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" Pilot study, funded by the Road Safety Trust, poses the problem of investigating the feasibility of a Pedestrian Trauma Database (PTD) with the ultimate purpose of supporting A&E departments, the UK Police Force (UKPF), the Coronial process as well as manufacturers vehicle safety design.

The initial project methodology was relying on reconstructing a large number of pedestrian collisions, using a detailed Human Body Model (HBM) and relate the HBM model organ trauma output to the real-world Post Mortem (PM) outcomes. Unfortunately, this methodology could not be implemented due to unexpected reduction of Police Force support staffing as well as a new procedure ~~of~~ for the courts.

As such the project "RoaD" devised a new mathematical derivation of trauma severity, or Organ Trauma Model (OTM), that was tested against three available accident cases, for which the collision information as well as the PM were available. It was found that the OTM model had true potential to build the PTD and was superior to the current methods used in the scientific community. It was however also discovered that the HBM has some inherent limitations as they cannot simulate blood loss, prompting ~~for~~ future HBM developments.

Thanks to the research from the "RoaD" team, a better understanding of the parameters influencing the trauma outcome of a pedestrian collisions have been highlighted. The "RoaD" Pilot Study concluded that a PTD could be created by coupling a mixture of HBM simulations with collision information for the NHS and WMAS databases to machine learning algorithms. A list of "Future Work" is provided in this report to address the next phase of this research.

"RoaD" has led to the funding of two PhD research projects between Coventry University and the University Hospital of Coventry and Warwickshire (£225,000 total value, start January 2021), the publication of one journal article (with one being written), the creation of unique traumatology extraction post-processing computer programme, six dissemination presentations, interest from the mechanical engineering research department of the Politecnico de Torino (Italy) and the Universite Gustave Eiffel (France), as well the software consultants ARUP Solihull (UK) (HBM pre-processing) and CADLM (FR) who are programming Machine Learning tools.

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Acknowledgments

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- The Road Safety Trust for having supported this work. The funding has helped Coventry University to galvanise a cutting edge research activity and make a breakthrough in modelling head trauma injury severity. The funding has been instrumental to forge new alliances and give momentum to this research.
- 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.

1. Background

The "RoaD" project proposal (Reducing Road Traffic Casualties through Improved Forensic Techniques and Vehicle Design), was written in 2017 by a group of likeminded senior researchers from different domains of expertise, all having the passion and commitment to create forensic and design tools as well as protocols to reduce pedestrian fatalities. Dr Wellings has worked more than 15 years in the imaging department of UHCW looking at road traffic collisions (RTC), Dr Davies has researched pedestrian protocols since 1999, as well as means of injury counter measures, while Dr Bastien, 13 years' experience in the field of industrial engineering computation in safety applications, which he has applied while researching and engineering the first pedestrian deployable bonnet using airbags on the Jaguar XK in 2004.

In 2015, Dr Bastien was approached by the UK Police force (UKPF) who were interested in investigating hit-and-run cases, as well as devising advanced computer techniques to support complex accident scenarios. It was proposed to use the latest human pedestrian computer model (THUMS 4.01 [1]), based on a virtual average height and weight male cadaver reconstructed in geometry and material properties, including all the vital organs (heart, liver, spleen, kidneys, brain white and grey matter). Dr Bastien and the UKPF concluded that matching each computed organ trauma to the actual Post Mortem (PM) would be the ultimate proof to extract the vehicle collision speed.

After seeking ethical approval and obtaining the appropriate security vetting, the UKPF provided Coventry University with one accident to analyse (provided 2015) using the standard THUMS human model in order to reconstruct this accident [2]. Overall, the pedestrian kinematics was believable (and proven later to be realistic [3]), however the trauma readings from the computer model were inconclusive and did not relate with the actual PM conducted on the deceased. The team then seeked the expertise of Prof Emeritus Clive Neal-Sturgess, ex director of the Birmingham Accident Research Centre (BARC) and a principal investigator for the EU FP6 project APROSYS (computing pedestrian injuries), who had in 2001 derived a traumatology theory [4][5][6], which had the potential to be implemented on Human Computer models for trauma severity extraction. That base theory had never been applied to accident reconstruction cases.

The research team was then able to ask a fundamental question, which was ***"Is it possible to calculate the trauma at organ level in a pedestrian collision? ". This research question then led to "Can a virtual CT-SCAN be computed?" and then to "Can a Pedestrian Trauma Database (PTD) be created as a function of vehicle profile and impact speed for A&E and Law enforcement applications?"***

2. Relevance of the Research

Various stakeholders were then 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 2014, 446 pedestrians died with an economic loss of £1.7m per pedestrian [9]. There were 5,063 seriously injured pedestrians each costing £220,000 to the NHS [10]. 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 a 2-year pilot study to create this PTD.

3. Initial Project Methodology

3.1 Proposed Methodology when the Pilot study was proposed to the RST

In order to build a PTD, the project required accident data, which contained detailed accident information (vehicle impact speed, vehicle pictures, etc.), the Post-Mortem, the CT-Scan, the pedestrian gender and age. There are no single databases in the UK, which contained all this combined data. STATS19 only provided the accident scenario, while RAIDS did not store CT-Scan data (RAIDS did not allow access to ageing information, because this was judged too specific and could lead to anonymity issues). Consequently, only accidents recorded by the UKPF were of interest and suitable.

As a result of the large number of variables in the study, it was decided to select study bounds for the vehicle, the deceased and the accident scenario. In order to control the vehicle frontend shape variable, the most frequent vehicle class involved in pedestrian collisions were selected. No vehicle older than 5 years would be selected in order to control the variation in vehicle stiffness. The sample of deceased used for this project will be between 20 and 50 years old male with a body shape between one standard deviation from the mean in height and mass. The project would select cases for which injury inducing impact would be a result of a collision consistent with a vehicle to pedestrian event, and would exclude secondary non-quantifiable injury inducing events. As such, the proposal would exclude accidents exceeding 35mph, for which the pedestrian would perform a somersault and perform multiple impacts with the vehicle, i.e. vehicle roof and boot lid and the road surface.

The project would request, for each relevant UKPF accident case, the consent of Coroners and Families to acquire datasets in the study (Figure 1). A Post Mortem (PM) would be conducted in each accident scenario to understand the cause of death. CT-Scans would be calibrated against the PM in order to build a knowledge base that would help to process CT-Scan faster and to create a virtual PM, which could in the future be used instead of a standard PM.

