POLITECNICO DI TORINO

Department of Mechanical and Aerospace Engineering

Master’s Thesis
in
Mechanical Engineering

Side impact crash studied with FE simulation and Human Body Model

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Abstract

In this thesis, a FE system was developed in order to reproduce a Euro NCAP side impact test of a mid-size sedan and analyse the injuries with a Human Body Model (HBM). The FE model simulates the impact between an Advance European Mobile Deformable Barrier (AE-MDB) and a 2012 Toyota Camry, where a driver HBM is positioned, at 50km/h. The HBM model chosen is the THUMS model, provide by Toyota. Before including the HBM into the simulation, several steps were performed to set properly the simulations. A footprint of the driver seat was created, then, the HBM was positioned using PIPER software and, at the end, a seatbelt model was created in order to secure the driver occupant to the seat. The result obtained with the FE simulation were analysed through several parameters in order to have a complete idea of the injury severity due to the impact. The use of the Human Body Model allowed to obtain more information than the normal dummy used in the crash tests and gave the opportunity to have a clearer and more faithful idea of the body's behaviour during the impact.

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Chapter 1: Preface

1.1 Introduction

Side impact crash injuries are one of the principal causes of fatality, a study of Insurance Institute for Highway Safety (IIHS) said that in 2017, 25% of the death on road accidents were caused in a side impact scenario [1] [2]. The main cause of fatal injury in these cases are the thorax damage, responsible for nearly 60% of deaths [3]. These facts remark the importance of the study of this case scenario and the development of new and modern active/passive security devices. The development of the NCAP program, in that sense, it was a significant effort for the evaluation of the new automobile designs for performance against various safety threats with a standard procedure [4]. The main problem of the NCAP program, however, is the high expense of each test, since the vehicle tested is no more usable (up to 4 cars needed for an assessment by Euro NCAP) [5]. To solve this problematic and have a better understanding of the injury mechanisms, Finite Element models were realized to reproduce the real case scenario. The Human Body Models, in this regard, were a huge step on the increasing of the quantity and accuracy of data related to human response to any kind of stress, including crash situations, so that currently they are able to provide a more realistic response than the normal dummy used in a real crash test [6]. With all these instruments today it is possible to simulate, with a fair accuracy, different impact crash and analyse a massive quantity of data. Thanks to all the continue evolving of the road security field, the number of fatalities is decreasing every

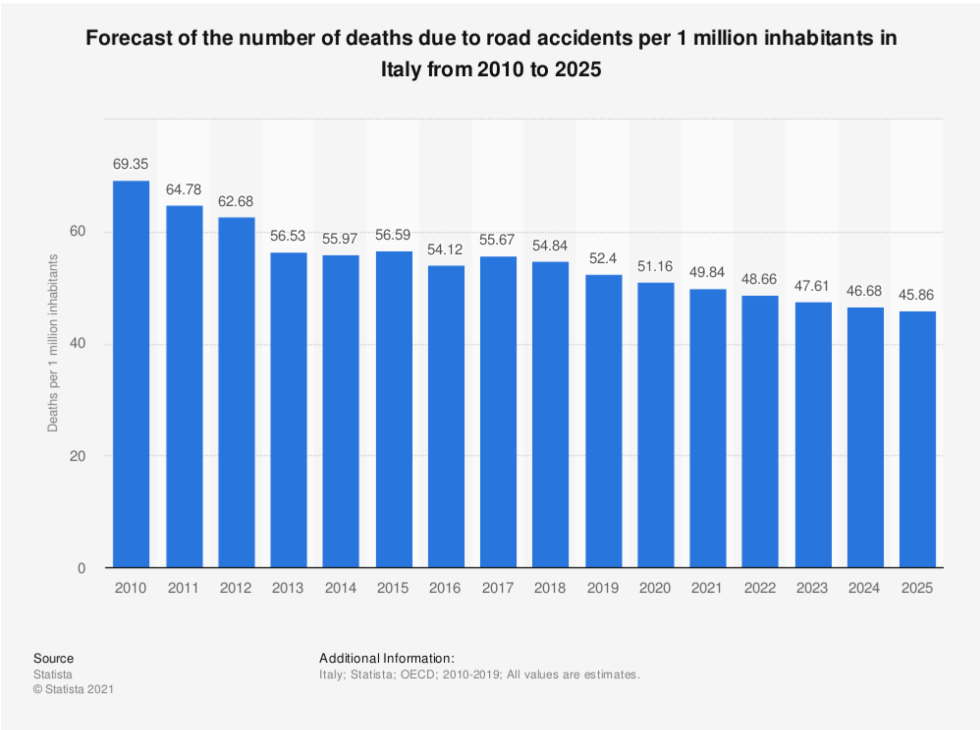


Figure 1.1 - Forecast of the number of deaths due to road accidents per 1 million inhabitants in Italy from 2010 to 2025

year. The instruments used in this thesis are just an example of why it was possible to achieve all this.

1.2 Purpose

The aim of this thesis is the simulation of a side impact crash, using a Finite Element simulation, and following the Euro NCAP regulation. A Human Body Model (HBM), able to simulate the reaction of a real body due to a crash scenario, was used in the simulation. Through some Injury Criteria, which will be discussed later, and the Euro NCAP score evaluation we are able to have a clear idea of the severity of the injury of the HBM. The car model used is a 2012 Toyota Camry provided by the Centre for Collision Safety and Analysis (CCSA). The impact object used, following the Euro NCAP standard procedure test, is a moving deformable barrier based on the 2013 Advanced European Movable Deformable Barrier (AE-MDB) Version 1.0 according to the Euro NCAP regulations and developed by Livermore Software Technology Corporation (LSTC). Finally, the last FE model used is the Total Human Model for Safety (THUMS) developed by Toyota. All the simulations were realized using LS-DYNA R9 Finite Element explicit code.

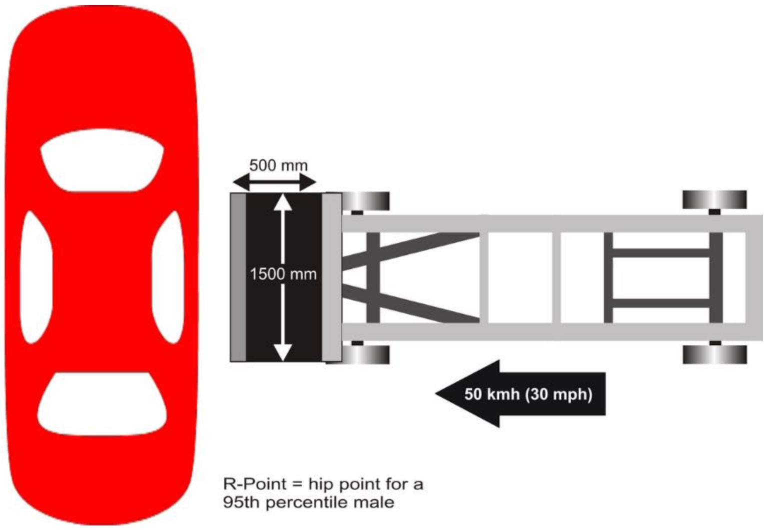


Figure 1 2 - Euro NCAP side impact

1.3 Roadmap

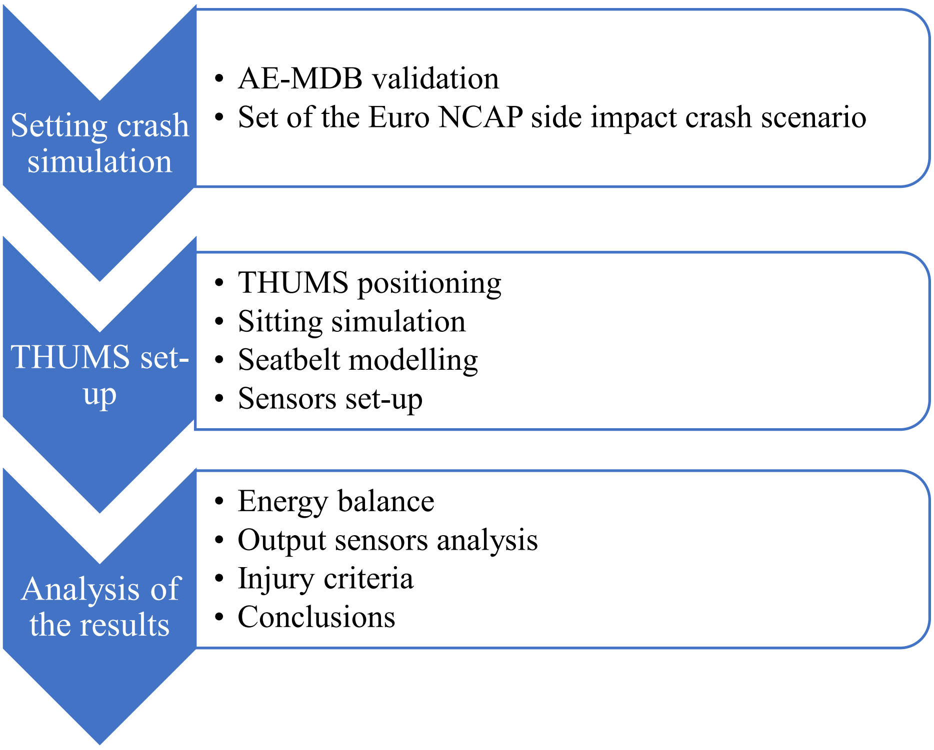


Figure 1.3 - Thesis roadmap

First of all, it was validated the Moving Deformable Barrier through the documentation provided by LSTC [7]. After this step an Euro NCAP full simulation without the occupant was run. Due to this first big effort most of the parameters for the FE simulation were set.

In order to include the driver in the model simulation some steps are necessary. The THUMS must be positioned in the standard driving position, following the Euro NCAP standard, using the PIPER Tool. Then the car environment needs some implementation. A sitting simulation, to simulate the real deformation of a normal driver seat, and a seatbelt model were provided in order to complete and launch a full simulation. Finally, a full set of sensors was implemented to obtain the output.

The final considerations are made analysing the data obtained and with the help of some Injury Criteria (IC).

Chapter 2: Literature Review

2.1 Euro NCAP [4] [5]

2.1.1 Introduction

The European New Car Assessment Programme (Euro NCAP) is a European voluntary car safety performance assessment programme based in Leuven (Belgium) and was founded in 1996.

It was created by the Swedish Road Administration, the Fédération Internationale de l'Automobile and International Consumer Research & Testing, backed by 14 members, and motoring & consumer organisations in several EU country. The project came to life after the release of the New Car Assessment Program (NCAP), introduced in 1979 by the US National Highway Traffic Safety Administration (NHTSA), where Euro NCAP took most inspiration.

Euro NCAP have provided several standard tests in order to evaluate the safety system adopted by the main constructors. With five stars review of many parameters the consumer can understand the safety rating of the vehicle.

Figure 2.1 - Euro NCAP 5-star review

The tests are not mandatory for the constructors, in fact the car models are chosen by the same Euro NCAP or sponsored by the manufactures, however, the value of Euro NCAP reports is recognised worldwide. This increases the competitiveness of the market in the security field and raises the safety standards. With over then 1800 new car tested the Euro NCAP is one of the most relevant voices in the automotive field of security. In this work the simulation will be set according to the Euro NCAP procedure of a side impact crash test.

2.1.2 Side impact testing protocol [8]

Side impact crashes are the second cause of death in car accidents, mainly for injuries of the chest and the head. This is caused by the massive energy generated in a car crash and the thinness of the side part of the car, where the door has to absorb a high amount of kinetic energy remaining in restricted constrains of deformation. A lot of safety systems were implemented by the constructors to ensure protection to the driver, torso airbags are one of the examples of this breakthrough. Euro NCAP have developed a standard protocol to rate the safety of the side protections of manufactures.

The Euro NCAP's standard includes a dummy, with several sensors, and a moving deformable barrier that is thrown against the vehicle at 50±1 km/h speed. The direction of impact is perpendicular to side of the car and pointed on the R-point, a parameter provided by the constructor, with a tolerance of ±25 mm. The barrier must be certified by Euro NCAP and respects some manufacture constrains. The weight it's supposed to be 950±20 kg with a wheelbase of 3000 mm for example. More details about the barrier construction and validation will be given in the next chapter.

Previously the crash test, some settings of the vehicle and the dummy as to be done.

- The car's tank as to be fill on the 90% of his capacity and all the others liquid containers as to be at full capacity.
- Measure the front and rear axle weights and determine the total weight of the vehicle. This weight is the "unladen kerb mass" of the vehicle.
- Measure and record the ride heights of the vehicle at all four wheels.

After this procedure, an object with a mass of the dummy (80kg) have to be placed in the driver seat and a 100kg mass as to be added in the rear compartment and the same measurements of before as to be repeat.

With all these data's collection the final setting of the vehicle is realized. A mass of the equivalent of the weight of the dummy (80kg) is positioned on the driver seat and the vehicle have to respect some checks. The vehicle mass can differ to the reference weight of a maximum of 1% and the axels loads can differ to the previous measurements with a tolerance of 5% for each parameter.

