Human Body Model and Passive Safety of Vehicles: Study of Injuries on abdominal organs using the Peak Virtual Power method (PVP)

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Nomenclature

AIS  Abbreviated Injury Scale
CIREN Crash Injury Research Network
kg  Kilograms
kJ  Kilojoule
km/h Kilometre per Hour
L  Length
m/s Meter per Second
MJ  Millijoule
MJ/s Millijoule per Second
mm Millimeter
ms Millisecond
NHTSA National Highway Traffic Safety Administration
PVP Peak Virtual Power
R²  Goodness of Fit Factor
s  Seconds
THUMS Total Human Model for Safety
v  Velocity
ρ  Density
ε  Strain
σ  Stress
%  Percent
Δt Change in time
Abstract

The Human Body Models (HBM) has opened a whole new world about the analysis of the injuries and the biomechanical results of car crashes. The level of details of these models together with the Finite Element Method (FEM), offer the possibility of getting closer to the real consequences of a car crash on the human body, in comparison with the traditional rigid dummies.

The aim of this thesis work is to evaluate the “Abbreviated Injury Scale” levels (AIS, risk to life scale) of possible injuries happening to the abdominal organs of a rear passenger during a car crash using an innovative injury criterion: The Peak Virtual Power method (PVP), an energy-based engineering indicator, linearly proportional to the AIS, that applies to all body traumas and severities.

In order to validate this method, an incident case from real life involving a vehicle impacting a rigid street furniture was simulated with FEM, reproducing the kinematics of the real accident. In this simulation, an accelerometer placed on the base of the B-pillar of the vehicle traced the longitudinal acceleration that was then applied to a sled model where the THUMS (Total Human Model for Safety) occupant was used, together with the seat assembly and front seat. From the sled model results on the abdominal organs under analysis, the virtual power was calculated. Through this data, a full set of AIS corridors including the other AIS levels curves was obtained. The PVP of the examined organs was then retrieved from the simulation conducted at the real case velocity and used to attain the AIS level of the injury according to the curves built before. This AIS level is finally compared with the one reported in the real-life accident report.

According to the outcomes of this comparison, the PVP method shows great accuracy in the evaluation of the AIS level of traumas sustained during a vehicle impact.
Preface

Thesis introduction

Many crash tests are conducted worldwide each year by different companies, with the aim to analyse the safety provided by vehicles to the occupants. These tests are standardised, and they are able to control as many variables as possible. However, it is not possible to recreate accurately the conditions of a real-life vehicle collision since they can be influenced by a great number of variables and scenarios. Such variability causes significant difficulty in recreating collisions, and thus in predicting the injuries suffered.

The purposes of this thesis work, done in collaboration with the Coventry University, are the following:

- Analyse the possibilities offered by using Human Body Models (HBMs) together with the software that takes advantage of the Finite Element Method (FEM) for the forecast and evaluation of soft tissues injuries that can happen to abdominal organs during car crashes, with the purpose of improving some vehicle elements to decrease the severity of injuries.

- Examine the abdominal injury patterns in frontal, near side and far side crashes from different international databases, to understand which abdominal organs are the most involved during car crashes, together with the expected type of injuries.

- Investigate on a new injury criterion developed at Coventry University by Professor C. Sturgess and Professor C. Bastien, the “Peak Virtual Power” method (PVP), that is able to determine for a particular car crash recreated in a virtual environment, the extent of the injuries suffered by the occupants.

The Finite Element Human Body Model used in this work to represent the vehicle occupant is the Total HUman Model for Safety (THUMS) 4.1 Academic Version, developed by Toyota Motor Corporation (Toyota Central R&D Labs. Inc.) and available at Politecnico di Torino.

For this thesis work, a real-life accident report taken from the NHTSA database has been analysed in order to be reconstructed digitally using the software LS-DYNA, validating the simulated impact with the photographic evidence from the NHTSA report.
The model was provided by Professor C. Bastien from Coventry University, with the aim of improving some details and working on a different motion method for the sled model. Once the simulation is validated, the PVP method is applied to evaluate the type of injuries suffered by the THUMS occupant to the abdominal organs, namely the liver and the spleen. The relationship between PVP, velocity and the Abbreviated Injury Scale (AIS) will then be analysed by comparing the results of the simulation with those reported on the medical reports of the accident, with any underlying causes of error being identified.

The first Chapter of the thesis will provide a brief overview on the current State of the Art of Human Body Models, describing their developments and improvements throughout the years.

In Chapter 2 the abdomen injury biomechanics will be investigated, starting from the definition of the Abbreviated Injury Scale. A concise anatomical description of the most important abdominal organs will be presented, focusing in particular on their position in the abdomen and their link with other elements. Finally, the soft tissues injury mechanics will be shortly described.

In Chapter 3 a brief overview of the mostly used injury criterions will be given, focusing in particular on the Compression Criterion, the Viscous Criterion and the Abdominal Injury Criterion, highlighting their main advantages and disadvantages.

In Chapter 4, an analysis of the abdominal injury patterns in frontal, near side and far side crashes has been conducted, taking the data from 3 different international databases (NASS, CIREN and LAB) and focusing on the influence of some vehicle elements on the occupants, like dashboard intrusion, restrain system and crash conditions.

In Chapter 5, the Peak Virtual Power method will be illustrated, focusing on its theory, the physical parameters influencing it and its relationship with the AIS injury levels.

In Chapter 6, the real-life accident to be recreated digitally will be analysed, describing its kinematics and the injuries suffered by the occupant taken as reference (the rear seat occupant). Moreover, a brief description of the simulation methodology will be presented, comparing the photographic evidence from the reports with the crush profile of the simulated model, together with the energy level validation of the simulation.

The application of the PVP method and its results are finally presented and examined in Chapter 7, where the PVP corridors (AIS curves) are shown together with the peak value of virtual power experienced by the liver and the spleen. A brief description of the methodology used to obtain the PVP corridors is also presented in this chapter.
1. Human Body Models HBM’s

Car crashes are one of the main responsible for human casualties in the entire world and due to this reason, since 1990s scholars have begun to explore different methods to forecast the possible injuries in case of accident. These studies made possible to evaluate technical solutions to be applied inside and outside the vehicles, able to prevent the observed injuries. Naturally, the more accurate these forecasts are, the more effective the technical solutions will be.

Over the last century, many different methods have been used, like volunteers or cadaver tests, however the most used are the crash dummies: anthropomorphic test devices used to evaluate crash safety measures for vehicles [1]. Unfortunately, their response to crashes and injuries is not the same with respect to the real human body. For these reasons, human modelling approach using the Finite Element (FE) method was introduced and it is now widely used in different disciplines.

The “Human Body Models - HBMs” are a bio-fidelic reproduction of the human body designed to be used in a finite element environment [1]. These models aim at simulating human body kinematics, behaviour and injury responses in different situations and in this thesis work they will be adopted for car crashes analysis. In the automotive field, even if Human Body Models are still not employed in homologation tests, the number of carmakers including them in their studies is nowadays increasing.

The main advantage of HBM with respect to crash dummies is the opportunity to make more accurate analysis of the consequences of the impact in different parts of the body. Crash dummies are based on sensors that evaluate accelerations, displacements and stress in particular areas of the body, while HBMs open the possibility of recreating parts and organs of the body including

Figure 1 THUMS occupant models for different percentiles [2]
materials and interactions with other body parts together with the possibility of evaluating many different parameters in each single element that form the organ itself.

From 1990s, many companies have been developing different types of HBMs, improving them with newer versions throughout the years. The one that we are using in this thesis work is the “Total HUman Model for Safety”, developed by Toyota Motor Corporation and Toyota Central R&D Labs., Inc [2]. In this model, the geometries of the human body parts are characterized by FE meshes and their material properties are defined by constitutive laws. The THUMS is based on an average size adult male (AM50%ile) model which has a height of 175 cm and a weight of 77 kg. Different versions were made of the THUMS, but the one used in this project is the 4.1.

![Figure 2 Soft Tissue Parts in Torso Model](image)
2. Abdomen injury biomechanics

The focus of the thesis work will be on the injuries suffered by the abdominal organs, in particular the liver and the spleen. Therefore, this chapter will develop an introduction on the biomechanics related to the abdomen organs, starting from an overview of the injury scales followed by a brief anatomical description of the organs in study and soft tissues injury mechanics. Usually in car crashes, the first evaluations on organ injuries are made on heart and lungs since traumas related to them are the most dangerous ones. However, organs like spleen and liver should not be underestimated since injuries associated to them can lead to a serious life threat even if not immediately after the crash.

2.1 Abbreviated Injury Scale (AIS)

The Abbreviated Injury Scale is an internationally accepted tool used for ranking injury severity, able to provide objective and repeatable evaluations for the traumatic consequences of vehicle occupants in case of impact, developed by the “Association for the Advancement of Automotive Medicine” (AAAM) and yearly updated [3].

According to the definition provided by the AAAM website: ‘AIS is an anatomically based, consensus derived, global severity scoring system that classifies an individual injury by body region according to its relative severity on a 6-point scale (1=minor and 6=maximal)” [4]. It basically identifies an injury using a numeric code that goes from 1 to 6 (Figure 3); level 1 is related to just a feeling of pain while level 6 indicates a mortal injury; level 5 indicates an injury that has 50%
probability of being fatal, while the other levels correspond to a progressive intermediate level of injury. Figure 3 puts in evidence how the AIS code is composed: it provides an intuitive description of which organ is affected and the type and severity of injury [3].

