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A proof of concept model to calculate white and grey matter AIS injuries in pedestrian collisions

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ABSTRACT

In the real world, the severity of traumatic injuries is measured using the Abbreviated Injury Scale (AIS) and is often estimated, in finite element human computer models, with the maximum principal strains (MPS) tensor. MPS can predict when a serious injury is reached, but cannot provide any AIS measures lower and higher from this. To overcome these limitations, a new organ trauma model (OTM2), capable of calculating the threat to life of any organ injured, is proposed. The OTM2 model uses a power method, namely peak virtual power, and defines brain white and grey matters trauma responses. It includes human age effect (volume and stiffness), localised impact contact stiffness and provides injury severity adjustments for haemorrhaging. The focus, in this case, is on real-world pedestrian brain injuries. OTM2 model was tested against three real-life pedestrian accidents and has proven to reasonably predict the post mortem (PM) outcome. Its AIS predictions are closer to the real-world injury severity than the standard maximum principal strain (MPS) methods currently used. This proof of concept suggests that OTM2 has the potential to improve forensic predictions as well as contribute to the improvement in vehicle safety design through the ability to measure injury severity. This study concludes that future advances in trauma computing would require the development of a brain model that could predict haemorrhaging.

Abbreviations: AIS: Abbreviated Injury Scale; ATD: anthropometric crash test dummy; DAI: diffuse axon injuries; MPS: maximum principal stress; OTM: organ trauma model; PM: post mortem; PVP: peak virtual power; SDH: subdural haematoma; THUMS: total human model for safety; UKPF: UK police force; VM: Von Mises

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Peak virtual power (PVP); pedestrian; accident reconstruction; injury prediction; Abbreviated Injury Scale (AIS); organ trauma model

1. Introduction

Automotive manufacturers design vehicles to meet legislative and consumer test protocols using anthropomorphic crash test dummies (ATD) and other free motion impactors with the purpose of creating safer vehicles for both occupants and pedestrians. Despite all their efforts, the increase in the number of fatalities has reached 1.19 million in 2023 (World Health Organisation 2023), which is no improvement since 2000. There are many parameters that can be attributed to this increase of death toll such as changes to age, gender, speeding, infrastructure etc.; however, the steady rise in numbers begs the question whether the design tools currently used in the design process namely crash test dummies, are adequate to reverse this trend. ATD and pedestrian free motion head impactors, for example, record displacements, accelerations and forces. During the vehicle design process, impact test 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) (AAAAM 2024). 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 six-point ordinal scale and provides a standardised terminology to describe injuries and ranks injuries by severity. The measurements from crash test dummies (Eppinger and Sun 1999; Schmitt et al. 2019) are related to head injury criteria (HIC) (Ljung et al. 1981; Rodden et al. 1983;

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Schmitt et al. 2019), neck injury criteria (NIC, Nij) (Auguste et al. 1996; Morris and Thomas 1996; Kleinberger et al. Parr et al. 2012), chest compression (Kent et al. 2003), viscous criteria (Viano and Lau 1988), femur loads (Kuppa et al. 2001; Rupp et al. 2003), etc. and can only be used to speculate on the probability of death. Also, these dummies have no internal organs; consequently, they are not useful in predicting soft tissue injuries in a deterministic manner. Human computer models, like the THUMS (THUMS 2024), have modelled the soft organ tissues (heart, kidneys, liver, spleen, liver, grey and white matter) and can output soft tissue maximum principal strains (MPS) (THUMS 2024; Viano 1989; Yoganandan et al. 1995) and pressures (Ward et al. 1980), which unfortunately only predict when AIS4 is reached (Sturgess 2001, 2002, 2010). MPS cannot provide any measures between AIS1 and AIS4, as well as it cannot predict when AIS 5 is present. As an example, if 20% MPS relates to AIS4, 10% is not necessarily AIS 2; it could be AIS 1, AIS 2 or AIS 3. MPS are standard outputs suggested by human computer models, which is a major limitation in injury severity computation prediction. This has also been documented in the THUMS 4.02 user manual where 'the validity of these indices and reference values requires further investigation and verification' (THUMS 2024). This article hence proposes a new organ trauma model (OTM2) to compute soft tissue trauma. The original OTM published using the work from Wen (Bastien, Sturgess, Christensen, Wen 2020) was based on the peak virtual power (PVP) method, which is proportional to the maximum rate of entropy production in human soft tissues (Schrodinger 1944). Using PVP, it was possible to predict closer head injury severities than using MPS, when compared to post mortem (PM) reports. The work from Wen, however, ignored vehicle localised stiffness and age effects. Wen assumed the pedestrian contact speed against the bonnet and windscreen to be same as the vehicle impact speed, which this publication will demonstrate is incorrect. The next improvement from the initial OTM model was published using the work from Cheng (Bastien, Sturgess, Davies, Hardwicke, et al. 2021; Bastien, Neal-Sturgess, Panno, et al. 2023; Bastien, Sturgess, Davies, Cheng 2020), who had implemented age in the human computer model. Cheng, however, still kept the same assumption of Wen regarding the impact speed and ignored localised vehicle stiffness and the effects of subdural haematoma (SDH) predictions. Wen and Cheng only used explicit computation to extract trauma responses, but none of their research captured which variables could affect trauma, as well as their relationships. This deficiency was addressed by Bastien, Neal-Sturgess, Davies, et al. (2021), who for the first time extracted an algebraic relationship, which explains the relationship between trauma severity, age, velocity and contact stiffness.

This article proposes a new and more advanced organ trauma model (OTM2), which includes the localised vehicle stiffness effects, age effects, as well as AIS adjustments when brain bleeding is predicted.

The article will initially provide detailed sections about improvements to the PVP prediction method, which will be followed by a description of the OTM2 model methodology, tested in three pedestrian collisions.

2. Including age and bleeding in PVP computation

A mathematical derivation was performed to link threat to life with the results of a finite element analysis (FEA) computation focused on a vehicle to pedestrian collisions. One of the innovations and challenges of this research was the coding of trauma and poly-trauma in a computer simulation. As there is no direct link between MPS and injury severity, it was proposed to use the PVP theory applied to soft organ tissues to compute their injury severity (Sturgess 2001, 2002, 2010).

2.1. Recapitulation of the PVP theory

PVP is based on the principle of the second law of thermodynamics; this law about inefficiency, degeneration and decay states that entropy (state of disorder) increases after each mechanical process. When a collision takes place, the entropy (represented here by PVP) always increases, never to return. A typical pattern of this behaviour is illustrated in Figure 1, where organ power goes up and down, while PVP keeps always to the maximum value at all times. PVP is proportional to the maximum rate of entropy production and as Schrodinger said 'a body reaches a maximum state of Entropy, which is death' (Schrodinger 1944).

PVP (Sturgess 2001, 2002, 2010) is derived using the Clausius–Duhem inequality which is from the rate-dependent form of the second law of thermodynamics, illustrated in Equation (1).

$$\sigma : \dot{\varepsilon} - \rho\left(\dot{f} + s\dot{T}\right) - \frac{1}{T} q \cdot \nabla T \geq 0 \tag{1}$$

Equation 1: Clausius–Duhem inequality.

where σ is the stress tensor, $\dot{\varepsilon}$, is the total strain rate tensor ρ is the mass density, f, is the Helmholtz free

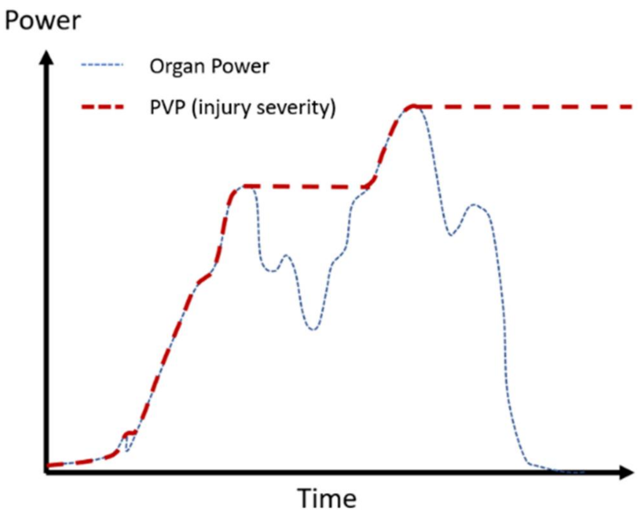


Figure 1. Power in an organ goes up and down, while trauma (represented by PVP) keeps on increasing (Bastien, Sturgess, Davies, Cheng 2020).

energy s is the entropy, T is the absolute temperature and q is the heat flux vector.

For a mechanical system, assuming the contribution of elasticity and heat flux are small, the constitutive relationships are (Equation (2)), with ε the strain tensor, T the temperature and D the damage tensor.

$$f = f\left(\varepsilon_{ij}^{e}, D_{ij,}, T\right) \tag{2}$$

Equation 2: Constitutive equations.

It has been hypothesised and demonstrated that the damage tensor was proportional to injury severity or AIS (Sturgess 2001, 2002, 2010). Following the fact that entropy keeps on increasing during a collision, Equation (3) is derived, illustrating the trauma process from Figure 1.

$$PVP \propto \max(\sigma \cdot \underline{\varepsilon}_{\mathrm{p}}) \propto AIS \tag{3}$$

Equation 3: Generic relationship between peak virtual power and threat to life, which are proportional.

The full derivation of these equations is provided in Appendix 1. The injury severity is coded via an AIS, which has been medically derived and listed in Table 1.

2.2. Proposed new relationship between PVP and human tissues

Human organ soft tissues in computer model (THUMS used in this study) are based on incompressible Kelvin–Maxwell viscoelastic material behaviours (THUMS 2024), and consequently, there is no plastic region. Therefore, the authors propose a dimensionally equivalent relationship from Equation (4), which considers the total strain.

Table 1. Abbreviated Injury Scale linking AIS level and risk to life (Cheng 2020).

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

$$PVP \propto \max(\sigma \cdot \underline{\varepsilon}_{total}) \propto AIS \tag{4}$$

Equation 4: Relationship between peak virtual power and threat to life applied to finite element human computer models.

2.3. Tensor justification to compute PVP

PVP in a finite volume of the body (at organ level, for example) is calculated by multiplying the localised Von Mises stress in that volume (σ_{VM}), by its speed of deformation (or Von Mises strain rate ($\dot{\varepsilon_{VM}}$)). As the load varies during the impact, organ power will vary while PVP will always take the maximum value (Figure 1).