The FE vehicle used in this simulation respect the Euro NCAP requirements and no validation had to be necessary in this work.

Now the dummy has to positioned. Following the Euro NCAP legislation, the dummy has to respect some constrains describe as follow:

- The torso of the dummy has to be positioned as close as possible to the driver seat and to the H-point

- The hands are supposed to be in contact with the steering wheel at a position of quarter to three.
- The left foot, since in the model a footrest is not provide, has to be positioned parallel to the floor in a rest position
- The right foot is positioned on the undepressed acceleration pedal, with the heel as far forwards as possible and in contact with the floor. The right foot should overlap the accelerator pedal with at least 20mm

After this crucial step, the seatbelt can be placed, and the test is ready to start.

2.1.3 Sensors Euro NCAP legislation on the side impact

Before the positioning of the dummy, the implementation of the sensors has to be done in order to collect all the parameters necessary to the evaluation of the safety of the vehicle.

On the car an acceleration sensor is placed to measure the later acceleration on the unstruck B-post.

Location	**Parameter**	**Minimum Amplitude**	**No of channels**
B-Post (unstruck)	Acceleration, A_y	150g	1
	Total Channels per Vehicle		1

Figure 2.2 – Car's accelerometer

On the trolley has to be placed an accelerometer on the Center of Gravity in order to measure the acceleration of impact Ay.

Location	**Parameter**	**Minimum Amplitude**	**No of channels**
Trolley C of G	Acceleration, A_y	150g	1
	Total Channels per Trolley		1

Figure 2.3 - Trolley's accelerometer

The dummy has to be implemented with some sensors as well, described in the following table.

Location	Parameter	Minimum Amplitude	No of channels
Head	Accelerations, A_x A_y A_z	250g	3
Shoulder	Forces, F_x F_y F_z	8kN	3
Thorax T1	Accelerations, A_x A_y A_z	200g	3
Thorax T12	Acceleration, A_y	200g	1
Ribs - Upper Middle Lower	Acceleration, A_y	700g	3
	Deflection, D_{rib}	90mm	3
Abdomen - Front Middle Rear	Forces, F_y	5kN	3
Backplate	Forces, F_x F_y	5kN	4
	Moments, M_y M_z	200Nm	
T12	Forces, F_x F_y	5kN	4
	Moments, M_x M_y	300Nm	
Pelvis	Accelerations, A_x A_y A_z	150g	3
Pubic Symphysis	Force, F_y	20kN	1
Femurs (L & R)	Forces, F_x F_y F_z	22kN	6
	Moments, M_x M_y M_z	350Nm	6
	Total Channels per Dummy		43
	1 x ES-2		43

Figure 2.4 - Dummy's accelerometers

At the end of this procedure the sensors implemented are 45.

2.2 Injury criteria

2.2.1 Introduction

Injury criteria have been developed to address the mechanical responses of crash test dummies in terms of risk to life or injury to a living human. The criteria have been derived from experimental efforts using human surrogates where both engineering parameters and injury consequences are observed and the most meaningful relationship between forces/motions and resulting injuries are determined using statistical techniques. Frequently criteria are developed, based on extensive analysis, for one size dummy (an adult) and these criteria are applied and translated to other size dummies (for example child) through a scaling process. This technique overcomes the influence of geometrical and material differences between experimental subject and the subject of interest assuming that are scale model of each other and that their property varies by relatively simple mathematical relationship. In this section, the main Injury Criteria (IC) are introduced [9].

2.2.2 Head Injury Criteria (HIC) [10]

The Head Injury Criteria (HIC) is one of the most widely used to calculate the damage suffered by the head. It is computed as:

$$HIC_{36} = (t_2 - t_1)\left(\left(\frac{1}{t_2 - t_1}\right)\int_{t_1}^{t_2} a_r dt\right)^{2.5}$$

Where:

- a_r is the head resultant acceleration
- 36 is the length of the corresponding time interval

The measurement value of the head acceleration is filtered according to CFC 1000.

2.2.3 Neck Injury Criteria (Nij) [10]

The Neck Injury Criteria (Nij) propose critical limits for all four possible modes of neck loading, tension or compression combined with flexion forward or rearward. It is computed as:

$$Nij = \frac{F_Z}{F_{int}} + \frac{M_y}{M_{int}}$$

Where:

- F_Z is the axial load
- F_{int} is the critical value used for normalization
- M_y is the bending moment
- M_{int} is the critical value used for normalization

The measured values of the tensile force and compression force are filtered with CFC 600.

2.2.4 Tibia Index (TI) [10]

The Tibia Index (TI) takes into account the axial force and the bending moment to which the tibia undergoes. It is computed as:

$$TI = \left|\frac{M_R}{(M_C)_R}\right| + \left|\frac{F_Z}{(F_C)_R}\right|$$

Where:

- $M_R = \sqrt{(M_x)^2 + (M_y)^2}$
- F_Z is the axial compression in z-direction
- $(M_C)_R$ is the critical bending moment
- $(F_C)_R$ is the critical compression force in z-direction

The measured value of the bending moment and axial force are filtered with CFC 600.

2.2.5 Viscous Criterion (VC) [10]

The Viscous Criterion (VC) is used for the chest area, one of the most suffered area of the body during the side impact, and assesses the risk of injury of the soft tissue injury due to a crush mechanism. In the side impact case, it considers the rib deflection. It is computed as:

$$VC = Scaling\ factor \frac{Y_{CFC180}}{Defconst} \frac{dY_{CFC180}}{dt}$$

Where:

- $Scaling\ factor$ is function of the dummy type used in the simulation
- Y is the rib deflection
- $\frac{dY_{CFCxxx}}{dt}$ is the velocity of deformation

- $Defconst$ is the dummy constant that is equal to the depth or width of half of the rib cage of the dummy used in the simulation

The measured values used were filtered with CFC 180.

Chapter 3: Finite Element models

3.1 Introduction

In the side impact crash simulation several FE models are involved. These models used the Finite Element Method (FEM) to predict the real behaviour of the component. To achieve this level various tests, static and dynamic, must be done in order to adjust the parameters of the model. The predictive accuracy of the model can be obtained comparing the outcome of the simulation with real data obtained in a controlled experiment. All the models used in this work have carried out this validation process and can predict with fair accuracy the behaviour of a real crash.

In the side impact crash scenario three main FE models are involved:

- A mobile deformable barrier (MDB) model, the impact object of this test, that will be through to the car at a velocity of 50km/h.
- A car model, a 2012 Toyota Camry, that will host the HBM during the crash
- A Human Body Model (HBM), that will be housed inside the cabin and, through different sensors collocated inside the model, will provide several outputs to understand the severity of the injury

In the following will be provided a brief description of the models.

3.2 Advanced European Movable Deformable Barrier model [11] [12]

The movable deformable barrier consists of two parts: a trolley and an impactor. The impactor consists of six single blocks of aluminium honeycomb, which have been processed to give a progressively increasing level of force with increasing deflection. An additional single element is attached of 60mm depth to the front of the lower row of blocks. Front and rear aluminium plates are attached to the aluminium honeycomb blocks. The barrier can be seen in details in Figure 3.1.

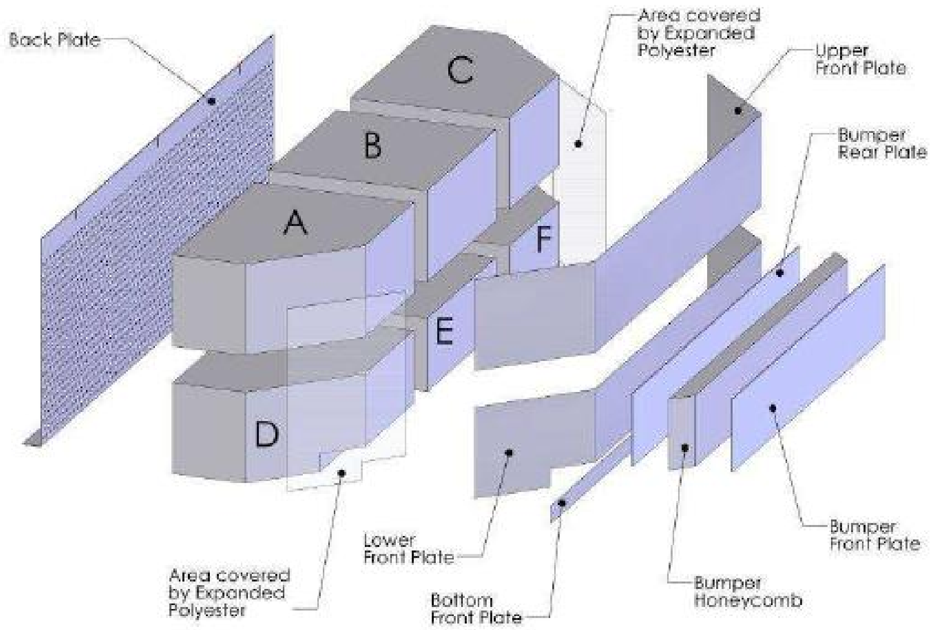


Figure 3.1 - AE-MDB barrier details

In this thesis a FE model of the AE-MDB is provided. The mobile deformable barrier has been developed by Livermore Software Technology Corporation (LSTC). The model is based on the Advanced

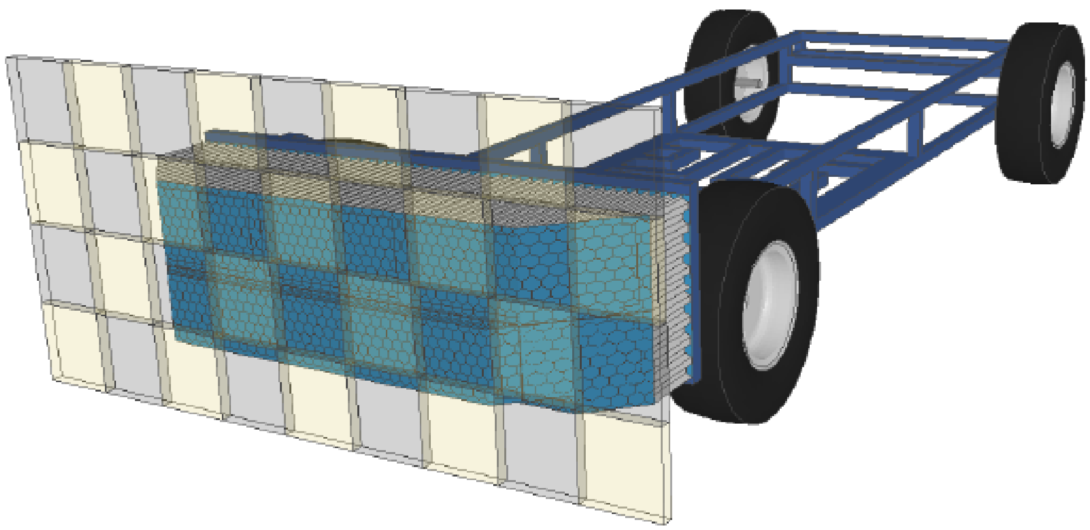


Figure 3.2 - AE-MDB FE model

European Movable Deformable Barrier Version 1.0 specification, released on 26th February 2013, as can be seen in Figure 3.2. The AE-MDB is made mainly by shell elements and recreate the real behaviour.

Some validations must be made to ensure the validity of the model. In particular, it was simulated a front impact against a wall at 35km/h in order to verify that the force-displacement graph fit with one provided by LSTC.

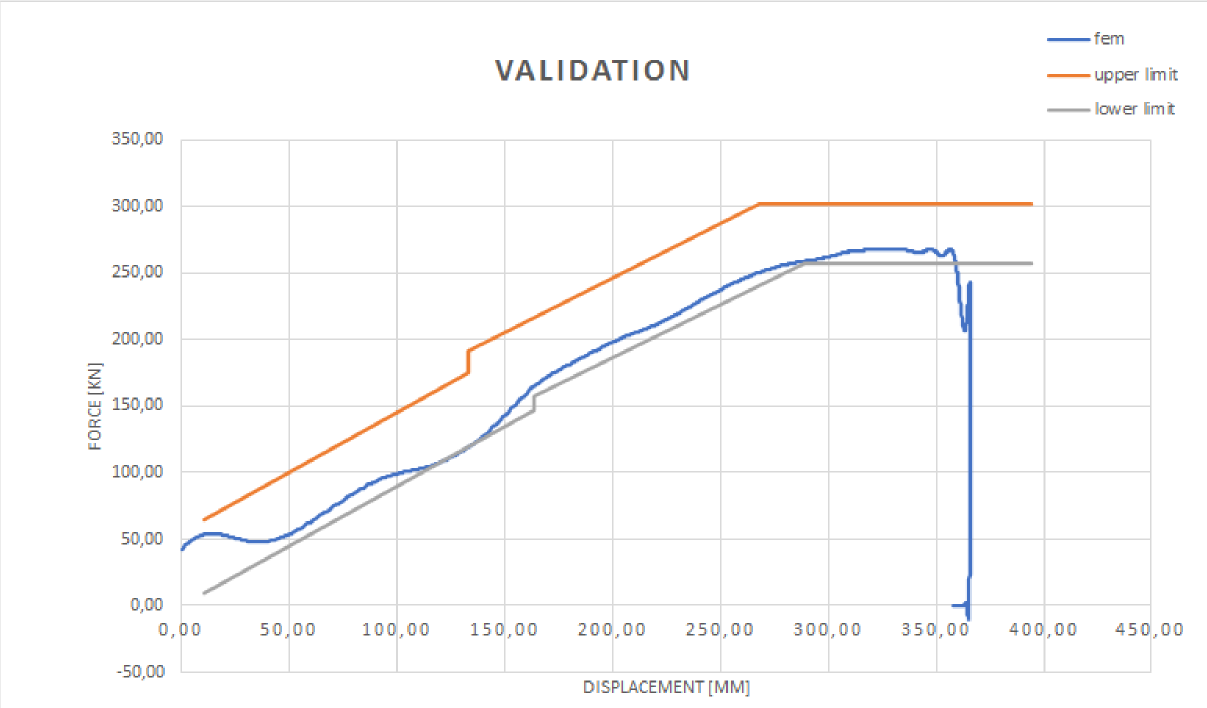


Figure 3.3 - Validation AE-MDB FE model

As can be seen from the diagram in Figure 3.3, the validation of the model results sufficient because the blue curve that shows the results of the simulation is between the given limits.

