Virtual Testing for Extended Vehicle Passive Safety (VITES)

Version: FINAL

by M Neale and C Oakley

Prepared for: Project Record: S0049/VF
Client: Vehicle Standards and Engineering Division, Department for Transport (Mr S Gillingham)

Copyright TRL Limited (October 2004)

This report has been prepared for the Department for Transport, Vehicle Standards and Engineering Division. The views expressed are those of the authors and not necessarily those of the Department for Transport.
This report has been produced by TRL Limited, as part of a Contract placed by the Department for Transport. Any views expressed are not necessarily those of the Department for Transport.

TRL is committed to optimising energy efficiency, reducing waste and promoting recycling and re-use. In support of these environmental goals, this report has been printed on recycled paper, comprising 100% post-consumer waste, manufactured using a TCF (totally chlorine free) process.
CONTENTS

Executive summary i

Abstract 1

1 Introduction 1

2 VITES WP3 3
  2.1 Task 3.1 – Identify accident conditions in which car occupants are not optimally protected by the current regulatory tests 3
    2.1.1 Sub-task 3.1.1 – Accident data analysis 3
    2.1.2 Model runs completed for Sub-tasks 3.1.2 to 3.1.4 11
    2.1.3 Effect of occupant disability 25
  2.2 Propose a virtual test procedure that extends the range of protection afforded to car occupants 28
    2.2.1 EuroNCAP simulations 29
    2.2.2 NSS Driver simulations 30
  2.3 Demonstrate the application of a virtual test procedure in one example 31

3 Discussion 33
  3.1 Summary of additional project outcomes 34

4 Conclusions 36

5 Future work 37

6 Acknowledgements 37
Executive summary

Current regulatory and consumer tests for cars are based on a small number of precisely defined test conditions using a 50th percentile dummy seated in an average driving position. As such, there are concerns that car designs may have become optimised to protect their occupants under this limited range of test conditions, with the result that occupants may now be at greater risk in other, non-tested conditions, including lower severity crashes. A solution to the problem would be to increase the number of tests, but it is considered impractical to require vehicles to undergo a sufficiently wide range of full-scale crash tests to account for the full range of potential crash conditions. As an alternative to physical testing it is anticipated that virtual testing (VT) procedures could be implemented within current test procedures to provide a more cost effective means of assessing the safety performance of vehicles over a wider range of impact conditions. In response to this proposal a European Commission 5th Framework project was awarded known as Virtual Testing for Extended Vehicle Passive Safety (VITES). The aims of the project were to address the issues involved in using VT to enhance current regulatory tests. The project was broken down into the following Workpackages (WP):

- WP1 – Virtual testing procedures and guidelines: Objective – To define general harmonised procedures and guidelines that will lead to a normative application of virtual testing in the passive safety field.
- WP2 – Stochastic simulation: Objective – To develop a method to predict the stochastic response of car crash tests caused by the scatter in the components of the system. In particular, the variability of regulated crash dummies was evaluated by means of stochastic analyses.
- WP3 – Extending the range of protection: Objective – To extend the range of protection currently afforded to car occupants by regulated testing, through the use of virtual testing of differing occupant sizes and positions under a range of crash conditions.

The Department for Transport (DfT) funded TRL to lead and contribute to WP3 of the VITES project. The principle aims of WP3 were to identify “gaps” in current regulations where VT could be used to enhance regulatory testing and to propose a VT procedure based on the identified “gaps”. Initially, UK accident data were analysed and the following three statistically proven “gaps” in regulations were identified:

1. a dip in the injury risk to drivers in the speed range 70-74 km.h⁻¹,
2. an increased injury risk to female passengers in frontal impacts and
3. an increased injury risk to female drivers in non-struck side (NSS) impacts.

A more in depth analysis of the individual accident cases for male and female drivers in NSS impacts was completed to determine the reasons for the increased injury risk to female drivers in this accident condition. It was found that the injuries were typically associated with average sized females driving super-mini vehicles involved in high speed NSS impacts. It appeared that the apparent “gap” in injuries was more an associated artefact of vehicle size than gender, with nearly 70% of the females in the NSS dataset driving super-minis. In contrast, the majority of the males for this data set were driving small and large family vehicles.

Simulated frontal, oblique and side vehicle impacts were completed with large and small vehicle models at speeds ranging between 30 and 70 km.h⁻¹, in order to investigate the influence that parameters such as, speed, impact direction, occupant size and type (ie dummy or human body model) have on injury risk. Predicted injury criteria and body segment trajectories of the occupant models were compared. Overall, for the simulated impact conditions investigated it was found that injury criteria predictions were generally below defined injury criteria threshold limits. However, it was found that the size and type of the occupant model has a significant influence on the predicted body response of the occupant model, which considerably influences the predicted injury risk. For simulated frontal impacts it was generally found that the extent of the frontal overlap led to larger injury.
predictions from the small vehicle model runs and lower injury predictions from the larger vehicle model runs. As one would expect, different impact speed and direction resulted in the occupant model striking different features of the vehicle interior and the manner in which these were struck, so altering the potential injury risk.

In comparison to a 50th percentile dummy model the 50th percentile human body model during simulated frontal vehicle impacts tended to move further forward in the seat and experienced greater head penetration into the airbag, greater lateral head rotation and less head rebound following head contact with the airbag. Predicted HIC values from the human body model were on average two to three times greater than those predicted by the dummy model, although all predicted HIC values compared were below 307, almost 70 % lower than the accepted injury threshold limit for HIC of 1000. During oblique vehicle impacts it was noticeable that the 50th percentile dummy head struck the modelled side head airbag while the head of the 50th percentile human body model passed under the airbag. This was also found to be a problem with smaller sized occupant models and implied that airbag systems may be optimised for 50th percentile dummy head strikes. For simulated frontal impacts it was found that injury predictions were on the whole lower for the 50th Hybrid III occupant model and greatest for the 5th percentile occupant model, implying that vehicle compartments may be optimised for 50th percentile dummy. In comparison to a 50th percentile dummy model the head of the 5th percentile dummy model rebounds off the frontal airbag leading to greater seat submarining and knee penetration into the knee bolster. The 95th percentile Hybrid III model tended to overload the restraint and airbag systems, moving further forward in the seat and experiencing greater knee bolster penetration.

Work was also completed in WP3 investigating the influence that an occupant’s disability may have on their safety in the event of an automotive accident. A short literature review together with analyses of the relevant and available statistical accident data on disabled occupant injuries was completed. A limited amount of accident data for disabled vehicle occupants was found. It was concluded from these findings that occupant disability is not typically recorded in police accident reports and that the number of accidents involving disabled occupants is possibly small. Furthermore, it was concluded from a review of all current international regulations relating to automotive and occupant safety that no specific regulations currently exist relating to the safety of disabled occupants in automotive vehicles.

Previous modelling work has identified that for certain impact conditions there are potentially hazardous body kinematics for occupants with certain types of disability (eg arm or leg amputees). As such, additional modelling studies were completed with the human body model to identify the disabilities and mechanisms that pose the greatest injury risk when occupants are wearing standard 3-point belt systems. The wearing of this belt system generally led to the following occupant dynamics that could pose an increased injury risk to disabled occupants: larger upper body rotations and a greater susceptibility to slipping out of the belt system. Additional modelling work was completed following this work to assess the improvements in safety that could be achieved for both disabled and non-disabled occupants wearing either of the following safety systems: standard 4-point belt system, 3-point belt system with pre-tensioners and load limiters, and a 4-point belt system with pre-tensioners and load limiters. The 4-point belt system with pre-tensioners and load limiters was found to provide the best overall improvement in safety for both disabled and non-disabled occupants.

Based on the work and results from WP3 a virtual test procedure was proposed that adopts simulated EuroNCAP side impact model predictions as a platform on which additional VT can be completed to enhance vehicle passive safety under a wider range of impact conditions. Currently the proposed procedure uses the identified “gap” in injuries to NSS drivers (with a statistically determined null hypothesis of no “gap” of less than 4 %) as an example of how virtual testing could be used to enhance and expand upon the accident conditions that are currently investigated in regulatory and consumer automotive tests.