In the case of brain injuries, biological tissues apparently fail in compression (the direction of the loading) when the brain impacts the skull (Fung 1981; Nigg et al. 2005). However, the Von Mises failure criteria, which is the vector result maximum shear stress, captures all states of stress, hence it is a relevant metric, unlike MPS which only represents the state of strain in the principal direction for force (tension/compression).

2.4. Algebraic formulation of trauma severity

By equating the organ kinetic energy and its deformation energy during the impact, it can be shown 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 (5)). The whole derivation, validation and justification of Equation (5) are provided in Appendices 2 and 3.

$$AIS \propto PVP = \frac{A_p}{2V_p}\sqrt{\left(\frac{\rho_p E_p \rho_c E_c m_p}{\rho_p E_p m_c + \rho_c E_c m_p}\right)} v_{t_0}^{3} \tag{5}$$

Equation 5: Generic algebraic derivation of PVP.
where:

- 'A_p' 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_p' is the volume of the organ (constant),
- 'ρ_p' is the density of the organ,
- 'ρ_c' is the density of the contact surface,
- 'm_p' is the organ mass,
- 'm_c' is the vehicle mass,
- 'E_p' represents the modulus of elasticity of the organ (Young's/Bulk modulus),
- 'E_c' represents the stiffness of the vehicle,
- 'v_{t0}' 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 (5) are sensible, as the higher the impact speed 'v', contact stiffness and heavier the object, the higher the injury severity.

An important fact is that, because the phenomenon is related to impact mechanics, the stress wave travels through tissues differently according to which part of 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). In such a scenario, head injuries will be lower on the forehead than the temple and occipital for a given impact speed.

2.5. Including age effect in PVP

2.5.1. Adjusting for brain stiffness

It has been evidenced that as people age, they become frailer (Svennerholm et al. 1997; Sack et al. 2011; Demontiero et al. 2012; Desmorat 2012; Lillie et al. 2016). Figure 2 illustrates this phenomenon, i.e. material properties are decreasing as a function of ageing. Consequently, age will alter the pedestrian's Young's modulus in Equation (5), which in turn will alter the PVP and AIS outcomes.

2.5.2. Adjusting for brain volume

The human head consists of a fleshy outer portion surrounding the bony skull, within which sits the brain. A previous study (Perel et al. 2009) has highlighted significant cortical thinning in the outer and inner tables of the frontal, occipital and parietal bones of females, predicting a loss between 36% and 60% of the original bone thickness from age 20 to 100 years. Cortical thickness changes in the males were found to be insignificant. However, it is the decline in bone quantity and quality that increases fracture risk in a progressive manner (Demontiero et al. 2012). It was found that loss of bone thickness, material elasticity and density were key outcomes of ageing (Figure 2). It can be observed that the mechanical properties of a male have indeed reduced by 20% when the pedestrian is 80 years old, compared to a 20-year-old pedestrian.

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 (Fung 1981). Previous work has generated a regression relationship linking brain volume and age (Demontiero et al. 2012), which is illustrated in Equation (6).

$$V_{age} = -0.0037 * age + 1.808 \tag{6}$$

Equation 6: Relationship between age and volume loss.

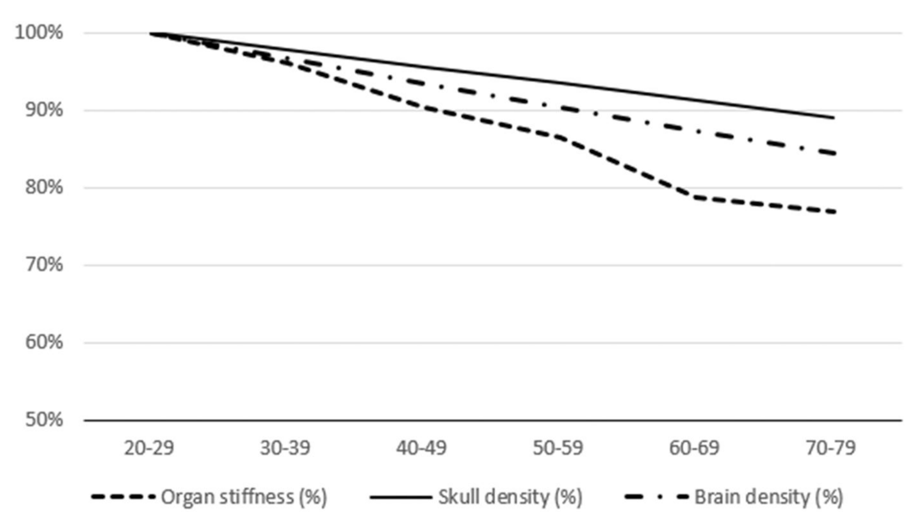


Figure 2. Male bone and organ performance as function of ageing.

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, while the skull was kept at the same volume.

2.6. Including bleeding in the PVP predictions

Another important point to notice is that, in Equation (5), V_p (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 represents the whole problem. 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 (5), as should bleeding occur, then V_0 will reduce. Therefore, PVP, and consequently AIS, will increase, which is as expected. On the other hand, should bleeding not been observed, then Equation (5) should provide the correct answer. To investigate bleeding, it is proposed to include the effects of SDH, which has been defined for an MPS value of 25.5% (Lillie et al. 2016). The problem then is to assert the AIS outcome from bleeding, as a small bleed could add '1' AIS level to the current trauma severity computed or '2' if the bleeding is judged to be important by the pathologist (Oeur et al. 2015). In some cases, the quantity of blood loss could be subjective; hence, for the purpose of being consistent and conservative, all instances of blood loss for the purpose of this study have a '+1' AIS increment on the base AIS computed. This methodology, used on falls, was previously published (Bastien, Sturgess, Davies, Cheng 2020) and managed to capture the AIS trauma severity and location from CT-Scans in two traumatic falls. It is proposed to investigate its accuracy in pedestrian collisions.

3. Creation of the new organ trauma model (OTM2)

3.1. Recapitulation of the initial OTM model

The initial derivation of the OTM model from Wen and Cheng calculated the PVP for each organ by simulating real collisions (vehicle and pedestrian). The PVP values from these collisions were compared to PVP values which were generated by human body models impacted using rigid impactors. As such, OTM should be impact stiffness dependant, as was discussed in Equation (5). This is a major limitation from OTM, which OTM2 will address in this section, as vehicle profiles do not have uniform stiffness.

By considering further scientific literature (Baker et al. 1974; Walder 2013), it was also observed that the threat to life increases by a cubic relationship when AIS is increased (Figure 3).

The map of PVP values, per organ, was created by extracting what PVP value was necessary, for a given impact speed, to cause organ tissue injuries (usually AIS 4), based on MPS. A typical map is represented in Figure 4. The cut-off injury values, used in this study, are listed in Table 2.

This is an 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 1^3/

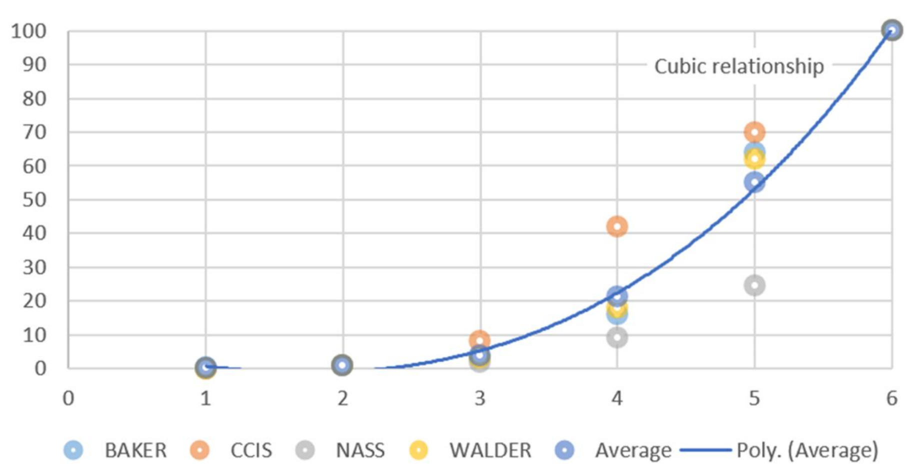


Figure 3. Relationship between threat to life and AIS (Baker et al. 1974; Walder 2013).

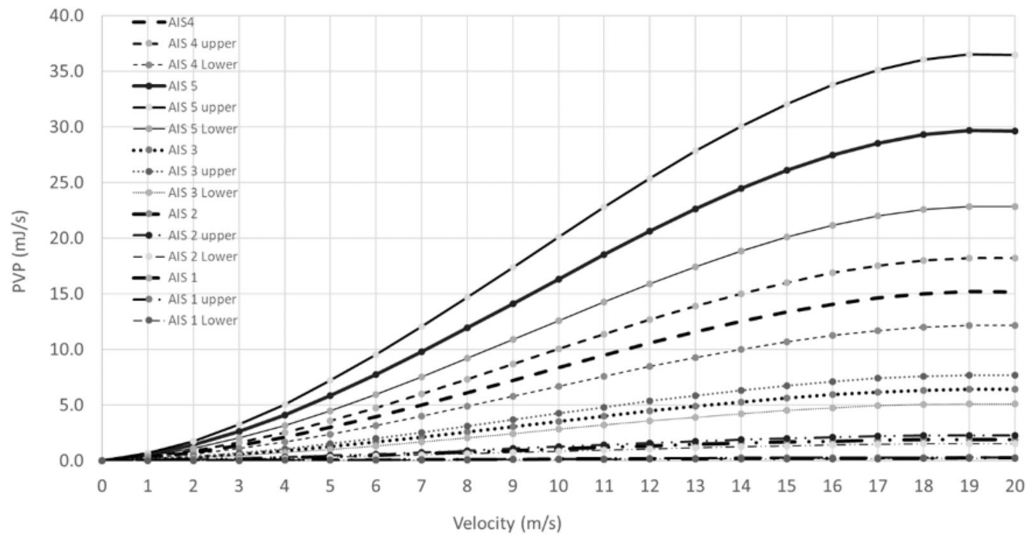


Figure 4. Organ trauma model for a head impact of the forehead against a rigid impactor (Cheng 2020).

Table 2. Injury trauma values used in THUMS (THUMS User Manual 2015).

Body part	Load	Threshold	AIS level
Brain contusion	Maximum principal strain	26% (Haojie and King 2010)	3
Diffuse axonal injury	Maximum principal strain	21% (Bain and Meaney 2000)	4

4^3, $2^3/4^3$, $3^3/4^3$ and $5^3/4^3$, respectively to create the full map of trauma injuries for that organ, creating an 'organ trauma model' (OTM).

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.