The model provided by LSTC is set for the validation so it include a *ae-mdb_version_R1.0_wall.k* and a *ae-mdb_version_R1.0_floor.k*, they has to be deleted from the *ae-mdb_version_R1.0_main.k* file.

Through the keyword *RIGIDWALL_PLANAR_FINITE will be created a new floor in the main file for all the model used, this procedure will be described in the next chapter.

The MDB model is ready for the simulation.

3.3 2012 Toyota Camry model [13] [14]

This model is a computer representation of a 2012 Toyota Camry mid-size passenger sedan for use in crash simulations. It was developed through a reverse engineering process by Centre for Collision Safety and Analysis (CCSA) researchers under a contract with the Federal Highway Administration.

Figure 3.4 - Comparison between the real Toyota Camry and the FE model

The reverse engineering process systematically disassembled the vehicle part by part as in past efforts. Each part was catalogued, scanned to define its geometry, measured for thicknesses, and classified by material type.

Figure 3.5 - Detail FE model

All data were entered into a computer file and then each part was meshed to create a computer representation for finite element modelling that reflected all the structural and mechanical features in digital form. Material data for the major structural components was obtained from manufacturer specifications or determined through coupon testing from samples taken from vehicle parts. The material information provided appropriate stress and strain values for the analysis of crush behaviour or failures in crash simulation. A comparison between the real car and the FE model is showed in Figure 3.4, besides in Figure 3.5 a detail vision of the FE model is presented.

The model was validated against several full-scale crash tests, include the side impact crash test but following the American side impact NCAP standard (SINCAP), different from the Euro NCAP for the velocity and the direction of impact of the mobile deformable barrier. In the figure below, the comparison between the real crash and the simulate one.

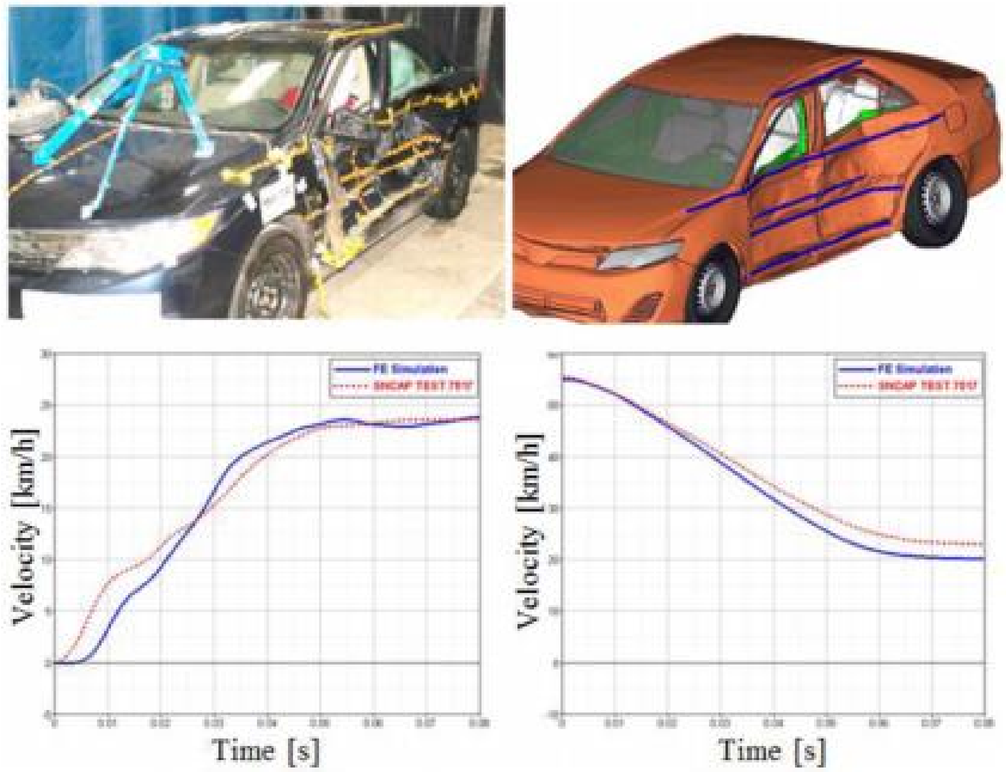


Figure 3.6 - Validation of the FE model in a SINCAP test

Reasonable correlations were obtained, as it can be seen from the graph of Figure 3.6, with a CORA rating of 0.92 for the vehicle velocity time history and 0.87 for the barrier kinematics. A side impact test with the same velocity and direction of impact of the Euro NCAP was also accomplished but no technical time history data was accessible from the conducted test [15].

The resulting Finite Element vehicle model has 2.25 million elements. It includes details of the structural, drivetrain, as well as the interior components allowing for integration of occupant (dummy) models in the simulations.

The model was provided already set for a NHTSA NCAP frontal full-width crash test, which mean a frontal impact against a rigid wall at 35 mph (56.327 km/h). Due to this reason a few changes must be made.

- On the model the keyword *INITIAL_VELOCITY must be deleted because in the Euro NCAP side impact the impacted vehicle is firm.
- The unit of measure must be change in according to the HBM model and the trolley, so the unit of measure were changed from mm/ton/s to mm/kg/ms.

- We need to include the car model in the main file created before through the keyword *INCLUDE.

The car is ready to be set for the simulation.

3.4 Human Body model [16]

The Human Body Model (HBM) is a Finite Element (FE) model of a human body created to replicate its biomechanics response of several cases. For the creation of the model a comparison between cadavers and FE model in many types of impact has been made in order to obtain a precise simulation of the real behaviour. The complexity and the fidelity of the model allow to overcome the limitations of a common dummy and simulate more realistic and complicate scenarios that otherwise would be difficult or impossible to analyse. Using an HBM every human movement can be reach and it can be positioned in impossible ways respect to a dummy. This allowed to use this kind of models to study the behaviour of the body in a lot of fields, from sport to aerospace. The implementation of more precise and specific sensors allows a more accurate analysis of the response and the development of new injuries criteria like the Peak Virtual Power method (PVP) [17].

In this thesis an HBM model called THUMS, made by Toyota Motor Corporation and Toyota Central R&D Labs., Inc., is provided. The acronym THUMS stands for Total Human Model for Safety and was the first virtual human body software when it launched in 2000. Several versions were provided during the years and from January 2021 the last version is freely available. The evolution of the THUMS is presented in Figure 3.7.

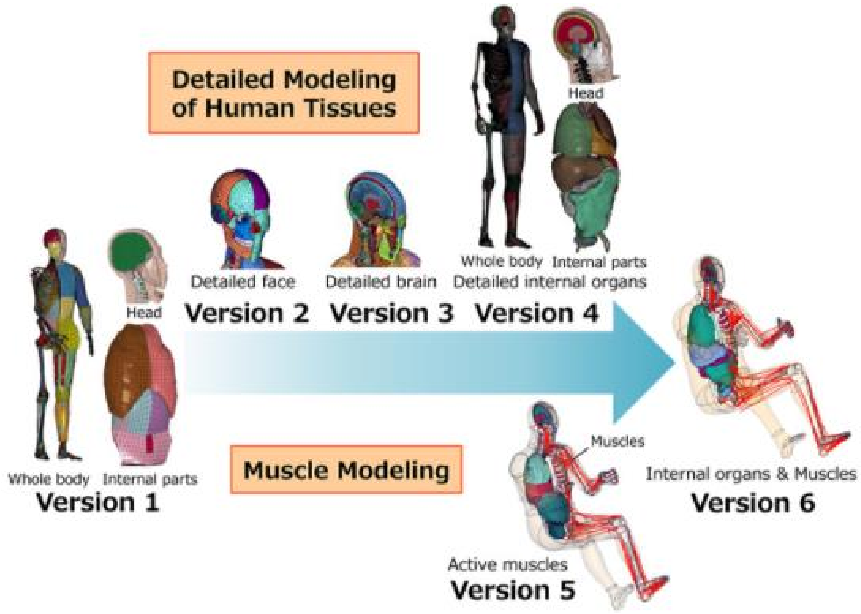


Figure 3.7 - THUMS evolution

For the side impact simulation, an adult male model (AM50%ile) with a height of 175cm and a weight of 77 kg is provided. The models include detailed head (face, skull, brain, and spinal cord), the skeleton, internal organs (heart, stomach, liver, etc.), and air cavities (including the lung). The model provided was obtained through a high-resolution CT scanning process in order to digitize the interior of the body and to generate precise geometrical data for each model part. The HBM recreate the anatomical features of each organ, tissue, and bones in a human body, associating the proper material properties to each

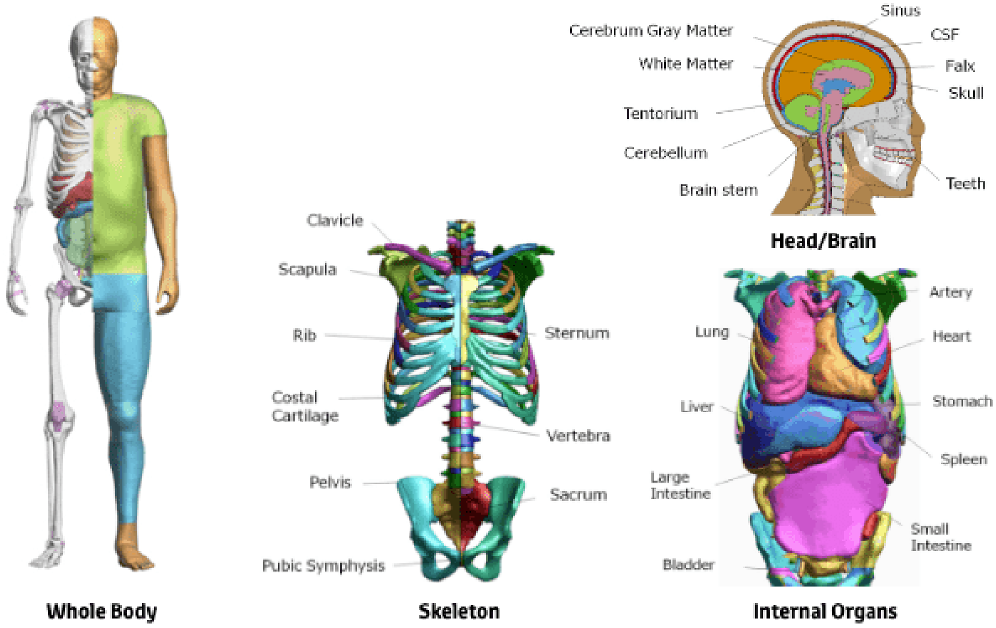


Figure 3.8 - THUMS details

body part as reported in literature. Therefore, the model can simulate brain and internal organ injury at a tissue level, as well as skeletal fractures and ligamentum injuries. The complexity of the THUMS is such as to be able to simulate the involuntary muscular movements of the human body. The model contains approximately 760,000 nodes and 1.9 million elements. The Figure 3.8 show some details of the THUMS model.

The model is provided in a standard position configuration as it can be seen from the figure below.

Figure 3.9 - THUMS model

The model requires a set and simulation positioning through the PIPER software. The procedure will be explained in the next chapter in the details.

Chapter 4: Pre-simulation process

4.1 Setting crash simulation

4.1.1 introduction

The aim of this FE simulation is to recreate in the best possible way the reality of the crash test, to do this is important to follow the standard set by Euro NCAP in the setting of the simulation environment. The critical points that require particular attention are:

- the definition of the trolley's position and velocity
- the definition of the contacts
- the definition of the controls

4.1.2 description of the simulation settings

The trolley is aligned to the R-point of the HBM and strikes perpendicularly to the left side of the car, as can be seen in the Figure 4.1. The correct position of the barrier is reached in LS-PP translating and rotating the MDB .