<table>
<thead>
<tr>
<th>AIS code</th>
<th>Injury severity</th>
<th>AIS% prob. of death</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Minor</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>Moderate</td>
<td>1–2</td>
</tr>
<tr>
<td>3</td>
<td>Serious</td>
<td>8–10</td>
</tr>
<tr>
<td>4</td>
<td>Severe</td>
<td>5–50</td>
</tr>
<tr>
<td>5</td>
<td>Critical</td>
<td>5–50</td>
</tr>
<tr>
<td>≥6</td>
<td>Unsurvivable</td>
<td>100</td>
</tr>
</tbody>
</table>

*Figure 4 AIS levels related to injury severity [3]*

2.1.1 Injury Severity Score ISS

AIS is the basis for the Injury Severity Score (ISS) calculation for a patient that suffered from multiple traumas. It is a global severity index used when multiple injuries are present. It is based on the evaluation of single injuries with the AIS scale and then defined as the sum of squares for the highest AIS scoring in the most affected three body region. Conventionally the value of the sum equal to 75 corresponds to a fatal injury [3]:

\[
ISS = AIS_1^2 + AIS_2^2 + AIS_3^2
\]
2.2 Abdominal organs overview and behaviour during crashes

The main difference among the abdominal organs is related to their structure, in particular if they are hollow or solid. As a matter of fact, liver, spleen and kidneys are the three solid organs that suffer from higher AIS level injuries during a car crash with respect to hollow organs like stomach and intestine, that are able to dissipate the impact energy in a better way. In this section a short anatomic description will be made followed by a brief description of their kinematics during car crashes.

2.2.1 Liver

The human liver is placed in the upper right portion of the abdomen, with a portion of it situated on the left side of the body (Figure 5). Both the diaphragm’s movement during breathing as well as the body’s posture will affect the liver’s exact location. The falciform ligament connects the anterior part of the liver to the anterior abdominal wall and the diaphragm. There are also ligaments connecting the superior borders of the liver to the diaphragm and ligaments running from the posterior fissure to the stomach. The falciform ligaments as well as the posterior fissures separate the liver into left and right lobes, with the right lobe being the larger of the two. The entire surface of the liver is encapsulated by peritoneum [5] [6].

![Anterior view of liver](image)

According to different databases related to car crashes, the liver is the most involved organ among the abdominal ones, usually suffering from AIS injuries of level 3-5, as it is possible to see in Figure 6, that represents the distribution of abdominal organs injuries in car crashes from 1977 to 2004 analysed in the NASS (National Automotive Sampling System) database [5]:

![Figure 6 Distribution of abdominal organs injuries](image)
From 1985, different experiments related to frontal crashes were made on human corpses and anesthetized pigs, leading almost always to AIS injuries of levels 3-5, together with ribs fractures. Lacerations were the most common injury type for the liver, mostly attributed to contact with components in the front of the occupant compartment, such as the steering assembly.

It is also interesting, due to the specific attachment system of the liver, to analyse its kinematic behaviour during a frontal crash (P. J. Arnoux, T. Serre , N. Cheynel , L. Thollon , M. Behr , P. Baque , C. Brunet), described by Figure 7 [7]:

1. in the first part of the accident, the liver is decelerating and shows a postero-anterior global displacement up to the contact with the ribcage.

2. Then, induced by the inertia of the liver and flection of the ribcage, an anterior posterior compression of the liver can be appreciated. This leads to a transverse strain effect and a sagittal rotation of the organ itself.

3. The rotation observed in the transverse plane is induced and limited by ribs curvature in the frontal part and by the vertebral column in the posterior part.

4. Finally, in the case of sub injury impact tests, a global relaxation in which the structure moves back to its initial position was observed.
2.2.2 Spleen

The spleen is positioned in the upper left portion of the abdomen, between the 9th and 11th ribs (Figure 8), behind the stomach, inferior to the diaphragm and superior to the left kidney. Its shape can be described as an irregular tetrahedron with an average weight of 150 g, but it becomes smaller in old age. It is enclosed in a fibro-elastic capsule, surrounded by peritoneum [5] [6].

Figure 7 illustration of the phases of the liver kinematics during the frontal deceleration in the transverse plan [7]

Figure 8 Location of abdominal organs relative to the spleen and the vertebral column [5]
As it is possible to see from Figure 6, the spleen is the second most involved abdominal organ during car crashes.

Not many researches have focused their attention on the spleen injuries during car crashes. One of the latest is from 2002: Professor Tamura studied the compressive properties of the spleen tissue, performing stress-relaxation compression tests to develop a quasilinear viscoelastic model [8]. Usually spleen injuries are caused by the impact with the left side of the occupant compartment [5].

### 2.2.3 Kidneys

The Kidneys are placed on the posterior wall of the abdomen, behind the parietal peritoneum of the abdominal cavity, lateral to the vertebral column, with the left kidney slightly higher than the right one. The kidneys are bean-shaped, with an average weight of 140g, and they are covered by a renal capsule [5] [6].

![Figure 9 Posterior view of the right kidney (left) and kidney cross section (right) [5]](image)

Due to their back position, kidneys are less involved in high AIS levels injuries with respect to liver and spleen. However, many studies have been made, focusing on their resistance to compression [8] [9].

### 2.2.4 Stomach and intestine

The digestive organs are usually less affected by severe injuries (AIS3+), as it is possible to see from Figure 6: in the NASS database, considering the time lapse between 1993 and 2000, they represent only the 11% of AIS3+ injuries [5]. However, taking into account not severe injuries (AIS 1-2), the digestive tract shows a higher percentage, with injuries mostly related to the seatbelt’s movement.
2.3 Soft tissue injury

In order to improve occupant protection systems, it is important to understand the mechanism of soft tissue injury. Over the years of research, it has become clear that soft tissue injury is induced by excessive deformation, that is rate sensitive. This is the reason why we cannot use criterions addressed to rigid structure like bones on thoracic and abdominal organs, since the rate sensitivity must be considered. This means to introduce impact velocity in relation with the compression.

The rate sensitive tolerance to compression of soft tissue injury was clearly demonstrated by a series of experiments made on rabbits by Lau and Viano [11], where the target soft-tissue organ in that study was the liver. It was found that when impact velocity varied from 5 to 20 m/s in frontal impacts, hepatic injury could range from minor to multiple lacerations at a constant maximum compression, \( C_{\text{max}} = 16\% \) of the abdomen. No visible injury occurred below a constant impact velocity of 8 m/s for 16% abdominal compression (Fig 10).

![Figure 10 Hepatic injury severity as a function of impact velocity and compression](image)
3. Main injury criterions

3.1 Compression Criterion

In 1972 Professor Kroell analysed a large data base of blunt thoracic impact experiments using cadavers and found that maximum chest compression was a superior indicator of chest injury severity [12].

Kroell’s research showed that human volunteers showed no injury with 20% of chest compression in quasistatic loading [12]. Higher compression values were tested on human cadavers: with a guided impact mass at impact velocity between 5 - 7 m/s, a compression above 20% was obtained and rib fractures occurred regularly consequently. Maximum compression of 40% induced multiple rib fractures and severe injuries to internal organs, indicative of flail chest.

Consequently, a tolerance level of 40% was defined for severe chest injury using the maximum compression as the Compression Criterion. This tolerance level was then extrapolated in the anthropomorphic dummy to be a maximum allowable deflection of 75 mm of the Hybrid III chest cavity [12].

Figure 11 Correlation between injury severity and compression [12]
3.2 Viscous Criterion

The viscous criterion was introduced at the end of the 1980s by Ian V. Lau and David C. Viano [13], two experts working at General Motors, and nowadays is still the most used injury criterion for soft tissues injuries analysis in crash tests, since it adapts very well to the data obtainable from the dummies. It refers to injuries of soft tissues of the thorax and abdomen, caused not only by high deformation values of these body parts, but also by high impact speed with very low deformation (blast injuries). This criterion considers that the human body, mostly characterised by viscoelastic materials, reacts on equal penetration, with higher loads increasing the speed of penetration. This implies an increased effect on the human body for the same intrusion, and therefore more severe injuries.

As it is possible to see from the left plot of Figure 12, the kind of injuries on which to focus on are the viscous ones, highlighted in yellow, for velocities of deformation between 3 to 30 m/s. When velocity of deformation is below 3 m/s the Compression Criterion becomes the best indicator of soft tissue injury. At those slow velocities, injury is essentially induced by crushing of the tissue. Above 30 m/s there will be blast injury at first to hollow organs [13].
In order to better understand this injury criterion, it is important to include some definitions related to thorax traumas [13]:

- **Viscous Criterion** = any generic biomechanical index of injury, potential for soft tissue, defined by rate sensitive torso compression.
- **Viscous response** = a time function formed by the product of the velocity of deformation V(t) and the instantaneous compression, C(t).
- **Viscous tolerance** = risk of injury associated with impact-induced Viscous VC. The maximum risk is related to the peak Viscous [VC]max.
- \( V(t) = \frac{d[D(t)]}{dt} \), the velocity of deformation. D(t) is the instantaneous deformation along the direction of the applied impact to the torso.
- \( C(t) = \frac{D(t)}{\text{Initial Torso Thickness}} \).

![Figure 13: The Viscous Criterion defined by the instantaneous deformation [13]](image)

Considering the thoracic model from Figure 12, the viscous criterion can be well understood from the plot in Figure 13: the instantaneous compression C(t) is evaluated from measurements made on the dummy through the Equation 1, and also from the deformation it is possible to obtain the velocity of deformation V(t):

\[
V(t) = \frac{d[D(t)]}{dt} \quad C(t) = \frac{D(t)}{D}
\]

*Equation 1 velocity of deformation and Compression rate [13]*
The viscous response is finally obtained by the product of these two values obtained, and from its plot the peak value is extrapolated and compared against a predetermined level of tolerance for the particular body region.

An example of application of the viscous criterion on abdominal organs is shown in Figure 14:

![Figure 14 of the probability of severe liver laceration (AIS 5) by the peak abdominal Viscous response, [VC]_{max}[13]](image)

The abdominal tolerance corresponds to [VC]_{max} = 1.2 m/s. (severe laceration of the liver or spleen AIS 5) [13]. Also Steering wheel induced, abdominal impact with a peak Viscous response of 1.4 m/s has a 50-50 chance of causing severe laceration of the liver [14].

### 3.3 Abdominal Injury Criterion

The abdominal injury criterion is a simpler form of the Viscous Criterion where the rate sensitivity is not considered. As a matter of fact, it is evaluated by multiplying the maximum penetration speed by the maximum abdominal compression measured. This criterion is considered a good substitute of the viscous one whenever this one cannot be properly measured [3].
4. Abdominal injury patterns in frontal, near side and far side crashes

In this paragraph, an analysis of the relevant literature on abdomen injuries in motor-vehicle accidents is presented, together with the tolerance and response of the abdomen in frontal and side impacts, in order to have an overview on the kind of injuries suffered by these organs in different crashes. Two databases were analyzed to determine the frequencies and patterns of abdomen injuries, as well as the crash and restraint factors associated with abdomen traumas inside of airbag-equipped vehicles:

- **NASS database (National Automotive Sampling System)**: case years are restricted from 1998 to 2004 and crashes were limited to front and side impacts. Occupants were limited to drivers and right-front passengers aged 16 or greater with vehicle model years limited to 1985 or later [5].