Overall it has been established from the VITES project that a considerable amount of work is needed in order to formalise and establish VT as an accepted and reliable means of expanding and enhancing current testing procedures. Specifically, more work is needed to improve the accuracy and reliability
of model predictions. Furthermore, there is a need to develop protocols on how predictions from
models in VT procedures will be analysed, interpreted and integrated within current test procedures
such as EuroNCAP. It is expected that work within the APROSYS consortia and the EEVC and ISO
working groups will provide effective platforms on which the current limitations of VT can be
resolved to allow standardisation of VT procedures. Ultimately, it is expected that VT will provide a
cost effective means of assessing vehicle occupant safety under a wider range of conditions more
representative of those observed in the real world.
Abstract

The UK Department for Transport (DfT) partly funded TRL’s involvement in Workpackage 3 (WP3) of a European Commission 5th Framework project entitled Virtual Testing for Extended Vehicle Passive Safety (VITES). The main objectives of VITES were to develop procedures and guidelines for virtual testing (VT) in order to enhance vehicle passive safety and reduce injury numbers for a wider range of automotive impact conditions. The principle aims of WP3 were to identify “gaps” in current regulations where VT could be used to enhance regulatory testing and to propose a VT procedure based on the identified “gaps”. Within WP3, UK accident data was analysed and the following three potential “gaps” in regulations were identified:

1. a dip in the injury risk to drivers in the speed range 70-74 km.h⁻¹,
2. an increased injury risk to female passengers in frontal impacts and
3. an increased injury risk to drivers in non-struck side impacts.

Model simulations were completed investigating the influence that accident features such as, speed, impact direction, occupant size and type (i.e. dummy or human body model) have on injury risk. It was found that the size and type of the occupant model has a significant influence on the predicted body response of the occupant model, which considerably influences the predicted injury risk. A virtual test procedure was proposed that adopts simulated EuroNCAP side impact model predictions as a platform on which additional VT can be completed to enhance vehicle passive safety under a wider range of impact conditions.

1 Introduction

Current regulatory and consumer tests for cars are based on a small number of precisely defined test conditions using a 50th percentile dummy seated in an average driving position. As a result, there is a concern that car designs may have become optimised to protect their occupants under this limited range of test conditions, with the result that occupants may now be at greater risk in other, non-tested conditions including lower severity crashes. One solution to the problem would be to increase the number of tests, but it is considered impractical to require vehicles to undergo a sufficiently wide range of full-scale crash tests to account for the full range of potential crash conditions. This matter can however, potentially be addressed using virtual testing (VT).

VT is a term in increasing use in Europe to refer to numerical simulation, or computer modelling, of test configurations, i.e. a vehicle can be tested in a ‘virtual’ sense. VT of vehicles is already an essential part of the design process – it is unlikely that a vehicle would pass the current frontal and side impact regulations, or receive a high EuroNCAP rating without a lengthy process of VT being undertaken by the manufacturer. VT is therefore an existing and rapidly developing technology.

It is now considered likely that at some stage in the future, VT will form a part of legislation. This could come about in many forms, for instance, sub-system modelling to qualify small modifications to vehicles that do not necessitate a full-scale test, modelling to assess the overall protection offered by a vehicle (considering all impact directions), or analysis of the restraint system performance in isolation from the vehicle structure. Before this technology could be used in a legislative framework, certain fundamental issues related to modelling need to be addressed, such as the stance of various legislating bodies and their attitude towards the principle of VT, what constitutes a validated model and who should carry out the virtual tests (i.e. the manufacturer or the legislating body).

An EC awarded project titled Virtual Testing for Extended Vehicle Passive Safety (Known as VITES) aimed to address these issues. The project was broken down into the following Workpackages (WP):

- WP1 – Virtual testing procedures and guidelines: Objective – To define general harmonised procedures and guidelines that will lead to a normative application of VT in the passive safety field.
- WP2 – Stochastic simulation: Objective – To develop a method to predict the stochastic response of car crash tests caused by the scatter in the components of the system. In
particular, the variability of regulated crash dummies was evaluated by means of stochastic analyses.

- WP3 – Extending the range of protection: Objective – To extend the range of protection currently afforded to car occupants by regulated testing, through the use of virtual testing of differing occupant sizes and positions under a range of crash conditions.

The DfT funded TRL to lead and contributing to WP3 of the VITES project and this report provides an overview of this work and the conclusions.
2 VITES WP3

The objective of WP3 was to extend the range of protection currently afforded to car occupants by regulated testing, through the use of virtual testing (VT) of differing occupant sizes and positions under a range of crash conditions. In addition to TRL Limited the contributors to WP3 of the VITES project were as follows:

- TNO automotive, Netherlands;
- Fiat Research Centre (CRF), Italy;
- BMW, Germany;
- Federal Highway Research Institute (BASt), Germany;
- Technical University of Graz (TUG), Austria;
- Birmingham Automotive Safety Centre (BASC), UK;
- Warsaw University of Technology, Poland.

In order to meet the objectives defined for WP3 the WP was broken down into the following work tasks:

i. Task 3.1 – Identify accident conditions in which car occupants are not optimally protected by the current regulatory tests;
ii. Task 3.2 – Propose a virtual test procedure that extends the range of protection afforded to car occupants;
iii. Task 3.3 – Demonstrate the application of a virtual test procedure in one example.

2.1 Task 3.1 – Identify accident conditions in which car occupants are not optimally protected by the current regulatory tests

Task 3.1 was broken down into the following six sub-tasks in order to investigate and identify the existence of “gaps” in current regulatory tests:

i. Sub-task 3.1.1 - Accident data analysis
ii. Sub-task 3.1.2 - Parametric studies regarding impact speed and direction
iii. Sub-task 3.1.3 - Protection of the human form compared to that of a dummy
iv. Sub-task 3.1.4 - Effect of occupant size and seating position
v. Sub-task 3.1.5 – Identification of “gaps” in current regulations
vi. Sub-task 3.1.6 – Effect of occupant disability

2.1.1 Sub-task 3.1.1 – Accident data analysis

The purpose of this sub-task was to analyse the accident databases available to the WP3 consortium in order to isolate the principle accident factors, such as impact speed, impact direction and occupant size, associated with high incidences of occupant injuries and fatalities. The work in the sub-task would help to identify the principle variables to investigate in sub-tasks 3.1.2 to 3.1.4 of the WP.

Three accident databases were available to the consortium; the UK Co-operative Crash Injury Study database (CCIS), the GIDAS database and the University of Graz database. For the investigation the following constraints were placed on the data analysed from each database:

- All occupants were belted;
- No rollover;
AIS 2+ injury cases only;
- Delta V or ETS greater than 10 km.h⁻¹;
- All occupants considered were aged 12+;
- Target vehicle manufactured 1990 and 1995 onwards;
- Only car-car impacts including the most severe impact only;
- Target vehicles to include sports cars and SUVs;
- Bullet vehicle to include vans and SUVs, but not trucks/light trucks.

An initial series of investigations were completed on each database looking at the absolute numbers of accidents, drivers and front seat passengers (FSPs) involved in the accidents, and their corresponding Maximum Abbreviated Injury Score (MAIS) for the whole body and individual body regions over the range of Delta V and Estimated Test Speeds (ETS) recorded for the accidents. Following this initial series of investigations the data analysis was restricted to the CCIS database on account of the larger data sets available in this database. Overall the CCIS data was analysed from the following perspectives:

- Impact direction (front/side);
- Impact location;
- Impact speed;
- Occupant type (driver or front seat passenger);
- Injury severity;
- Body region injured;
- Occupant gender;
- Occupant size;
- Mass ratio of the accident vehicles;
- Vehicle age.

Throughout the project the CCIS database was reviewed several times so as to consider updates in the contents of the CCIS accident database.

The obtained information from the CCIS database was analysed to determine whether there were any significant artefacts in the data that could be considered as “gaps” in current regulations. T-statistic tests were carried out on the observed “gaps” to establish their statistical significance, by either, comparing a predicted outcome in the accident data with an actual outcome in the data, or by comparing two outcomes from the accident data to determine the significance of the observed difference. The assumption made in the T-statistic test is that the data has a normal distribution and that the null hypothesis is that there is no difference in the compared results.