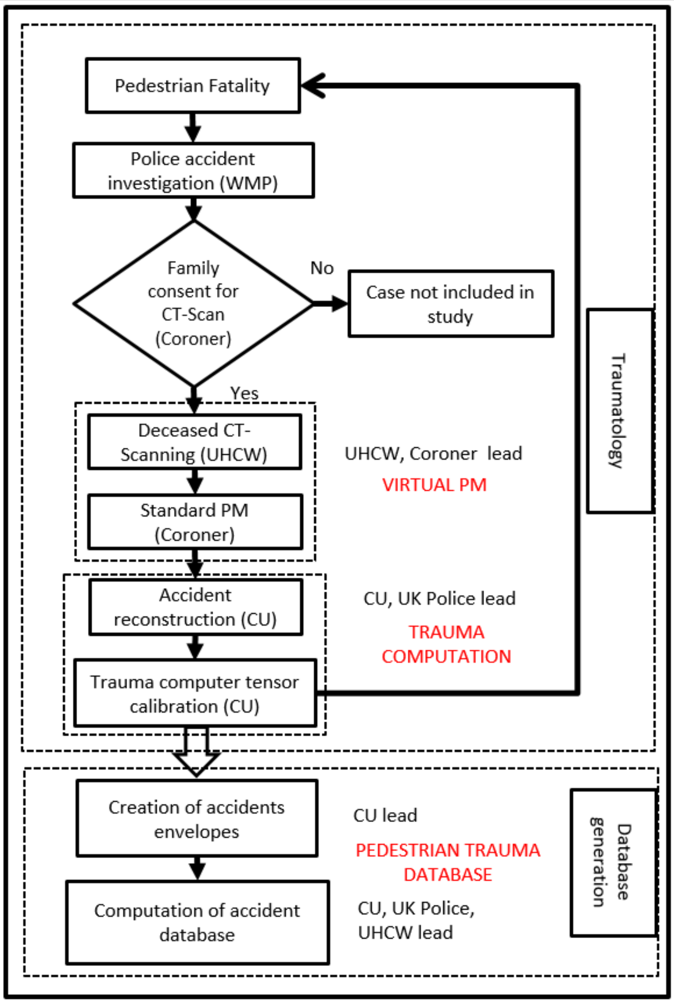


Figure 1: Original "RoaD" project flow chart

Both the CT-Scan and PM will then be used to compare the trauma severity location in each organ and their trauma predictions computed during the accident reconstruction phase. Once the trauma severity and location could be accurately computed, then it was proposed to create virtual accidents, involving different vehicle shapes, vehicle speeds and pedestrians of different anthropometries to generate the PTD.

3.2 Events influencing a change of methodology

In November 2017, when the 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.

Since the Conservative government came to power, both in coalition and after, the UKPF service has been reduced (officers and staff), including Police Community Support Officers (PCSO). The UKPF were then "under-staffed, over-worked and over-stretched" [11]. In 2010 there were 79,500 police staff working for forces in England and Wales. By March 2016, this number had dropped to 61,668, representing a cut of nearly 23% in the police staff workforce [11]. There is a move from the government (Home Secretary) to increase Police funding by £450 million in 2018 [12]. This fund will however be used mostly for counter terrorism and digitisation of the Police force and not on road policing. There is still a goal to drive efficiency; consequently, the UKPF is going through in-depth reforms. The number of patrol cars has reduced by 30% since 2016 [13][14][15][16][17]. The UKPF have Senior Investigating Officer (SIO) on call to respond to Road Traffic Collision (RTC) fatalities, as well as to secure the road where the collision took place as a matter of priority, to gather evidence (on the ground as well as witness statements) for court proceedings as fast as possible and to ensure that the body is retrieved, transferred to the hospital and the coroner is made aware of the fatal collision.

Another new challenge in performing such research was the process of the court. The original "RoaD" project setup was to work alongside "live" court cases, with the research running in parallel with the prosecution. When it was agreed in principle in December 2016, this was not seen as a major issue. However, in 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 [18]. Consequently, any data, even anonymised, which had been provided to a third party must be made known to the defendant, even if the purpose of the research is not for litigation purpose. This means that the CT Post Mortem (CTPM) once performed would have to be disclosed, and have all findings observed from the CTPM scans as part of "RoaD" explained. It was therefore not possible to use the CTPM or perform any computer trauma modelling while the case was "live", as the Defence could contact the "RoaD" research team and gather information that may be used in court to cast doubts within the jury. If a CTPM was performed and the results not analysed, it would still have to be disclosed to the defence. This could complicate the court case. The most logical approach would be to request the data once the case has been finalised at court, hoping that all PM / CTPM and accident data are then available for the right "RoaD" parameters. In general, it takes 6 months for a court case to be finalised, which was not compatible with the timing of this project (2 years).

The research sought to understand if a basis for a trauma model could be calculated mathematically and if this was possible from the small sample size obtained by the UKPF and the Coroner. The "RoaD" project had to make do with the information it already had, i.e. three 'useful' accident cases in which all the information had been provided before the start of the project, waiting for the next batch of accident data after being processed by the Courts. In May 2019, eight accidents were made available to CU. After analysis on the UKPF premises, it became evident that only four more were meeting the criteria set in the study. As the UKPF were still undermanned and due to a departmental change (the "Accident

Investigation" department was transferred to "Forensics") they were not able to provide with the needed PM, in-spite of numerous attempts.

3.3 New Methodology direction for "RoaD"

This new methodology will create a mathematical representation of trauma, or Organ Trauma Model (OTM), and will test it against three accidents provided by the UKPF (Table 1) by comparing the predicted trauma of a pedestrian collision (Figure 2) 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 2: Typical pedestrian kinematics during collision

4. New Project Methodology

4.1 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 [4][5][6]. 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 3, where power goes up and down, while PVP keeps always to the maximum value at all time.

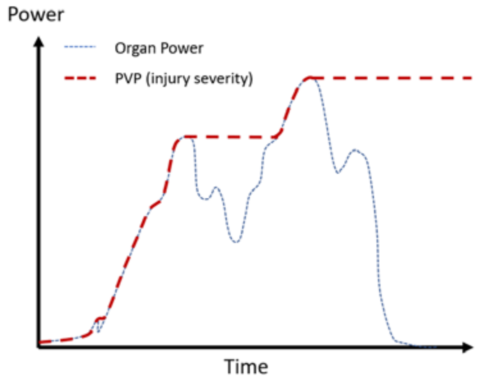


Figure 3: Power goes up and down, while trauma (represented by PVP) keeps on increasing [7]

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 3).

