17.35	0.0980
White Matter	19.61	16.15	0.0980

Table 8: Summary of Renault Clio brain velocities

Appendix 2: Trauma Plots – Case 2 (Renault Clio)

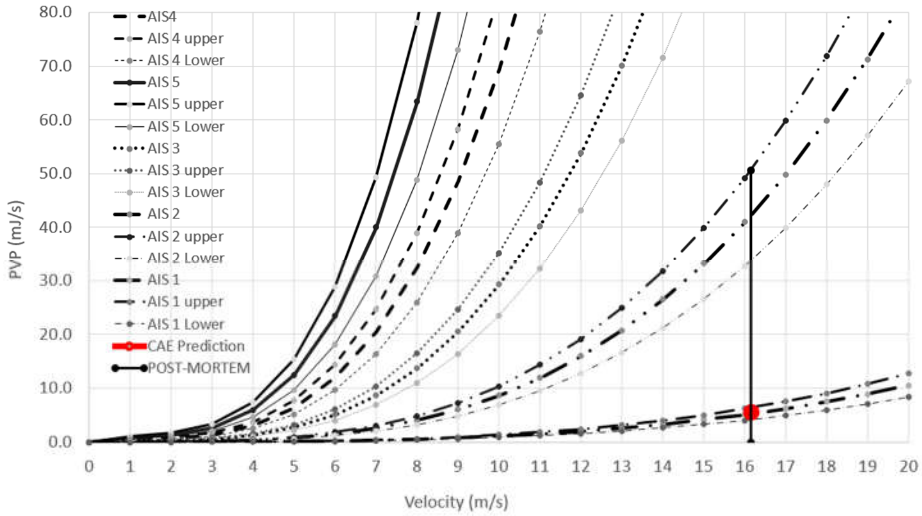

Figure 14: Renault Clio - White Matter Trauma

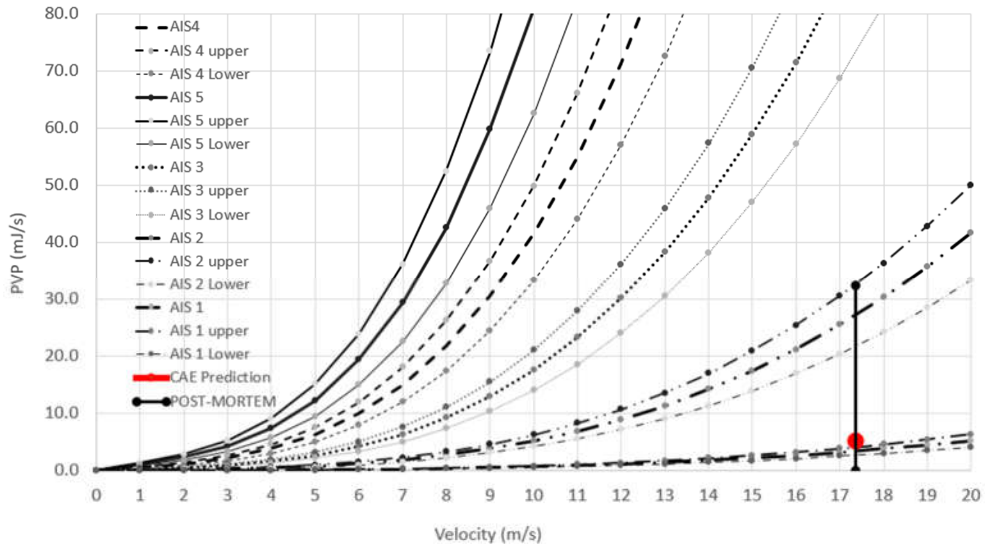

Figure 15: Renault Clio - Grey Matter Trauma

Appendix 3: Velocity Plots – Case 3 (Mercedes Benz)

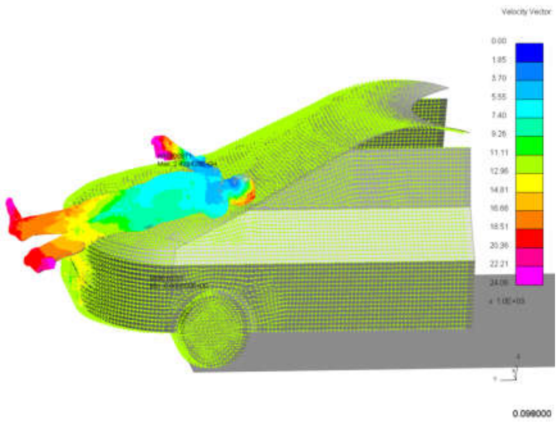

Figure 16: Mercedes Benz - Collision Velocity Pattern (mm/s)

Figure 17: Mercedes Benz - Brain velocity plot (White Matter (right), Grey Matter (Left)