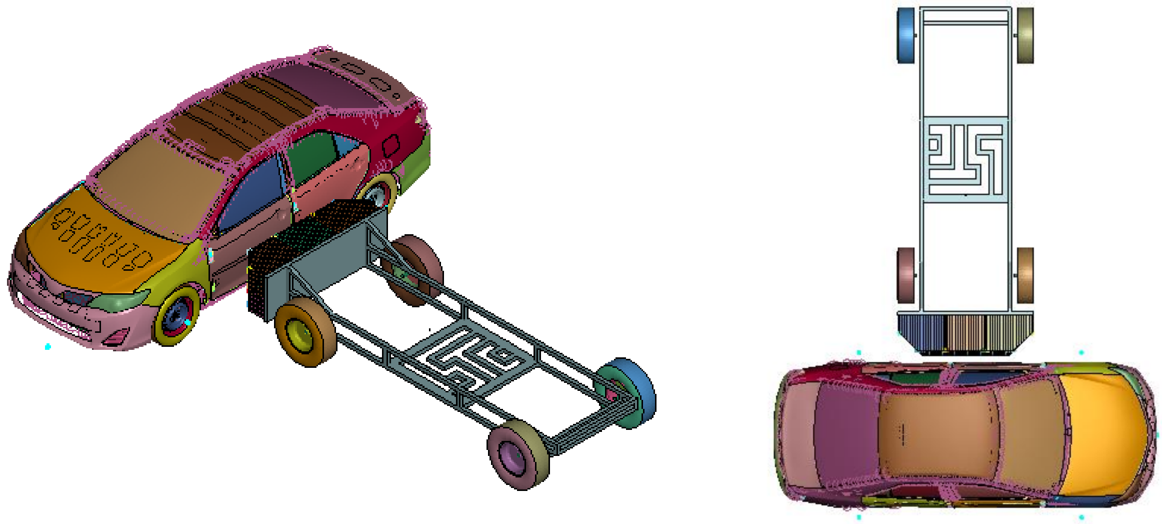


Figure 4.1 - Euro NCAP side impact in LS-PP

Following the required standards, the car is firm while the moving deformable barrier impacts it with a fixed speed of 50 km/h. The velocity of the trolley is set with the *INITIAL_VELOCITY keyword, were a *NODE_SET of the AE-MDB was created. It is important to be consistent with the units of measurement.

The simulation contains many contact definitions and there are different aspect and various parts to consider, nevertheless some of them are already defined in the initial FE model of the vehicle and the AE-MDB. The contact between the deformable barrier and the vehicle must be defined, to do this the keyword *CONTACT_AUTOMATIC_SURFACE_TO_SURFACE is recommended by LS-DYNA. Two sets of parts for the definition of the contact have been created, one of the car and the other on the barrier. On LS-PP, in the keyword's card, the part set of the car is defined as slave and that of the barrier as master.

It is now necessary to create a floor that will recreate the interaction between the wheels and the ground, to do this the keyword *RIGIDWALL_PLANAR_FINITE is used. A high friction coefficient of 0.9 has been chosen to simulate the optimal situation of tire grip. For the planar dimension it is required to also consider the possible translation of the vehicle after the impact. The floor created on LS-PP is visible in the Figure 4.2.

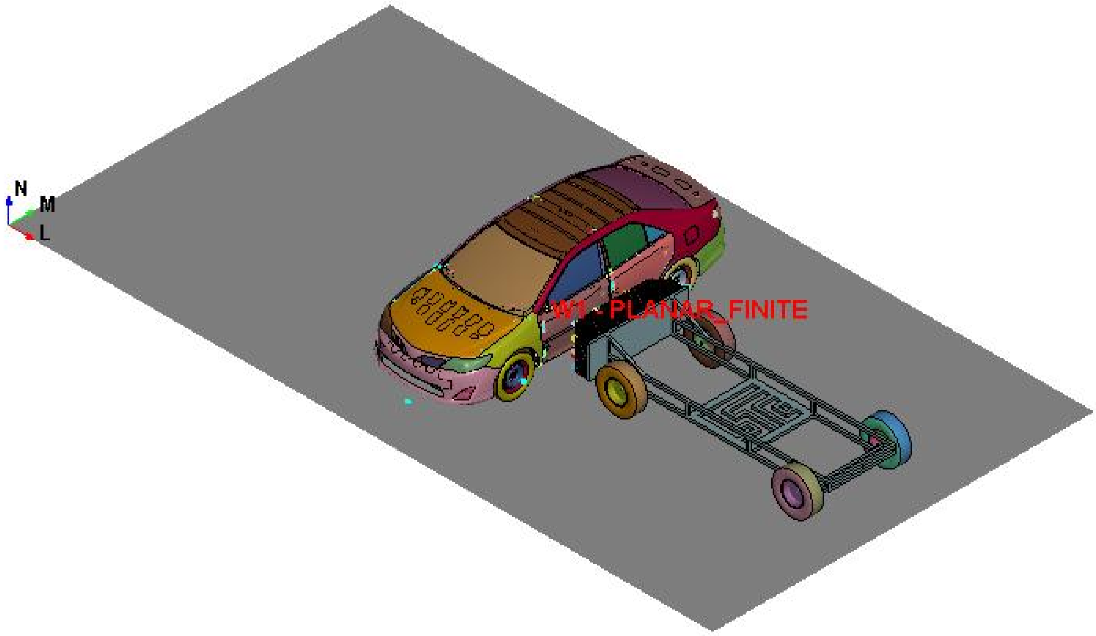


Figure 4.2 - PLANAR_FINITE

Another important aspect that needs to be set in order to create the simulation in the correct way are the control cards. Control cards have been added to fully run and improve the simulation. It has been added the *CONTROL_ENERGY to visualize the trend of the hourglass energy and to understand from these data if the simulation results are acceptable. To have more accurate simulations it has been added also the *CONTROL_CONTACT card that has been used to specify some parameter as the initial penetration and the contacts between rigid bodies, this control card allows to improve the definitions of contact given previously. It is necessary at this point to fix the duration of the simulation, it has been seen from various reports, focused on the crash test simulations, that the peak of acceleration on the driver is always before 100ms. This term of duration is therefore fixed through the *CONTROL_TERMINATION card. The full set of controls is listed:

- *CONTROL_ACCURACY
- *CONTROL_BULK_VISCOSITY
- *CONTROL_CONTACT
- *CONTROL_CPU
- *CONTROL_ENERGY
- *CONTROL_HOURGLASS
- *CONTROL_OUTPUT

- *CONTROL_SHELL
- *CONTROL_SOLID
- *CONTROL_SOLUTION
- *CONTROL_TERMINATION
- *CONTROL_TIMESTEP

4.2 Sitting simulation

4.2.1 introduction

When an occupant sits inside a vehicle, the seat deforms in its soft part, like the cushion, due to the weight of the person. To represent in the best of the ways the reality it is necessary therefore to carry out a sitting simulation. What is obtained to the end of the simulation is a deformed seat under the static load of the HBM that comes later included in the model previously described of the car. This practice allows not to have penetrations and a better behaviour between the body and the seat.

4.2.2 Description of the process

This simulation requires the following models to be run:

- HBM model:
  because of the high computational cost due to the great detail of the HBM, simplification can be made to the model. It can be assumed with a particularly good approximation that the deformation of the HBM is negligible in this type of simulation. Starting from the original model of the HBM, the parts corresponding to the skin are selected and exported with their section and material properties. Once a new subsystem has been created, *MAT_RIGID is assigned to each part, thus creating a model containing only rigid skin. In the following figures it can be seen the HBM model before and after this operation.

Figure 4.3 - Comparison between full THUMS model and the rigid skin

- Driver's seat:
  the FE model of the undeformed driver seat is exported from the FE car model, creating a new subsystem, as can be seen in Figure 4.4.

Figure 4.4 - Driver seat subsystem

In order to carry out this simulation, the seat must be fixed in the space, so rotational and translational degrees of freedom are locked by the command *BOUNDARY_SPC_SET. In particular, these constrains are applied to the seat attacks as shown in the Figure 4.5.

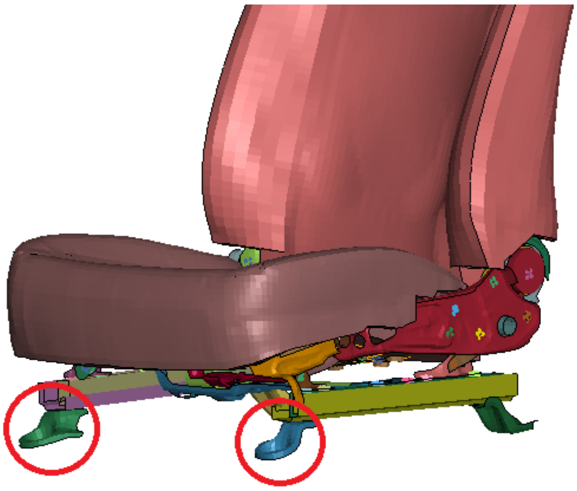


Figure 4.5 - Details of the seat attacks constrained

The movement of the HBM is given by the keyword *BOUNDARY_PRESCRIBED_MOTION_RIGID with a fixed displacement of 50 mm in x positive direction and 80 mm in z negative direction as in the practice in automotive companies to deform the seat cushions. This process is visible in Figure 4.6.

The keyword *CONTACT_AUTOMATIC_SURFACE_TO_SURFACE is the one suggested to define the contact between the skin and the seat.

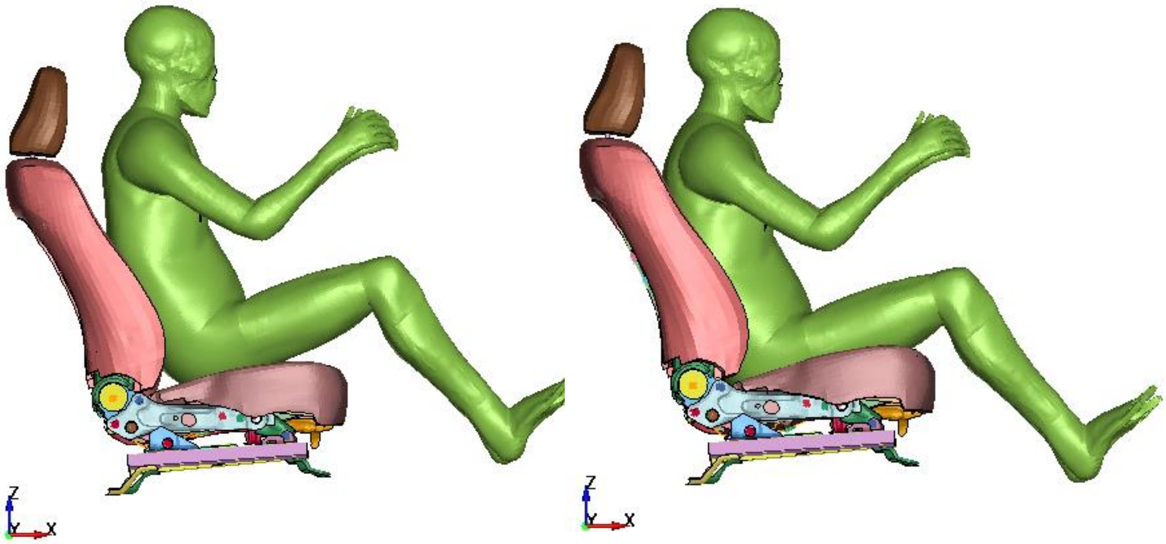


Figure 4.6 - Sitting simulation: first and last step of simulation

At the end of the simulation, a deformed driver's seat is saved, and the model is included in the FE car model. The result can be seen in Figure 4.7.

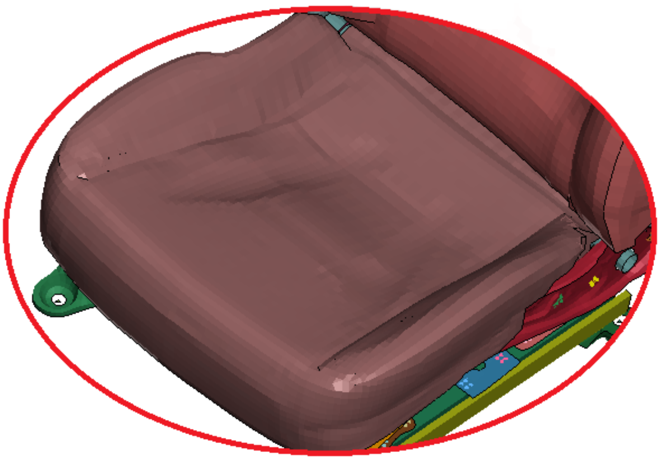


Figure 4.7 - Detail of the deformed seat cushion

4.3 THUMS positioning

4.3.1 Introduction

In this section the positioning procedure will be explained.