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 [8]

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 stretches 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% [8]	3
Diffuse Axonal Injury (DAI)	Maximum principal strain	21% [9]	4
Heart	Maximum principal strain	30% [10]	4
Liver	Maximum principal strain	30% [11]	4
Spleen	Maximum principal strain	30% [10]	4
Kidney	Maximum principal strain	30% [11]	4

Table 3: Injury trauma values used in THUMS [13]

By considering further scientific literature [4][5][6], it was observed that the threat to life increases by a cubic when AIS is increased (Figure 4).

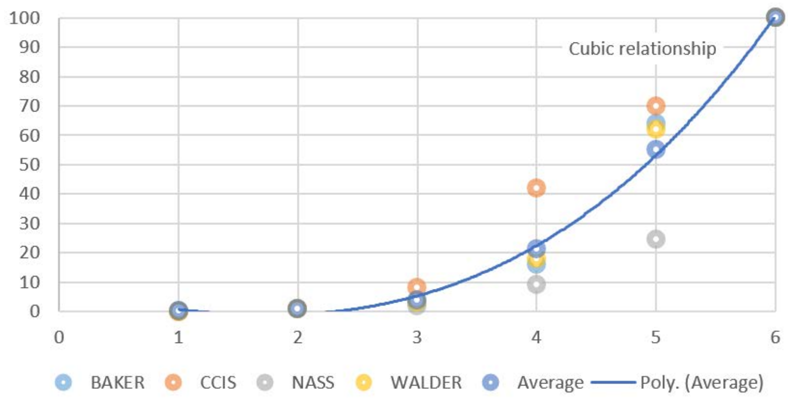


Figure 4: Relationship between Risk to Life and AIS [7]

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 5. It has been possible to include error corridors (upper and lower) for each AIS value by considering the spread of data from Figure 4.

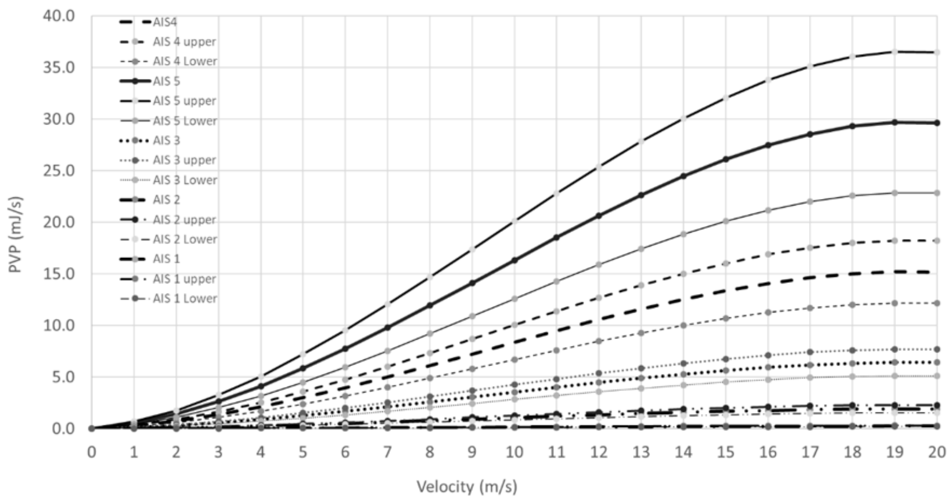


Figure 5: Typical Organ Trauma Model (OTM) starting from AIS4 and then deriving the other levels [8]

As an example, looking at Figure 5, the following arbitrary scenarios can be concluded (Table 3):

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.

4.2 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):

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

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 make are sensible, 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 older people, the frailer they become [19]. It can be therefore assumed that material properties are decreasing as a function of ageing.

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 [30]. Previous work has generated a regression relationship linking brain volume and age (V_{age}) [31], 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.

It was found that loss of bone thickness, material elasticity and density were key outcomes of ageing (Figure 7). 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.

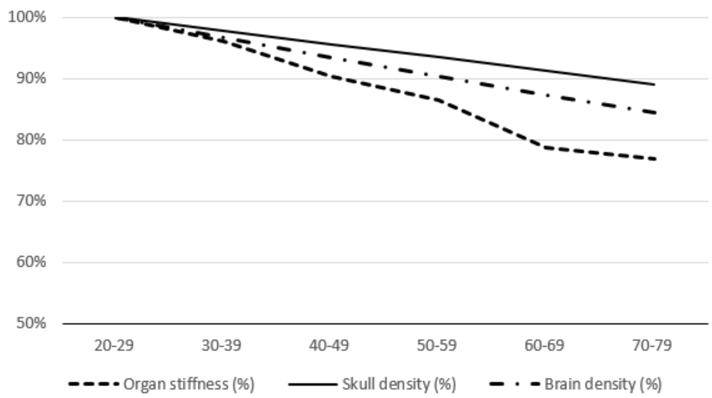


Figure 6: Bone and Organ Performence as function of ageing [30][31]

Equation 2 can be therefore modified to highlight which terms are age dependant (Equation 4).

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

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 8), at a set impact speed, to be injured, which is consistent with what is observed in real life.

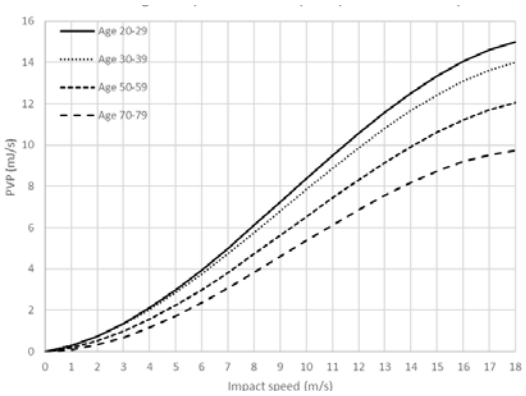


Figure 7: Illustration of a typical brain white matter AIS 4 trauma response as a function of age [8].