A number of potential “gaps” were identified in the CCIS data. However, on account of small sample sizes, for the majority of these potential “gaps” there was very little evidence of any statistical significance with the exception of the following three accident scenarios.

i. Accident scenario 1: Drivers in frontal impacts – Drop in injury risk at an ETS of 65-69 km.h⁻¹ and a Delta V of 70-74 km.h⁻¹

Figure 2.1 and Figure 2.2 respectively detail the percentage distribution of MAIS 2+ injuries with respect to DeltaV and ETS. Also presented in the figures is the predicted distribution of Mais 2+ injuries assuming a normal distribution of injuries over the presented ranges of Delta V and ETS. These predicted values were used to complete a statistical comparison of the observed and predicted injuries at the separate speed ranges in order to test the significance of the observed drops in injury.
risk at the ETS of 65-69 km·h⁻¹ and Delta V of 70-74 km·h⁻¹. The probability of a null hypothesis that there is no drop in injury risk was found to be 0.029 for Delta V and 0.086 for ETS indicating that the observed drops in the percentage of MAIS 2+ injuries are statistically significant. The validity of the result is compromised slightly by the fact that the statistical methods used can be sensitive to low sample sizes. This point is particularly relevant to the result for Delta V where there were only eight cases forming the sample size in the speed range 70-74 km·h⁻¹. Twenty cases formed the sample size for the ETS speed range 65-69 km·h⁻¹ but the result for ETS was less significant than that for Delta V. Even so, for the moment it is inferred from the results that there is a higher probability of an injury at a Delta V and ETS lower than 70-74 km·h⁻¹ and 65-69 km·h⁻¹ respectively. It is implied from the results that vehicles provide a much greater level of protection at one particular impact speed.

Figure 2.1. Percentage of MAIS 2+ drivers in frontal impacts v Delta V for accident vehicles produced from 1990 onwards

Figure 2.2. Percentage of MAIS 2+ drivers in frontal impacts v ETS for accident vehicles produced from 1990 onwards
ii. Accident scenario 2: Female passengers in frontal impacts are at a greater injury risk than males

Figure 2.3 compares the percentage of MAIS 2+ injuries to the sample of male and female passengers included in the data analysis. Statistical analysis of the difference in the injuries to male and female passengers found a null hypothesis of no effect of 0.006, ie less than 1 %. Sample sizes of the data were comfortably large at 93 males and 275 females and provided additional confidence in the significance of the result that in frontal impacts female passengers are at a greater injury risk than males. The comparable analysis of male and female drivers found a probability score of 0.959 corresponding to a high probability that there is little difference between the injury risks to female drivers in frontal impacts compared with their male counterparts.

![Figure 2.3. Percentage comparison of MAIS 2+ injuries to male and female passengers in frontal impacts for 1995 onward vehicle data](image)

### Figure 2.3. Percentage comparison of MAIS 2+ injuries to male and female passengers in frontal impacts for 1995 onward vehicle data

iii. Accident scenario 3: Female drivers in non-struck side impacts are at greater risk than males

Data samples investigated for this accident scenario were 106 males and 72 females for 1990 onwards vehicle data and 70 males and 45 females for the 1995 onward vehicle data. Figure 2.4 and Figure 2.5 compare the percentage of MAIS 2+ injuries for male and female drivers from the two vehicle data sets. Probability of a null hypothesis of no effect was 0.028 and 0.033 respectively for the 1990 and 1995 onward vehicle data sets respectively.
A more in depth analysis of the individual accident cases for male and female drivers in non-struck side (NSS) impacts was completed to identify the possible reasons for the increased injury risk to female drivers. The distribution of these accident cases with respect to the vehicle type, MAIS injury level, ETS and driver mass ratio was analysed as shown in Figure 2.6 and Figure 2.7. The figures show that the injuries to female drivers in NSS impacts are commonly associated with females driving super-mini vehicles involved in high speed side impacts. It is also inferred from Figure 2.7 that the females are not necessarily small (ie 5th percentile), but in the majority of cases could be considered average sized. The apparent gap of injuries to female drivers in NSS impacts therefore appears to be more an associated artefact of vehicle size than gender, with nearly 70% of the females in the NSS dataset driving super-minis. In contrast, the majority of the males for this data set were driving small and large family vehicles. It was also noted that the most likely cause of injuries to super-mini drivers...
In NSS impacts was due to the occupant striking the opposite side or centre console of the vehicle interior.
<table>
<thead>
<tr>
<th>ETS (km/h)</th>
<th>Car Size</th>
<th>MAIS 0-1</th>
<th>MAIS 2+</th>
<th>MAIS 0-1</th>
<th>MAIS 2+</th>
<th>MAIS 0-1</th>
<th>MAIS 2+</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Supermini</td>
<td>M F</td>
<td>M F</td>
<td>M F</td>
<td>M F</td>
<td>M F</td>
<td>M F</td>
</tr>
<tr>
<td>0 - 15</td>
<td>III</td>
<td>IV</td>
<td>I</td>
<td>III</td>
<td>I</td>
<td>II</td>
<td>I</td>
</tr>
<tr>
<td>16 - 30</td>
<td>V</td>
<td>VI</td>
<td>III</td>
<td>I</td>
<td>XI</td>
<td>I</td>
<td>X</td>
</tr>
<tr>
<td>31 - 45</td>
<td>I</td>
<td>II</td>
<td>II</td>
<td>III</td>
<td>II</td>
<td>I</td>
<td>IV</td>
</tr>
<tr>
<td>46 - 60</td>
<td>II</td>
<td>II</td>
<td>II</td>
<td>II</td>
<td>II</td>
<td>I</td>
<td>I</td>
</tr>
<tr>
<td>61 - 75</td>
<td>I</td>
<td>II</td>
<td>II</td>
<td>II</td>
<td>II</td>
<td>I</td>
<td>I</td>
</tr>
<tr>
<td>76 - 90</td>
<td>III</td>
<td>I</td>
<td>III</td>
<td>II</td>
<td>II</td>
<td>I</td>
<td>I</td>
</tr>
<tr>
<td>90 +</td>
<td>I</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>10</td>
<td>12</td>
<td>6</td>
<td>11</td>
<td>16</td>
<td>2</td>
<td>4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Car Size</th>
<th>MAIS 0-1</th>
<th>MAIS 2+</th>
<th>MAIS 0-1</th>
<th>MAIS 2+</th>
<th>MAIS 0-1</th>
<th>MAIS 2+</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supermini</td>
<td>Male</td>
<td>Female</td>
<td>Male</td>
<td>Female</td>
<td>Male</td>
<td>Female</td>
</tr>
<tr>
<td>16</td>
<td></td>
<td>21</td>
<td>20</td>
<td>4</td>
<td>21</td>
<td>6</td>
</tr>
</tbody>
</table>

1 DUE TO Object in vehicle

Figure 2.6. Distribution of non-struck side male and female drivers according to injury level, ETS and vehicle type
Figure 2.7. Distribution of non-struck side male and female drivers according to body mass index
2.1.2 Model runs completed for Sub-tasks 3.1.2 to 3.1.4

The predictions from a series of model runs were compared to investigate the issues defined for sub-tasks 3.1.2 to 3.1.4. The models used in the numerical simulations were validated in WP1 of the project and included full-scale Finite Element (FE) vehicle models of a small family car and a large executive car, together with comparable MADYMO driver and front seat passenger (FSP) compartment models of the same vehicles, as shown in Figure 2.8.

A variety of MADYMO occupant models were fitted into the MADYMO compartment models for the model runs, providing predictions of injury risk, body kinematics and body loads. These included 5th, 50th and 95th percentile ellipsoid models of the Hybrid III, Eurosid dummies and equivalent sizes of the faceted human body model.

It was intended that the model runs would assess possible occupant injury risks under a wide variety of impact conditions. A core matrix consisting of eleven frontal/oblique and eight side impact conditions were decided upon based on an understanding of the current and prospective regulatory impact tests and the preliminary results obtained from the accident data analysis of sub-task 3.1.1. Details of these model runs are presented in Figure 2.9 and Figure 2.10. An additional one off impact condition of interest, involving a 90° car-car combined front and side impact, as shown in Figure 2.11, was also investigated with the large executive vehicle model only. Problems and time constraints were encountered in investigating the injury risk of all modelled occupant types and sizes under the full array of impact conditions detailed in Figure 2.9 to Figure 2.11 for both the large and small vehicle models. As such, a selection of the proposed model runs was completed and as many of the reliable predictions from these model runs were analysed for the purposes of investigating the issues of sub-tasks 3.1.2 to 3.1.4.
The procedure for obtaining injury risk predictions for the separate impact conditions initially involved completing full-scale simulations of the impacts with the FE vehicle models. The gross vehicle motion of the modelled FE vehicle was then imposed on the equivalent MADYMO vehicle compartment model. An exception to this general procedure concerned side impacts into the small family FE vehicle model where there was no equivalent MADYMO compartment model. In this instance the small family FE vehicle model included an FE Eurosid dummy model in the driver position of the vehicle during simulated driver side impacts. Injury predictions for this set of simulations were obtained directly from the FE model. However, because the human body model is programmed in a different code to that used in the construction and running of the small family
vehicle model it was not possible to investigate the human body model’s predictions under this set of impact conditions.