As an example, looking at Figure 4, the following arbitrary scenarios can be concluded (Table 3):

3.2. Creation of the improved organ trauma model (OTM2)

OTM2 will address the fact that OTM calibrates PVP with rigid impactors. OTM2 will therefore perform a calibration at the point of contact between the pedestrian and the vehicle. A methodology which consists of three steps is proposed and illustrated in Figure 5:

- The first step is the accident reconstruction phase, whereby three accidents provided by the UK Police Force (UKPF) are modelled. This accident reconstruction will recapture the collision event, by creating vehicles from their blueprints. These vehicles will be split as per their EuroNCAP pedestrian stiffness zoning (EuroNCAP 2024) which will individually be represented by stiffness characteristics matching their real-world test performance. The pedestrians will be aged by scaling their mechanical properties, as per Figure 2, and their brain sized and massed to their anthropometry. Once the accidents are computed, the full kinematics are extracted and compared to the damage observed (denting or smudge) on the vehicles to ensure that the reconstruction is correct. Following this verification, the PVP values for the brain for each collision as well as each organ velocity just before the impact are extracted.
- The second step is the trauma calibration phase at the actual vehicle contact point, by creating an OTM2 model. When a vehicle collides with a pedestrian, the head contacts the windscreen at a specific location, at a specific local impact speed and at a specific local head angle relative to the vehicle. At that specific contact location, there will be a specific vehicle panel stiffness. When all these parameters are combined, then a specific injury is generated. The OTM2 model

Table 3. Hypothetical scenarios extracted from Figure 4.

Impact speed (m/s)	PVP (mJ/s or mW)	AIS extracted from Figure 4
9	7.5	4
14	25	5
19	10	4 (as it is closer to the AIS 4 corridor than the AIS 3 corridor)

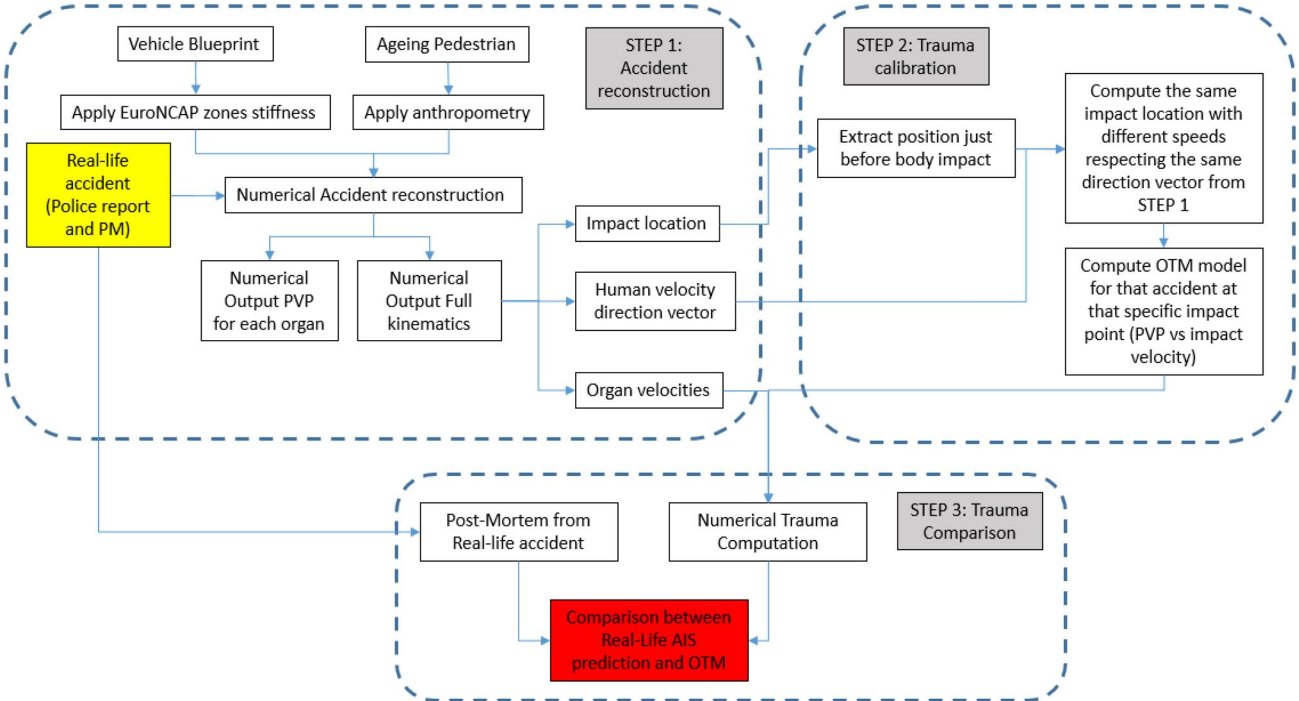


Figure 5. Methodology to test the mathematical OTM model.

represents all the organ trauma injury severity outcomes for that specific location, head impact angle and vehicle stiffness. For this specific OTM2 model, it is possible to extract the head injury severity (AIS) response as a function of head-to-windscreen contact speed. Using the initial collision animation (actual vehicle collision), the full pedestrian kinematics from step 1 are 'rewound' and positioned few millimetres from the bonnet (typically 3.0 mm). Using the same local direction vectors from the real impact at the time of head contact, the head is then projected at the real contact point at arbitrary velocities, usually 2 higher and 2 lower than the actual impact speed. Using the PVP responses generated from these arbitrary impact velocities, a polynomial function is created and then converted into an OTM2 model. This OTM2 model will have a similar shape as Figure 4. In order to extract the actual AIS from the real accident, the PVP from the true collision speed is laid over the OTM2 graphs. It was checked that the head impact location was reasonably constant, and it was observed that the variation in head impact location varied only by 4 mm, which is negligible when compared to the size of the impact area. The effect of this location variation will be reviewed in the results section and commented upon.

The velocity of interest is the impact velocity perpendicular to the windscreen, which is the main contributor to the blunt trauma impact. As such, all velocities extracted in global coordinates (aligned with the vehicle) have been converted into windscreen coordinates (Table 4).

Table 4. Windscreen angle relative to the horizontal plane at the head impact point.

Vehicle	Windscreen angle (°)
Renault Clio	28.4
Toyota Corolla	23.0
Mercedes Benz	28.9

- Finally, the third step will overlay the PVP and orthogonal brain impact velocity responses from the first step against the OTM2 model built in the second step to extract the AIS value. This AIS value will be compared to the value obtained in the real-life scenario from the PM. It is proposed that the OTM2 concept method is valid if both values have the same or similar AIS ordinal values.

In this study, it is proposed to focus only on brain injuries.

4. Results

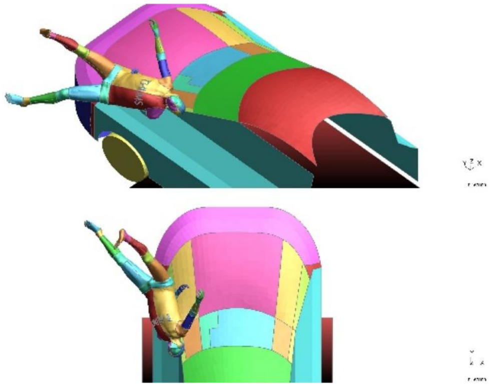
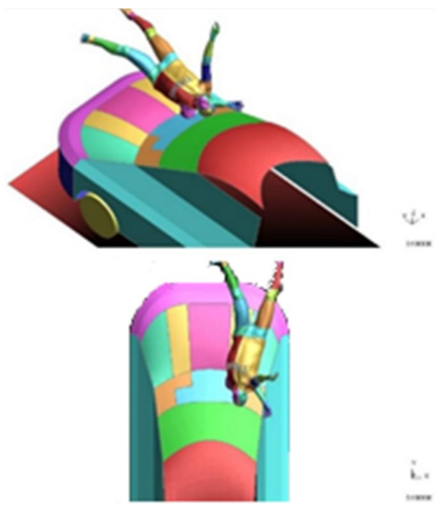
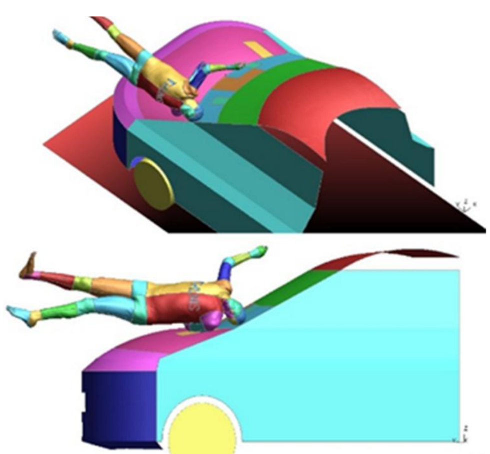
4.1. Accident reconstruction

Three accidents provided by the UKPF force were reconstructed. The details of each accident are listed in Table 5 and the pedestrian damage and kinematics in Table 6.

Table 5. UKPF cases studied.

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 6. Vehicle damage and pedestrian kinematics (Wen 2019; Cheng 2020).

Case id	Pedestrian kinematics	Vehicle damage
1		
2		
3		

The vehicle geometries were reconstructed from blueprints (Toyota Corolla EuroNCAP scoring; Renault Clio EuroNCAP scoring; Benz B180 EuroNCAP scoring) and their respective local stiffness calibrated against EuroNCAP pedestrian test results (Martinez et al. 2007).

4.2. Toyota Corolla brain trauma results

Step 1: Extraction of pedestrian kinematics and PVP during the accident

The authors have performed numerous analyses to reconstruct these collisions, matching the pedestrian anthropometry and focussing on the initial bumper contact point, which leg was hit, the vehicle damage and where the head was landing on the windscreen. Some video information was too sensitive to be provided to the authors, hence the outcomes of this numerical study was provided to the UKPF, who have selected the most probable computer simulation, considering also the torso effect landing on the bonnet, i.e. matching vehicle damage. The UKPF force consists of experts in accident reconstruction and they report to the UK coroner and the courts. This team was satisfied that the reconstruction provided by the authors was credible and as accurate as possible.

Resultant velocities of the whole analysis are plotted in Figure 6 (standard FEA output from a post-processor); the same is done for the velocities in the white and grey matters in Figure 7. The white and grey matters head velocity components Vx, Vy and Vz are then extracted and projected orthogonally to the windscreen using the angles from Table 4. The maximum orthogonal velocity for each case is presented in Table 7.

During this step, the PVP was extracted, as well as the white and grey matter velocities at the time of impact (Table 6). It could be noticed, in this instance, that these velocities at the moment of impact were different from the vehicle impact speed, as illustrated in Figures 6 and 7.