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 6:

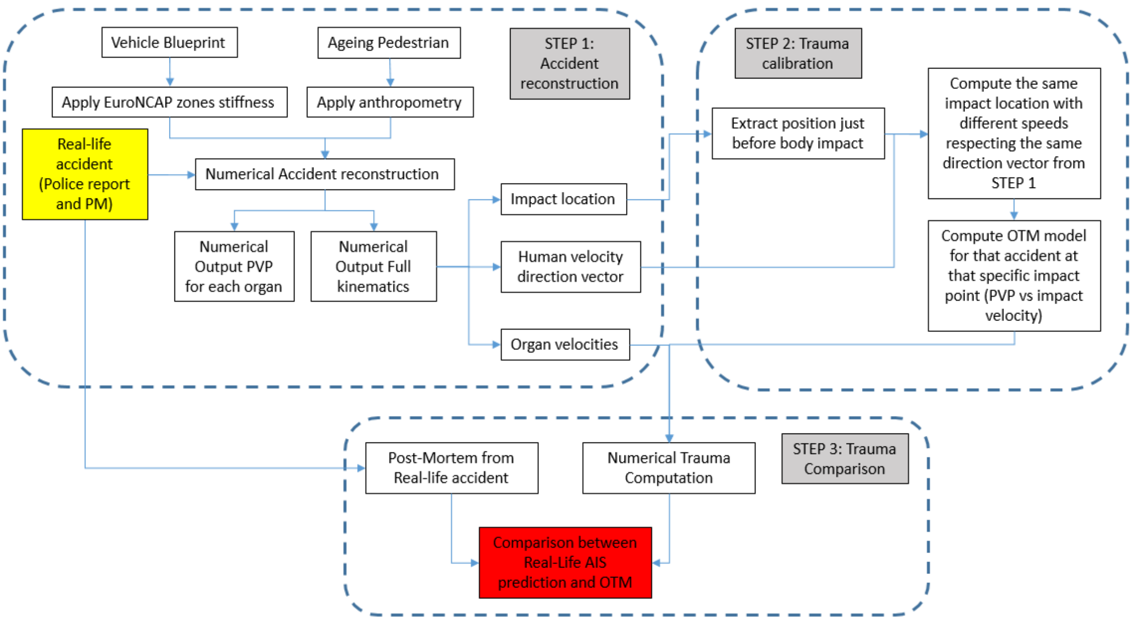


Figure 8: Methodology to test the OTM Model

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 would recapture the collision event, by creating vehicles from their blueprints. These vehicles were split as per their EuroNCAP pedestrian zoning [20][21][22], which was represented by stiffness characteristics matching their real world test performance [23]. The pedestrians will be 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.

5. Results

5.1 Accident Reconstruction

Three accidents provided by the UKPF force were reconstructed. The details of each accidents the pedestrian damage and kinematics are presented in Table 4.

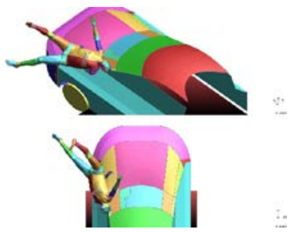
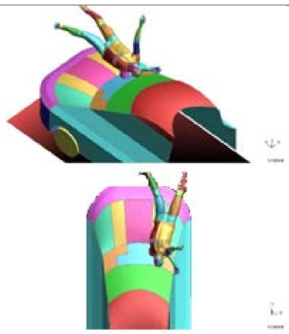
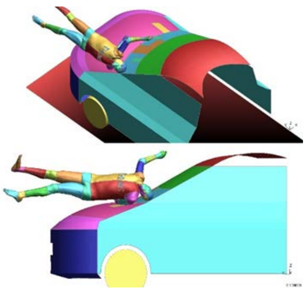
Case id	Pedestrian Kinematics	Vehicle Damage
1		
2		
3		

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 [20][21][22].

5.2 Trauma Computation and Results

Toyota Corolla Brain Trauma Results

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

The accident is 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 4). 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 9 and Figure 10.