Relevant selections of the predictions from the model runs were compared and analysed for sub-tasks 3.1.2 to 3.1.4. Predicted injury criteria values were compared for the analyses, although in general these all tended to be below injury criteria threshold limits. This presented difficulties in interpreting the model’s predictions with respect to identifying “gaps” in the regulations. Consequently, further to the predicted injury values, more emphasis was placed on analysing and interpreting the body segment trajectories of the various occupant models and the possible implications that differences in these responses might have on injury risk.

2.1.2.1 Results sub-task 3.1.2 – Parametric studies regarding impact speed and direction

Relevant model predictions compared in sub-task 3.1.2 were obtained from the following model runs:

- Small family FE side impacts with 50th percentile driver Eurosid dummy model sat on the struck side of the vehicle.
- Small family frontal impacts at 20% and 40% overlap at both 30 km.h⁻¹ and 50 km.h⁻¹ with driver and FSP Hybrid III 50th percentile occupant models.
- Large executive frontal impacts at 20% overlap at 50 km.h⁻¹ and 40% overlap at 50 km.h⁻¹ and 70 km.h⁻¹ with driver and FSP Hybrid III 50th percentile occupant models.
- Large executive 90° car-car impact with human body models.

For these model runs predicted HIC, VC and chest compressions were typically between 14-291, 0.01-0.72 m.s⁻¹ and 3.1-46.9 mm respectively. Exceptions to these findings included the 50 km.h⁻¹ rear axle side impact on the small family car in which the peak predicted VC value was 1.02 m.s⁻¹. This impact condition caused limited compartment intrusion, but increased the vehicle rotation resulting in a more severe impact on the occupant model from the door and B-pillar. Also, high HIC values of between 968 and 3401 were predicted for the occupant models in the large executive vehicle compartment model for the 40% overlap impact at 70 km.h⁻¹. This was attributable in the case of the driver occupant model to the airbag bottoming out during the model run allowing the head to strike the steering wheel as shown in Figure 2.12.

Figure 2.12. Driver response for 70 km.h⁻¹ and 40% overlap impact for the large executive MADYMO compartment model

Overall, higher impact speeds led to higher injury predictions. This was consistent with higher levels of intrusion for the simulated side impacts with the small family vehicle model. For the frontal...
overlap impacts with the small family vehicle models an increase in overlap generally led to an increase in the magnitude of the injury predictions. In contrast, for the large executive vehicle model runs an increase in impact overlap for the frontal model runs led to reductions in the magnitude of the predicted injury criteria.

For the side impacts on the small vehicle model it was found that impacts occurring at +30 degrees were more severe to the driver than those at -30 degrees. Figure 2.13 shows that the +30° impacts caused the head to strike the B-pillar, with intrusion increasing the loading on the Eurosid ribs. For the –30° impact there was a higher level of intrusion into the compartment, which led to higher levels of abdominal and pelvis loading, whereas the HIC remained low as the head missed the B-pillar in the 30 km.h\(^{-1}\) impact and only underwent a glancing blow of the B-pillar at 50 km.h\(^{-1}\).

![Small family car side impact at +30°](image1)
![Small family car side impact at -30°](image2)

**Figure 2.13. Comparison of driver occupant responses for a +30° and -30° side impact into the small family FE vehicle model at 50 km.h\(^{-1}\)**

For the bullet vehicle in the large executive car-car impacts, Figure 2.14 shows that the occupant model experienced a large amount of lateral movement within the confines of the compartment model. This resulted in the belt moving up around the neck of the driver occupant model. This response could place injurious loads on the front and side of the neck, which may not be considered in the current injury criteria that are defined for the necks of dummies.

![0ms](image3)
![100ms](image4)

**Figure 2.14. High neck loading on 5th, 50th and 95th human body occupant driver models for the bullet vehicle impact in the 50 km.h\(^{-1}\) car to car impact of the large executive vehicle model**

2.1.2.2 Results sub-task 3.1.3 - Protection of the human form compared to that of a dummy

As regulatory tests are performed with dummies there are concerns that vehicle designs are being optimised to reduce the injury risk to dummies rather than real humans. The intentions of this sub-task were therefore to identify potential problems in using dummies for assessing injury risks by
comparing the injury predictions from dummy and human body models under equivalent impact conditions.

The relevant model predictions compared in sub-task 3.1.3 were limited to the following model runs:

- Driver and FSP Hybrid III and Human body models in the large executive vehicle for impacts of 20 % and 40 % overlap at 50 km.h⁻¹
- Driver and FSP Hybrid III and human body models in the large executive vehicle for 30° barrier impacts at 50 km.h⁻¹
- Driver and FSP Hybrid III and human body models in the large executive vehicle model for the 60° rigid wall impact at 70 km.h⁻¹
- Driver and FSP Hybrid III and human body models in both bullet and target large executive vehicle models for the 90° car-car impact at 50 km.h⁻¹

HIC was the only injury criteria compared for this sub-task as the remaining injury criteria are specific to the structural response of a dummy rather than that of a human. Consequently, there exist inconsistencies when comparing dummy injury criteria predicted by a human body model with those predicted by a dummy.

Overall, predicted HIC values for the model runs investigated in this sub-task ranged between 17.7 and 307. For the frontal overlap large executive model impacts, predicted HIC values for the driver and FSP human models were between two and three times greater than those predicted by the Hybrid III model. Similarly, the predicted HIC value for the human driver model in the 30° barrier impact at 50 km.h⁻¹ was over 80 % greater than that predicted by the Hybrid III model. In comparison to the Hybrid III model it was generally found for frontal impacts that the human model travels further forward in the seat, penetrates further into the frontal airbag, experiences greater lateral head rotation and less head rebound, as shown in Figure 2.15. Similar differences in the dynamic responses of the human body and Hybrid III models were noticeable in the predicted results from the 90°, 50 km.h⁻¹ car-car large executive vehicle model impact. The higher lateral rotation of the human head towards the side structures of the modelled vehicle suggests that under higher severity impacts the head may strike stiffer internal structures of the vehicle compartment leading to higher predictions of HIC.

It was uncertain if the side head airbags would fire under the 60° rigid wall impact at 70 km.h⁻¹. Consequently, two simulated compartment model runs of the large executive vehicle model impact into a 60° rigid wall at 70 km.h⁻¹ were completed in which the side head airbags did and did not fire. In contrast to the previous model predictions it was found for these model results that HIC values predicted by the human body model for both the driver and FSP were lower than those predicted by the Hybrid III model. Considerable differences were also observed in the body segment trajectories of the occupant models depending on whether the side head airbag did or did not fire. In the instance when the airbag did fire both occupant models strike the side door at approximately the same time. However, the Hybrid III rebounds off the door and the head of the Hybrid III model bounces off the head side airbag. In contrast, the human body model stays in contact with the side door for longer and on account of a greater flexibility in the neck the human head slips under the side head airbag model after an initial contact. These differences are shown in Figure 2.16. The possibility therefore exists that the airbag may be optimally tuned for the responses of a Hybrid III dummy, but this may not be adequate to protect a real human head.
Figure 2.15. Comparison of predicted human body (blue) and Hybrid III (pink) responses for the large executive vehicle impact at 40% overlap and 50 km.h\(^{-1}\).

With no side head airbag firing both occupant models again slide towards the driver’s door, but the increased lateral flexion of the human body model neck allows the head to penetrate further beyond...
the confines of the vehicle compartment as bounded by the door glass. This predicted response is shown in Figure 2.17. No contact was defined between the head and the door glass in these model runs as the contact characteristics for this interaction were unknown and there also existed the possibility that under the 60 degree rigid wall impact the door glass may shatter if it is not reinforced or laminated. Figure 2.17 shows that for the 60 degree rigid wall impact without side head airbag firing there exists the possibility of the human head experiencing a higher injury risk as a result of striking either a toughened pane of glass or unsafe structures beyond the confines of the vehicle compartment. This same extension of the head outside the confines of the vehicle was also observed for other sizes of human body models under equivalent impact conditions, as shown in Figure 2.18.

Figure 2.17. Comparison of predicted human body (blue) and Hybrid III (pink) responses for the large executive vehicle 60 degree rigid wall impact at 70 km.h\(^{-1}\) (without airbag firing)

Figure 2.18. 5\(^{th}\), 50\(^{th}\) and 95\(^{th}\) human model driver response during 60 degree rigid wall impacts at 70 km.h\(^{-1}\) in the large executive vehicle model (No side head airbag firing)
2.1.2.3 Results sub-task 3.1.4 – Effect of occupant size and seating position

Regulatory and consumer testing typically use 50th percentile Hybrid III dummy models set in one particular position within the vehicle compartment. The intentions of this sub-task were to identify potential areas of increased risk to different sized occupants under equivalent impact conditions and the influence that seating position has on injury risk.