Step 2: Creation of the OTM2 model for this specific accident

The pedestrian kinematics was 'rewound' back in time, and repositioned 3 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 OTM2 model for each organ, comparable to Figure 4.

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

Looking at Figure 8, it can be seen that for both grey and white matter, there is a potential of blood loss, as the MPS values are exceeding 25.5%. The AIS value computed using the PVP method will be therefore increased by '+1'.

The white and grey matter brain velocities of the actual impact are remapped on the OTM2 trauma graphs, as shown in Figures 9 and 10. For completeness,

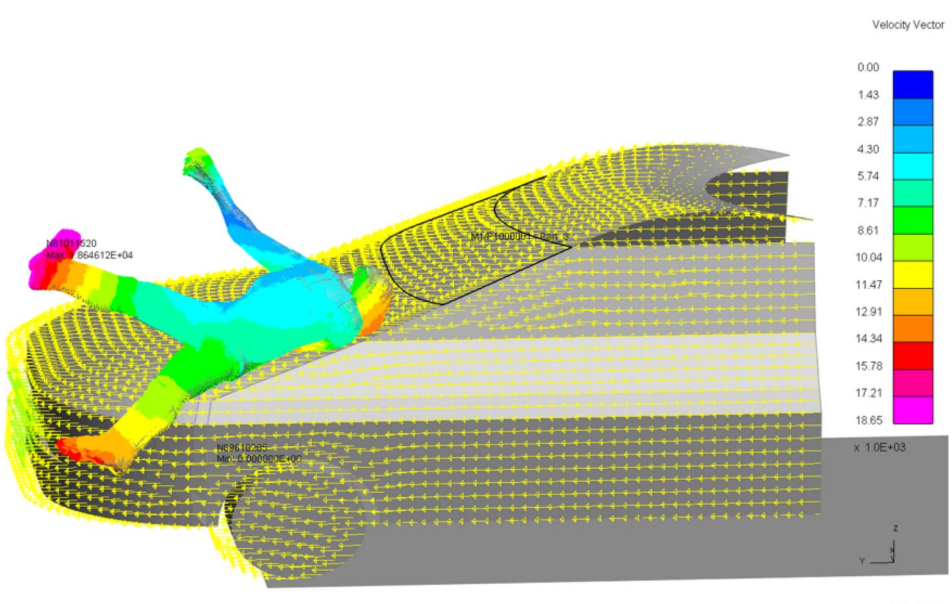


Figure 6. Toyota Corolla – collision velocity profile (mm/s).

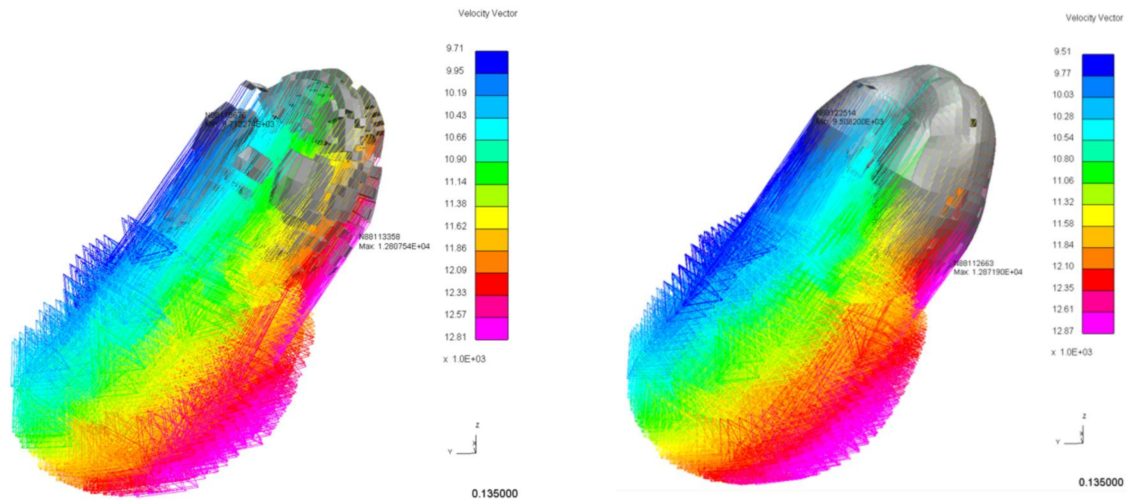


Figure 7. Toyota Corolla – brain velocity plot (grey matter (right), white matter (left)) – units (mm/s).

Table 7. Summary of Toyota Corolla brain velocities (at the time of impact).

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

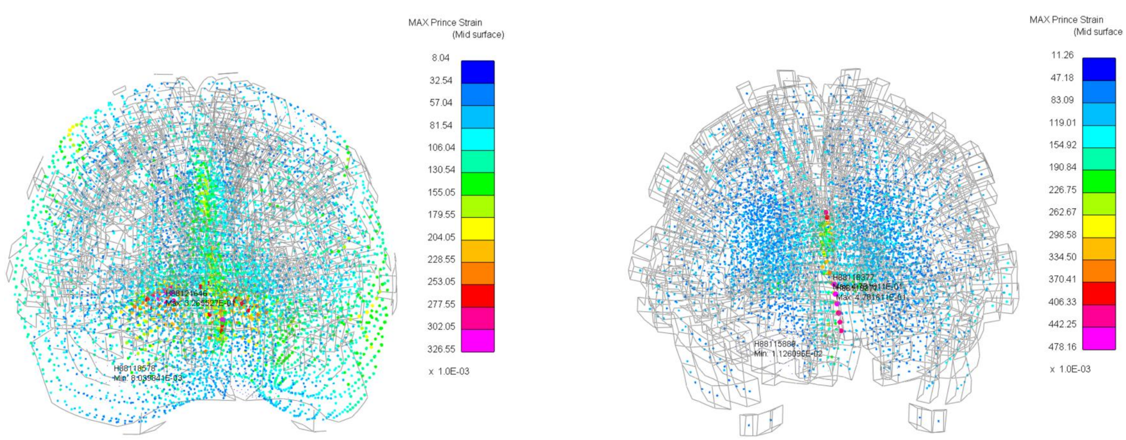


Figure 8. Toyota. Maximum principal strain observed during the impact (grey matter – left; white matter – right).

the results from the collision simulation including the full kinematics have also been included, to test whether the repositioning method was acceptable.

The collision impact speed was 11.2 m/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 Figures 9 and 10, the AIS value for the white matter is 2 (at 7.89 m/s) and the grey matter 1 (at 7.53 m/s).

The process is repeated for Case 2 and Case 3. Their kinematics and trauma plots can be found in Appendices 4–7. The mathematical parameter fits for the three collisions are provided in Appendix 8.

In all the cases, the head injury predictions were similar to the PM results, as shown in Table 8. 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,

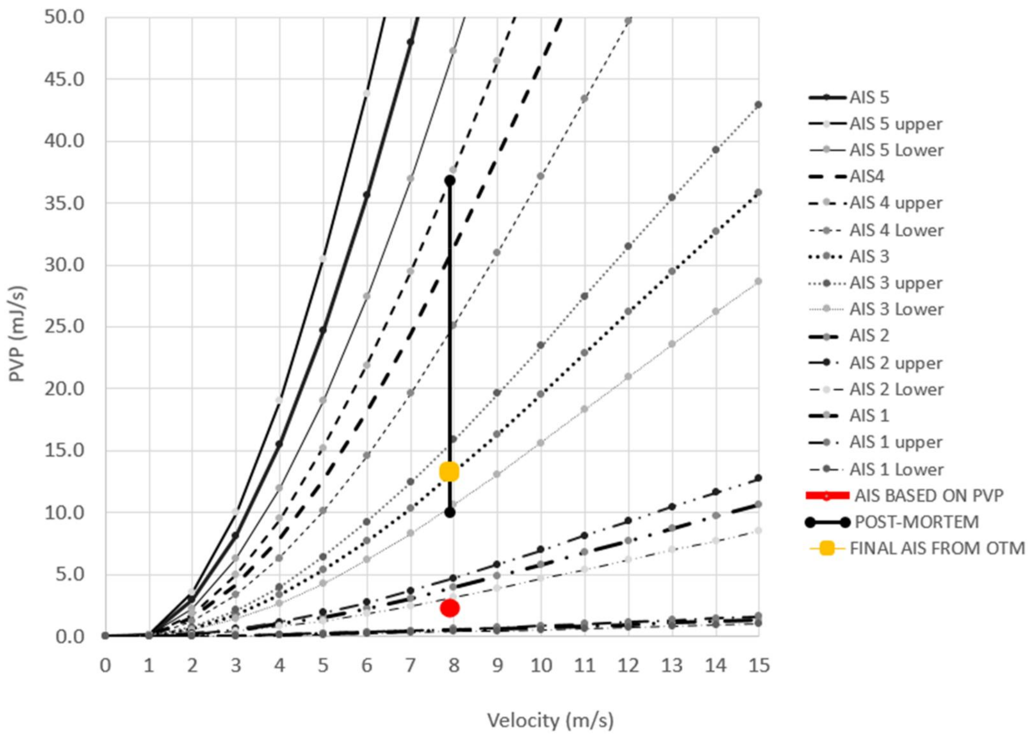


Figure 9. Toyota Corolla – white matter trauma.

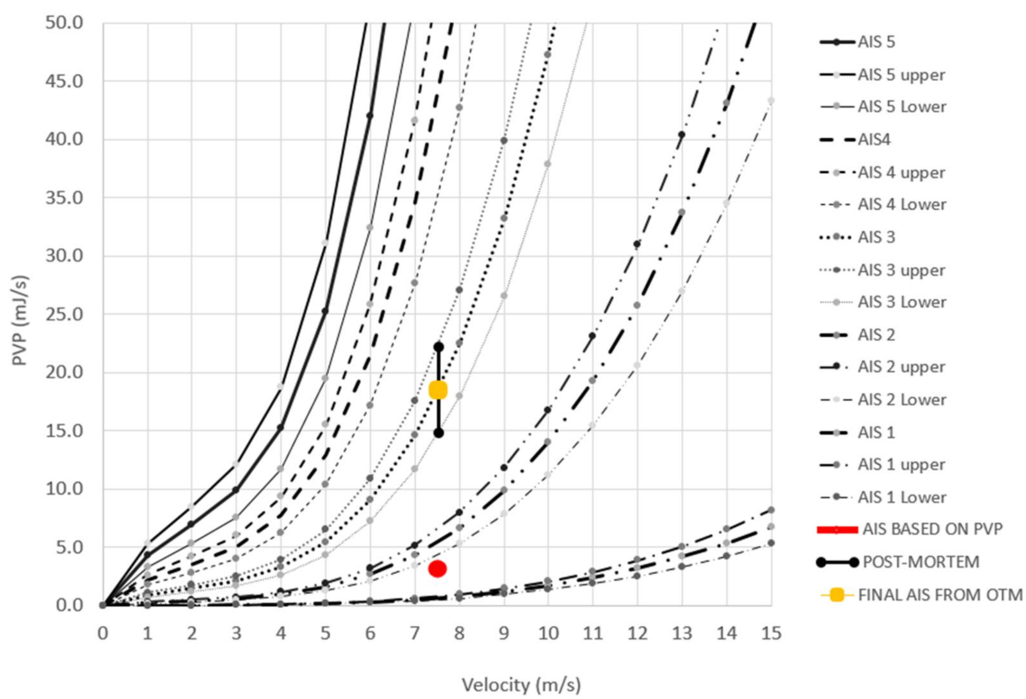


Figure 10. Toyota Corolla – grey matter trauma.