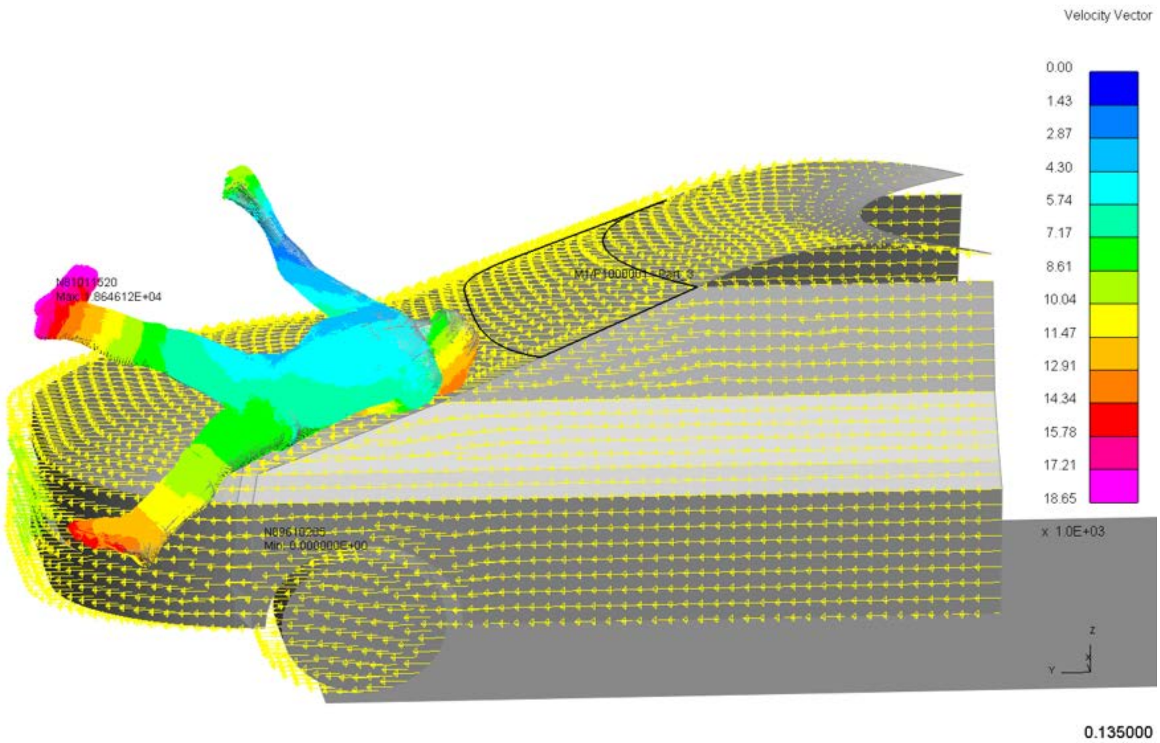


Figure 9: Toyota Corolla - Collision Velocity Profile – Units: mm/s

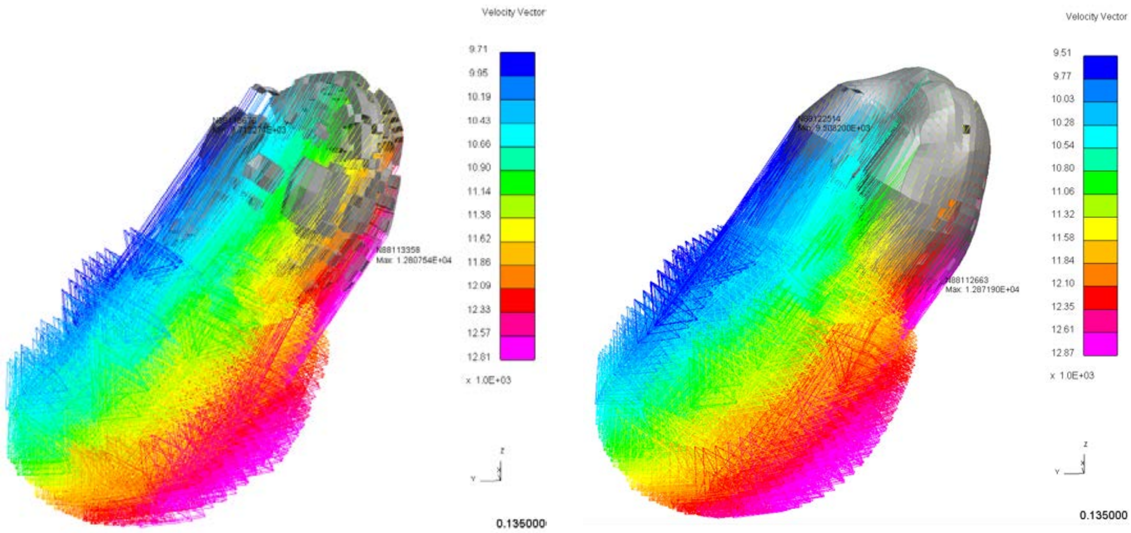


Figure 10: Toyota Corolla - Brain velocity plot (White Matter (right), Grey Matter (Left)) – Units: mm/s

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)

<u>Step 2: Creation of the OTM model for this specific accident</u>

The pedestrian kinematics is ‘rewound’ back in time, and repositioned 5 mm from the bonnet surface, just prior to contact. This step is performed so that the pedestrian hits the same location of the vehicle (as the collision is unique). The pedestrian is 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 5.

<u>Step 3: Overlay step 1 and step 2 to extract trauma value</u>

The white and grey matter brain velocities of the actual impact are remapped on the OTM trauma graphs, as shown in Figure 11 and Figure 12.

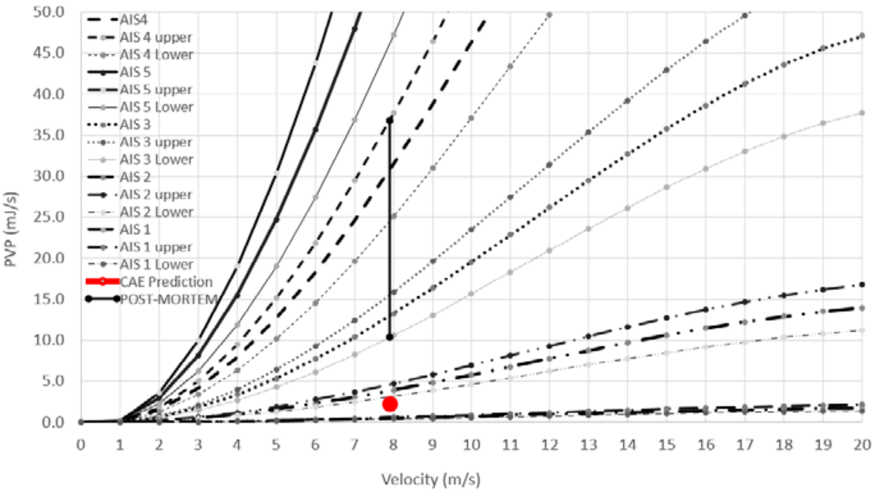


Figure 11: Toyota Corolla - White Matter Trauma

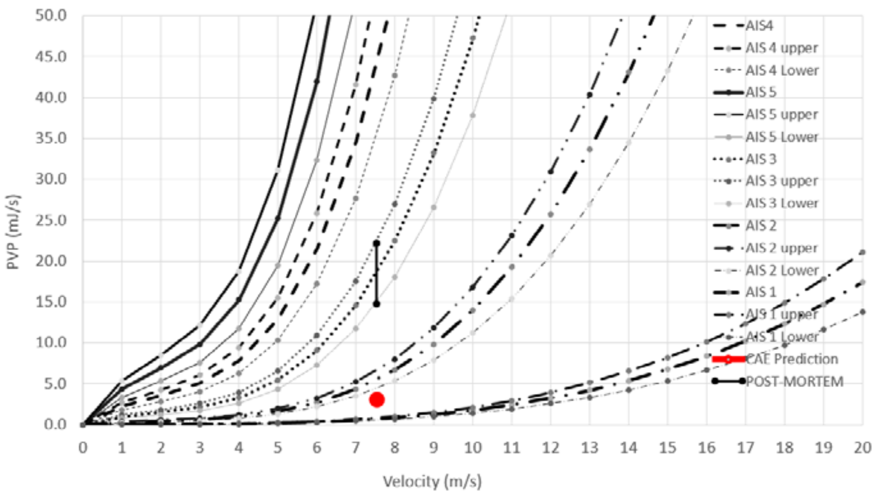


Figure 12: Toyota Corolla - Grey Matter Trauma

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) is adjusted to match the true organ speeds, Looking at Figure 11 and Figure 12, the AIS value for the white matter is 2 (at 7.89m/s) and the grey matter 1 (at 7.53m/s). The process is 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 6. When no evidence was recorded in the PM, it did not necessarily mean that there is no injury, but that there is 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)" [32]. 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 11 and Figure 12 as the vertical 'bar', representing the most probable range of PM outcomes

All the study results are listed in Table 6. 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	CAE Prediction	MPS THUMS (Appendix 6) (AIS estimation)
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	2	48% (AIS 4 > 21%)
		Grey Matter	Brain Contusion	3	2	32% (AIS 3 > 30%)
Renault Clio (2)	No evidence of skull fracture and brain showed no evidence of contusion	White Matter	No evidence	0-2	1	127% (AIS 4 > 21%)
		Grey Matter	No contusion	0-2	1	113% (AIS 3 > 30%)

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	2	72% (AIS 4 > 21%)
		Grey Matter	Brain Contusion	3	1	58% (AIS 3 > 30%)

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.