The relevant model predictions compared in sub-task 3.1.3 were limited to the following model runs:

- Small family frontal impacts at 20 % and 40 % overlap at both 30 km.h\(^{-1}\) and 50 km.h\(^{-1}\) with driver and FSP Hybrid III 5th, 50th and 95th percentile occupant models
- Large executive frontal impacts with 20 % and 40 % overlap with both human body and Hybrid III occupant models
- Large executive 90th car-car impact at 50 km.h\(^{-1}\) with Eurosid, Hybrid III and human body occupant models.

**Small Family Vehicle** - For the small family frontal vehicle impacts values of HIC, VC and chest compression respectively ranged between 4.7 to 439, 0.048 to 0.456 m.s\(^{-1}\) and 14.6 to 40.3 mm. As shown in Figure 2.19, with the exception of chest compression, the highest injury predictions for the driver were constantly predicted by the 5th percentile Hybrid III model inferring that under the small family frontal impact conditions, small occupants are less well protected. Noticeably, the HIC predictions from the 50th percentile Hybrid III occupant models were almost consistently lower than those predicted by the remaining Hybrid III occupant models. It is implied from this set of model predictions that there may be some degree of optimisation in vehicle safety performance for 50th percentile Hybrid III dummies.

Considerable differences in the predicted dynamic responses of the Hybrid III dummy models were observed for the small family offset frontal vehicle impacts. As shown in Figure 2.20, the 50th percentile dummy model generally had a very balanced and controlled dynamic response during the simulated impact. However, for the 5th percentile dummy the head rebounds following contact with the frontal airbag leading to submarining and greater knee penetration into the knee bolster. For the 95th percentile Hybrid III the restraints and airbag are overloaded by the increased mass of the occupant model. During the simulated impact the 95th percentile Hybrid III moves further forward in the seat compared with the 50th percentile Hybrid III model and experiences greater intrusion into the knee bolster. The excessive degree of 95th percentile Hybrid III knee penetration into the bolster of the compartment model suggests that the contact characteristics defined for this feature in the compartment model did not anticipate such high loading.
Figure 2.20. Comparison of 5th, 50th and 95th Hybrid III model responses for a 40% overlap impact in the small family vehicle at 50 km.h⁻¹

**Large Executive Vehicle** - Injury criteria predictions from the large executive frontal impact model runs were of a similar magnitude to those obtained from the small family vehicle model. In contrast to the predictions obtained from the small family vehicle model runs the 5th percentile Hybrid III model consistently provided the lowest predictions of HIC for the large executive model, as shown in Figure 2.21.

![Comparison of Driver and FSP Injury Responses by Occupant Size](image)

Figure 2.21   Comparison of Driver and FSP Injury Responses by Occupant Size

In general, the dynamic response of the various sizes of occupant model for the large executive model runs were similar to those obtained for the small family frontal vehicle impacts. As shown in Figure 2.22, the 5th percentile occupant dummy model in the large executive vehicle frontal impact...
experiences some head re-bound and a degree of seat submarining, while the 95th percentile occupant model again travels further forward in the seat due to the increased loading on the restraint systems.

![Image of Hybrid III dummy model responses for a large executive vehicle 40% overlap impact at 50km.h⁻¹](image)

**Figure 2.22.** 5th, 50th and 95th Hybrid III dummy model responses for a large executive vehicle 40% overlap impact at 50km.h⁻¹

Figure 2.23 and Figure 2.24 respectively illustrate the differences in the body trajectories of the Hybrid III driver models for the rigid 60th rigid wall impact when the side head airbag is fired and when it is not. With no side head airbag firing the head of the 5th percentile dummy model slides off the frontal airbag towards the door, but the seat belt prevents the ejection of the head beyond the confines of the vehicle compartment. This same response is observed for the impact when the side head airbag is fired, as the head of the 5th percentile Hybrid III dummy model misses the side head airbag, as shown in Figure 2.25. Both the 50th and 95th percentile models strike the side head airbag when it is fired. However, without side head airbag firing the head of the 50th percentile Hybrid III dummy falls outside the confines of the vehicle as no contact definition is defined between the head and the simulated door glass. For the larger 95th percentile Hybrid III occupant model the head strikes the non-inflated side head airbag when it is not fired resulting in an artificially high HIC value of nearly 3000. These results emphasise the importance of knowing when and which restraint systems will operate for impact conditions that are to be investigated as this can significantly influence the predicted injury responses from the models.
Figure 2.23. Comparison of 5th, 50th and 95th Hybrid III occupant model responses for a large executive vehicle impact into a 60 degree rigid wall at 70 km.h⁻¹ (No side head airbag firing)

Figure 2.24. Comparison of 5th, 50th and 95th Hybrid III occupant model responses for a large executive vehicle impact into a 60 degree rigid wall at 70 km.h⁻¹ (With side head airbag firing)
The influence of front seat passenger fore-aft position on the injury predictions of the 5th percentile Hybrid III dummy model were investigated for the small family 20 and 40% overlap frontal impact model runs at 50 km.h⁻¹. Three seat positions were investigated matching the fore-aft seat positions of the 5th, 50th and 95th percentile Hybrid III driver models in the small family vehicle compartment model. The 5th percentile occupant was studied to clarify the finding from the accident data study that small female passengers appeared to be at an increased injury risk in frontal impacts. The injury predictions from these model runs are shown in Figure 2.26. The general findings are that as the position of the seat is moved aft, the 5th percentile Hybrid III dummy interaction with the frontal airbag reduced, as shown in Figure 2.27. This generally led to lower HIC, but higher VC predictions.

Figure 2.25 5th Percentile Hybrid III dummy head missing the side head airbag during a large executive vehicle impact into a 60 degree wall at 70 km.h⁻¹

Figure 2.26. Comparison of 5th Percentile Hybrid III passenger predicted injury responses for small family frontal vehicle impacts as the fore-aft seat position is altered
2.1.2.4 Identification of ‘gaps’ in current regulations

The results from sub-tasks 3.1.1 to 3.1.3 were analysed to establish a more coherent picture on the existence of possible “gaps” in current regulations. Three such “gaps” were statistically identified from the accident data analysis as follows:

- For drivers in frontal impacts a drop is observed in injury risk at an ETS of 65-69 km.h\(^{-1}\) and a Delta V of 70-74 km.h\(^{-1}\);
- Female passengers in frontal impacts are at a greater injury risk than males;
- Female drivers in NSS impacts are at greater risk than males.

The data set supporting the first observed “gap” was small and as such limited confidence could be placed on the existence of a drop in injury risk to drivers at a specific range of impact speeds. Furthermore, there were no obvious results from the modelling that could be used to categorically support the findings from the accident data analysis. It was identified that it would be difficult to use modelling to support the findings for the first two identified “gaps” due to a lack of understanding surrounding the specific impact conditions that contribute to these “gaps”. The specific impact conditions associated with injuries to NSS female drivers were better understood and as such it was decided to complete a purpose designed model run to further investigate this result from the accident data analysis using the available WP3 consortium models.
The small family vehicle model as described in section 2.1.2 was used in the setup of the purpose designed model run. In the simulation the vehicle model was struck on the passenger side by a mobile deformable barrier travelling at an initial speed of 80 km.h\(^{-1}\). A 50th percentile side occupant dummy model was fitted in the driver seat of the vehicle model for the simulation. Images from the model run are shown in Figure 2.28. These clearly show the occupant model traversing to the struck side of the vehicle during the impact and the head striking the intruded door. Injury predictions for this model run were HIC = 2190 and a 3ms head acceleration of 155g. The modelling work previously completed did identify that human models possess greater flexibility in the spine and neck than dummy models. As such it is anticipated that the injury risk for a human body model exposed to equivalent impact conditions to those presented in Figure 2.28 may be higher than those predicted for a Eurosid dummy. Despite this limitation the model run proved that the identified “gap” from the accident data analysis could be adequately represented in a simulation. It was decided that this accident condition provided the ideal accident scenario that could be investigated by means of VT. Consequently, additional work on the potential of VT NSS impacts was completed in tasks 3.2 and 3.3 of WP3, as described in sections 2.2 and 2.3.