The positioning of the THUMS was made in order to respect the standard procedure of an Euro NCAP side impact test, described in the 2.1.2 chapter. For the positioning process two software where used, PIPER software and LS-DYNA. The PIPER software can be used to scale and position Human Body Models for impact while LS-DYNA is used to simulate the positioning. The route to follow for positioning is as follows:

1. Positioning of the THUMS through the PIPER software functionality
2. Creation of a script for the positioning simulation for LS-DYNA with the scripting feature of PIPER
3. Simulation with LS-DYNA

4.3.2 Positioning through PIPER software

The first step is to create and include a simplify environment model of the inside of the vehicle focusing on the driving position and with the introduction of the deformed seat previously created. This model will help the user in the positioning of the HBM. The environment created is show in the Figure 4.8.

Figure 4.8 - Environment subsystem positioning

The environment model is imported in the PIPER interface and it must be fitted against the THUMS respecting the Euro NCAP standard. The result should be as in the Figure 4.9.

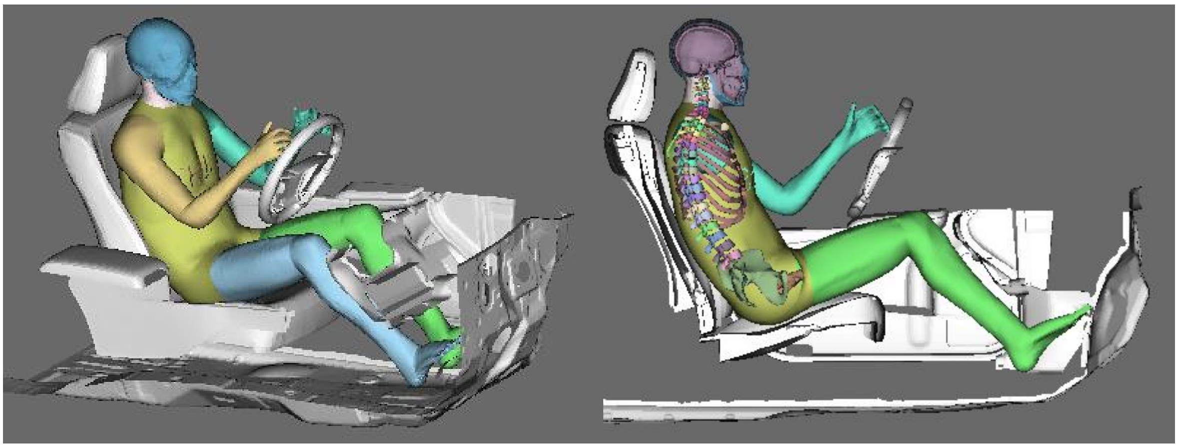


Figure 4.9 - Environment positioning, isometric and section plane view in the PIPER interface

The positioning of the THUMS was made mainly using 2 features of PIPER, the *landmark* positioning, and the *joint* positioning, functions highlighted in Figure 4.10.

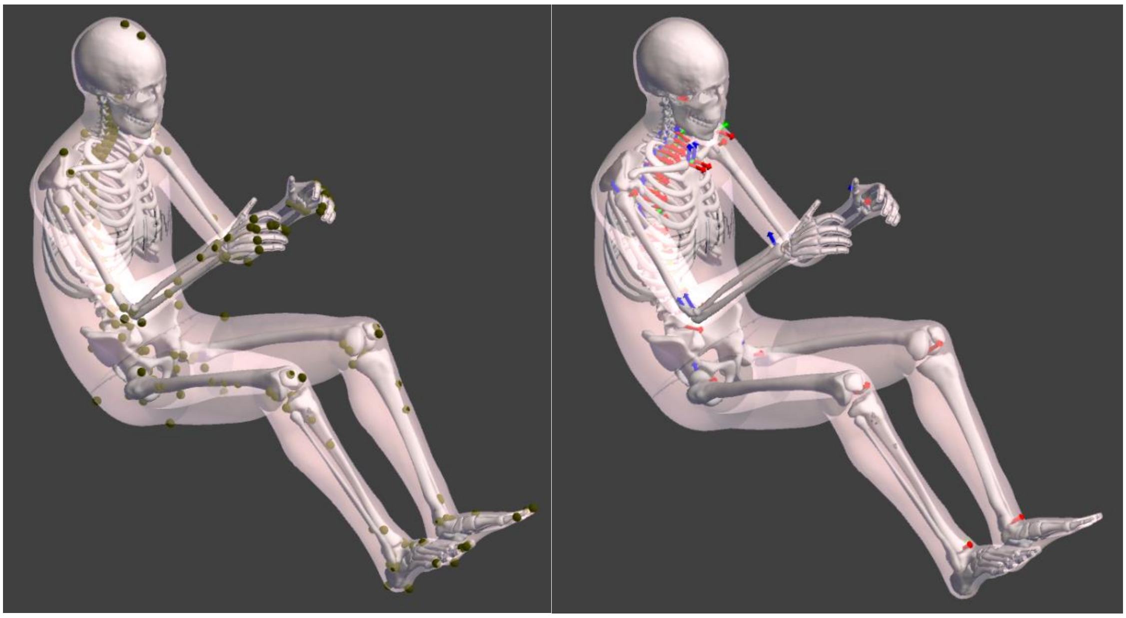


Figure 4.10 – Landmark and joint visualization in PIPER

The model has in fact several landmarks in order to identify the critical points for the positioning and joint to ensure the rotation of the parts up to their functional biological limit.

After the rotation of a joint or the movement of a landmark, the *control* feature must be run to simulate the movement. In this phase the entire model will adapt to the single movement previously defined. A particular care has to be made on the control, check the *auto stop* mode and uncheck the *collision* mode. The first control stop the positioning when the landmark goal is reach (otherwise the script is continuing write), the second one is useless because eventual compenetrating verification is not needed due to the final simulation will be run on another software (LS-Dyna).

The feature *fixed bones* were used to fix some portions of the body during the positioning of every main region of the body to not influence the complete positioning of some parts with the general movement of the model due to a single movement.

Figure 4.11 - Fixed bones example for upper limb positioning

The procedure started with the positioning of the lower limb and then moving to the higher limb. After iterative steps, the positioning of the model the Euro NCAP standard were made.

To be able to use the model, however, a simulation of the positioning must be made with a FE solver. A script file must be made to set the FE simulation. This is provided through the *scripting* feature, were, after saving the history of the positioning through the *update* function a few files for the simulation are obtained:

- *CURVE.k*
- *ele_beam.k*
- *main.k*
- *motion.k*
- *nodeset_PIPER.k*
- *noeuds_extr_beam.k*

Including on the *main.k* file the main file of the THUMS the simulation can be run. The results after having run LS-DYNA are the following.

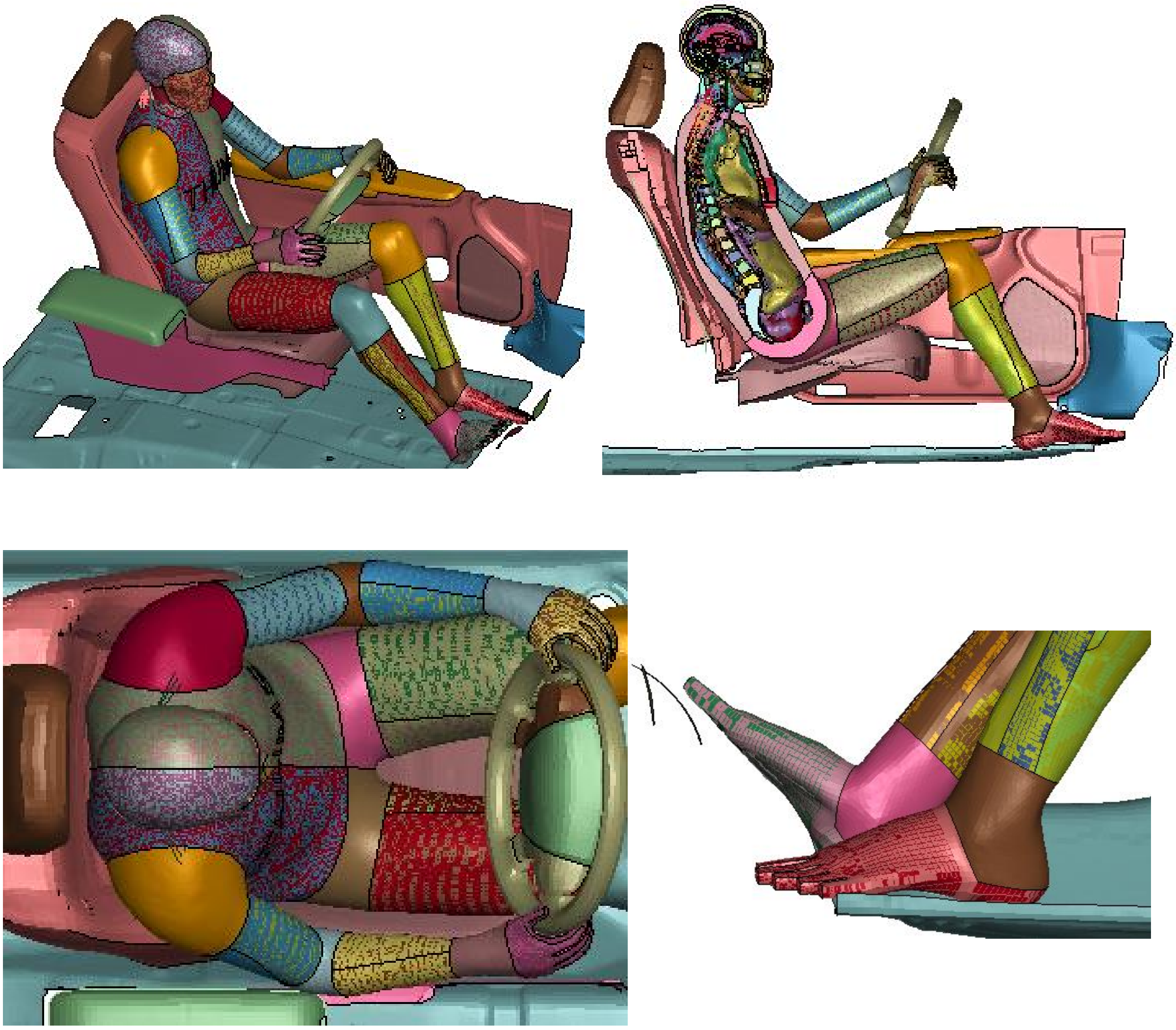


Figure 4.12 - In the figures in the top the isometric and the section view of final position, in the figures in the bottom some details of the hands and the feet positioned

As can be seen from the Figure 4.12 the positioned THUMS respect the requirement of the Euro NCAP dummy positioning described in the chapter 2.1.2.

The model of the THUMS was then included in model and accurately located. To unsure the contact between the parts a *PART_SET of the driver seat and of the HBM was created and a keyword *CONTACT_AUTOMATIC_SURFACE_TO_SURFACE was added on the model.

4.4 Seatbelt modelling [18] [19]

4.4.1 Introduction

One component that has not yet been addressed is the seatbelt. These are explicitly required by the Euro NCAP protocol in which it is stated that the driver is secured on his seat during the crash test. This component is not present in the initial FE vehicle model, so it must be created. To do this, the HBM must first be placed in the correct position inside the car. The whole routine to create the seatbelts is done on LS-PP.

4.4.2 Seatbelt routine

The belt chosen for the simulation is a three-point-seatbelt, like the one in the Figure 4.13 composed by:

- B-pillar belt
- Shoulder and torso belt
- Lap belt

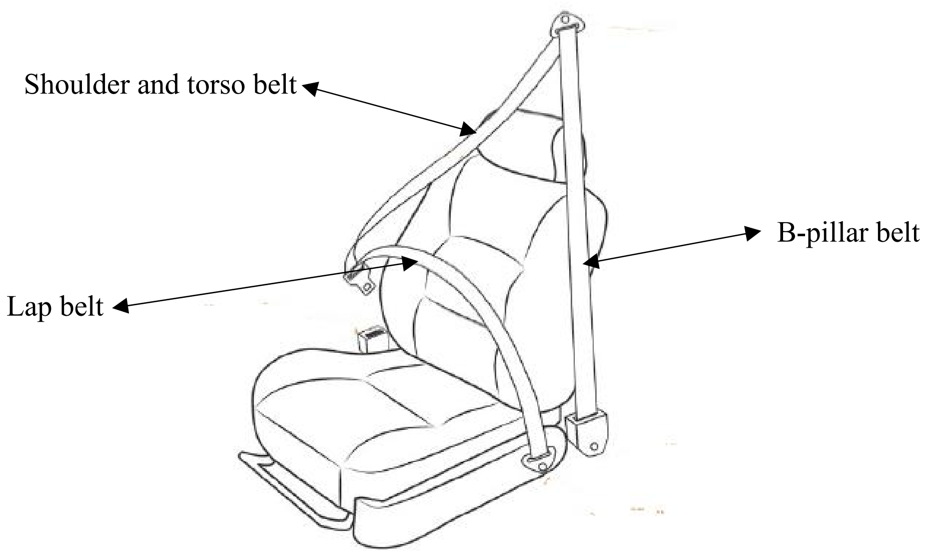


Figure 4.13 – three-point-seatbelt components

Each one of these belts is created independently, so in the end you will have various parts that make up the whole belt together. The belt can be shaped in diverse ways depending on where they are located and on their function. The first belt to be created is the B-pillar belt, this is modelled as a segment belt, i.e., with 1D elements, it can be done this because this belt does not interact with the dummy and therefore reduces the computational weight. The other two belts are instead modelled with a mixed structure, in which there are 2D elements that are better to make realistic the behaviour that the belt has with the body of the occupant. In order to create the seatbelt some FE models are necessary:

- The driver's seat previously deformed
- THUMS positioned
- The vehicle structure used by the belt as anchors

The anchors are those parts of the vehicle to which belts pass or are connected and they are:

- D-rings
- The point in which the belt is fixed to the frame
- The point in which the belt comes out from the retractor

The exported parts useful for the belt definition are shown in the Figure 4.14.