Organ	Resultant Velocity in car line (m/s)	Resultant velocity perpendicular to the windscreen (m/s)	Time (s)
Grey Matter	18.12	17.34	0.0980
White Matter	18.12	16.15	0.0980

Table 9: Summary of Mercedes Benz brain velocities

Appendix 4: Trauma Plots – Case 3 (Mercedes Benz)

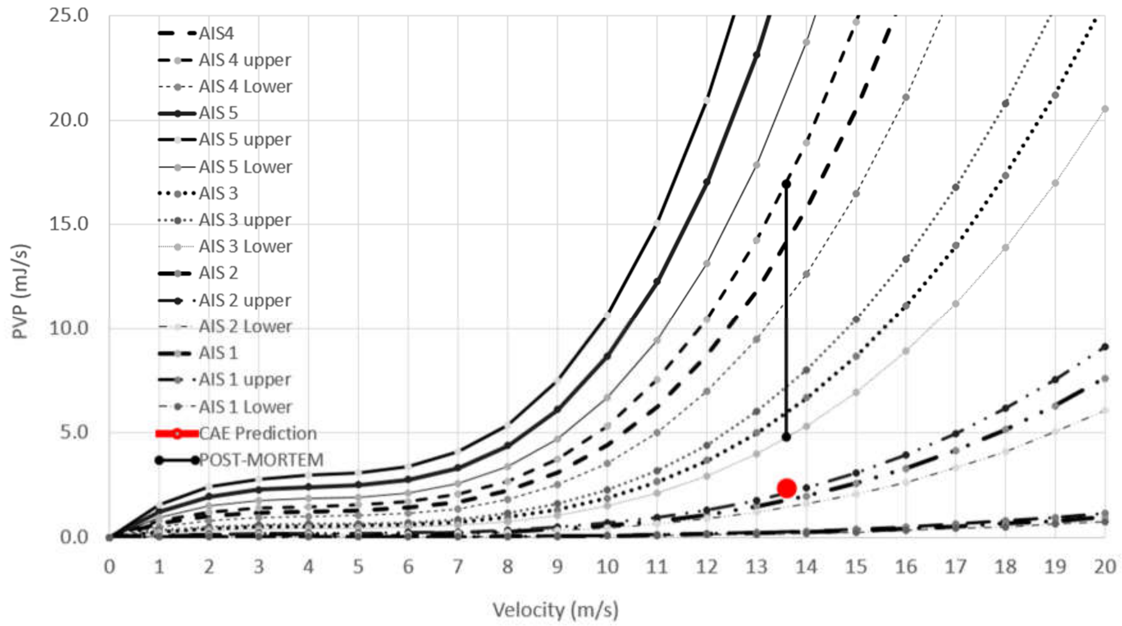

Figure 18: Mercedes Benz - White Matter Trauma

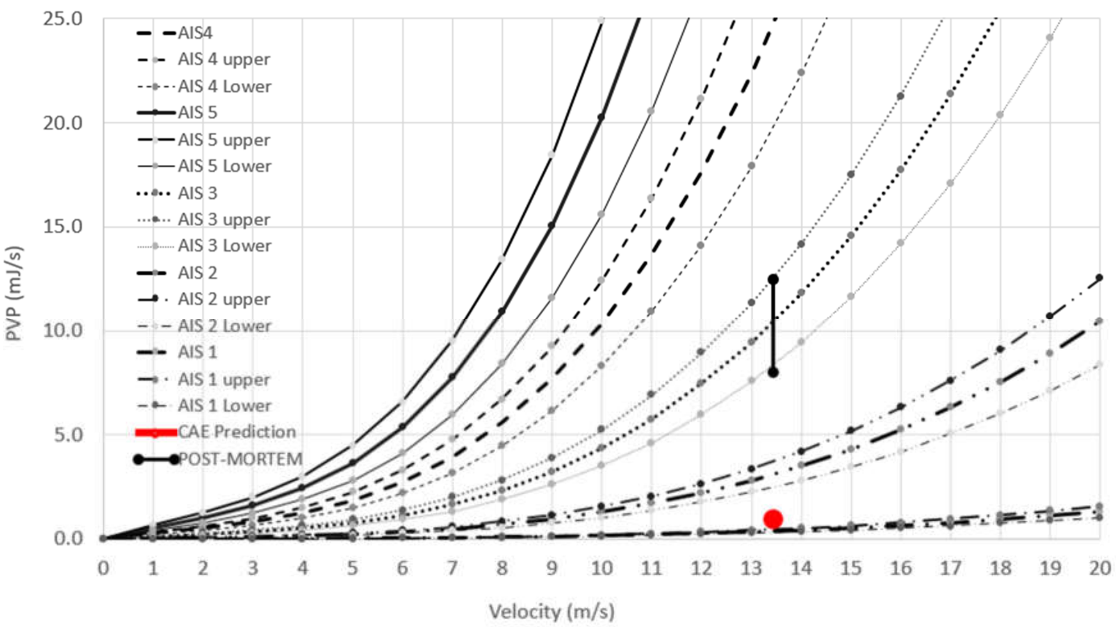

Figure 19: Mercedes Benz – Grey Matter Trauma

Appendix 5: Mathematical Fits (AIS4) for the 3 Collisions

Trauma Calibration Parameter Values				
Parts Identifier (White Matter) – right hand side	white_matter_cerebrum_r		88000100	
Parts Identifier (White Matter) – left hand side	white_matter_cerebrum_l		88000120	
Parts Identifier (Grey Matter) – right hand side	gray_matter_cerebrum_r		88000101	
Parts Identifier (Grey Matter) – left hand side	gray_matter_cerebrum_l		88000121	