- **CIREN database (Crash Injury Research)**: data analysed are from year 2005, and all occupants with an AIS 2+ abdomen injury were included. Even if the emphasis in CIREN is on later-model vehicle years, there are few occupants who sustained abdomen injuries in crashes on older vehicles [5].

Finally, an overview is presented over the influence of vehicles’ elements on injuries suffered by the abdominal organs, like the type of restraint system, the occupant seat, the age and the crash severity influence. The data are taken from a French database containing information on cars accidents from 1970 to 2005: the Accidentology, Biomechanics and Human Behaviour (LAB) database developed by Renault and PSA Peugeot Citroën for approximately 40 years [15].
4.1 NASS Database

In this database, the risk of injury for different body regions was assessed for frontal, near-side, and far-side crashes evaluating injury levels for AIS 2+, AIS 3+, and AIS 4+ [5].

- For AIS 2+ injuries, in all three categories of impact, abdomen injury ranks 5\textsuperscript{th} in risk of injury behind head, thorax, lower extremity, and upper extremity.
- For AIS 3+ injuries, abdomen ranks 4\textsuperscript{th} in risk for near-side crashes, and 5\textsuperscript{th} for frontal and far side impacts.
- For AIS 4+ injuries, as shown in Figure 15, abdomen ranks 3\textsuperscript{rd} in risk behind head and thorax for frontal and side impacts. Even if abdominal organs injuries are behind more relevant organs like lungs, heart and brain, from this plot it is evident that this kind of abdominal injuries must not be underestimated, since they can lead, with the pass of the time, to severe risks for the health of the occupants. Moreover, it can be assessed that the side impacts are more relevant for what concerns injuries to organs like liver and spleen, and this is in accordance with the lateral positioning of these two types of organs.
Figure 16 shows the risk of AIS 2+ injury for the liver, spleen, kidney, and hollow organs for drivers and passengers in frontal, near-side and far-side impacts, including also the risk of two or more rib fractures.

As it is possible to see from the plot, in frontal crashes, the liver is the most frequently injured organ for drivers, while spleen injuries are more relevant for right-front passengers. This may be due to the orientation of the shoulder belt relative to the locations of the liver and spleen for drivers and right-front passengers. Hollow organs are the next most frequently injured abdominal organs in frontal crashes for both drivers and right-front passengers, while kidney ranks last [5].

In near-side impacts, the liver is the most frequently injured abdominal organ for right-front passengers, while spleen injuries are more relevant for drivers, clear consequence of the anatomical position of these two organs [5].

In far-side impacts, drivers have the highest risk of kidney injury, followed by liver, spleen, and hollow organs. For right-front passengers in far-side impacts, the abdominal organs injured in order by injury risk are liver, kidney, spleen, and hollow organs [5].

Moreover, it is interesting to analyse the risk of injury to abdominal organs related to the crash severity measured in miles per hour (mph), as it is possible to see from Figure 17: In all types of crashes, injury risk for all abdomen organs increases with crash severity.
4.1.1 Factors affecting abdominal injury risk: restrain system

The effect of restraint on the risk of abdomen injury is shown in Figure 18 for both frontal (left plot) and near/far-side impacts (right plot) [5]. From the left plot it is evident that in frontal impacts, using a three-point belt, the rate of both AIS 2+ and AIS 3+ abdomen injuries is reduced, taking also into account the airbag deployment, while from the left plot it is possible to assess that abdomen injury risk for unbelted occupants is 3 to 8 times higher than the one of belted occupants. The risk of abdomen injury is essentially the same with and without airbag deployment, indicating that airbags do not appear to be a significant factor in reducing the risk of abdomen injury in frontal impacts [5].
4.1.2 Factors affecting abdominal injury risk: rib fracture

The previous analyses made clear the incidence of rib fracture on abdominal organ injury. Each occupant with an AIS 2+ injury was evaluated whether they sustained a liver, spleen, or kidney injury, together with 2 or more ribs fractured (i.e., an AIS 2+ rib fracture) or zero or one rib fractures [5]. The percentage of injured occupants with AIS 2+ and without AIS 2+ rib fractures are shown in Figure 19 according to abdominal organ injured and crash type.

![Percentage of injured occupants with and without AIS 2+ rib fractures by crash type and abdomen organ injured](image)

As it is evident from the plot, for all crash directions and for each abdomen organ, the percentage of injured occupants without rib fracture and abdomen injury was very small relative to the percentage of occupants with rib fracture and abdomen injury. Since the presence or absence of rib fracture seems to be related to crash severity, belt loading and crash type, an analysis was performed to estimate the risk of abdomen injury with and without rib fracture versus crash severity including belt use and occupant position.

In frontal impacts, the probability that a belted driver sustains a liver injury is 16 times higher with AIS 2+ rib fractures than without; for the spleen, injury probability is 30 times higher, and for the kidney 12 times higher, highlighting the close relation between rib fracture and abdominal organ injury.
4.2 CIREN Database

In the CIREN database, most occupants sustained from 3 to 9 coded injuries, although there are some occupants with over 20 coded injuries [5]. Figure 20 shows the percentage of occupants with injuries to different abdominal organs, where it is evident that half of occupants sustained injuries to the liver and/or spleen, 15% sustained kidney injuries, and approximately one-third sustained injuries to the remaining abdominal organs.

The 526 occupants in the dataset sustained a total of 1,663 AIS 2+ abdominal injuries [5]. Figures 21 and 22 describe the types of injuries sustained by drivers and right-front passengers according to the impact type. There were 245 drivers involved in frontal impacts, and 63% of them sustained only one abdominal injury. Moreover, there were 50 right-front passengers involved in frontal impacts that sustained abdominal injury, and 34 of them (68%) sustained only one abdominal injury.
injury. It is evident that the CIREN database shows very similar results with respect to the NASS database for what concerns abdominal organs injured in frontal crashes: liver and spleen are still the most injured, followed by kidneys and hollow organs (stomach and intestine).

The CIREN database also gives an overview about the other 2 types of accidents, left-side and right-side impacts, as it is possible to see from Figure 22:

As it is evident from the plots, the anatomical position of the organs is the main reason behind the injuries sustained, depending on the type of accident [5]: the spleen is positioned in the left side of the abdomen, consequently a left side impact will involve major injuries to the left side of the abdomen of the driver, and so to the spleen; vice versa for the liver that is positioned in the right side of the abdomen: right side impacts will affect more the liver of right-front passengers.
4.3 Influence of crash conditions (LAB database)

Data on the injuries of the abdominal organs related to the type of restraint system, the occupant seat, and the crash severity are presented in this paragraph, retrieved from the French database “Accidentology, Biomechanics and Human Behaviour (LAB)”, developed by Renault and PSA Peugeot Citroën [15]. For the investigation, the Energy Equivalent Speed (EES) is used: it is a virtual speed for which the kinetic energy characterizing the vehicle at that given speed is equivalent to the entire energy dissipated by the vehicle through the real deformations analyzed ad posteriori.

First, the distribution of the occupants involved and injured with the relative injury risks is presented in Table 1 against the severity of the crash, represented by the EES:

<table>
<thead>
<tr>
<th>EES</th>
<th>AIS 3+</th>
<th></th>
<th>Hollow organs</th>
<th>solid organs</th>
</tr>
</thead>
<tbody>
<tr>
<td>40-49 km/h</td>
<td>Injured (n)</td>
<td>71</td>
<td>31 (39%)</td>
<td>48 (61%)</td>
</tr>
<tr>
<td></td>
<td>Involved (n)</td>
<td>2586</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Injury risk (%)</td>
<td>2.75</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50-59 km/h</td>
<td>Injured (n)</td>
<td>131</td>
<td>96 (52%)</td>
<td>87 (48%)</td>
</tr>
<tr>
<td></td>
<td>Involved (n)</td>
<td>1922</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Injury risk (%)</td>
<td>6.82</td>
<td></td>
<td></td>
</tr>
<tr>
<td>60-69 km/h</td>
<td>Injured (n)</td>
<td>121</td>
<td>67 (42%)</td>
<td>94 (58%)</td>
</tr>
<tr>
<td></td>
<td>Involved (n)</td>
<td>992</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Injury risk (%)</td>
<td>12.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>70-79 km/h</td>
<td>Injured (n)</td>
<td>49</td>
<td>37 (50%)</td>
<td>37 (50%)</td>
</tr>
<tr>
<td></td>
<td>Involved (n)</td>
<td>199</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Injury risk (%)</td>
<td>24.62</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>Injured (n)</td>
<td>372</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Involved (n)</td>
<td>5699</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1 Influence of the crash severity on AIS 3+ abdominal injury risk and types of organs involved [15]

As it is possible to see from the table 1, the EES, i.e., the severity of the crash, significantly influences AIS3+ abdominal injury risk, while no significant difference in the injury frequencies was observed between the type of organ injured and the different EES classes.
4.4 Dashboard intrusion

The distribution of the occupants involved, the distribution of the occupants injured and the injury risks are presented in Table 2 as function of the dashboard intrusion [15]:

<table>
<thead>
<tr>
<th>Dashboard Intrusion</th>
<th>AIS 3+</th>
<th>Hollow organs</th>
<th>solid organs</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤24 cm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Injured (n)</td>
<td>202</td>
<td>155 (55%)</td>
<td>127 (45%)</td>
</tr>
<tr>
<td>Involved (n)</td>
<td>4022</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Injury risk (%)</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>25-44 cm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Injured (n)</td>
<td>63</td>
<td>26 (30%)</td>
<td>60 (70%)</td>
</tr>
<tr>
<td>Involved (n)</td>
<td>445</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Injury risk (%)</td>
<td>14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>45 cm +</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Injured (n)</td>
<td>47</td>
<td>14 (22%)</td>
<td>49 (78%)</td>
</tr>
<tr>
<td>Involved (n)</td>
<td>160</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Injury risk (%)</td>
<td>29</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Injured (n)</td>
<td>312</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Involved (n)</td>
<td>4627</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2 Influence of the dashboard intrusion on AIS 3+ abdominal injury risk and type of organ involved [15]

According to the data, higher is the intrusion of the dashboard and higher is the AIS level of the injury sustained by the abdominal organs, due to the contact with dashboard components. However, a significant difference was observed between hollow and solid organ injury frequencies as function of the dashboard intrusion: For low levels of intrusion, hollow organs were more frequently injured than solid ones, while for intrusion levels greater than 25 cm, injuries to the solid organs were predominant.