![Small Family NSS simulated vehicle impact](image)

**Figure 2.28** Small Family NSS simulated vehicle impact

The modelling work raised/highlighted concerns with issues that need to be addressed in order for VT to become a formalised part of regulatory or consumer testing procedures. Listed below are the main challenges that have been identified from the modelling work that need to be addressed:

- As a virtual test procedure may assess the injury risk to different sizes and types of occupants under a variety of impact conditions different from those currently tested it is more difficult to anticipate the interactions between the modelled occupant and its interior. As such it is important that adequate geometrical detail and material data is used in the construction of the models to ensure that correct contacts, and therefore accurate predictions of injury risk, are obtained from the models.

- Models used in VT procedures need to be robust enough to consider impacts under a wide range of impact conditions to ensure that model runs do not end prematurely due to poor model structure. It is also necessary to develop the confidence that predicted results obtained from models are accurate and believable.

- The human body model is considered a better option than a dummy model for assessing injury risk in a vehicle interior. However, additional work is needed to confirm the model’s performance under non-standard impact conditions. Furthermore, specific human body model injury criteria need to be developed for the model, which currently predicts injury values and injury thresholds which are only relevant for dummies.
• If the procedure of any virtual testing includes imposing motion from a test vehicle or full-scale model onto a multibody compartment model it is important to ensure that the measured motion of the vehicle provides an accurate representation of the vehicle’s kinematics and is not affected by localised vibrations of the vehicle structure. Imposing inaccurate motions of the vehicle onto a multibody compartment model will adversely affect the predictions of injury risk.

• It is important that restraint systems are accurately modelled. This requires an understanding of when and if the various restraint features will trigger during the course of an impact which may be very different from the impact conditions which are currently considered in regulatory and consumer tests.

2.1.3 **Effect of occupant disability**

Sub-task 3.1.6 of WP3 was designed to investigate the influence that an occupant’s disability has on their safety in the event of a vehicle accident and involved the following phases of work:

• A literature review and preliminary analysis of computer simulation results
• A sled test modelling investigation of the most dangerous cases of occupant disability
• A sled test modelling study evaluating the effectiveness of different types of restraint systems in protecting disabled occupants
• A modelling investigation of the influence that the vehicle compartment has on a disabled occupant’s injury risk
• An investigation of the current regulations concerning the transportation of disabled passengers in cars

2.1.3.1 **Literature review and preliminary analysis of computer simulation results**

A short literature review together with analyses of the relevant and available statistical accident data on disabled occupant injuries was completed. A limited amount of accident data for disabled vehicle occupants was found. It was concluded from these findings that either the number of accidents with disabled occupants is negligible, or the reason for the lack of data is due to the fact that occupant disability is not recorded in police accident reports.

The predictions from previous modelling work investigating the injury risk to disabled occupants in vehicle accidents were analysed. The indications from these predictions were that for certain impact conditions there are potentially hazardous body kinematics for occupants with certain types of disability (e.g., arm or leg amputees).

2.1.3.2 **A sled test modelling investigation of the most dangerous cases of occupant disability**

The injury risks to disabled occupants were investigated in MADYMO simulated sled tests using three different 50th percentile occupant models: Hybrid III ellipsoid and facet models, and the human body model. All three models were modified to simulate occupants with the following disabilities:

• Occupant without right arm – WRA
• Occupant without left arm – WLA
• Occupant without legs – WL
• Occupant without legs below knees - WLBK

In addition to the modified models, simulated sled tests were completed with the unmodified occupant models to provide a baseline comparable able bodied occupant response. The responses of the
restrained occupant models in a basic three-point belt system were simulated under two acceleration pulses peaking at 10 and 15 g.

General trends of motion for the Hybrid III models and the Human body model were very similar. The WRA and WL modelled disabilities were considered the most hazardous as far as the relative rotational motions of the upper torso were concerned and were also more susceptible to slipping out of the 3-point belt system. Overall, in comparison to the non-modified occupant models it was inferred from the models’ predictions that WRA and WL disabled occupants are not sufficiently protected by the 3-point belt system. Comparing the occupant models, the range of predicted body motions was found to be very different with the human body model demonstrating a greater degree of flexibility and a better biofidelic response. On account of its improved biofidelic behaviour it was decided that the human body model should be used to investigate modifications to the restraint system design that could be used to mitigate the increased injury risk of disabled occupants in automotive accidents.

2.1.3.3 Sled test modelling study evaluating the effectiveness of different types of restraint systems in protecting disabled occupants

Simulated sled tests were completed to assess whether alternative restraint system designs to the 3-point belt system could be used to reduce or eliminate previously identified undesirable injury mechanisms for disabled occupants such as slipping out of the belt system and excessive relative rotation of the upper torso. The following three restraint system designs were investigated:

- 4-point safety belt
- 3-point safety belt with pre-tensioners and 4 kN load limiters
- 4-point safety belt with pre-tensioners and 4 kN load limiters

The human body model was used in all model runs and with the exception of the restraint systems the model set up and boundary conditions were identical to the sled tests described in section 2.1.3.2.

In comparison to the 3-point belt system the 4-point belt system dramatically reduced upper body rotation and prevented body segments from slipping out of the belt system especially for the WL, WRA and non-modified occupant models. However, better restraint of the upper part of the body led to submarining, greater neck flexion and abdominal loading/deflection, as shown in Figure 2.29. The use of the 4-point belt system also resulted in slightly higher injury predictions although these were still below injury threshold limits.

Figure 2.29. Comparison of human body response with and without modelled disabilities for the 4-point belt system
In comparison to the 3-point belt system, the three-point belt with pre-tensioner and load limiters reduced submarining but caused greater back and head flexion. Predicted injuries were slightly higher than for the 3-point belt system without pre-tensioning and load limiters, but lower than those predicted when the 4-point belt system was recreated in the sled tests. However, even with the load limiters and pre-tensioner there was still a high degree of upper body rotation and a risk of body segments slipping out of the 3-point restraint. This was particularly true for the WL modelled occupant as shown in Figure 2.30.

Figure 2.30. Comparison of human body response with and without modelled disabilities for the 3-point safety belt system with pre-tensioner and load limiters

The 4-point restraint with pre-tensioning and load limiters provided many of the benefits associated with the other designs of restraint system investigated, reducing both rotation and occupant submarining. Injury predictions for these model runs were not as low as for the 3-point belt system with pre-tensioning and load limiters, but were lower than the injury predictions obtained from the simulated sled tests in which the standard 4-point belt system was modelled.

2.1.3.4 Modelling investigation of the influence that the vehicle compartment has on a disabled occupant’s injury risk

A MADYMO compartment model was developed based on the dimensions of a FIAT Cinquecento and included the following components: seat, floor with foot board, belts and restraints. The WRA occupant human body model was fitted into the compartment model as this occupant type was considered to possess the greatest injury risk based on the previous simulated sled test investigations. The acceleration pulse used to load the compartment model peaked at 26 g.

With disability it was observed that the head struck the dashboard when the occupant was fitted with a regular 3-point belt system leading to above threshold predictions of HIC. However, the head was prevented from striking the dashboard when the WRA occupant model was fitted with the 4-point restraint system with pre-tensioning and load limiters. Additional simulations were completed, which demonstrated that the presence of an airbag would prevent head impacts with the vehicle interior and reduce injury loads in the neck.

2.1.3.5 Investigation into the current regulations concerning transportation of disabled passengers in cars

A review of the current international regulations relating to automotive and occupant safety was completed. No specific references were found in the reviewed regulations and standards relating to necessary safety requirements for disabled occupants. It was concluded that no regulations or standards currently exist relating to the safety of disabled occupants in automotive vehicles.
Propose a virtual test procedure that extends the range of protection afforded to car occupants

As detailed in section 2.1, the main finding of task 3.1 of WP3 was the discovery of an elevated injury risk to female drivers of small vehicles in high speed NSS impacts. This discovery was derived from both statistical analysis of accident data from the UK CCIS accident database and demonstrated in full scale simulated impacts with a small family FE vehicle and occupant model. A virtual test procedure was proposed incorporating the NSS impact case as an example of the means by which VT could be used to enhance and expand upon the accident conditions that are currently investigated in regulatory and consumer automotive tests.

The EuroNCAP test procedures currently provide significant impetus for advances in automotive safety above the minimum performance levels prescribed by regulations and it was agreed by the WP3 consortium contributors that these procedures could provide a baseline point of reference and framework on which any future VT procedures could be based. In the instance of the NSS impact conditions the following general VT procedure was proposed:

- Complete standard regulatory (EuroNCAP) side impact simulation as a baseline and validate against test results.
- Repeat simulation with different sizes of human body model
  - Identify differences in the kinematic response of dummies compared with the human body model
  - Identify differences in injury criteria between dummy and human body models
  - Adjust and verify test (NCAP) modifiers
  - Assess injury risk to occupants of different sizes
- Complete virtual test impact (NSS impact from WP3 studies)
  - Complete simulation with human body model
  - Full vehicle motion and intrusion needs to be modelled accurately
  - Simulations repeated with different occupant sizes
  - Predicted results from VTs need to be integrated with physical test results (ie. star rating in EuroNCAP)
  - Studies limited to investigations of injury criteria and vehicle intrusion and could not for instance be used to study compartment access post impact.