6. Discussion

In Case 1, the PM is stating that subarachnoid haemorrhage was observed in the white matter and the brain "appeared diffusely swollen to a mild degree", which suggests that the DAI has just been reached, hence the white matter PM AIS has to be 3 to 4. The MPS method is suggesting at least an AIS 4, while the PVP method an AIS 2. It can be observed that the comments from the PM, which are the interpretation from the coroner, and that the AIS level is in this instance a function of how much blood is observed during the autopsy. 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.

Considering Table 6, it can be observed that the brain injury values are an exact match for Case 2, where the injuries have not been evidenced during the PM. This has been well captured by the PVP method, while the MPS method gave injury severity predictions much higher than the PM (suggested AIS3 for grey matter and AIS4 for white matter, as when the critical MPS is reached, it is not known when the next AIS level is reached). In this scenario, there was no bleeding, hence the OTM's model outcome is as expected (Equation 2), as discussed in the "Theoretical Derivation of Trauma" section 4.2 of this report.

Case 3 has a similar PM outcomes as Case 1, however it has to be noted that the MPS method suggests a higher prediction compared to the PM. Again, when the critical MPS is reached for AIS3 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 maybe a new brain model would be necessary to capture the bleeding effect which is recorded in the PMs.

These results also may 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. 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.

7. "RoaD" Pilot Study Final 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 delivered a new method (OTM) to extract brain trauma which is more accurate than current MPS method, used against real worlds accident cases (each taking one day to compute on 160 processors, two weeks to build each vehicle and one month to find all the accident parameters required to reconstruct the pedestrian kinematics). 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 and exciting, 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 to model 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.

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 this PTD, 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 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 methods 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.

8. 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**
   This activity is important as the NHS have access to trauma data (TARN), including CT-SCANs, gender, age, pre-existing medical conditions, mass, anthropometrical dimensions etc… while WMAS have first-hand access to the accident information. As it stands, after numerous discussions with Mr Andy Rosser (Head of Research for West Midlands Ambulance Service University NHS Foundation Trust), it has been evidenced that the accident data collection (pictures, videos, witness statements) was not consistently collected, nor analysed at a later stage for accident reconstruction purpose. Making the data coherent between NHS and WMAS would provide another source of useful accident information which would provide a full dataset for machine leaning training. Part of this task will include an accident reconstruction phase also using machine learning to include vehicle dent patterns, pedestrian gait, crossing speed, vehicle speed,

vehicle geometry, vehicle stiffness characteristics to create a full set for machine learning. Initial discussions with WMAS have suggested that this was feasible at a local hospital with the prospect to train the whole of WMAS ambulance staff. Extra data could be also obtained from RAIDS provided that ageing, gender and anthropometry were provided by the DfT. Discussions are still on-going. This work be a 2 year full time research for a Post-Doc: £150,000 + software = £200,000 (estimated).

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. The current dataset could be used to investigate whether the real-world PM could be replicated, extending to thorax and abdomen organs. This work is also very challenging and important, as it would allow to create a specific accident which could be used to populate a machine learning approach, as well as provide the OEM with a tool which would allow them to test their vehicle design against a human population. This tool could also be used as a Forensic tool for the UKPK and allow the use of virtual PM, for specific accident cases.
   This work be a:
   - 3 year full time research for a Post-Doc: £225,000 + software = £250,000 (estimated)
   - Or 1 PhD funded by RST (£100,000) for 3.5 years -> Coventry University would provide another PhD free of charge.

9. "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

- Scheduled: "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)
- "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 July 2020. 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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Appendix 1: Velocity Plots – Case 2 (Renault Clio)

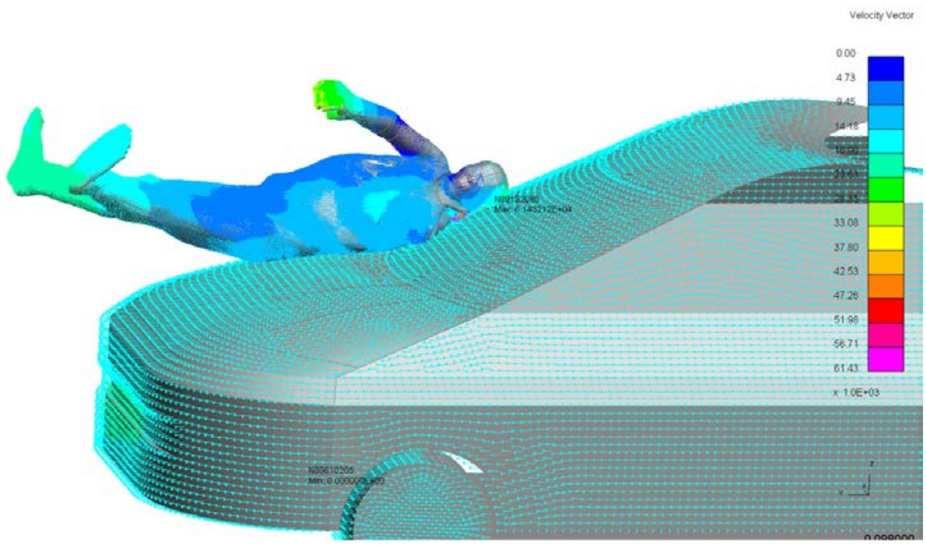

Figure 13: Renault Clio - Collision Velocity Pattern (mm/s)

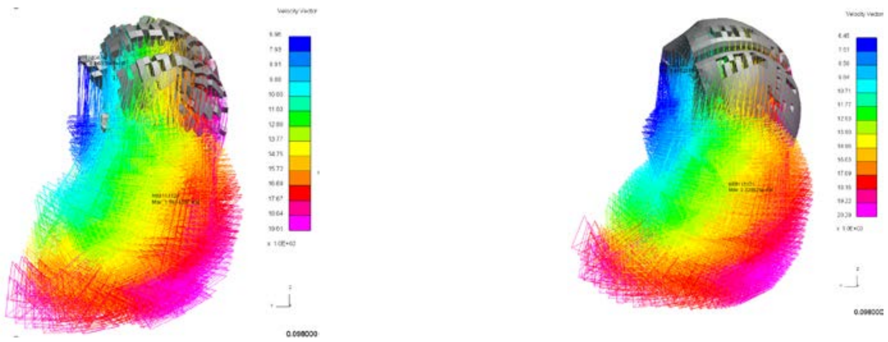

Figure 14: Clio - Brain velocity plot (White Matter (right), Grey Matter (Left)