Moreover, the dashboard intrusion increases monotonically with the crash severity, thus, EES and the dashboard intrusion are strongly correlated, as it is possible to see from Figure 23:
4.5 Restrain system

In the dataset, different type of restrain system were considered [15]:

- SB = 3-point static belt
- RB = 3-point retractor belts
- RB+P = 3-point retractor belt with pretensioner
- RB+P+AB = 3-point retractor belt with pretensioner and frontal airbag

For each restraint system, the number of occupants involved, the number of occupants injured and the risk of injury are given in Table 3 [15]:

<table>
<thead>
<tr>
<th>EES</th>
<th>AIS 3+</th>
<th>Unbelted</th>
<th>SB</th>
<th>RB</th>
<th>RB+P</th>
<th>RB+P+AB</th>
</tr>
</thead>
<tbody>
<tr>
<td>40-49 km/h</td>
<td></td>
<td></td>
<td>33</td>
<td>15</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Injured (n)</td>
<td>33</td>
<td>3</td>
<td>15</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Involved (n)</td>
<td>781</td>
<td>166</td>
<td>800</td>
<td>148</td>
<td>206</td>
</tr>
<tr>
<td></td>
<td>Injury risk (%)</td>
<td>4.23</td>
<td>1.81</td>
<td>1.88</td>
<td>1.35</td>
<td>0.49</td>
</tr>
<tr>
<td>50-59 km/h</td>
<td></td>
<td></td>
<td>31</td>
<td>15</td>
<td>49</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Injured (n)</td>
<td>434</td>
<td>99</td>
<td>634</td>
<td>172</td>
<td>226</td>
</tr>
<tr>
<td></td>
<td>Involved (n)</td>
<td>7.14</td>
<td>15.15</td>
<td>7.73</td>
<td>3.49</td>
<td>4.42</td>
</tr>
<tr>
<td>60-69 km/h</td>
<td></td>
<td></td>
<td>32</td>
<td>7</td>
<td>30</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>Injured (n)</td>
<td>152</td>
<td>34</td>
<td>329</td>
<td>98</td>
<td>193</td>
</tr>
<tr>
<td></td>
<td>Involved (n)</td>
<td>7.14</td>
<td>20.59</td>
<td>7.12</td>
<td>15.31</td>
<td>11.92</td>
</tr>
<tr>
<td>70-79 km/h</td>
<td></td>
<td></td>
<td>11</td>
<td>2</td>
<td>11</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Injured (n)</td>
<td>23</td>
<td>4</td>
<td>69</td>
<td>13</td>
<td>46</td>
</tr>
<tr>
<td></td>
<td>Involved (n)</td>
<td>47.83</td>
<td>50</td>
<td>15.94</td>
<td>7.69</td>
<td>32.61</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>107</td>
<td>27</td>
<td>105</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>Injured (n)</td>
<td>1390</td>
<td>303</td>
<td>1832</td>
<td>431</td>
<td>671</td>
</tr>
</tbody>
</table>

Table 3 Abdominal injury risk for front seat occupants for different restraint systems as a function of EES [15]

The results show that the use of belts together with retractors (last three columns of table 4) corresponds to an abdominal injury risk reduced by a factor of 1.6 relative to static belts. The risk decreased from 16% for static belts alone to 7% for any type of restraint using retractors, while no significant difference of AIS 3+ abdominal injury risk was observed between the different combinations of safety devices using belt retractors [15].
The hollow organs and solid organs injury frequencies are reported in Table 4 as a function of the type of restraint systems:

<table>
<thead>
<tr>
<th></th>
<th>%hollow</th>
<th>%solid</th>
<th>%hollow</th>
<th>%solid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unbelted</td>
<td>23%</td>
<td>77%</td>
<td>23%</td>
<td>77%</td>
</tr>
<tr>
<td>SB</td>
<td>63%</td>
<td>38%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RB</td>
<td>55%</td>
<td>45%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RB+P</td>
<td>50%</td>
<td>50%</td>
<td>58%</td>
<td>42%</td>
</tr>
<tr>
<td>RB+P+AB</td>
<td>62%</td>
<td>38%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4  Hollow and solid organ injury frequencies as a function of the type of restraint system [15]

The results show a significant difference between belted and unbelted occupant hollow organ injury frequencies, as well as for solid organs between belted and unbelted occupant. However, among belted occupants no significant difference was observed between hollow and solid organ injury frequencies [15]. Particular attention must be paid for unbelted occupants: solid organs were more frequently injured while for belted occupants, injuries to hollow organs were predominant.

Although the results showed an increase of the AIS 3+ abdominal injury risk with the use of a static belt compared to non-restraint occupants, it must be emphasized that the fatality rate was proved to be significantly reduced using static seat belts [15].
4.6 Summary of abdominal injury patterns

From the data analysed from the different database, it is possible to highlight the following findings [15]:

- The abdominal injury risk increases with crash severity, and the most vulnerable unbelted occupants are drivers where solid organ injuries are predominant regardless of dashboard intrusion and occupant seating position.

- For belted occupants, hollow organs are more frequently injured for drivers and right front passengers. However, solid organs injuries are predominant when the dashboard intrusion is greater than 25 cm.

- For belted drivers and front seat non drivers, no significant difference was noted on the injury pattern while the introduction of retractor belts significantly decreases the AIS 3+ abdominal injury risk for front seat occupants.

It must be noted that for belted passengers, the lack of intrusion can result in injuries primarily located where the body is in contact with the seatbelt (including the abdomen) while for unbelted occupants the injuries are likely to occur in any body area hitting the interior of the vehicle during the crash (head, thorax and knees first) [15].
5 Peak Virtual Power method (PVP)

Injury’s criterions like Compression or Viscous Criterion were conceived to be applied to crash dummies, full-scale Anthropomorphic Test Devices (ATD) instrumented to record data such as velocity of impact, forces, moments and decelerations suffered during a collision [1]. However, the introduction of Human Body Models made these criterions obsolete, since they are not able to take full advantage of the possibilities offered by HBMs. Biomechanical injuries result in the straining or separation of biological tissues, and that is why strain is often analysed in organ injury studies. However, strain-based indicators do not consider time effects (duration) and cannot predict trauma location.

This is why a new Organ Trauma Model (OTM) has been introduced in 2001 by Doctor Neal-Sturgess: the Peak Virtual Power method (PVP), able to calculate the risk to life based on the severity of any organ injury [16] [17] [18].

The PVP is an energy-based engineering indicator, proposed as an injury criterion, derived from the rate dependent form of the 2nd law of thermodynamics using the Clausius-Duhem inequality, considering that the irreversible work transferred to a human body during an impact is equivalent to the injury suffered [16]. It is linearly proportional to the AIS levels of injury and applies to all body regions and severity of injury. Consequently, the Viscous Criterion itself can be considered as an alternative form of virtual power.

Unfortunately, a disadvantage of the PVP analysis for injury prediction is that it is not able to predict haemorrhaging of organs after the impact [18]: this would be detected by injury reports and may affect the result of any comparison between simulated injuries and those observed, since internal haemorrhages can change drastically the AIS level of a particular trauma.

On organ/tissue level, PVP is proportional to the AIS injury level, and can be extracted using the formula from the Equation 2:

\[ PVP \propto AIS \propto \max(\sigma \cdot \varepsilon) \]  

*Equation 2 Peak Virtual Power (PVP) formulation [18]
PVP is calculated using Von Mises vector resultant, by multiplying the stress $\sigma$ by the strain rate $\dot{\varepsilon}$, keeping the maximum value while the impact event is taking place, as illustrated in Figure 24:

![Figure 24 Illustration of the PVP Concept [18]](image)

These physical dimensions are easily obtainable through a software that takes advantage of the Finite Element Method, which also allows to examine each single element of every organ to easily locate the injury. It is evident from the previous figure, that the Trauma related to the maximum value of the PVP remains present during the impact and does not reduce when the load is removed [18].

### 5.1 Physical parameters influencing the PVP

During an accident, the kinetic energy of the organ is converted into strain energy, which is highlighted in Equation 3 [17]:

\[
\text{Organ kinetic energy} = \text{Organ strain energy}
\]

\[\text{Equation 3 Conversion of Energy from Kinetic into strain during the impact [17]}\]

Converting these two energies in well-known mathematical formulas, formulating the mass with density $\rho$ and volume, it is possible to link stress and velocity of the element analysed, and considering the strain rate $\dot{\varepsilon}$ (velocity over length), PVP can be written as in Equation 4 [17]:

\[
PVP = \frac{1}{L} \sqrt{\rho \frac{E}{v^2}}
\]

\[\text{Equation 4 Final Derivation of PVP as a function of geometry and material properties [17]}\]
It is evident from this formula that PVP depends on the organ material property (E and \( \rho \)), together with its size and shape, described by the L parameter. Consequently, PVP is direction dependant, meaning that the injury sustained will depend on the impact direction [18].