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) (Road Safety Trust 2006). Consequently, for trauma injury severities cases not observed in the PM, a probable PM range has been included and is illustrated in Appendices 5 and 7. Appendix 9 is providing the trauma injury estimation using the standard THUMS recommended output, as per Table 2.

4.3. Results summary for the three collisions

All the study results are listed in Table 8.

5. Discussion

In Case 1 (Table 8), 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 at least a 3. The MPS method is suggesting at least an AIS 4. The grey matter MPS predictions were accurate (AIS 3). For the Toyota, the injury severities for both the white and grey matter were also computed as AIS 3. This severity was calculated by adding '1' AIS to the AIS 2 initially computed by the OTM because SDH was evidenced, i.e. MPS > 25.5%, in Appendix 8. This is a good match to the PM.

Considering Table 8, in the case of the Renault Clio, the OTM model suggests a minor injury (AIS 1), which is compatible with the PM; however, the MPS levels suggest that SDH occurred (Appendix 8), hence an injury severity of AIS 2. The PM did not record any blood loss, indicating that the PM may be questionable.

Finally, in the case of the Mercedes Benz, the white matter and grey matter threat to life were computed to be AIS 3 and AIS 2, respectively. The initial injuries severities were calculated as AIS 2 and AIS 1 and were then increased by +1 because haematoma was observed on both white and grey matter.

The fact that most AIS levels obtained using the MPS method is confirming that even the overall trauma is not a uniaxial event, which the MPS tensor is describing. Using Von Mises, which can be re-written as the vector of maximum shear stress, is therefore a correct assumption.

It can be noted from the forensic pathologist report that evidence of blood loss in the brain increased the injury severity level. The THUMS model is using a Lagrangian method, which implies 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 hydrodynamics (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.

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. Overall, the MPS over-estimates the injury, while PVP under-predicts should bleeding occur. This study suggests that a new brain model may be necessary to capture the bleeding effect that 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 may be 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 (Toyota Corolla EuroNCAP scoring; Renault Clio EuroNCAP scoring; Benz B180 EuroNCAP scoring). Another method of vehicle modelling, for example using the APROSYS bonnet stiffness corridors, may be another venue of investigation.

On another matter, the true brain PVP value comes from the direct strike, i.e. reading the PVP value when the pedestrian is run over standing. It can

Table 8. Study results for brain injuries.

Vehicle (Case id)	PM report details	Organs/Tissue	Injury	AIS from PM	CAE prediction	MPS THUMS (Appendix 9) (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	3 (2 + 1)	48% (AIS 4 > 21%)
		Grey matter	Brain contusion	3	3 (2 + 1)	32% (AIS 3 > 26%)
Renault Clio (2)	No evidence of skull fracture and brain showed no evidence of contusion.	White Matter	No evidence	0–2	2 (1 + 1)	127% (AIS 4 > 21%)
		Grey Matter	No contusion	0–2	2 (1 + 1)	113% (AIS 3 > 26%)
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	3 (2 + 1)	72% (AIS 4 > 21%)
		Grey Matter	Brain contusion	3	2 (1 + 1)	58% (AIS 3 > 26%)

Table 9. Accuracy of OTM PVP predictions against direct head strike.

	White matter PVP prediction (mW)			Grey matter PVP prediction (mW)		
Vehicle	Three-step method from this article	Value from direct strike	Error (%)	Three-step method from this article	Value from direct strike	Error (%)
Toyota	2.5	2.3	8.0	2.5	3.1	24.0
Clio	5.1	5.7	12.0	5.0	5.0	0.0
Benz	2.5	2.4	4.0	1.0	5.0	0.0

be seen from Table 9 that the PVP prediction accuracy between the OTM three-step prediction method from this article and a direct strike varies from 0.4% to 24.0%.

As discussed previously, it not possible to build the OTM using a direct strike, as changes in the vehicle impact speed changes the pedestrian kinematics and the contact point. Therefore, using the three-step OTM2 method is a necessity. In the three-step method, the orthogonal velocity to the windscreen is used to create the OTM2 model and currently ignores the tangential component. The discrepancy in PVP responses suggest that in some cases, the tangential velocity has to be considered when creating the OTM2. In the case of the Toyota Corolla, the windscreen is shallower than the Clio and the Benz (23° vs 28.4° and 28.9°); hence, this may suggest that more sliding could be present and less orthogonal force. In such cases, the OTM2 model predicts higher PVP values, hence only using orthogonal velocity appears to lead to more pessimistic predictions. Note that these more pessimistic predictions still do not affect the trauma outcome predictions, as the injury severities still remain AIS 2. Hence the difference has no consequence on the three impact cases. If this has no injury prediction consequences in these cases, future work should address these discrepancies and include the velocity tangential effects.

An important consideration is that it is not known whether each of these accidents involved a head impact to the ground, which may 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

The research has produced a unique method to compute the different levels of trauma severity in the brain white and grey matter. Unlike the standard MPS method, which can only state whether a critical injury severity has been reached, this improved organ trauma model (OTM2) provides the capabilities to extract the full range of AIS levels (1 to 5), which is a unique feature.

During this work and deriving the OTM2 fundamental mathematical equations, it became apparent that a Lagrangian formulation of any finite element based human body model (HBM) has no capability to model accurately bleeding, as the elements have a constant volume during the whole duration of the computation. To overcome this limitation the OTM2 method has included a correction factor in this study to consider SDH, based on 25.5% MPS threshold (Lillie et al. 2016). It has been hypothesised that the final AIS value has to be the addition of '+1' AIS level to the AIS obtained by the OTM method. This AIS value increase choice was made as it was plausible based on the limited number of accident data. Although these three cases spanned a wide range considering the number of dimensions of the input parameters, it is acknowledged that this might not be sufficient. Unfortunately, due to data limitations, this represented the most comprehensive validation possible. In the future, more cases are necessary to statistically refine this hypothesis.

In any case, when comparing the two methods against three accidents, it was observed that the OTM2 PM's predictions were more accurate than MPS. The MPS method predicted AIS 5, when the PM suggested no injuries. Overall, the PMs computed by the OTM2 method are plausible, suggesting that the OTM2 opens a new way of assessing human brain injury severity and provide additional granularity above and beyond present methods.

The research has highlighted that there may be a need to review the brain model and include means to model bleeding, may be by adding an SPH or ALE formulation. It is believed that the OTM method can also be used for thorax and abdomen soft tissue organs.

7. Further work

The above research is presented as an exploratory proof of concept investigation based on a limited data set. The results of this investigation provide a level of confidence in the proposed approach. The authors will continue seeking for collaborations and investigate this method further to test its robustness.

It is proposed to refine the modelling of the bleeding by including ways to include bridging veins, within the THUMS head model, which are the major contributions to brain bleeding. This way, it will be possible to refine the accuracy and consistency of the AIS bleeding compensation.

It is proposed to refine the OTM2 method to minimise the PVP prediction discrepancies between a direct strike and the three-step PVP predictions. This may entail including the head tangential velocity as part of the OTM2 build.

It is also envisaged to revisit the vehicle geometry and stiffness characteristics to refine the accuracy of the OTM2 model. Following this, the work will be extended to analyse the thorax and abdomen organ injury severity responses using the same method, as well as contact more partners to increase the data samples to further test the OTM2 method.

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Appendix 1: Theoretical derivation of PVP

PVP is derived using the Clausius–Duhem inequality which is from the rate dependent form of the second law of thermodynamics, illustrated in Equation (1).

$$\sigma : \dot{\varepsilon} - \rho\left(\dot{f} + s\dot{T}\right) - \frac{1}{T} q \cdot \nabla T \geq 0 \tag{A1.1}$$

Equation A1.1: Clausius–Duhem inequality.
where:

- σ = stress tensor
- $\dot{\varepsilon}$ = total strain rate tensor
- ρ = mass density
- f = Helmholtz free energy
- s = entropy
- T = absolute temperature
- q = heat flux vector

For a mechanical system, assuming the contribution of elasticity and heat flux are small, the constitutive relationships are (Equation (2)), with epsilon the strain tensor, T the temperature and D the damage tensor,

$$f = f\left(\varepsilon_{ij}^{e}, D_{ij,}, T\right) \tag{A1.2}$$

Equation A1.2: Constitutive equations.

Equation (2) is differentiated (Equation (A1.3)) and reinserted in Equation (1) to give Equation (4).

$$\dot{f} = \frac{\partial f}{\partial \varepsilon_{ij}^{e}} \dot{\varepsilon}_{ij}^{e} + \frac{\partial f}{\partial D_{ij}} \dot{D}_{ij} + \frac{\partial f}{\partial T} \dot{T} \tag{A1.3}$$

Equation A1.3: Differentiating the constitutive equations.

$$\sigma_{ij} \dot{\varepsilon}_{ij}^{p} \geq \rho \frac{\partial f}{\partial D_{ij}} \dot{D}_{ij} \tag{A1.4}$$

Equation A1.4: Clausius–Duhem inequality applied to damage mechanics.

The damage tensor is proportional to injury severity or AIS. Following the fact that entropy keeps on increasing during a collision, Equation (3) is derived.

$$PVP \propto \max\left(\sigma \cdot \underline{\varepsilon}_{p}\right) \propto AIS \tag{A1.5}$$

Equation A1.5: Generic relationship between peak virtual power and threat to life, which are proportional.

Appendix 2:

Algebraic derivation of trauma severity (1/5)

This section is a mathematical proof to the derivation of the trauma severity, based on PVP. Three scenarios will be considered: (1) pedestrian is deformable and the vehicle rigid; (2) vehicle and pedestrian sharing the same criteria and (3) vehicle and pedestrian sharing different criteria in order to derive trauma severity. The rigour and validity of the final derivation of Equation 3 will be verified by confirming that (1) and (2) can be re-derived by reducing the impact assumptions.