In light of the proposed VT procedure additional modelling work was completed within the scope of this WP task to investigate in more detail the modelling methodologies and procedures that may typically be employed to carry out a VT procedure as defined above. In addition, the previous compartment modelling work completed in WP3.1 did not simulate the vehicle intrusion resulting from the impact conditions investigated and the potential influence that this has on an occupant’s injury risk. As such, work was also completed in this task to determine the influence that vehicle intrusion has on an occupant’s injury risk and the impact that this would have on the results from a VT procedure if the intrusion were not accurately modelled. The modelling work was conducted in two phases: the first investigating the modelling methods and approaches for simulating the standard EuroNCAP side impact conditions and the second investigating the modelling methods and approaches for simulating the NSS virtual impact test conditions. Work was completed in both modelling phases to investigate the influence that accurate modelling of the vehicle intrusion has on the models’ predictions. The work was limited by the vehicle and compartment model’s available to the WP3 consortium which included both compartment and full FE vehicle models of a large executive and small family vehicle. For the purposes of this investigation the FE and compartment models of the large executive vehicle model were used for all the modelling work.
2.2.1 EuroNCAP simulations

Initially a full-scale EuroNCAP side impact simulation was completed with the large executive FE vehicle model, as shown in Figure 2.31, in order to obtain the full kinematics and intrusion response of the vehicle test. The kinematics and intrusion response from the FE simulation were then applied to the compartment model, as shown in Figure 2.32, in order to obtain predicted injury responses for the impact. This approach to modelling the injury response within the framework of a VT procedure is considered more desirable as the detailed model in Figure 2.31 is computationally intensive. Transferring the required information to a multi-body compartment and occupant model improves the computational efficiency of running the models.

![Figure 2.31. Large executive vehicle model in EuroNCAP side impact simulation](image)

![Figure 2.32. MADYMO multi-body compartment model of the large executive car](image)

Repeated model runs were completed with the multi-body compartment model with and without simulated door intrusion to consider the influence that this has on the predicted response from the model. Differences in the body trajectories of the occupant model for these model runs are shown in Figure 2.33 and comparisons of some of the injury predictions from these model runs are shown in Figure 2.34. As shown, with the exception of the head resultant acceleration, predicted chest deflections, sternum resultant acceleration and pelvis resultant acceleration are significantly greater when the door intrusion is simulated. Without simulated door intrusion the predicted peak resultant head acceleration is approximately 40 g (33 %) greater than that predicted when the door intrusion is simulated.
Figure 2.33. Comparison of MADYMO compartment model simulations without (a) and with (b) simulated door intrusion

Figure 2.34. Comparison of predictions from compartment model simulations completed with (blue line) and without (pink line) simulated door intrusion for a EuroNCAP side impact

2.2.2 NSS Driver simulations

The use of the large executive vehicle compartment model to simulate NSS impacts conflicted with the findings from the accident data results, which indicated that the injuries were mainly associated with drivers of super-mini vehicles rather than large executive type vehicles. In an attempt to re-create more accurately the environment of a super-mini the driver seat in the compartment model was positioned 0.65 m from that of the passenger seat as shown in Figure 2.35. This measure is consistent with measures of seat positions in super-mini vehicles completed under the European 5th Framework project PRISM. Furthermore, in order to simulate a high speed NSS impact the nodal displacements of the deforming structures modelled in the EuroNCAP conditions (50 km.h\(^{-1}\)) were multiplied by a factor of 1.6 in order to re-create an assumed NSS impact velocity of 80 km.h\(^{-1}\). A faceted human body model was used in the multi-body compartment model and as in the EuroNCAP model studies simulations were completed with and without door intrusion.
The influence that simulating door intrusion has on the behaviour of the occupant model is shown in Figure 2.36. Up to the point of head impact there is very little difference in the trajectories of the occupant models. Whether door intrusion is simulated or not the images in Figure 2.36 show that the restraint has very little impact on restraining the occupant motion in this type of impact. Later on in the impact the images also highlight the importance of simulating the intrusion of the door structures for this impact. When the door intrusion is not simulated there is no head contact and this significantly alters the injury predictions for the head. As well as emphasising the observations from the accident data study the results also confirm the absence of these type of injuries in larger vehicles as possibly considered in the impact with no simulated door intrusion.

2.3 Demonstrate the application of a virtual test procedure in one example

A PowerPoint presentation was produced providing a general overview of the findings and conclusions from the VITES project. Included within this presentation are details of the methods and processes proposed and investigated in section 2.2 on how VT could be employed to enhance and best fit into current regulatory and consumer testing. It is hoped that the presentation will provide a demonstration to interested parties on the current considered methods and approaches that should be adopted in a standardised test procedure incorporating VT. A copy of the PowerPoint demonstrator presentation was forwarded to the DfT for their records.
Figure 2.36. Comparison of NSS simulated impacts without (a) and with (b) simulated door intrusion
3 Discussion

The principle objectives of WP3 of the VITES project were to identify “gaps” or accident conditions which pose a greater injury risk to vehicle occupants and to propose a virtual test procedure that could be used to extend and enhance the level of protection to vehicle occupants. Several conditions were identified as potential “gaps” based on an analysis of accident data. A VT procedure has been proposed that attempts to address the identified “gap” relating to the greater injury risk to drivers of super-mini vehicles in high velocity NSS impacts (2.2). Although the proposed procedure provides an indication of how VT may be applied in test procedures, it has been identified that additional work is needed before VT becomes an accepted and standardised procedure that can be used in regulations and standards to enhance occupant safety (2.1.2.4).

Difficulties were encountered in identifying the existence of “gaps” based on the predictions from a series of simulated impacts. The principle difficulty related to the fact that the simulated impact conditions resulted in predicted injury values which were generally all below injury threshold limits. As such there was no obvious injury risk associated with the impact conditions investigated. In addition, it is recognised that the investigation was limited by the fact that the simulated impacts were completed with only two vehicle models representing two specific vehicle types. Consequently, any “gaps” that may have been identified in the models’ predictions would most likely be specific to the two vehicle types only and not representative of the injury risks associated with the complete vehicle fleet. Ideally the simulated impacts should have been completed with a complete fleet of vehicle models or with a series of models representing a sample of vehicle models forming the main vehicle types found on the roads. The two vehicle models used in the study were unfortunately the only models made available for the WP3 consortium.

Despite the limitations associated with the simulations completed under WP3 some general areas of concern in occupant safety practices were identified in the predicted results from the models. These are:

1. For instance, it was noticeable during simulated oblique impacts that the 5th percentile model was loaded on the neck by the diagonal belt and missed inflated side head airbags which appeared to be specifically designed for use with 50th percentile dummies.

2. In addition, considerable differences were observed in the behaviour and predicted injury risks to human body models compared with Hybrid III dummy models under equivalent impact conditions, emphasising the potential differences in the real human response compared with that of a dummy.

3. The simulated impacts have also served to identify problems that need to be resolved if VT is to become a standardised procedure within regulatory testing. For instance, it was noted that when the models were used to simulate impact conditions beyond those for which they had been designed, model runs often ended prematurely due to model instabilities.