The PVP theory also considers the fact that the occupant wears a seatbelt, suggesting that their respective trauma injury is a function of a cubic of the impact velocity for belted and a square for unbelted occupants, as it is assessed in Equation 5 [17]:

\[
PVP \propto AIS \propto V^2 \text{ [unbelted occupants]} \quad PVP \propto AIS \propto V^3 \text{ [belted occupants]}
\]

*Equation 5 Relationship between PVP and velocity for unbelted occupants and belted occupants [17]*

### 5.2 PVP and AIS injury levels

In order to relate the peak virtual power experienced by an organ to the relative AIS injury, it is important to build the PVP corridors, a plot with the PVP on Y axis and impact velocity on X axis with the curves representing the AIS levels from 1 to 5. To do so, the model under analysis is simulated with different impact velocities, and for each simulation, the virtual power is extracted from the first element of the organ reaching the value of strain equivalent to the AIS 4 level of injury, that varies according to the type of organs displayed in table 5 [16]:

<table>
<thead>
<tr>
<th>Tissue/Organ</th>
<th>Currently-used injury measurement</th>
<th>Injury description</th>
<th>AIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brain grey matter</td>
<td>Maximum 30% principal strain</td>
<td>Brain contusion</td>
<td>3-4</td>
</tr>
<tr>
<td>Brain white matter</td>
<td>21% maximum principal strain</td>
<td>Diffuse Axonal Injury (DAI)</td>
<td>4</td>
</tr>
<tr>
<td>Heart</td>
<td>30% maximum principal strain</td>
<td>Rupture</td>
<td>4</td>
</tr>
<tr>
<td>Liver</td>
<td>30% maximum principal strain</td>
<td>Rupture</td>
<td>4</td>
</tr>
<tr>
<td>Spleen</td>
<td>30% maximum principal strain</td>
<td>Rupture</td>
<td>4</td>
</tr>
<tr>
<td>Kidneys</td>
<td>30% maximum principal strain</td>
<td>Rupture</td>
<td>4</td>
</tr>
<tr>
<td>Skull</td>
<td>Maximum 3% plastic strain</td>
<td>Fracture</td>
<td>2-3</td>
</tr>
</tbody>
</table>

*Table 5 currently used injury criterion on brain and organs and corresponding AIS level [18]*

Once the element is identified, the value of stress corresponding to that particular time frame is extracted and multiplied by the strain rate, obtaining the virtual power corresponding to AIS 4 injury for that impact velocities [18]. This couple of data is represented by a point in the PVP corridors plot, and together with the points obtained from different impact velocities simulations, it is possible to extract the AIS 4 curve through a quadratic relation, being the type of equation that interpolates in the better way the experimental data.
Once the AIS 4 level curve is obtained, the AIS curves related to levels 1, 2, 3 and 5 can be produced by multiplying the virtual power required for AIS 4 by the ratio of the cube of the AIS level numbers, as is shown in Equation 6 [17]:

\[ PVP_{AIS-A} = PVP_{AIS-4} \times \frac{A^3_{AIS-A}}{4^3} \]

Equation 6 AIS Scaling for AIS 1-5 [17]

Hence the ratio of AIS5, AIS3, AIS2 and AIS1 taking AIS as reference are 125/64, 27/64, 8/64 and 1/64 respectively.

An example of PVP corridors plot is shown in Figure 25, taken from the work of C. Bastien and C. Neal-Sturgess [18] [19], where the PVP method has been applied for brain contusions in frontal impacts:

![PVP Corridor of Brain Contusion in Frontal Impact and Prediction Bounds](image)

*Figure 25 PVP corridors of brain contusion in frontal impact (C. Bastien, C. Neal-Sturgess) [18]*

The PVP corridors trace the whole trauma response of an organ in a certain impact direction, for a determined impact speed.

Finally, the virtual power value of each element of the organ analysed is extracted, and the highest one (the peak virtual power) is highlighted and placed in the PVP-Impact speed plot, in order to recognize what type of AIS injury level the organ suffered at the real impact speed of the accident [20].
6 Real life accident analysis

The real-life accident data and the FEM models reproducing it were provided by Professor C. Bastien from Coventry University, with the proposals of improving some details and trying an alternative method to apply the pulse to the sled, finally comparing the results with the ones already obtained in previous analysis.

Data on the accidents were obtained from CIREN database, provided by the NHTSA. The photos of the vehicle/environment included in the database and the written reports have been used to recreate in the most realistic way the collision for the purpose of the simulation.

In order to simplify the simulations and the comparison between virtual model and real case, 2nd-row occupants have been used exclusively: unlike occupants in 2nd-row seats, occupants in 1st-row are usually provided with frontal airbags, with the aim to reduce the levels of injuries suffered by the occupants [22]. Airbags have a variety of geometries: this information is not easy to acquire for the general public, so this makes the accurate modelling of the airbag deployment very difficult. This inaccuracy is enhanced by the addition of seatbelt pre-tensioners and load limiters, whose information is not available from the reports, and if assumed incorrectly it may result in injuries not found in the case occupant.

Moreover, frontal occupants frequently come into contact with interior fittings and fixtures such as: centre consoles, dashboards, glove compartments and storage pockets; even if it is possible to gain information about vehicle interior geometry and recreate it in an accurate way, it would require considerable time and acts as an additional source of potential error [22].

Furthermore, potential discrepancies in results due to seat positioning are avoided by only concerning cases for occupants of 2nd-row, since their seats are not adjustable.

Case organs

The organs that will be analysed in the virtual model are the liver and spleen. The AIS rating of the injuries suffered by these organs will be compared directly with the chosen case medical reports, through the construction of AIS curves produced by the PVP evaluation of the organ and velocity of the impact. In cases which organs have not been reported as being damaged, it is to be assumed that the AIS rating is a maximum of 1.
6.1 Critique of selected case

6.1.1. Case 591142661

The case analysed involves a Volkswagen Rabbit that collides with a tree (diameter >30mm) at an estimated velocity of 48km/h (13.3m/s) [21]. The case occupant analysed, seated in the 2nd-row left seat, is a 16-year-old male with a height of 1870mm and a mass of 84kg.

According to the report, the vehicle impacted the tree while it was coming out of a left curve and beginning to negotiate a sweeping right curve. The vehicle travelled left of the centerline and the driver steered right trying to keep the roadway (Figure 26); due to this, the vehicle was undergoing lateral velocity in addition to forward velocity. However, this lateral velocity was assumed to be 0m/s in the simulation due to no information being provided on the vector of the lateral velocity, resulting in a simulation velocity of 13.3m/s acting directly along the vehicle x-axis.
6.2 Real life injury analysis

The occupant sustained injuries to only 1 of the 2 focus organs, which can be seen in Table 6:

<table>
<thead>
<tr>
<th>Organ</th>
<th>AIS Name</th>
<th>AIS level</th>
<th>Injury Causation Scenario (ICS)</th>
<th>Involved physical component</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIVER</td>
<td>Liver, laceration, simple capsular tears; &lt;=3cm parenchymal depth; &lt;=10cm long; minor; superficial</td>
<td>2</td>
<td>Crash (pick)</td>
<td>Belt restraint webbing/buckle</td>
</tr>
<tr>
<td></td>
<td>Liver laceration minor (OIS Grade I or II)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

According to the report, no injuries were sustained by the spleen, so the absence of injury information can be compared with injury levels resulting from the simulation: injuries will not be expected in the simulation which did not occur in the case collision [21].

In Figure 6 it is displayed a visual representation of all the injuries suffered by the occupant during the accident, which are reported in detail in APPENDIX A:

![Figure 6: Injury Distribution for Case 591142661](image-url)
according to injury n.5 (abrasion to the neck skin Appendix A) and injury n. 6 (upper shoulder skin contusion Appendix A) the contact between the occupant’s lower neck and the shoulder belt caused skin abrasions/contusions; this suggests that the belt was positioned high on the occupant’s shoulder, an information that can affect the kinematics of the upper body during impact.

6.3 Methodology for Accident simulation

The collision has been recreated in LS-DYNA using the speeds and accident geometry specified by the data of the report already analysed, and divided in two different kind of simulation models in order to reduce the time and complexity of calculations:

- The first type of simulation involves the vehicle impacting the obstacle at different speeds including the one of the real accident. The occupant was not included, and the internal details of the vehicle like seats, dashboard, etc. have been removed in order to have a lighter model for simulation purposes. Furthermore, various accelerometers were placed in different positions of the rear part of the vehicle, to trace the acceleration along the X axis. The accelerometer placed on the B-pillar of the vehicle was chosen to trace the acceleration since it showed less noise.

- The second type of simulation consists in a sled model composed by the THUMS model, the seat, the seatbelt and the front seat. The seatbelt provided in the test is a reproduction of the fitment characteristics listed on the case report. The acceleration traced from the vehicle model simulation was applied to the sled model without including an initial velocity, since it is assumed that right before the impact, the THUMS and the seatbelt are still with respect to the vehicle reference system, hence the resulting interaction between them is consistent with the realistic impact. Finally, the sled test was carried out also at different initial velocities (namely 5 m/s, 10 m/s and 14 m/s), to be able to get the organ trauma model from the liver and the spleen, where the Peak Virtual Power value will be located.
6.4 Vehicle impact reconstruction (First type simulation)

The base vehicle chosen for the first type simulation is the 2010 Toyota Yaris, as it provides comparable protection with the Volkswagen Rabbit subject vehicle: to match the case vehicle, it has been modified by distributing mass across the vehicle (1435kg) [22]. Both vehicles achieve a “Good” rating in the frontal moderate overlap test conducted by the IIHS. Furthermore, it can be seen from Figure 28 that the frontal impact mechanics between the two vehicles are comparable, with minimal cabin deflection, slight footwell intrusion and the contact between the nearside wheel and the wheel-well rear wall not resulting in loss of sills’ structural stability.

However, a disadvantage of this approximation is the difference in the way the bonnet buckles compared to the Volkswagen one, buckling at a point further forward than the one observed in the Yaris.

The vehicle model provided by Coventry University (Christophe Bastien, Cameron Jake Hans-Brooker) [22] has been simulated again in the local cluster with an initial velocity equal to that found in the impact report, facing the direction of the impacted object. The simulation had a termination time of 0.4 seconds to allow the vehicle to dissipate most of its kinetic energy. In the first type of simulation, involving the vehicle impacting the obstacle, the tree is modelled as a cylindrical rigid wall, of diameter 350mm. The diameter, and position of the tree in relation to the vehicle, has been estimated using photographical evidence from the collision scene and impact geometry from the case vehicle, as it is possible to see from Figure 29.
6.4.1 Crush profile validation

In order to validate the behaviour of the vehicle during the collision in the FEM software, post-impact simulation screen captures were compared with photographic evidence as it is possible to see starting from Figure 30 to Figure 34. From these analyses, conclusions can be drawn about simulation accuracy. No force plots are available for the case vehicles: therefore, vehicles were compared visually and energetically.