The proof concludes that trauma is fundamentally proportional to the square of the velocity (also proven by accident data, $R^2 > 0.9$). The use of an existing empirical data set for pedestrian accidents has shown that this relationship may be further refined by including an additional velocity term to provide a cubic relationship ($R^2 > 0.95$). The authors chose the cubic approach for the work reported in this article, while the squared relationship would have also been acceptable.

1. Assuming that the pedestrian is deformable and the vehicle rigid

The impact kinetic energy of the pedestrian at t_0 is converted into strain energy (deformation) and kinetic energy. This is a time-dependant relationship. V_{t0} is the impact speed, while σ_t and v_t are the stress and speed generated inside the system as the time passes.

$$\frac{1}{2} m {v_{t_0}}^2 = \frac{{\sigma_t}^2}{2E} vol + \frac{1}{2} m {v_t}^2$$

VP (virtual power) is the product of the stress and the strain rate. If the equation above is rearranged to make stress the subject and then multiplied through by strain rate the result is an equation for VP that is time dependent:

$$\sigma \dot{\varepsilon} = VP(t) = \frac{v_t}{L} \sqrt{\rho E\left({v_{t_0}}^2 - {v_t}^2\right)}$$

PVP is the maximum value of $VP(t)$. $VP(t)$ is maximum (proven in Appendix 3) when:

$$v_{t_0} = v_t \sqrt{2}$$

giving

$$PVP = \frac{v_{t_0}}{\sqrt{2}L} \sqrt{\rho E\left({v_{t_0}}^2 - \left[\frac{v_{t_0}}{\sqrt{2}}\right]^2\right)}$$

reducing to

$$PVP = \frac{1}{2L} \sqrt{\rho E} {v_{t_0}}^2$$

Conclusion

In this configuration, trauma severity, or PVP, is proportional to the square of the velocity (aligned with impact direction); however, the trauma severity would be lower if the vehicle is not rigid, i.e. deforms, hence the next formulation, considering the vehicle deformable.

Algebraic derivation of trauma severity (2/5)

2. Assuming that the pedestrian and the vehicle share the same stiffness characteristics

If a constant stiffness 'E' is assumed for the vehicle and the pedestrian, then:

$$\frac{1}{2} m {v_{t_0}}^2 = \frac{\sigma^2}{2E} vol + \frac{{\sigma_t}^2}{2E} vol + \frac{1}{2} m {v_t}^2$$

This then becomes

$$\sigma = \sqrt{\frac{m\left({v_{t_0}}^2 - {v_t}^2\right)}{2 * \frac{vol}{E}}}$$

Taking account that density = mass/volume, then:

$$\sigma = \sqrt{\frac{m\left({v_{t_0}}^2 - {v_t}^2\right)}{2 * \frac{m}{E\rho}}}$$

reducing to

$$\sigma = \sqrt{\frac{\rho E\left({v_{t_0}}^2 - {v_t}^2\right)}{2}}$$

Hence, if the collision partners share the same characteristics the stress, in comparison to the previous example, is reduced by $1/\sqrt{2}$

As VP is the product of the stress and the strain rate:

$$\sigma\dot{\varepsilon} = VP = \frac{v_t}{L}\sqrt{\frac{\rho E({v_{t_0}}^2 - {v_t}^2)}{2}}$$

Note that the strain rate is the same for both collision partners in this example. Further the maximum value can be found (Appendix 3) when:

$$v_{t_0} = v_t\sqrt{2}$$

giving

$$PVP = \frac{1}{2L}\sqrt{\frac{\rho E}{2}}{v_{t_0}}^2$$

Again, trauma severity is proportional to the square of the impact velocity (aligned with impact direction). It can be here noted that when both partners deform, PVP is lower, which is logical. The stiffness of the vehicle is therefore important.

Algebraic derivation of trauma severity (3/5)

3. Assuming that the pedestrian and the vehicle share the different stiffness characteristics

Assuming that the collision partners have different stiffness characteristics (c is car and p is pedestrian):

$$\frac{1}{2}m{v_{t_0}}^2 = \frac{{\sigma_t}^2}{2E_c}vol_c + \frac{{\sigma_t}^2}{2E_p}vol_p + \frac{1}{2}m{v_t}^2$$

The full equation where both collision partners are deformable and have different values of E is shown below:

$$\sigma = \sqrt{\frac{m({v_{t_0}}^2 - {v_t}^2)}{\frac{vol_c}{E_c} + \frac{vol_p}{E_p}}}$$

VP is the product of the stress and the strain rate then for the pedestrian, hence:

$$\sigma\dot{\varepsilon}_p = VP = \frac{v_t}{L_p}\sqrt{\frac{m_p({v_{t_0}}^2 - {v_t}^2)}{\frac{vol_c}{E_c} + \frac{vol_p}{E_p}}}$$

Taking account that density = mass/volume.

$$VP = \frac{v_t}{L_p}\sqrt{\frac{m_p({v_{t_0}}^2 - {v_t}^2)}{\frac{m_c}{\rho_c E_c} + \frac{m_p}{\rho_p E_p}}}$$

VP tends to a maximum value (Appendix 3) when:

$$v_{t_0} = v_t\sqrt{2}$$

giving:

$$PVP = \frac{1}{2L_p}\sqrt{\left(\frac{\rho_p E_p \rho_c E_c m_p}{\rho_p E_p m_c + \rho_c E_c m_p}\right)}{v_{t_0}}^2$$

Again, trauma severity is proportional to the square of the vehicle impact velocity (aligned with the impact direction).

Algebraic derivation of trauma severity (4/5)

Assuming that L is the ratio between the contact area A and the volume V of the pedestrian.

$$AIS \propto PVP = \frac{A_p}{2V_p}\sqrt{\left(\frac{\rho_p E_p \rho_c E_c m_p}{\rho_p E_p m_c + \rho_c E_c m_p}\right)}{v_{t_0}}^2$$

The equation above is the generic algebraic formulation of trauma severity.

It can be noted that the injury severity is also dependant on the contact area, hence the vehicle profile.

Conclusion

AIS is a function of:

- the contact area between the vehicle and the pedestrian,
- Volume of material supporting the area impacted,
- pedestrian mass, density and stiffness,
- vehicle mass, density and stiffness,
- Impact speed (speed orthogonal to the impacted structure),
- Ageing, as material properties and volume are age dependant.

4. Verification of the generic algebraic formulation of trauma severity

If both partners have the same characteristics (Section 1), then the generic equation reduces to:

$$PVP = \frac{1}{2L_p}\sqrt{\frac{\rho E}{2}}{v_{t_0}}^2$$

If we refer back to previous example (Section 2) and assume that collision partner is rigid then

$$PVP = \frac{1}{2L_p}\sqrt{\left(\frac{\rho_p E_p \rho_c m_p}{\frac{\rho_p E_p m_c}{E_c} + \rho_c m_p}\right)}{v_{t_0}}^2$$

As E_c tends to infinity, the term containing E_c tends to zero and can be discarded, hence:

$$PVP = \frac{1}{2L_p}\sqrt{\left(\frac{\rho_p E_p \rho_c m_p}{\rho_c m_p}\right)}{v_{t_0}}^2$$

or

$$PVP = \frac{1}{2L_p}\sqrt{\rho_p E_p}{v_{t_0}}^2$$

Algebraic derivation of trauma severity (5/5)

5. Generic algebraic formulation of trauma severity and real-life accident evidence

The generic equation below is the generic algebraic formulation of trauma severity:

$$AIS \propto PVP = \frac{A_p}{2V_p}\sqrt{\left(\frac{\rho_p E_p \rho_c E_c m_p}{\rho_p E_p m_c + \rho_c E_c m_p}\right)}{v_{t_0}}^2$$

This equation is compatible with real-life accident published evidence illustrated in Figure A2.1.

It can be noticed that for serious (AIS3) and fatal accident (AIS4+) that the correlation exponent is at least 0.96 for a squared interpolation and 0.99 for a cubic interpolation. This is showing that there is already a very strong relationship between AIS and the square of the impact velocity, hence proving the generic algebraic formulation of

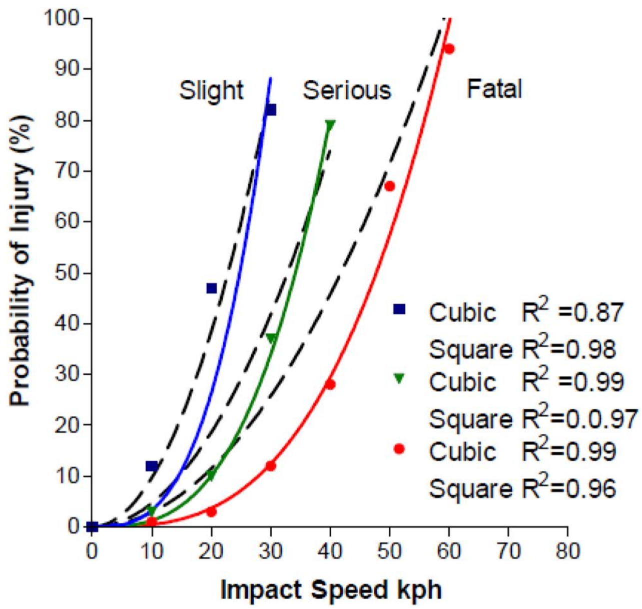

Figure A2.1. Pedestrian accident cases: relationship between threat to life (AIS) and vehicle impact speed (Sturgess 2002).

trauma severity derivation is reasonable and representative of the trauma severity representation phenomenon. In the case of fatal injuries, the polynomial fit is already very good (0.96), however, it is even more accurate with a cubic exponent, suggesting that the cubic formation can capture more accurately, but marginally more accurately than a squared relationship, the real-life events of the fatality phenomenon. Hence as the calibration will be based on AIS4, the authors have decided to use a cubic interpolation. Note that this choice does not void the validity of the generic algebraic formulation of trauma severity formulation derived in Appendix 2.

$$AIS \propto PVP = \frac{A_p}{2V_p}\sqrt{\left(\frac{\rho_p E_p \rho_c E_c m_p}{\rho_p E_p m_c + \rho_c E_c m_p}\right) {v_{t_0}}^3}$$

Appendix 3: Derivation of the maximum of PVP

Finding the maximum of:

$$\sigma\dot{\varepsilon} = VP = \frac{v_t}{L}\sqrt{\frac{\rho E({v_{t_0}}^2 - {v_t}^2)}{2}}$$