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)

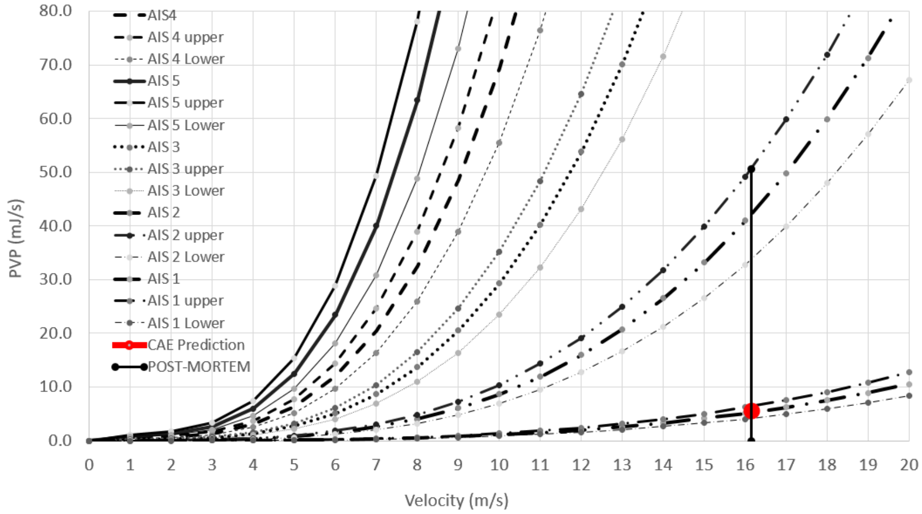

Figure 15: Renault Clio - White Matter Trauma

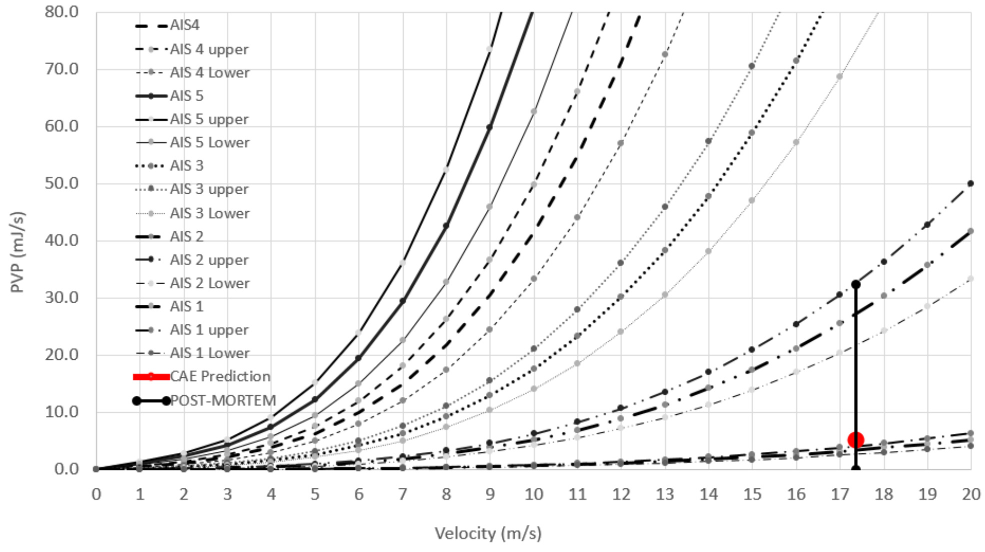

Figure 16: Renault Clio - Grey Matter Trauma

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

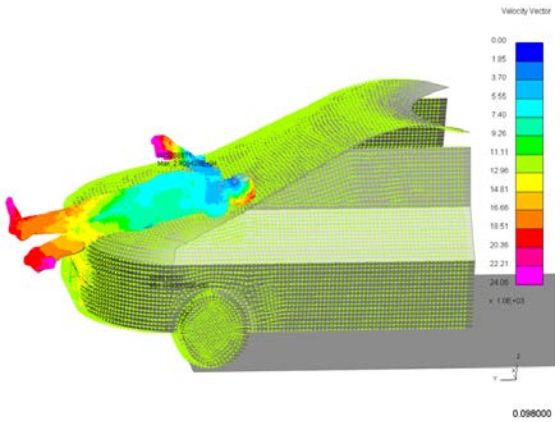

Figure 17: Mercedes Benz - Collision Velocity Pattern (mm/s)

Figure 18: 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)