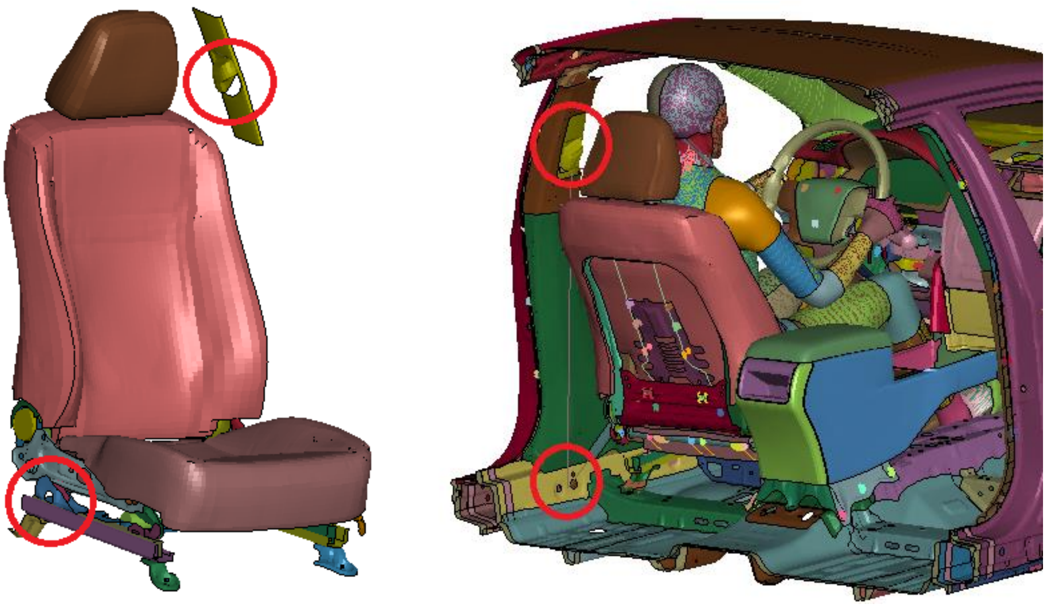
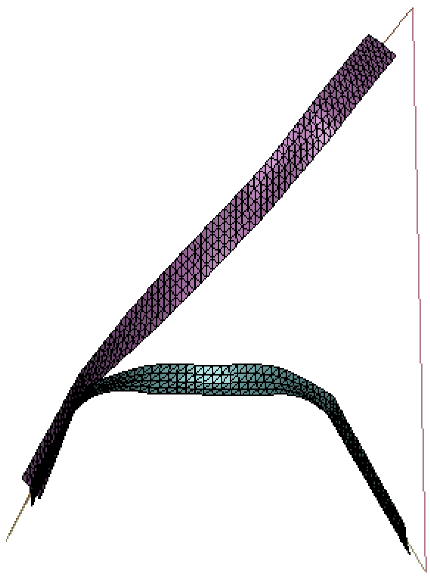


Figure 4.14 - Anchors in the FE model

There is a routine for creating belts on LS-PP. Through the *Occupant Safety* and using the *Seatbelt Fitting* command these can be modelled. To be able to do this, it is necessary to create sets of segments on the parts of the THUMS involved in each belt in order to wrap them precisely around the body. Once the segment sets have been created, a set of points must be specified for each belt to create it. It is especially important that the end and the start points of two consecutive belts are the same to ensure that they work. The result of this process is visible in Figure 4.15. The interface that opens with the command *Seatbelt Fitting* can be used to define several parameters such as the number of elements in the belt or its width. A triangular mesh has been used by default on LS-PP as can be seen in the Figure 4.15.



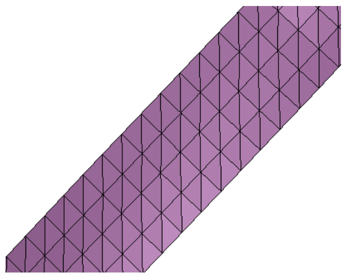


Figure 4.15 - Seatbelt model and detail of the seatbelt mesh

After this routine has been carried out, the material and section property must be assigned to the belts, these are assigned manually. After the belts have been created, it is necessary to define some elements that are present in the real vehicle but absent in the FEM one:

- Retractor
- D-rings
- Sensor
- Pretensioner

Since these elements were not present in the model, they were placed by observing the inside of the real car with photos.

RETRACTOR

This element is placed in the lower part of the B-pillar, this element is created with the keyword *ELEMENT_SEATBELT_RETRACTOR, in this card it is necessary defining the retractor node. It is important that the node coincides with the one chosen for the creation of the belt. A parameter that can be set is the time delay, which is set to zero as a first approximation and indicates the time that elapses between the activation of the sensor and that of the retractor. The position of the retractor is visible in Figure 4.16

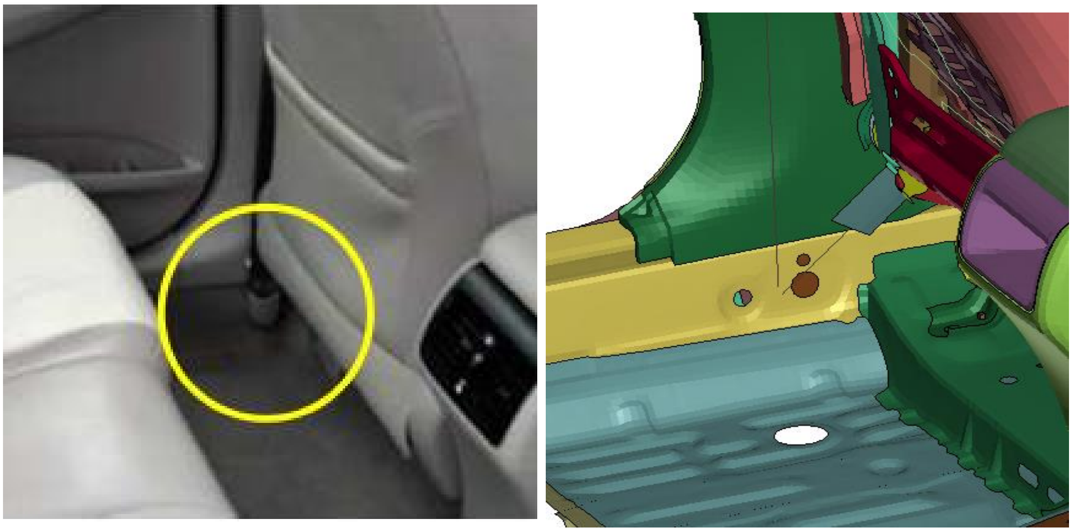


Figure 4.16 - Comparison of the position of the retractor in the real car and in the FE model

D-RINGS

The d-rings are two elements that allow the belt to slide, they are defined with the keyword *ELEMENT_SLIPRING, in this card you have to define a node (the slipring node) on the fixed structure and two seatbelt elements that have that node coincident. One D-ring is present at the top of the B-pillar and the second one in the buckle area. For the second, an existing rigid part of the seat was chosen. The comparison between the real and the simulated D-ring is shown in Figure 4.17.

Figure 4.17 - Comparison between the D-ring in the real car and in the FE model

SENSOR

The sensor is created with the keyword *ELEMENT_SENSOR, it is necessary to set a time at which these triggers. When the sensor triggers then the retractor and pretensioner start working.

PRETENSIONER

This element is created with the keyword *ELEMENT_PRETENSIONER, type 5, the *pyrotechnic retractor*, was chosen. A delay time of zero is set as a first approximation. The Figure 4.18 shows the final result.

Figure 4.18 - THUMS positioned with the seatbelt model

4.5 Set-up of the sensors

In order to obtain biomechanical results from the performed crash test simulation, it is necessary to include in the THUMS model a series of sensors that are required by the above-mentioned protocol. In fact, the THUMS developed by Toyota Motors Corporation does not have a pre-installed set of sensors as reported: *"users need to specify the entities for output such as nodes, elements, materials and cross section, in order to output data such as acceleration, velocity, displacements, forces, stress, strain and energy"*.

In this work, an existing example of sensors system, made for previous activities by Germanetti [20] [21] has been used. Some modifications have been implemented in order to better comply with the Euro NCAP requirements for the dummy outputs. The additional components are needed to register the loading during the side impact in specific areas such as: shoulder, upper neck, lower neck, pelvis and lower limbs. In Figure 4.19, the complete set of accelerometers and load sensors is shown.

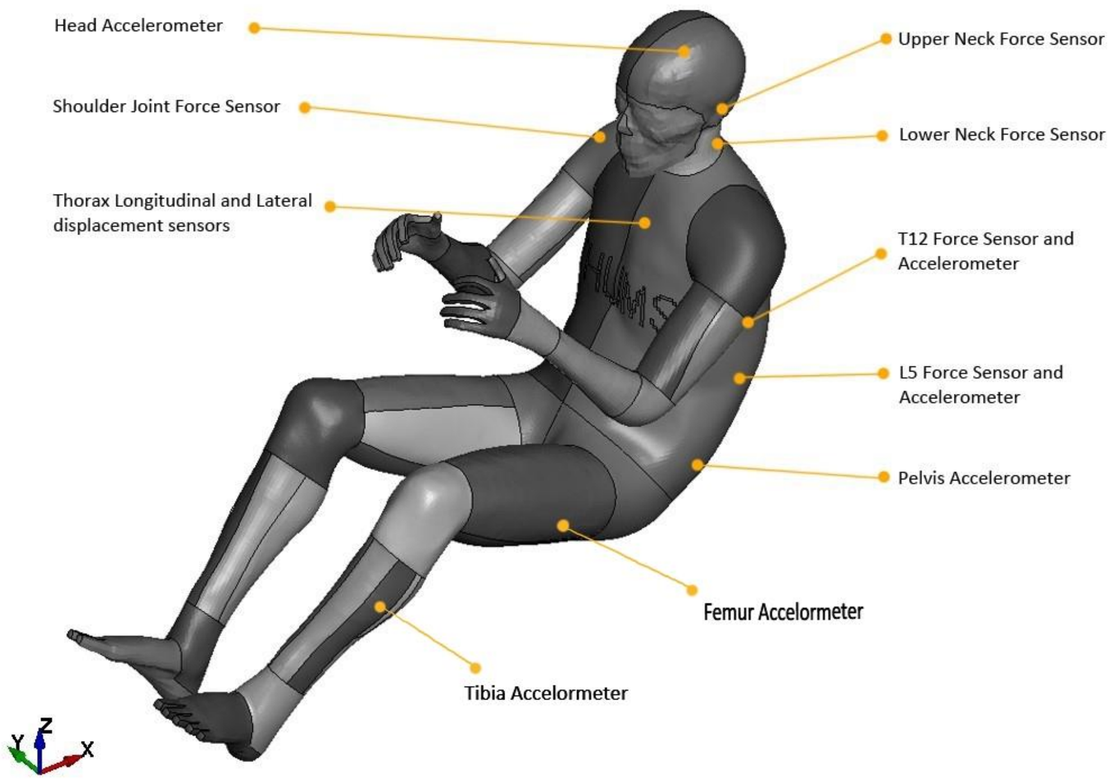


Figure 4.19 - Set of sensors

4.5.1 Head sensor

The model is equipped with an accelerometer sensor able to record the head movement in the three direction of space. For a proper implementation inside the THUMS, a small part of the brain visible in Figure 4.20, the *third ventricle left*, has been converted to rigid and used as an accelerometer. This operation is important in order to obtain cleaner and more stable results from the accelerometer defined on those elements. In LS-DYNA the sensor is modelled through the *ELEMENT_SEATBELT_ACCELEROMETER keyword.