PVP = a.V^3+b.V^2+c.V				
Parameter Values		a	b	c
Case 1: Toyota Corolla	White matter	-0.0217	0.746	-0.6537
	Grey matter	0.0765	-0.4207	1.2828
Case 2: Renault Clio	White matter	0.1025	-0.4064	0.7509
	Grey matter	0.0765	-0.4207	1.2828
Case 3: Mercedes Benz	White matter	0.0148	-0.1844	0.8078
	Grey matter	0.0051	-0.0206	0.133

Appendix 6: Maximum Principal Strain Responses

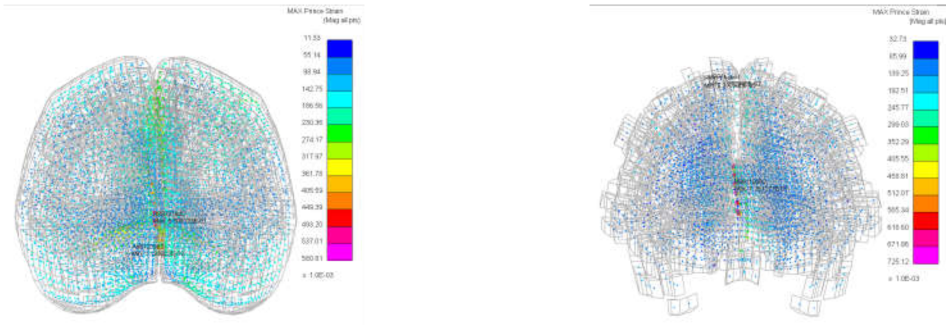

Figure 20: Mercedes Benz. Maximum Principal Strain observed during the impact (Grey Matter – Left; White Matter – Right)

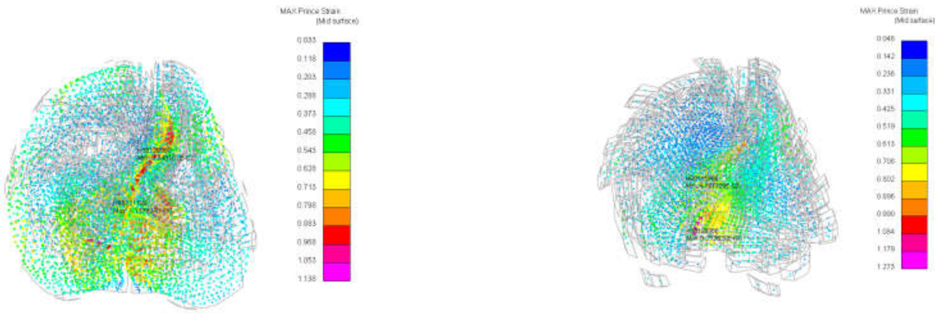

Figure 21: Renault Clio. Maximum Principal Strain observed during the impact (Grey Matter – Left; White Matter – Right)

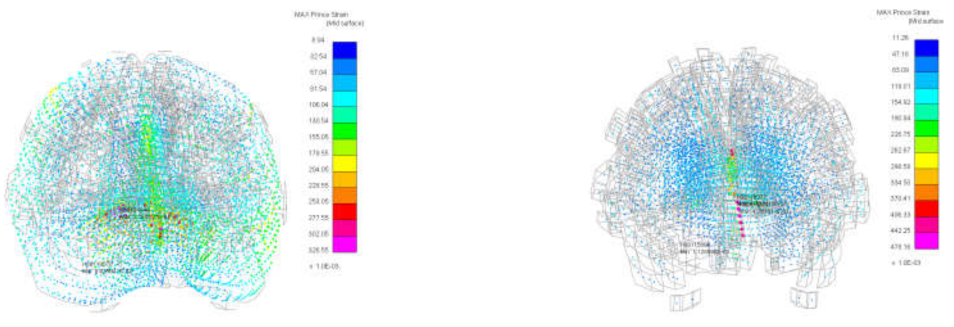

Figure 22: Toyota. Maximum Principal Strain observed during the impact (Grey Matter – Left; White Matter – Right)