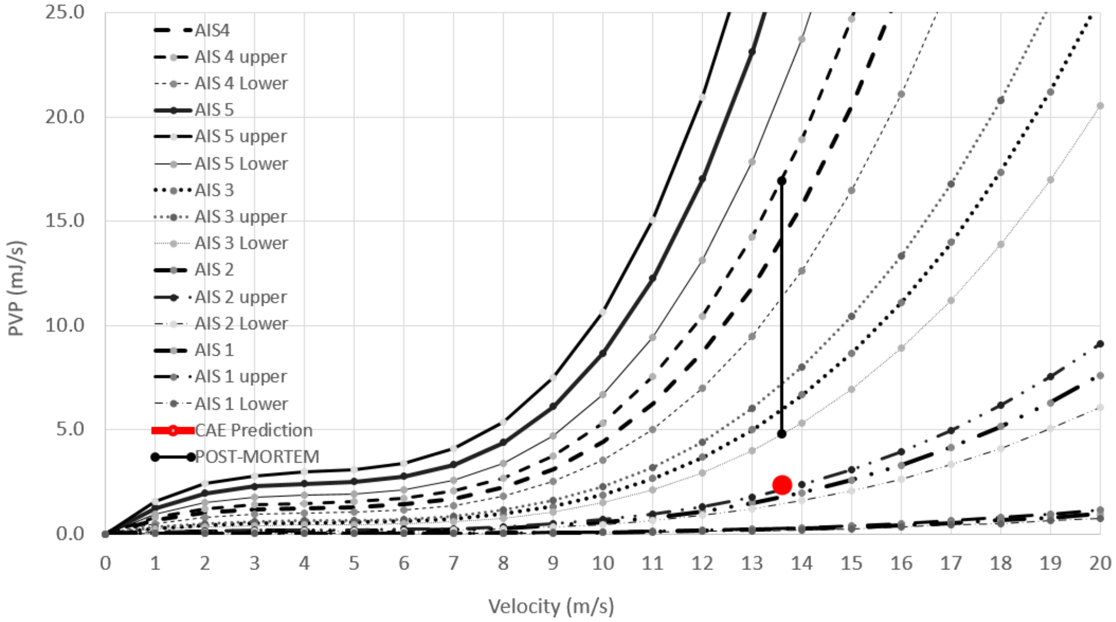

Figure 19: Mercedes Benz - White Matter Trauma

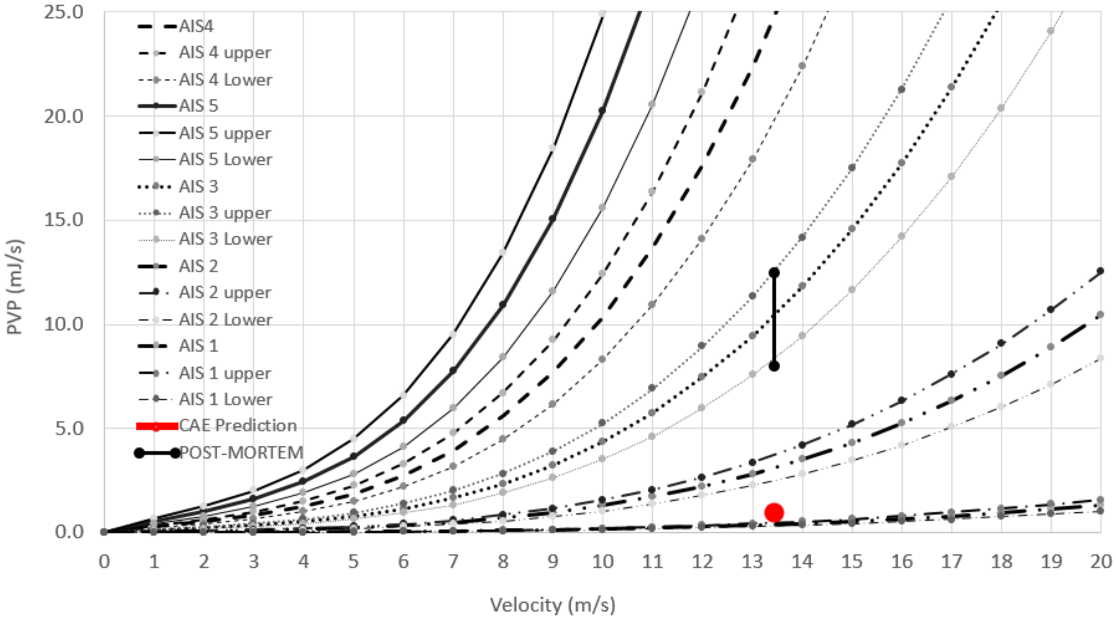

Figure 20: Mercedes Benz – Grey Matter Trauma

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

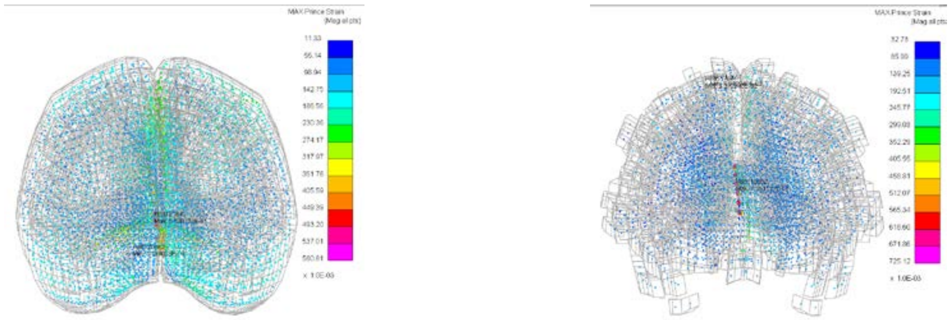

Figure 21: Mercedes Benz. Maximum Principal Strain observed during the impact (Grey Matter – Left; White Matter – Right)

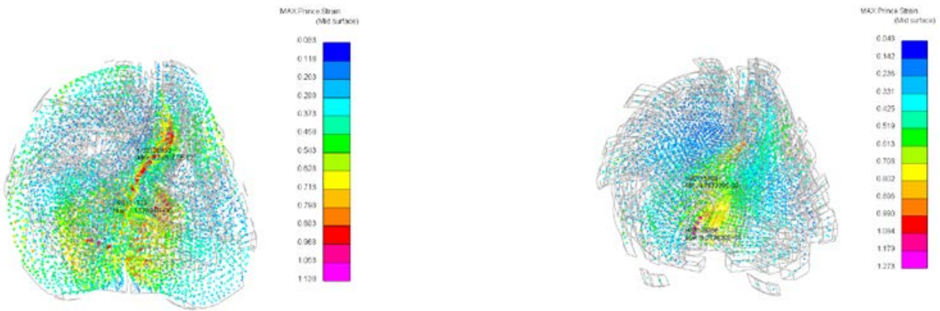

Figure 22: Renault Clio. Maximum Principal Strain observed during the impact (Grey Matter – Left; White Matter – Right)

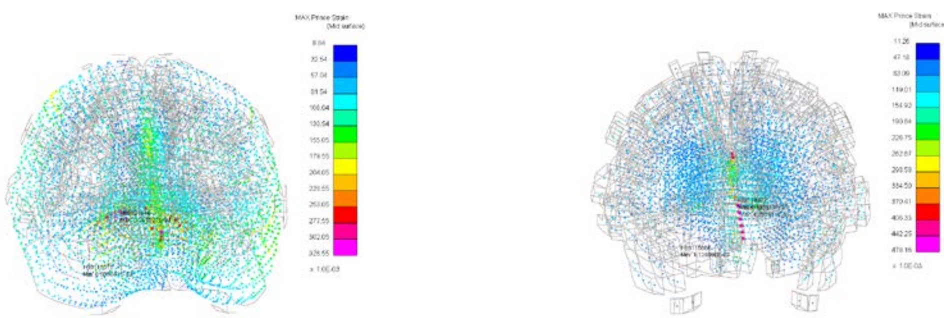

Figure 23: Toyota. Maximum Principal Strain observed during the impact (Grey Matter – Left; White Matter – Right)