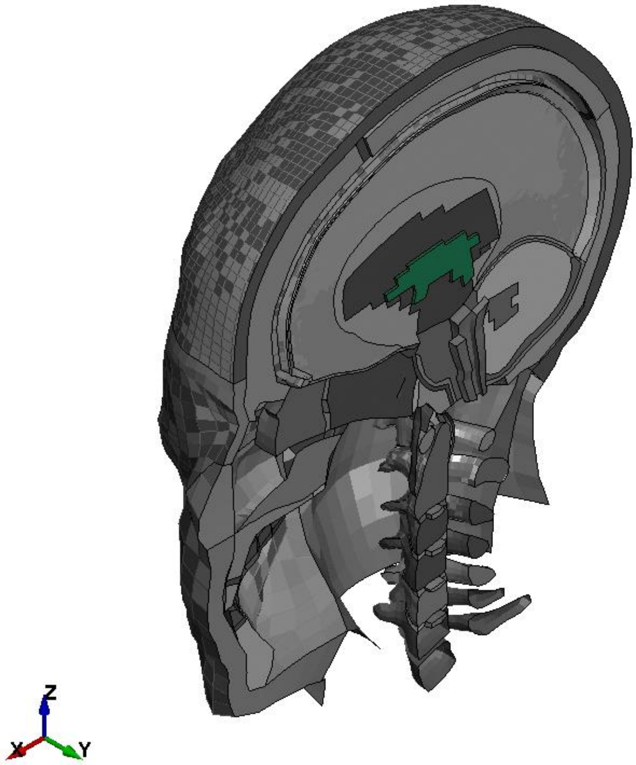


Figure 4.20 - Head accelerometer

4.5.2 Neck sensors

It is important to specifically evaluate the behaviour of the neck because this area of the body is subject to high loads during a side impact. Two different sections are monitored: the upper neck and the lower neck and the same strategies for implementing the sensors are adopted in both areas. Load sensors are modelled by using the keywords *CROSS_SECTION_SET in order to define load cells being on the C1 vertebrae and the C7 vertebrae, and *CROSS_SECTION_PLANE for defining planes crossing the upper area of the neck and the lower area of the neck, as it is visible in Figure 4.21. Is important to remind that the planes defined previously are referred to specific parts, i.e., head, C1 vertebrae and C7 vertebrae. These sensors record both the loads transmitted through the neck and the moment to which it is subject.

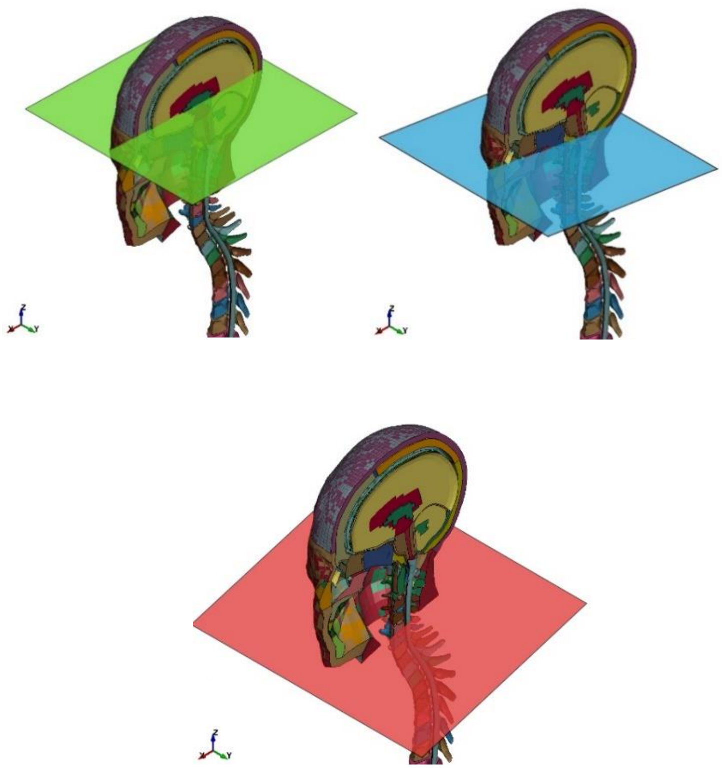


Figure 4.21 - Cross_section_planes: head (green), upper neck (blue), lower neck (red)

4.5.3 Thorax and pelvis sensors

Multiple sensors are positioned in the thorax for describing the upper part of the body. Two accelerometers are positioned in vertebrae T12 and L5 defined similarly to the one present in the head: the vertebrae are converted to rigid, and the sensor is defined on these nodes. On those same vertebrae load sensors are also modelled. 1D discrete elements have been connected in the lateral direction between shoulder ribs, upper thorax ribs, middle thorax ribs, lower thorax ribs, upper and lower abdominal ribs in the lateral direction. These elements are useful to measure the displacement, in particular for the deflection of the ribcage.

Additionally, a load sensor is also positioned at the meeting point of the iliac crests in the Symphysis for measuring the lateral forces transmitted by the pelvis. Figure 4.22 shows the configuration of the thorax and pelvis sensors set.

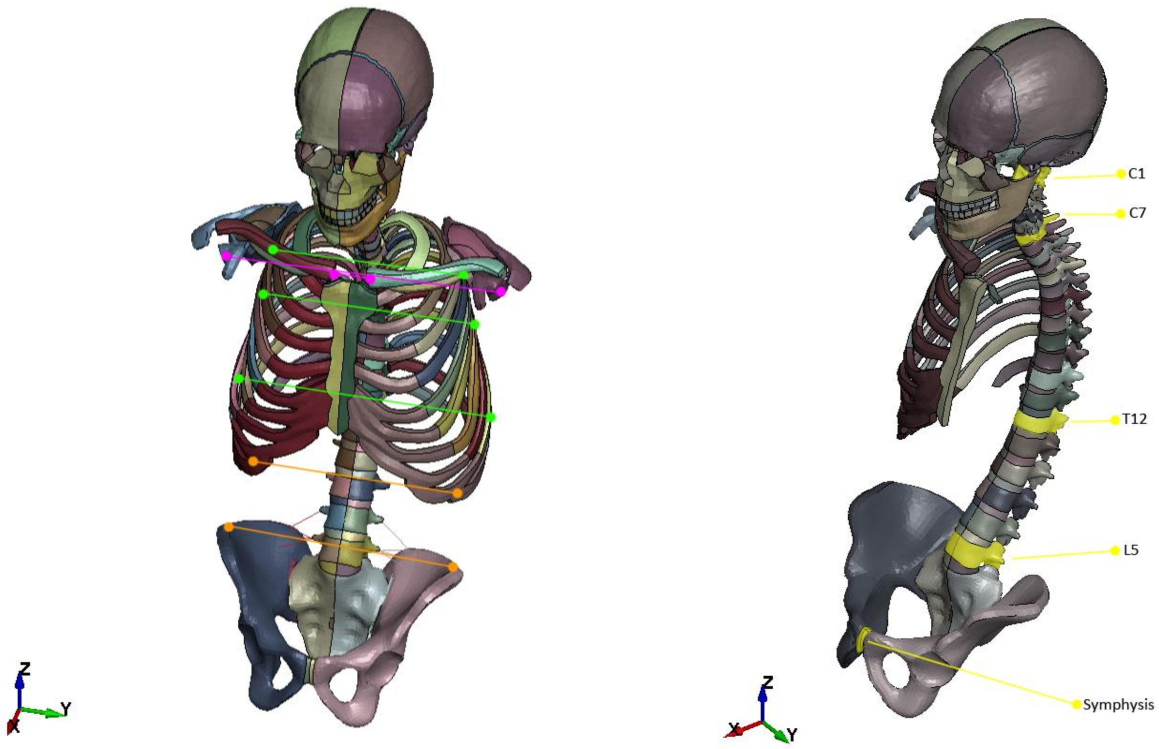


Figure 4.22 - Thorax and pelvic sensors

4.5.4 Rib cage sensor

It is possible, in order to analyse in details the deformation of the thorax and of the spine, to position markers on ribs and vertebrae so that it is possible to visualize instant by instant the deformation of the thorax circumference or the spine alignment. *DATABASE_HISTORY_NODES_ID cards are used to define these markers set and they monitor:

- *Cervical Vertebrae*
- *Thorax Vertebrae*
- *Lumbar Vertebrae*
- *Chest Ribs*: 4 chest bands have been defined at different height, as can be seen in Figure 4.23

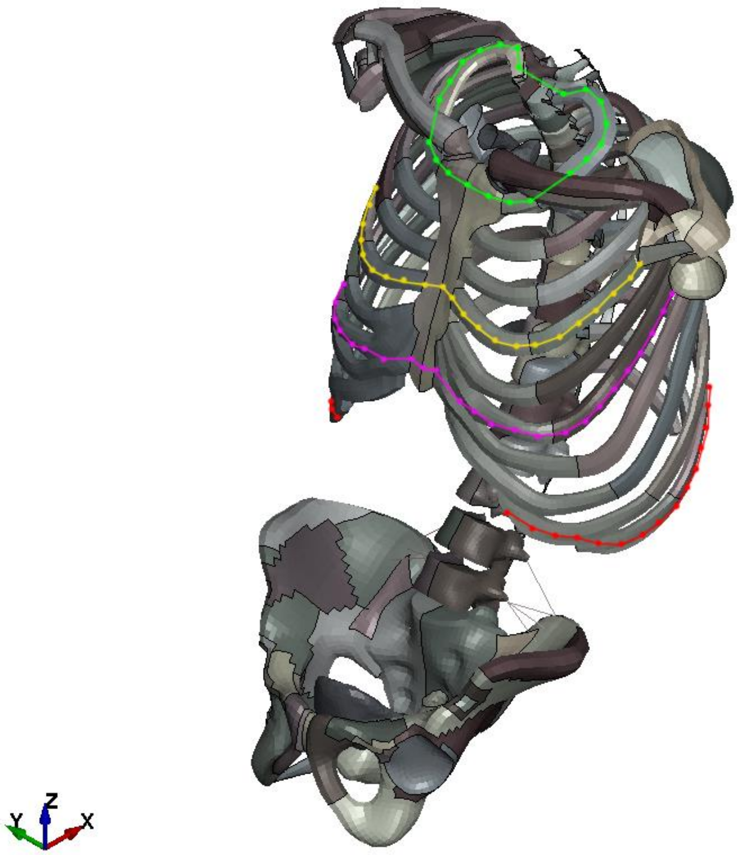


Figure 4.23 - Rib cage sensors

4.5.5 Internal organs volume sensor

The high detail provided by the THUMS model, instead of the classic dummies, allows to further analyse the possible injuries occurring to the human body model during an accident beyond what prescribed the Euro NCAP protocol since by nature, it has been designed to regulate the use of a real dummy, the World SID to be more specific. Specific sensors have been modelled for analysing the behaviour of the internal organ by using *AIRBAG_SIMPLE_PRESSURE_VOLUME keywords. These LS-DYNA cards can provide data on the change in volume of a closed surface and its normalized surface variation. In this work the organs groups taken into consideration for further analysis, and visible in Figure 4.24, are:

- *Ribcage:* Enclosed surface of Pleura and Diaphragm
- *Right Lung:* Enclosed surface of Right Pleura Visceralis (Green)
- *Left Lung:* Enclosed surface of Left Pleura Visceralis (Orange)
- *Heart:* Enclosed surface of Pericardium
- *Pancreas:* Enclosed surface of Pancreas
- *Spleen*: Enclosed surface of Spleen
- *Liver*: Enclosed surface of Liver
- *Stomach*: Enclosed surface of Stomach (Red)
- *Small Intestine:* Enclosed surface of Small Intestine (Yellow)
- *Large Intestine:* Enclosed surface of Large Intestine (Purple)
- *Abdomen*: Enclosed surface of Peritoneum and Diaphragm

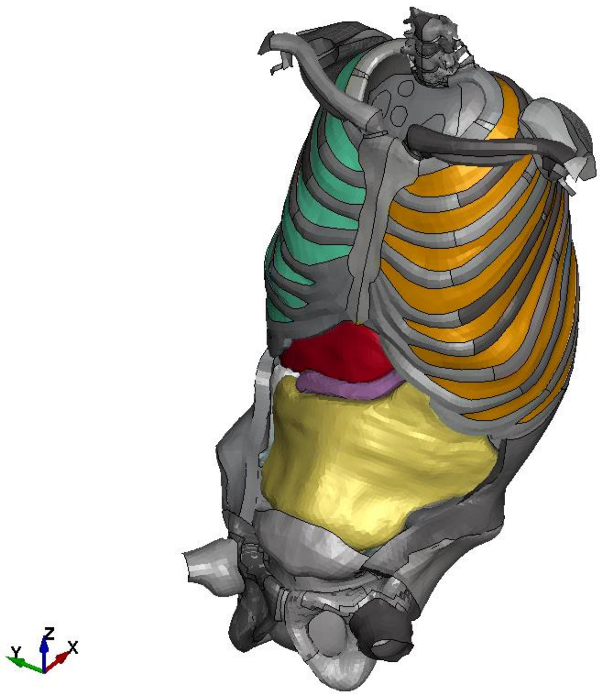


Figure 4.24 - Internal Organs

4.5.6 Lower limbs sensor

Following the Euro NCAP protocol, data from the lower limbs must be analysed. In order to obtain these results, some *CROSS_SECTION_PLANE were inserted on both right and left femur and tibia as was done previously on the neck. To obtain the accelerations, *SEATBELT_ACCELEROMETER on rigid cubes, already implemented in previous work, are used. They are shown in Figure 4.25.