Top View comparison

From the top view comparison, (Figure 30) the collapse method of the vehicle’s front impact zone is validated, since both impacts are localised around the impacted tree, with the driver side bonnet leading edge moving rearward by a considerable magnitude compared to the passenger side. In the simulation, the trailing edge of the bonnet can be seen to contact the leading edge of the windscreen, primarily on the driver’s side, and this is also observed in the case vehicle. The only difference between the two cases is on the fender: on the simulated vehicle it collapsed inward, rather than outward like in the case vehicle. However, this will not influence much the kinematics of the vehicle impact, since it is not a structural component and it is made of low-gauge metal. Finally, the roof of the vehicle does not undergo considerable deformation in either scenario.
The A-pillar seems to experience minor buckling localised approximately around half of the way up the windscreen span in both scenarios (Figure 31): even if the buckling observed is only minor and does not compromise cabin integrity, it highlights a structural weakness that can be dangerous if the vehicle impacted the object at a higher velocity. Moreover, in the simulation there is a contact between the wheel and the rear wall of the wheel well, as observed in the case vehicle. However, the part of the door near the wheel-house of the case vehicle undergoes minor deformation, but this is unlikely to affect significantly the deceleration of the vehicle.

Figure 30 Top view comparison between case vehicle and simulation [21]

Figure 31 Left Side view comparison between case vehicle and simulation [21]
**Frontal View comparison**

From the frontal view of the vehicle, it is evident that all lateral crash members have been pushed rearward by the impact, with the driver’s side longitudinal beams (coloured in pink) being more damaged than their counterparts on the passenger side. Comparing the simulation data to the ones of the case vehicles proves that both deformed by an equivalent magnitude (Figure 32).

However, the front wheels orientation at the end of the simulation does not match that of the case vehicle, and this is due to the wheels being positioned neutrally in the simulation prior to impact: this would not be true in the case vehicle since, according to the report, the driver was attempting to regain the carriageway by employing a right steering input.

![Case Vehicle – Frontal View](image1)

![Simulation – Frontal View](image2)

*Figure 32 Frontal view comparison between case vehicle and simulation [21]*
**Left-A Pillar comparison**

The driver’s side A-pillar area of the simulation accurately reproduced the damage found on the case vehicle: the buckling method of the base is comparable, together with the movement of the door away from the body shell and the failure of the connection between the windscreen and the surrounding frame (Figure 33).

<table>
<thead>
<tr>
<th>Case Vehicle – Left A-Pillar</th>
<th>Simulation – Left A-Pillar</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
</tr>
</tbody>
</table>

*Figure 33 Frontal view comparison between case vehicle and simulation [21]*

**Right Profile comparison**

The right side of the vehicle suffered minimal deformation due to the position of the impacted tree near the left-hand side of the vehicle. The passenger side fender is the only part which experiments local deformation in both cases (Figure 34).

<table>
<thead>
<tr>
<th>Case Vehicle – Right Profile</th>
<th>Simulation – Right Profile</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
</tbody>
</table>

*Figure 34 Frontal view comparison between case vehicle and simulation [21]*
6.4.2 Energy level validation and Acceleration trace

![Whole Model Energy during Impact](image)

*Figure 35 Energy Levels during Impact*

In Figure 35, the total energy absorption during the impact is shown: the kinetic energy is reduced by 123kJ, and this is comparable with the NHTSA accident report estimation of 134.4kJ [21]. This discrepancy is probably due to the vehicle movement occurring at the end of the simulation, where the kinetic energy of the vehicle has a value of 6kJ: if this kinetic energy is assumed to be reduced to 0kJ, the total energy absorbed at the end of the impact event would equal 129kJ, resulting in a smaller 8.5% difference [22].

Accelerometers were placed on several parts of the rear seat frame and the signal with the least noise (accelerometer 5, located on the base of the B-pillar) is then chosen as an output for the acceleration along X axis, filtered with a C60 filter in accordance with SAE J221 (Figure 36).
6.5 Improvement of sled model and application of motion (Second type simulation)

The second type of simulation consisted in a sled model composed by the THUMS occupant, the seat, the seatbelt, and the front seat (Figure 38). This model was also provided by Dr Christophe Bastien at Coventry University, with the aim of improving some of its characteristics and applying a different method for the motion of the model.

6.5.1 Occupant

The occupant was simulated using a male 50th percentile THUMS model, chosen respectively for its ability to model forces on the internal organs in an accurate way. This level of detail is necessary for the calculation of AIS injuries since the maximum strain rate experienced by the organs must be calculated.

Moreover, unlike models such as the Hybrid-III Dummy, the THUMS model is anthropometrically accurate in all planes of movement: this directional accuracy is fundamental for the project, as the vehicles move in the y-z plane in addition to the z axis, causing the occupant to move away from the x-z plane [22].

The mass or height of the THUMS occupant was not modified from the original model in order to simplify the creation of the sled. This may affect the kinetic behaviour and cause inconsistency between the model and the occupant, but the change was not possible [22].

6.5.2 Sled geometry

The sled consists of a simple rigid seat frame modelled as 2D elements, with material stretched between the top and leading edges. A seat modelled with 3D elements for the foam of the seat would have improved the accuracy of the results, however due to simplicity of simulation, and so CPU runtime, a simple seat was chosen [22].

In the base vehicle, seatbelt pre-tensioners and load limiters from rear seats were not present, so they were not modelled in the simulation. Moreover, due to instabilities happening during the simulation and the lack of data for the loading curves of the case vehicle, a retractor was not included.
In the real accident, the occupant impacted with the back side of the front passenger seat: this probably affects the kinematics of the occupant during the impact, so in the simulation model a second simplified seat was included in front of it, using the same fabric material as the sled. This fabric was then hooked up to a rigid base to ensure that, whilst maintaining compliance, it does not deform excessively. The distance between the rear seat squab leading edge and front seat backrest was estimated to be 250mm from case photos (Figure 37).

The footwell plate has been modelled with a single rigid quad element, and together with the front passenger’s seat backrest is then constrained to the occupant seat base via a rigid body, constraining the movement in all 6 degrees of freedom and allowing the sled and its surrounding parts to move together, as it is evident from figure 38 [22].

For what concerns the occupant posture, detailed information regarding the position at the time of impact was not available for the chosen case, so the model occupant has been positioned in a neutral posture, with the arms positioned above the thighs and the feet positioned flat on the floor (Figure 38).
6.5.3 Improvements of Sled model

As mentioned before, the provided sled model needed some improvements, so part of the work focused on analysing it in order to decide which parts needed to be modified:

- The contact between the arms and the front seat was not included in the original model, as it is possible to see from left image of Figure 39. The keyword “CONTACT AUTOMATIC SURFACE TO SURFACE” was used to define the contact of the arms. The fingers were not included due to instabilities in the contact with the front seat, but
this should not influence the kinematics of the abdominal organs in analysis. The result of the added contact is visible in the right part of Figure 39.

- The seatbelt contact with the thorax and abdomen of the THUMS presented some issues in particular with the interaction between the skin and the fabric: many modifications were applied and different attempts were made, like creating a set part for the seatbelt, whose set was originally divided between shell and fabric, or modifying certain parameters of the seatbelt. After all this some improvements were obtained, in particular solving the sticking interaction between the shoulder skin and the seatbelt and improving the interaction of thorax skin with the fabric, as it is possible to see from Figure 40 and 41.

![Figure 41 comparison of thorax skin interaction with seatbelt between original model (left image) and improved model (right image)](image1)

![Figure 40 comparison of shoulder skin interaction with seatbelt between original model (left image) and improved model (right image)](image2)
Unfortunately, after these modifications the model still presented some instabilities in terms of out of ranges forces that showed up in some nodes of the skin under the seatbelt. That is why the final model still presented some sticking interaction between the shoulder and the seatbelt, although less relevant than the original model. However, this imperfection was accepted since it does not affect the kinematics of the abdominal organs in an incisive way. Furthermore the contact of the seatbelt with the abdomen was acceptable, and this is fundamental for what concerns the impact energy absorbed by the abdominal organs. Finally, the remaining modification are explained in the following lines:

- The friction coefficient between the seat and the occupant was assumed to be 0.46 (Granta Design 2018) [23]. The frictional coefficient between the occupant and the safety belt was set to 0.6 in the original model, while in the improved model it was reduced to 0.3 so that the contact between the skin and the seatbelt fabric was less troublesome from the simulation point of view, as it is possible to see on Figure 41. The contact between the belt and the occupant had a soft setting value of 1: this was included due to the higher levels of simulation stability achieved with the setting in place.

- The termination time for the sled model was set to 0.064 seconds, time at which the kinetic energy of the impact was completely absorbed by the occupant.

- The time interval between the outputs of the simulations (DATABASE BINARY D3PLOT keyword) was reduced to 2E-3 seconds (from 10E-3 seconds) to collect more information from the animation of the model and identify the most problematic areas.

- The time step size for mass scaled solutions DT2MS (CONTROL TIMESTEP keyword) was decreased to 0.62E-6s in order to increase the stability of the model.
6.5.4 Application of motion to the improved model

The X pulse traced from the vehicle model, displayed in Figure 42, was applied to the sled model with the LOAD_BODY_X keyword, since it is the acceleration felt by the occupant and represented its motion during the accident. This is the main difference compared to the original model, since it implemented motion by tracing rotations and displacements of the vehicle that were then applied to the sled model.

However, the improved model does not implement the keyword INITIAL_VELOCITY that provides the velocity of the impact (13.3 m/s according to the accident report) to the occupant inside the sled model. It was assumed that even if the abdominal organs do not move with the initial velocity of the impact, their movement compared to the one of the seatbelt, responsible of the main injuries to the organs, that moves with the same acceleration, would be valid in the vehicle reference system.

While this was done for the model representing the original accident, for what concerns the models used to plot the PVP corridors (the AIS levels curves), the motion was provided through the INITIAL_VELOCITY keyword only, using different velocity values, in order to build a more generalised plot that could be valid for various models of the same accident implementing little modifications and variations.