4. There were also often situations where the model detail was not adequately defined for the impact conditions, such as compartment models having no side structure, which prevented the simulation of side or oblique impacts with these models. In some of the simulated impacts contact definitions were not adequately or accurately defined and vehicle compartment intrusion was not simulated in any of the model runs, which ignored features of a vehicle impact that can have a considerable influence on increasing the injury risk to the occupant. Problems were also experienced in correctly simulating the response of the modelled restraint and airbag systems for the investigated impact conditions. Suppliers of these safety restraint systems are often reluctant to divulge specific details concerning the performance of their systems which is needed to accurately represent the performance of these systems in simulated vehicle impacts. As such this transfer of information would need to be looked into further and addressed if VT in regulated procedures was to be conducted by organisations other than the restraint system suppliers. This is a major issue to be resolved on a philosophical level …..
It is understood from the VITES project work that simulations are adequately developed in a number of key areas. Currently, simulations can be adequately developed to simulate the responses of various sizes and types of occupant model (eg human body and dummy), restraint systems and vehicle designs under a wide variety of impact conditions. Despite the current simulation capabilities it has also been confirmed from the VITES project work that additional work in a number of additional key areas is needed before VT can become a standardised test procedure for assessing and enhancing occupant safety. Within the scope of WP3 it has generally been found that the accuracy and reliability of models needs to be improved. Testing in a virtual environment beyond current impact test conditions also possibly requires the development of more relevant injury criteria for the impact conditions investigated. Furthermore, injury threshold limits specific to the predicted injury criteria from the human body model are needed, as the majority of the limits currently used by the model are specific to the responses of dummies. Having achieved accurate and robust model predictions there is also a need to develop protocols on how predictions from models in VT procedures will be analysed, interpreted and integrated within current test procedures such as EuroNCAP. The ADVISER tool developed within WP1 of the VITES project provides a starting point on which these protocols could be developed, although additional work is needed to improve and enhance the capabilities of this tool. It is expected that work within the APROSYS consortia and the EEVC and ISO working groups will provide an effective platform on which the current limitations of VT can be resolved in order to allow standardisation of VT procedures.

Although a significant amount of work is needed to formalise and establish VT as an accepted and reliable means of expanding and enhancing current testing procedures, it is anticipated that this work will provide a number of significant benefits. It is expected that VT will provide a more cost effective means of assessing vehicle occupant safety under a wider range of impact conditions more representative of those observed in the real world than current regulatory physical testing. This will be assisted through the use of human body models that should be able to provide a more biofidelic response and better predictions of injury risk compared with dummy models.

3.1 Summary of additional project outcomes

Further to the initial objectives of the VITES project a number of additional valuable outcomes have arisen from the work as detailed in section 2. These additional outcomes can be summarised as follows:

- Section 2.1.2.2 - In comparison to the 50th percentile Hybrid III model it was generally found for frontal impacts that the 50th percentile human body model travels further forward in the seat, penetrates further into the frontal airbag, experiences greater lateral head rotation and less head rebound off the frontal airbag. The higher lateral rotation of the human head towards the side structures of the modelled vehicle suggests that under higher severity impacts the head may strike stiffer internal structures of the vehicle compartment leading to higher predictions of HIC.

- Section 2.1.2.2 - During equivalent simulated oblique vehicle impacts it was noticed that the head of the 50th percentile Hybrid III model rebounds off the side head airbag, whereas the head of the 50th percentile human body model slipped under the side head airbag. It was implied from these model predictions that airbag designs may be optimally tuned for the responses of a Hybrid III dummy, but this may not be adequate to protect a real human head response.

- Section 2.1.2.3 - For simulated frontal vehicle impacts in a small family vehicle model it was found that predicted injury measures were almost consistently lower for the 50th percentile Hybrid III model than equivalent predictions from its 5th and 95th counterparts under equivalent simulated impact conditions. It is implied from this set of model predictions that there may be some degree of optimisation in vehicle safety performance for 50th percentile Hybrid III dummies.
Section 2.1.2.3 – During simulated oblique impacts with a large executive vehicle model it was not certain if the side head airbags would fire under these impact conditions. As such simulations were repeated with and without side head airbag firing. With side head airbag firing it was found that the head of the 95th percentile Hybrid III dummy model struck the inflated airbag resulting in a predicted safe head impact. Without airbag firing the head of the 95th percentile dummy model struck the non-inflated side head airbag resulting in an artificially high HIC of 3000. These results emphasise the importance of knowing when and which restraint systems will operate for impact conditions that are to be investigated as this can significantly influence the predicted injury responses from the models.

Section 2.1.2.4 - Virtual testing has been successfully used to simulate a pre-identified accident condition and allow detailed investigations of this accident condition to take place.

Section 2.1.2.4 - As a virtual test procedure may assess the injury risk to different sizes and types of occupants under a variety of impact conditions different from those currently tested it is more difficult to anticipate the interactions between the modelled occupant and its interior. As such it is important that adequate geometrical detail and material data is used in the construction of the models to ensure that correct contacts, and therefore accurate predictions of injury risk, are obtained from the models.

Section 2.1.2.4 - Models used in VT procedures need to be robust enough to consider impacts under a wide range of impact conditions to ensure that model runs do not end prematurely due to poor model structure. It is also necessary to develop the confidence that predicted results obtained from models are accurate and believable.

Section 2.1.2.4 - The human body model is considered a better option than a dummy model for assessing injury risk in a vehicle interior. However, additional work is needed to confirm the model’s performance under non-standard impact conditions. Furthermore, specific human body model injury criteria need to be developed for the model, which currently predicts injury values and injury thresholds which are only relevant for dummies.

Section 2.1.2.4 - If the procedure of any virtual testing includes imposing motion from a test vehicle or full-scale model onto a multibody compartment model it is important to ensure that the measured motion of the vehicle provides an accurate representation of the vehicle’s kinematics and is not affected by localised vibrations of the vehicle structure. Imposing inaccurate motions of the vehicle onto a multibody compartment model will adversely affect the predictions of injury risk.

Section 2.1.2.4 - It is important that restraint systems are accurately modelled. This requires an understanding of when and if the various restraint features will trigger during the course of an impact which may be very different from the impact conditions which are currently considered in regulatory and consumer tests.

Section 2.1.3.5 - It was concluded that no regulations or standards currently exist relating to the safety of disabled occupants in automotive vehicles.
4 Conclusions

The principle objectives of WP3 of the VITES project were to identify “gaps” or accident conditions which pose a greater injury risk to vehicle occupants and to propose a virtual test procedure that could be used to extend and enhance the level of protection provided to vehicle occupants. Based on the results of both studies of accident data and the predictions from a series of parametric model runs, a better understanding of the potential “gaps” that exist in current regulations has been achieved and an understanding of the influence that parameters such as impact speed, direction, occupant size and type and seating position have on an occupant’s injury risk. The findings from this work have contributed to the development of a proposed VT procedure and the identification of the difficulties that must be overcome in order to establish VT as a standard procedure within regulations. Overall, the main conclusions of the work completed under WP3 of the VITES project are as follows:

- Based on studies of accident data three statistically significant accident conditions were identified that pose an increased injury risk to vehicle occupants. These are:
  1. a dip in the injury risk to drivers in the speed range 70-74 km.h\(^{-1}\),
  2. an increased injury risk to female passengers in frontal impacts and
  3. an increased injury risk to drivers in non-struck side impacts.

- Based on the findings from model predictions it is concluded that accident parameters such as the impact type, impact speed, occupant size and occupant type (dummy or human body model) have an influence on the predicted injury risk to vehicle occupants.

- In comparison to physical testing, which relies on uni-directional dummies to provide predictions of injury risk, VT is able to use human body models which can provide a more representative understanding of the injury risks to vehicle occupants under any loading conditions (ie multi-directional occupant models)

- The VITES WP3 consortia have made an initial proposal of a VT procedure that can be used to enhance and expand upon current safety test procedures applicable to automotive vehicles. This recommends that VT be incorporated within the EuroNCAP test procedures as this provides the current driving force for automotive safety.

- The proposed VT procedure is based on the injury risk to drivers of super-mini vehicles in high velocity non-struck side impacts.

- It is anticipated that VT has the potential to efficiently verify the protection afforded to vehicle occupants under additional and more realistic accident conditions.

- Human models can be used within VT procedures to provide biomechanical justification for current EuroNCAP modifiers
5 Future work

It has been identified through WP3 of the VITES project that additional work is needed in order to establish VT within regulatory test procedures. This report has determined that future work should consider the following areas:

- Human models can be used within VT procedures to provide biomechanical justification for current EuroNCAP modifiers
- Procedures are needed to define the requirements of vehicle models that will be used in VT procedures to ensure that they are robust and provide reliable model predictions
- Work is needed to improve the accuracy of model predictions including the development of better validation data
- Work is needed to improve the accuracy of the human body model’s predictions and specific injury criteria and tolerance limits are needed for these models.

6 Acknowledgements

The work described in this report was carried out in the Vehicle Safety and Engineering Department of TRL Limited. The authors are grateful to the UK Department for Transport and to the European Commission for their contributions in funding this work. Additional gratitude is also expressed to the following organisations that contributed to the work completed under WP3 of the VITES project:

- TNO automotive, Netherlands;
- Fiat Research Centre (CRF), Italy;
- BMW, Germany;
- Federal Highway Research Institute (BASl), Germany;
- Technical University of Graz (TUG), Austria
- Birmingham Automotive Safety Centre (BASC), UK
- Warsaw University of Technology, Poland