This equation can be re-written as:

$$VP \propto {v_t}^2\left({v_{t_0}}^2 - {v_t}^2\right)$$

Therefore

$$VP \propto -{v_t}^4 + {v_t}^2.v_{t_0}^2$$

The maximum can be found by differentiating against ${v_t}^2$

$$\frac{d\left({v_t}^4 - {v_t}^2.{v_{t_0}}^2\right)}{d{v_t}^2} = 0$$

giving:

$$2.{v_t}^2 = {v_{t_0}}^2$$

Hence:

$$v_{t_0} = v_t\sqrt{2}$$

Appendix 4: Velocity plots – case 2 (Renault Clio)

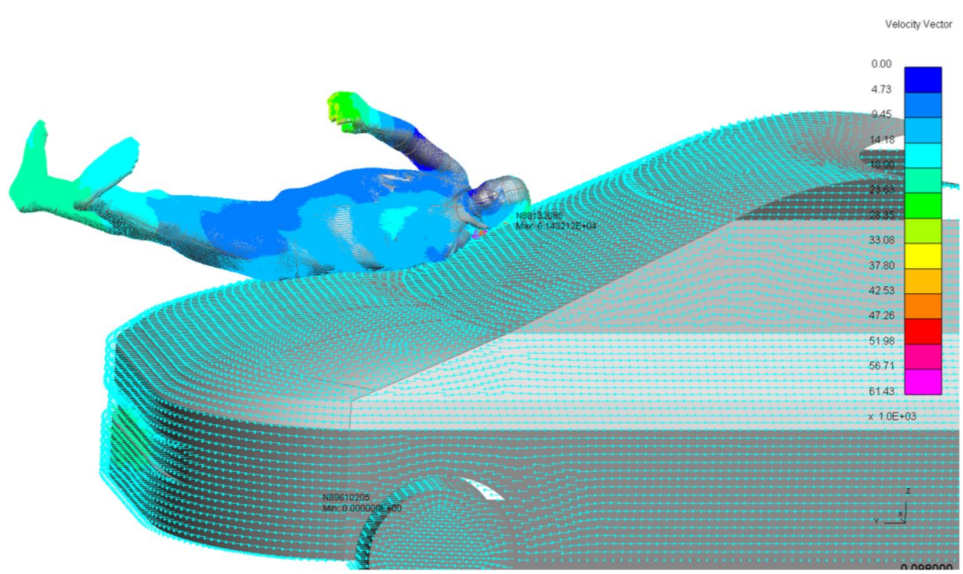

Figure A4.1. Renault Clio – collision velocity pattern (mm/s).

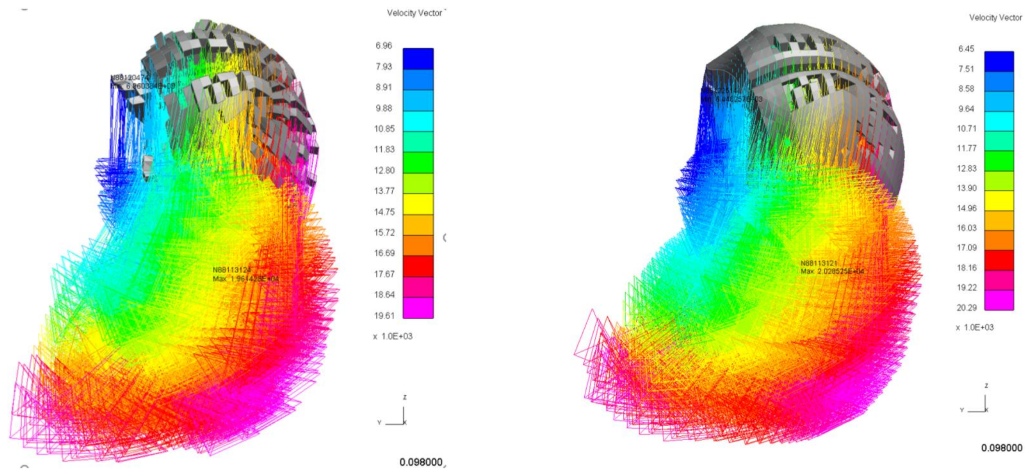

Figure A4.2. Renault Clio – brain velocity plot (white matter (left), grey matter (right)).

Table A4.1. Summary of Renault Clio brain velocities.

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

Appendix 5: Trauma plots – case 2 (Renault Clio)

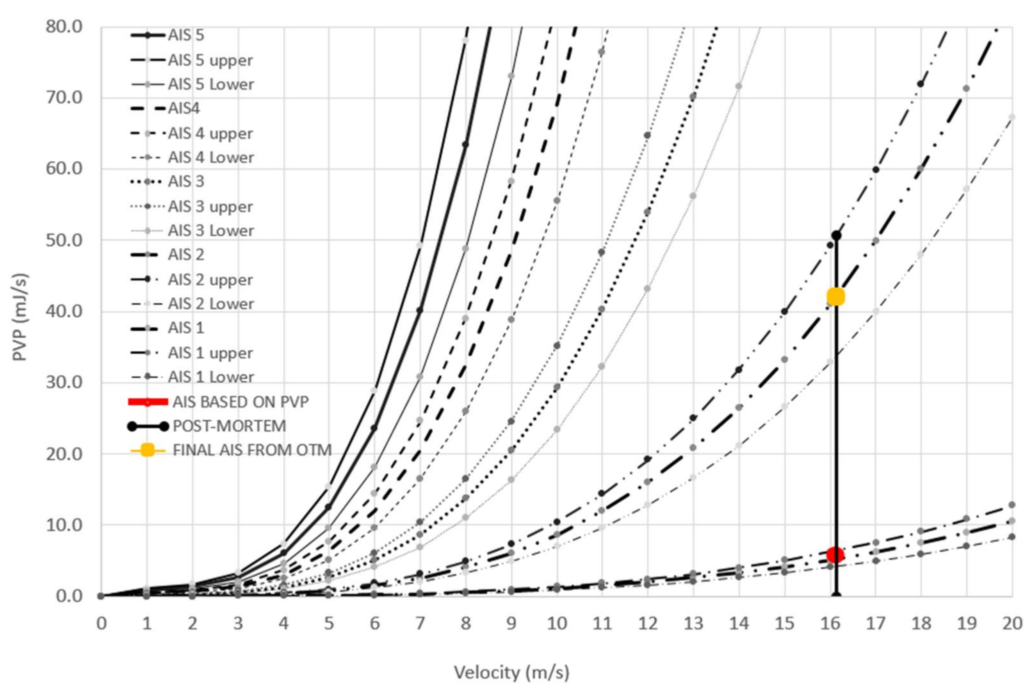

Figure A5.1. Renault Clio – white matter trauma.

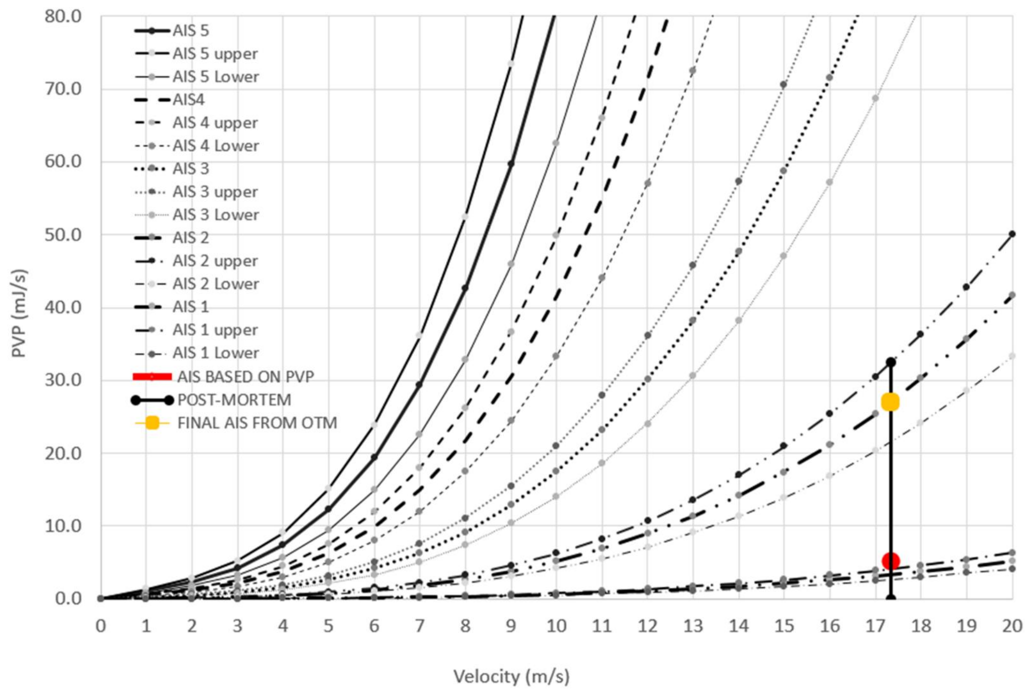

Figure A5.2. Renault Clio – grey matter trauma.

Appendix 6: Velocity plots – case 3 (Mercedes Benz)

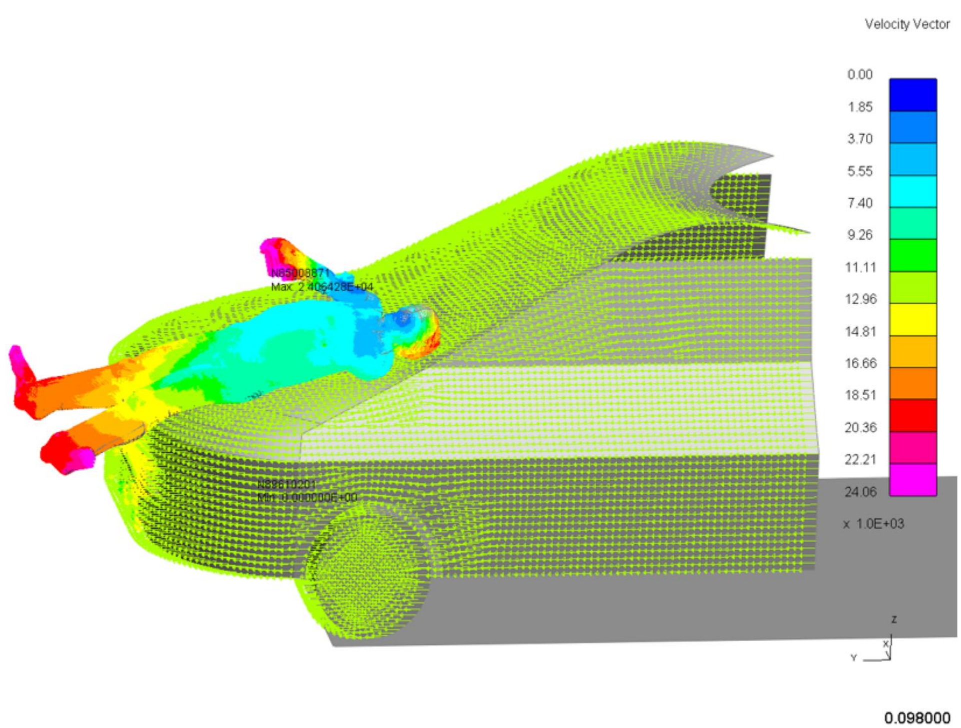

Figure A6.1. Mercedes Benz – collision velocity pattern (mm/s).