## 7 Organ Trauma Model and PVP results

In this paragraph the results of the PVP analysis made on the simulated models are presented, starting from a visual comparison of the consequences of the accident on the occupant between real case and simulation, arriving to the peak virtual power evaluation and location in the PVP corridors plot.

Through the HyperView software, the occupant’s liver and spleen of the sled simulations launched at different velocities (namely 5 m/s, 10 m/s and 14 m/s) were examined to calculate the trend of the virtual power, and the obtained values were used to define the PVP corridors. Finally, the evaluated Peak Virtual Power is located on the same plot in order to identify the AIS level of the injury suffered by that organ.

### 7.1 Visual comparison of occupant resultant trauma

Each step of the sled model simulation, and so its kinematic behaviour, is reported in Figure 44: it involves movement positive in both the Y and X axis, with the head of the occupant moving downward as the seatbelt tenses the chest and shoulder. A compression of the knees can be appreciated from the second frame of the Figure, where the occupants’ left leg contacts the seatback with a higher force than the right, and this behaviour is validated by the penetration marks observed on the front seat of the case vehicle (Figure 43), caused by forward movement of the rear occupant’s lower limbs. Due to the seat being repositioned after the impact, it is not possible to estimate and compare its deformation with the simulated one.
Figure 44 kinematic behaviour of the sled simulation
Moreover, the contact of the hands and the wrist with the front seat due to the sliding of the hand, is validated by the photographic evidence of Figure 43, where a slight mark of contact in the zone of the front seat is visible. Unfortunately, it is impossible to forecast the exact position of the hands of the occupant during the real accident, and therefore a neutral position of the arms and hands has been chosen for the simulation.

Furthermore, the deformation caused by the ankle to the seat (highlighted by the lowest mark in the right image of Figure 43) can be seen to occur also in the simulation model (Figure 45) with the lower shin and ankle making a strong impact with the seat back, resulting in localised deformation of the skin and muscles.

Finally, as can be seen from Figure 46, the simulation occupant suffered from skin abrasions across the torso and lower neck region, validated by the injury report of the real case.
7.2 Construction of PVP Corridors (AIS curves)

The sled model is simulated with different velocities, namely 5 m/s, 10 m/s and 14 m/s in order to obtain the PVP corridors plot where the AIS levels curves can be found. The highest velocity simulation (14 m/s) is the first one to be examined: using the graphical plotting of maximum principal strain (Figure 48 for the liver and Figure 49 for the spleen), the first element to pass 30% value is identified by locating the one undergoing maximum strain during the frame of the simulation where the global strain first surpassed 30%. Due to the number of elements characterising the organ (over 10,000 elements), it is not possible to identify exactly the first one that surpasses the 30% maximum principal strain. This is why this simplification may lead to the incorrect element being chosen; however, the time difference between the chosen element and the first to surpass 30% is minimal due to both occurring within the same frame of the animation, so it is an acceptable approximation.

The same element identified from the highest velocity impact is used also for the other velocities, and the method followed to extract the virtual power value from each simulation is explained in the plot from Figure 47:

![Figure 47 Virtual Power value extraction method](image-url)
In order to extract the virtual power value, the Stress value of the element has to be multiplied by the strain rate value, according to Equation 2, tracing the result for the time at which the 30% max principal strain is reached. To do so, the method in Figure 47 is applied:

1. Once the element is identified, its maximum principal strain plot is obtained, and the time at which the element first surpasses the 30% is identified and saved.
2. The Von Mises stress against the time curve of the element is extracted.
3. The Von Mises strain against the time curve of the element is extracted.
4. The Von Mises strain curve is differentiated in order to obtain the strain rate curve.
5. Finally, the stress and strain rate curves are multiplied, obtaining the plot of the PVP against the time. On this plot, at the time saved from point 1, the Virtual Power value is extracted.

This virtual power value obtained will be the Y coordinate of the PVP corridors plot, with the impact velocity as X coordinate.

### 7.2.1 Liver element identification

![Liver strain distribution and element location (14 m/s)](image)
In Figure 48 the location of maximum strain on the liver can be observed. From the graphical representation it is evident that the zone with highest strain is located in the upper zone of the liver. This may be explained by the position of the organ itself and the configuration of the seatbelt: the way the liver moves during a frontal impact, as described in Figure 7, validates this kind of strain distribution, together with the compression produced by the seatbelt itself. This location is the same for all tested velocities and element 84317547 is the first to undergo 30% max principal strain: this suggests that the kinematics of the occupant do not change significantly, beyond becoming more exaggerated, as velocity increases.

### 7.2.2 Spleen element identification

![Spleen strain distribution and element location](image)

*Figure 49 Spleen strain distribution and element location (14 m/s)*
In Figure 49 the location of maximum spleen loading can be observed at the interface between the spleen and ribcage. This remains the same for all impact velocities and is caused by the contact between the organ and the ribs, due to the position of the organ itself as it is possible to see from Figure 50. The element first to reach the 30% maximum principal strain is identified as element 84343054.
7.3 PVP Corridors for abdominal organs

7.3.1 PVP Corridors parameters

After conducting the above procedure on both focus organs (liver and spleen) for all simulations, it is possible to plot the virtual power as a function of the velocity of the vehicle impact. This plot allows the virtual power requirement for an AIS 4 injury to be plotted as a function of the vehicle impact velocity [18]. The Equation of the curve is to be in the format of a quadratic line:

\[ y = mx^2 \]

The fit results in the following R\(^2\) values, attaining a high level of statistical accuracy:

<table>
<thead>
<tr>
<th>Organ</th>
<th>R(^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liver</td>
<td>0.9984</td>
</tr>
<tr>
<td>Spleen</td>
<td>0.9909</td>
</tr>
</tbody>
</table>

*Table 7 coefficient of determination for the AIS 4 curves of liver and spleen*

Once the AIS 4 curve is obtained (APPENDIX C), the traces for AIS 1, 2, 3 and 5 can be produced following the method described in paragraph 6.2, and the resultant plots are displayed in Figures 51 and 52.

It is important to highlight that the PVP corridors are valid only for the specific type of accident created for: consequently, they cannot be used for other conditions or type of accidents, and even in the same one, if certain boundary condition change, the PVP corridors must be recalculated.
7.3.1 Liver PVP Corridors

Following the method explained above, it is possible to highlight the correlation between the virtual power absorbed by the organ and the type of injury expected. For the liver case, according to the PVP corridors shown in Figure 51, the energy values absorbed are much higher than the spleen ones, and this is related to the greater energy absorbed during the impact by the liver. Moreover, it is possible to see that increasing the velocity of the impact, even with a lower energy absorbed, the AIS level of injury will be higher, highlighting the strict correlation between virtual power and velocity of impact.
7.3.1 Spleen PVP Corridors

For the spleen case in Figure 52, the energy values absorbed are much lower compared to the livers’ PVP corridors, meaning a lower impact consequence on the organ. However, this also implies that equal values of energy will induce higher AIS levels of injuries compared to the liver.

Figure 52 Spleen PVP corridors
7.4 Impact Velocity Peak Virtual Power and results analysis

Taking advantage of the script produced at Coventry University [22], the peak virtual power of each organ is calculated. This script was used on the simulation model characterised by the pulse characteristics of the case impact velocity (13.3 m/s). The output provides a virtual power value for every element of the organ at each time frame: as it is possible to imagine, the quantity of data output is very large (more than 800 .csv files with 3000 rows and 52 columns each with a total of more than 2.6 million data, just for the liver), so a MATLAB script (Appendix B) was created to analyse all these data in order to extrapolate the peak value (peak virtual power of the organ). The output values for each organ, filtered with filter C180 in order to eliminate the peak values coming from disturbances, are shown in table 8: the unit of measure is in mW (mJ/s), consequently these values are ready to be inserted on the PVP corridors plot.

<table>
<thead>
<tr>
<th>ORGAN</th>
<th>PVP (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liver</td>
<td>251.2</td>
</tr>
<tr>
<td>Spleen</td>
<td>81.4</td>
</tr>
</tbody>
</table>

Table 8 Peak Virtual Power values for abdominal organs

From the values of obtained PVP, a great discrepancy appeared between the order of magnitude of the results and the one of the values from the PVP corridors, meaning that the occupant of the simulation suffered injuries of AIS level 5+ for both organs, instead of AIS 2 for the liver and AIS 1 for the spleen as reported on the medical reports of the accident.

The Peak Virtual Power method is very sensitive for what concerns the characteristics of the HBM used and the boundary conditions defined for the simulation. The simplifications made for the sled model may have been responsible for these discrepancies in values: in fact, if the simulation model does not represent accurately each condition of the real case, inconsistencies may appear. Some possible reasons will be discussed in the following:

- A first reason may be associated to the occupant itself: the person involved in the accident was a 16-years-old, while the THUMS represents a 39-years-old. It is well known that at younger age the characteristics of the human body are different from an older human body, and this probably influenced the type of injuries sustained; the body of a younger person is able to better absorb the energy from an impact, due to the particular characteristics of bones and soft tissues with respect to the ones of an older person [6].
This evidence could explain the differences in the expected injuries between the real case and the simulation.

- Another relevant distinction between the THUMS used for the simulation and the occupant is the height: the HBM measures 1.75m while the height of the occupant of the real accident is 1.87m. This disparity could have influenced the interaction between the thorax and the seatbelt itself, in particular around the shoulder zone. Being taller, the occupant of the accident may have a different interaction with the seatbelt in comparison with the THUMS, and this may have contributed to the difference of the injuries between the model and the real case.

- In the simulated model, the THUMS has been positioned in a neutral position that may not have been the same one of the occupant right before the accident: unfortunately, it is not possible to know the exact position of the 16-years-old, and this may have influenced the results of the calculations.

- The simplified seat modelled for the sled may have interfered with the results: the friction value set for the fabric may not reproduce in a realistic way the sliding between the THUMS and the seat, thus leading to a heavier contact between the HBM itself and the seatbelt, and consequently to a higher AIS level of injury for the abdominal organs. Moreover, using 2D elements instead of 3D elements for the seat modelling may have influenced the kinematics of the HBM occupant, leading to a more severe impact compared to the real one.