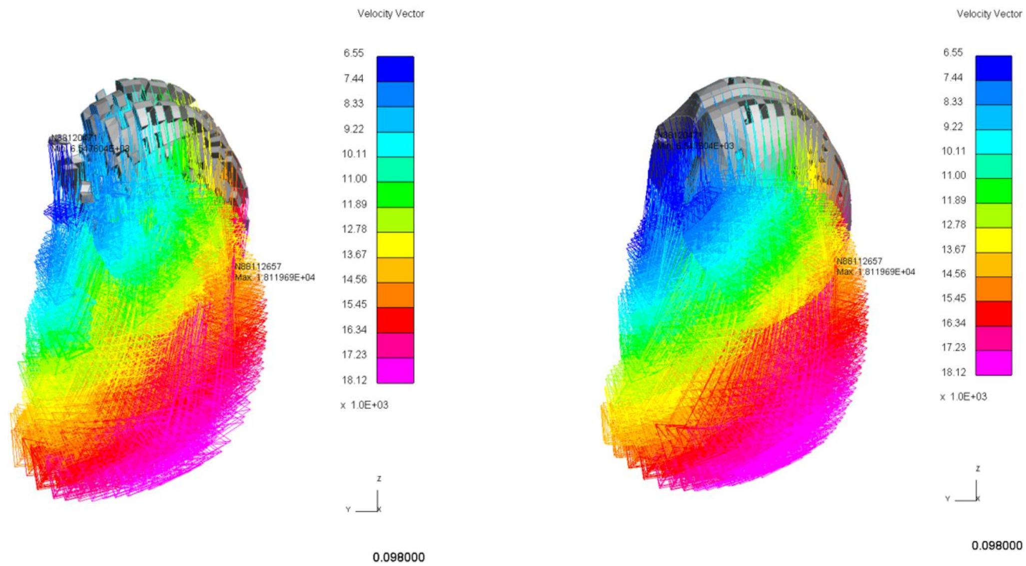

Figure A6.2. Mercedes Benz – brain velocity plot (white matter (left), grey matter (right)).

Table A6.1. Summary of Renault Clio brain velocities.

Organ	Resultan 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

Appendix 7: Trauma plots – case 3 (Mercedes Benz)

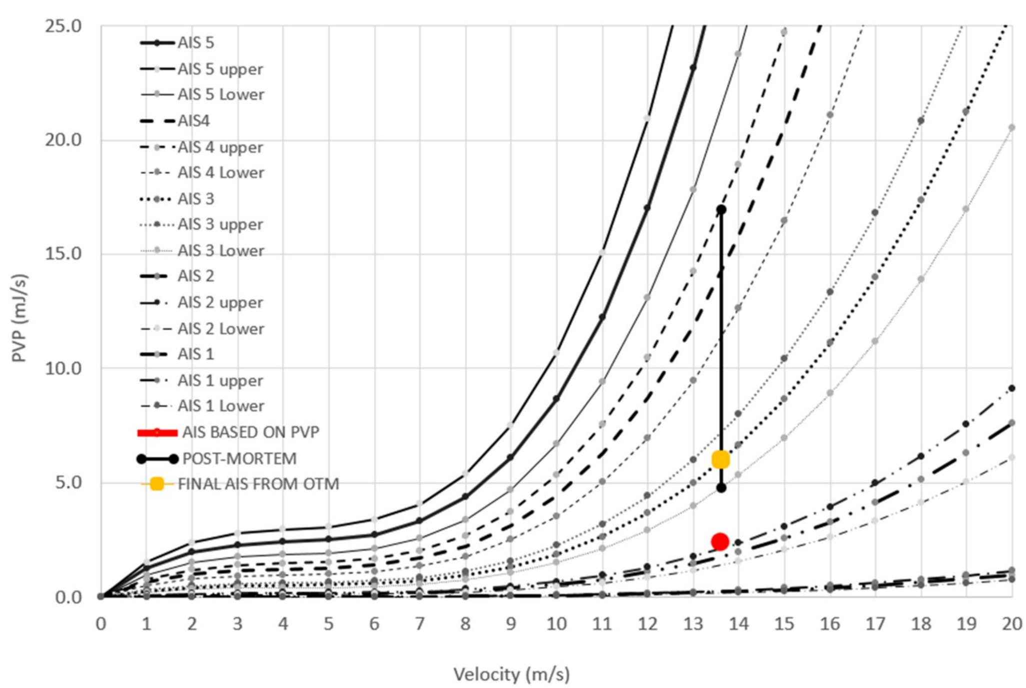

Figure A7.1. Mercedes Benz – white matter trauma.

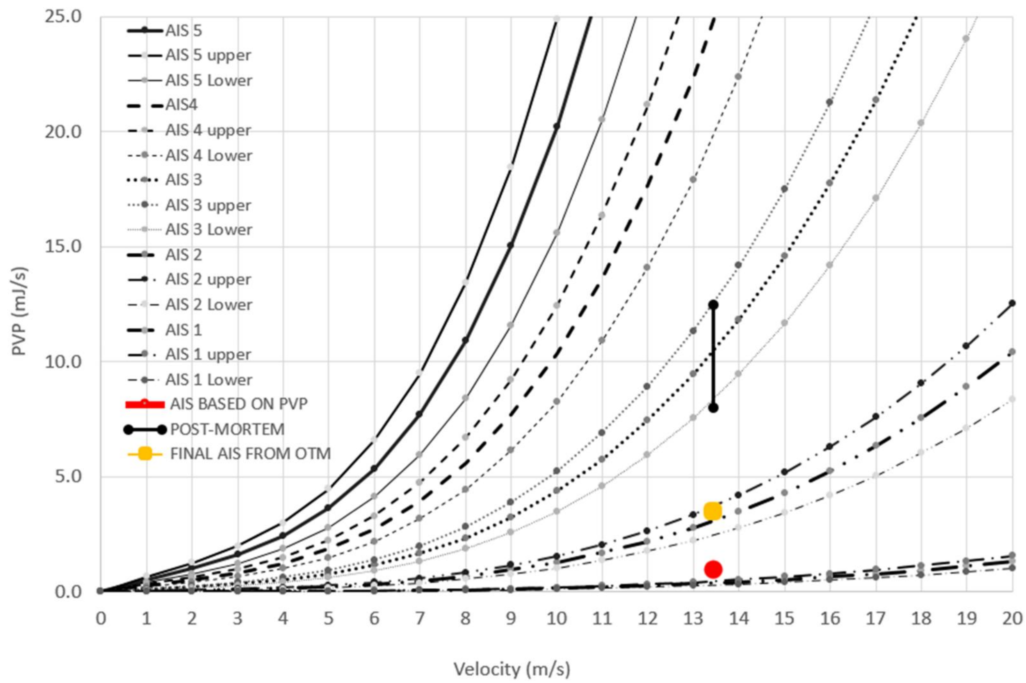

Figure A7.2. Mercedes Benz – grey matter trauma.

Appendix 8: Mathematical fits (AIS4) for the three 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 9: Maximum principal strain responses

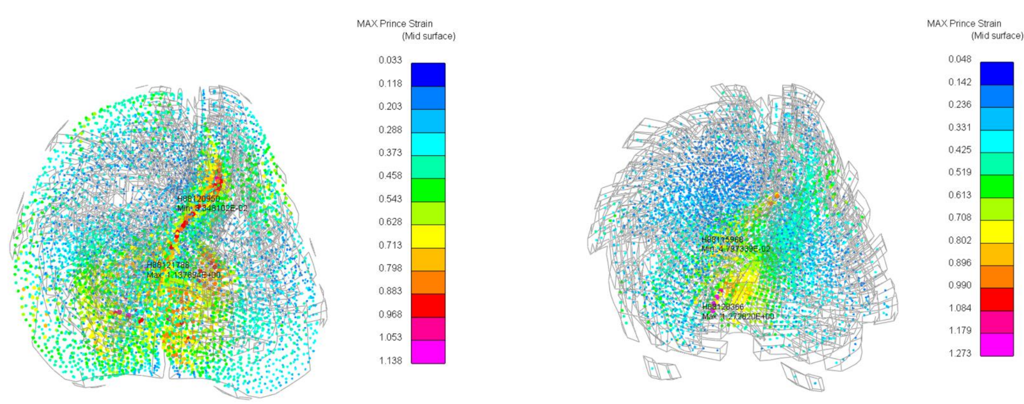

Figure A9.1. Renault Clio. Maximum principal strain observed during the impact (grey matter – left; white matter – right).

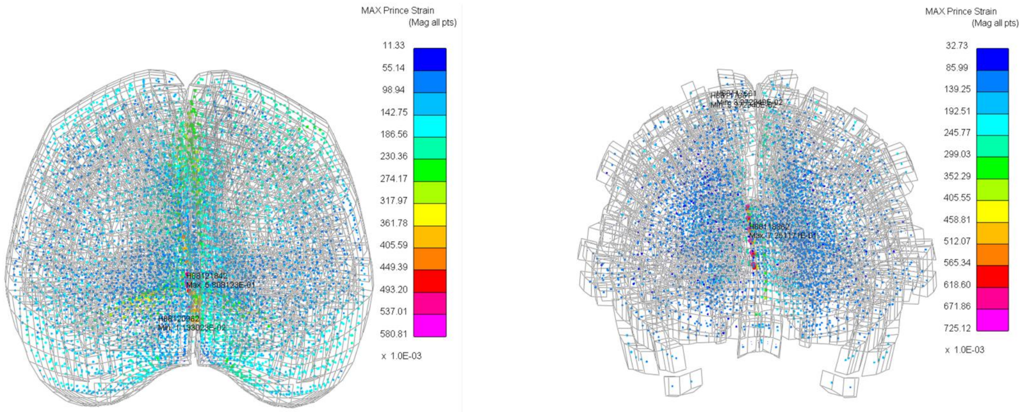

Figure A9.2. Mercedes Benz. Maximum principal strain observed during the impact (grey matter – left; white matter – right).