- The friction values used for both seatbelt and seat may have caused a major distortion of some elements of the THUMS, leading to unrealistic results of energy absorbed.

- Although it may have not influenced the results in a relevant way, the absence of gravity acceleration inside the model may have changed the kinematics of the occupant leading to a different interaction with the seatbelt. The first idea was to compare the results with the ones previously obtained by the Coventry University analysis: the original model did not include the gravity, and for sake of comparison it has not been included either in the improved model.

- Finally, the THUMS occupant of the sled model does not take into account the apparel of the occupant during the impact: the clothes that the 16-years-old could have dressed during the impact may have absorbed part of the energy of the interaction between the
seatbelt and the body, thus leading to a lower AIS level injury with respect to the one suffered by the HBM of the simulation.
Study of Injuries on abdominal organs using the Peak Virtual Power method (PVP)
8 Conclusions

In this thesis work the Peak Virtual Power method, an innovative injury criterion, has been used to investigate abdominal organs injuries suffered by a car crash occupant.

As highlighted in chapter 4, during a car crash the liver and the spleen are the most involved abdominal organs [5], and this is the reason why their injuries have been taken into consideration in the analysis of the virtual simulation of the accident recreated. The AIS injury levels assigned to those organs after a car accident are usually the highest for the abdominal region, due to their anatomical characteristics and position. Commonly, after an accident, the heart and lungs are the first examined organs, since a high AIS level of injury related to them can lead to severe consequences for the health of the occupant. However, in this project emerged that injuries to abdominal organs must not be underestimated, since even if after the impact major injuries are not observed, over the time these traumas can lead to severe effects for the human body.

The usage of Human Body Models in the studies and analysis of this project, brought out that the injury criterions described in chapter 3, generally used by many companies for crash tests analysis, do not take advantage of all the possibilities offered by the HBMs, where every physical or biomechanical quantity can be extrapolated and measured from each single part of the body itself. These older criterions are suitable for dummies that can implement only sensors and accelerometers for particular parts of their structure. The introduction of HBMs implied the need of a new Organ Trauma Model (OTM), able to calculate the risk to life based on any organ injury severity, in particular for soft tissues. The PVP method can be considered as a forerunner for these trauma evaluations made on Human Body Models like the THUMS used in this project.

This thesis work started from the recreation of the real-life car crash: the graphical comparison made in chapter 7 and 8 between the photographic evidence of the accident and the screen captures of the simulation validated the truthfulness of the virtual reproduction. The crush profiles are largely comparable between the case and simulated vehicle, and this is critical for the accuracy of the traced acceleration that will be applied to the occupant seat sled. Once the models were validated, the PVP method was applied in order to study evaluate the injuries suffered by the liver and the spleen of the occupant.

The Peak Virtual Power method, described in chapter 5, is an energy-based engineering indicator that considers the irreversible work transferred to a human body during an impact equivalent to the injury suffered [17]. The HBMs and the Finite Element method offer together the possibility
of employing this innovative criterion for car crash consequences analysis, whose advantages can be summarised as follows:

- They are able to locate with great accuracy the organs’ area of the injury and to relate the energy value absorbed during the impact to an AIS level.

- They are able to predict what elements of the vehicle are responsible for the injuries suffered by the vehicle occupant (like seatbelts, dashboard, seats, etc.), suggesting the possible modifications or improvements that can be implemented to the vehicle structure and safety elements in order to prevent as much as possible these types of traumas. For example, in this thesis work emerged that the position of the lower part of the seatbelt assembly is the main responsible for the injuries associated to the abdominal organs. For this reason, it would be interesting to implement a possible improvement of this component, like the inclusion of a pretensioner or a different anchorage point in order to prevent high AIS levels of injuries to those organs.

Unfortunately, being the PVP still in progress, some disadvantages of this method became clear during the development of this project:

- It is not able to predict haemorrhaging of organs after the impact: this would be detected by injury reports and may affect the results of any comparison between simulated injuries and those observed, since internal haemorrhages can change drastically the AIS level of a particular trauma.

- Being a very accurate method for injury evaluation, it implies a great accuracy in the reconstruction of the accident: as it emerged from the results of chapter 8, a great discrepancy between the expected injury results and the effective ones appeared. This very high virtual power value measured for both the liver and the spleen can be related to the simplifications applied to both vehicle and sled models. Moreover, the different boundary conditions considered for the simulation and the different motion method applied for the sled could have influenced the final results, together with the anatomical differences between the THUMS HBM used for the sled and the 16-years-old occupant of the real accident.

These considerations imply that, in order to make effective the PVP method for the evaluation of the injuries suffered by the occupant, the virtual model of the accident must reproduce as faithfully as possible the real accident.
Finally, the PVP corridors must be re-defined every time a modification is implemented in the simulation. From the research point of view this would not be a problem, but from a company perspective, due to the short time of development related to a new car model, this method would appear inadequate since it would take lot of time to be applied for all the accident conditions simulated in the tests.
Study of Injuries on abdominal organs using the Peak Virtual Power method (PVP)
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“A Generic Trauma Severity Computer Method Applied to Pedestrian Collisions” Christophe Bastien, Clive Neal-Sturgess , Huw Davies


“A study into the prediction of abdominal organ injuries through the use of peak virtual power as an indicator of injury severity for rear seat occupants” Cameron Jake Hans-Brooker, Dr Christophe Bastien, 2019


### 10 APPENDIX A - Injury summary of case 591142661 [21]

<table>
<thead>
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<tbody>
<tr>
<td>1</td>
<td>5420264</td>
<td>Mesenteric laceration complex: Mesentery, laceration, massed; avulsion: complex; tissue loss</td>
<td>Inferior/Lower</td>
<td>1</td>
<td>860.29 OTHER INJURY TO SMALL INTESTINE WITHOUT OPEN WOUND INTO CAVITY</td>
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<td>2</td>
<td>5408264</td>
<td>Colon laceration massive (OIS Grade IV and V); Colon (large bowel); laceration, massive; avulsion; complex; tissue loss; transaction; large areas of tissue devitalization or devascularization</td>
<td>Inferior/Lower</td>
<td>2</td>
<td>864.44 INJURY TO SIGMOID COLON WITHOUT OPEN WOUND INTO CAVITY</td>
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<tr>
<td>3</td>
<td>5408222</td>
<td>Colon (large bowel); laceration, no perforation; partial thickness; &lt;50% circumference (OIS I, II); Colon laceration no perforation (OIS Grade I or II)</td>
<td>Inferior/Lower</td>
<td>3</td>
<td>865.41 INJURY TO ASCENDING (RIGHT) COLON WITHOUT OPEN WOUND INTO CAVITY</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>5418222</td>
<td>Liver; laceration, simple capsular tear; &lt;5cm parenchymal depth; &lt;=10cm long; minor; superficial (OIS II); Liver laceration minor (OIS Grade I or II)</td>
<td>Right</td>
<td>1/2</td>
<td>864.02 LACERATION OF LIVER, MINOR, WITHOUT MENTION OF OPEN WOUND INTO CAVITY</td>
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<tr>
<td>5</td>
<td>5902021</td>
<td>Neck/Throat; Skin abrasion</td>
<td>Left</td>
<td>910.03 abrasion or frication burn of face, neck, and scalp except eye, without mention of infection</td>
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<td></td>
</tr>
<tr>
<td>6</td>
<td>7904021</td>
<td>Upper Extremity Skin contusion</td>
<td>Left; Shoulder</td>
<td>922.00 contusion of shoulder region</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>4904021</td>
<td>Chest Skin contusion (OIS Grade 1)</td>
<td>Left</td>
<td>922.1 contusion of chest wall</td>
<td></td>
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<tr>
<td>8</td>
<td>7902021</td>
<td>Upper Extremity Skin abrasion</td>
<td>Right; Elbow</td>
<td>923.00 contusion of shoulder region</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>7902021</td>
<td>Upper Extremity Skin abrasion</td>
<td>Right; Hand/Digits;</td>
<td>913.0 abrasion or frication burn of elbow, forearm, and wrist, without mention of infection</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>6904021</td>
<td>Back Skin contusion</td>
<td>Left; Inferior/Lower;</td>
<td>922.2 contusion of abdominal wall</td>
<td></td>
<td></td>
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<tr>
<td>11</td>
<td>6902021</td>
<td>Back Skin contusion</td>
<td>Right; Central</td>
<td>911.0 abrasion or friction burn of trunk, without mention of infection</td>
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<tr>
<td>12</td>
<td>5904021</td>
<td>Abdomen Skin contusion</td>
<td>Whole Region; Inferior/Lower;</td>
<td>922.2 contusion of abdominal wall</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>5902021</td>
<td>Abdomen Skin abrasion</td>
<td>Whole Region; Inferior/Lower;</td>
<td>911.0 abrasion or friction burn of trunk, without mention of infection</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>5408102</td>
<td>Colon (large bowel); contusion; laceration (OIS I); Colon contusion (OIS Grade I)</td>
<td>Inferior/Lower</td>
<td>864.41 INJURY TO ASCENDING (RIGHT) COLON WITHOUT OPEN WOUND INTO CAVITY</td>
<td></td>
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</tr>
</tbody>
</table>
11 APPENDIX B - MATLAB script for PVP extrapolation

The output of the Coventry University Script is composed by a large number of .csv files each one of them including a large amount of data. In order to find the maximum value inside all these files (that is the peak virtual power suffered by the organ) it was necessary to program a MATLAB script that is able to read all the files inside a folder, through the function “tabularTextdatastore”, placing them in a table. After being converted in a numerical matrix, through easy functions the script is able to evaluate the maximum value inside the matrix.

ds = tabularTextDatastore('DESTINATION FOLDER');
T = readall(ds);
P=table2array(T);
maxv=max(P);
M=max(maxv);
12 APPENDIX C – AIS 4 curve fits

Liver AIS 4

\[ y = 0.04x^2 - 0.1353x + 0.0382 \]
\[ R^2 = 0.9984 \]

Spleen AIS 4

\[ y = 0.0027x^2 + 0.0213x - 0.0121 \]
\[ R^2 = 0.9909 \]