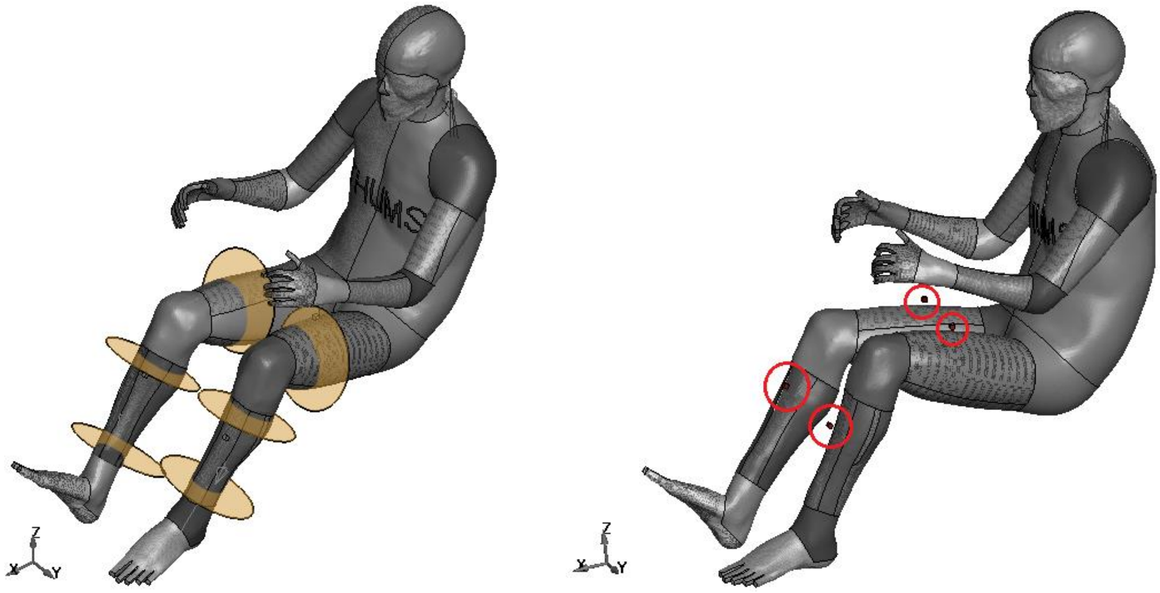


Figure 4.25 - Lower limbs sensors: cross_section_planes (left), accelerometer (right)

Chapter 5: Results

5.1 Overview

The simulation is then launched through the cluster of the HPC@POLITO, a powerful tool furnished by the Politecnico di Torino and managed by the Department of Automation and Computer Science (DAUIN) of the Politecnico, that correspond in calculation resources and technical support for academic and didactic research activities using centre systems. The main two cluster used in this thesis work were the Legion and the Hactar cluster. The simulation was completed in 40 hours and 35 minutes with 64 cores on 2 nodes and CPU efficiency 99.68%. The memory utilized is 27.38 GB.

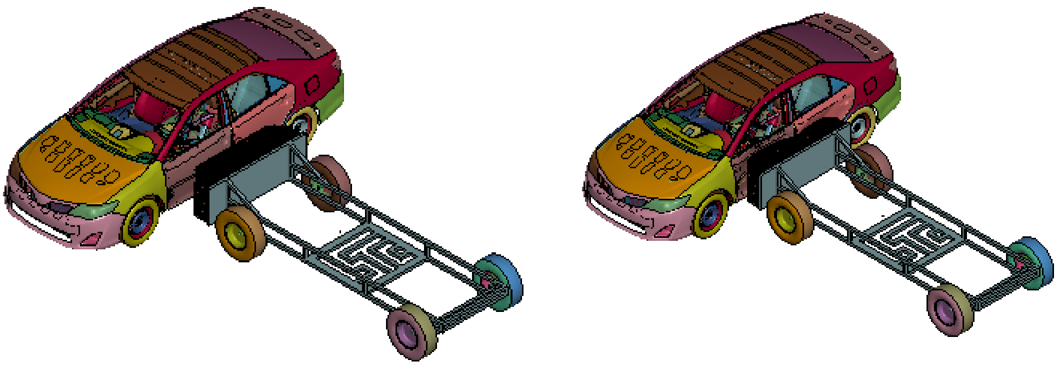


Figure 5.1 - Isometric view - t = 0ms on the left and t = 20ms on the right

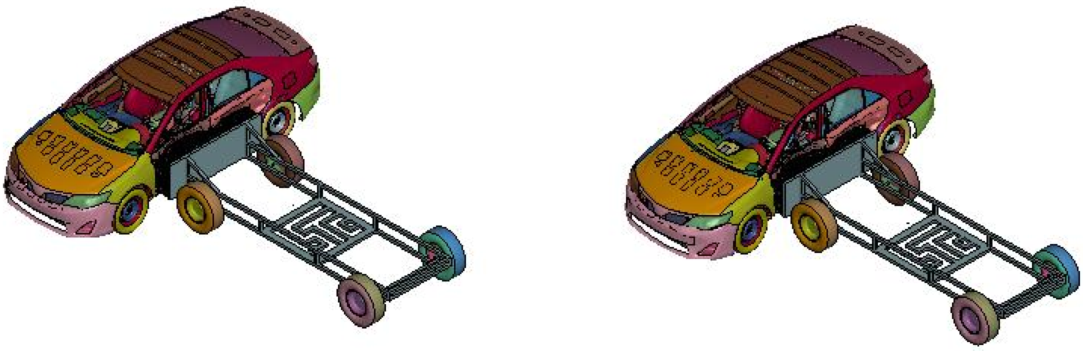


Figure 5.2 - Isometric view - t = 40ms on the left and t = 60ms on the right

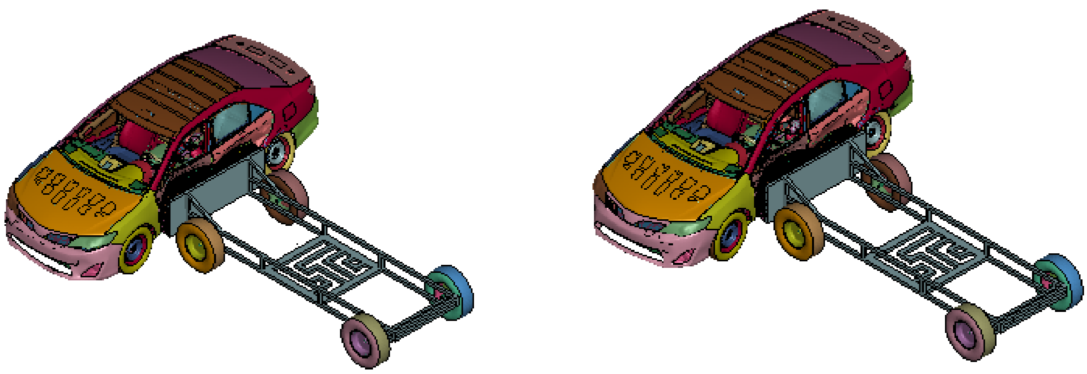


Figure 5.3 - Isometric view - t = 80ms on the left and t = 100ms on the right

Figure 5.4 - Front view - t = 0ms on the left and t = 20ms on the right

Figure 5.5 - Front view - t = 40ms on the left and t = 60ms on the right

Figure 5.6 - Front view - t = 80ms on the left and t = 100ms on the right

As can be seen from the figures from 5.1 to 5.6, the simulation was fully run, and the behaviour respects a real side impact scenario with the Euro NCAP standards. We can notice that the head suffer a significate displacement from the original position, as will be seen from subsequent results, the head results one of the main injured part of the dummy.

In the following the results of the simulation will be presented, in particular:

- Energy analysis
- Car and trolley sensor analysis
- THUMS sensors analysis
- Injury criteria
- THUMS spine deformation
- Euro NCAP score evaluation

5.2 Energy analysis

The energy balance takes into account several energies components, in particular:

- Total energy
- Kinetic energy
- Internal energy
- External work
- Sliding interface energy
- Hourglass energy

The energies are a preliminary indicator of the success of a simulation. The energy plot is show in the Figure 5.7.

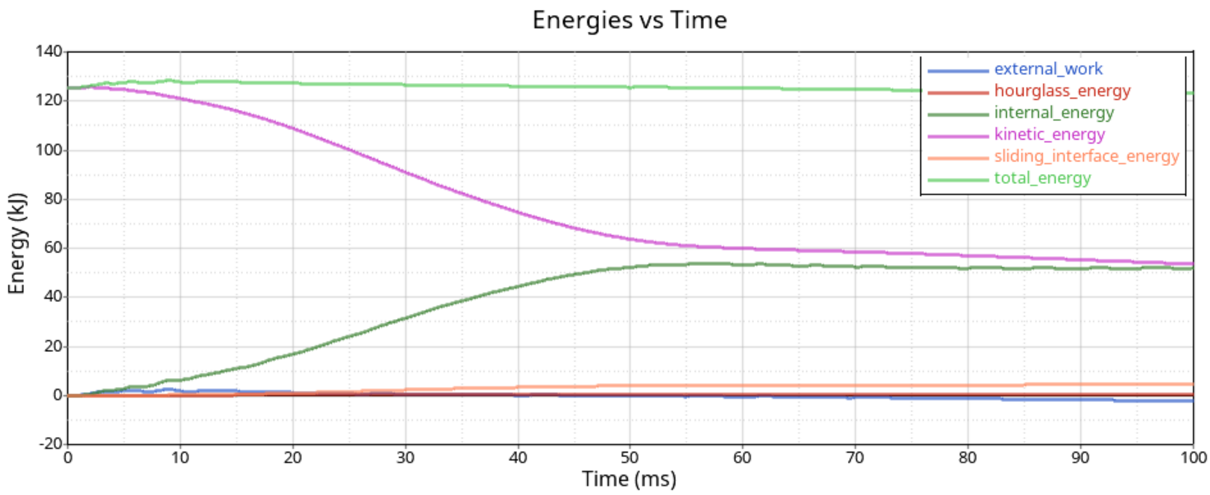


Figure 5. 7 - Energies vs time

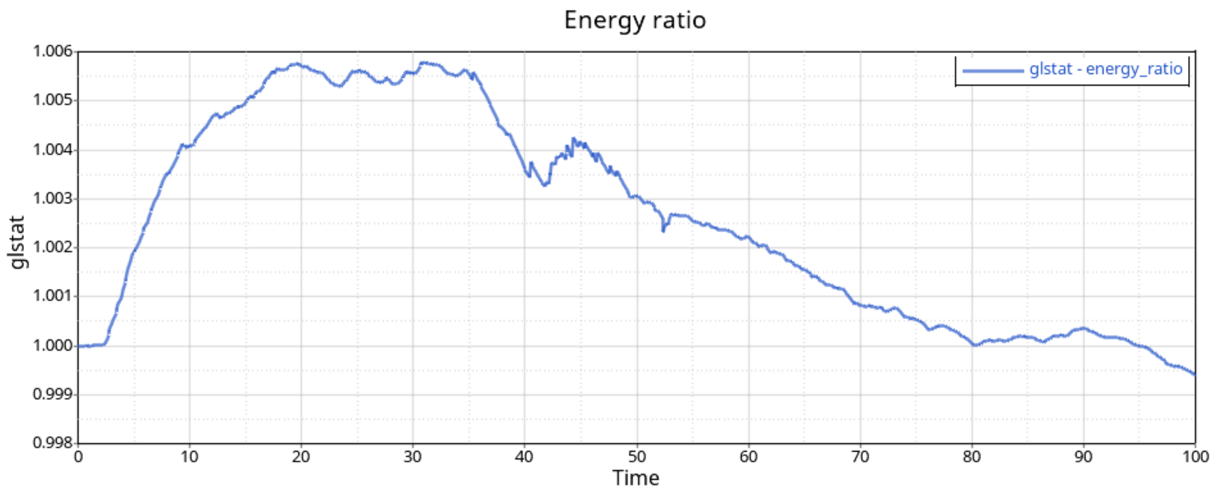


Figure 5.8 - Energy ratio

As can be seen in the Figure 5.7, the total energy slightly increases after few milliseconds for then decrease slowly, however the order of size of the increase is considered acceptable. The trend of the kinetic and internal energy is correct. The hourglass energy, a parameter that is correlated with the zero-energy mode of deformation that produce zero strain and no stress, should be under the 10% of the total energy respecting to the LS-Dyna guidelines and as can be seen, this constrain is respected. The energy ratio, define as following:

$$e_{ratio} = \frac{E_{tot}}{E_{tot}^{0} + W_{ext}}$$

should be close to the unity to have a satisfactory behaviour, and this is accomplished as can be seen from the Figure 5.8.

5.3 Car and trolley sensor analysis

In the following the results of the AE-MDB and of the Toyota Camry accelerometer are presented.

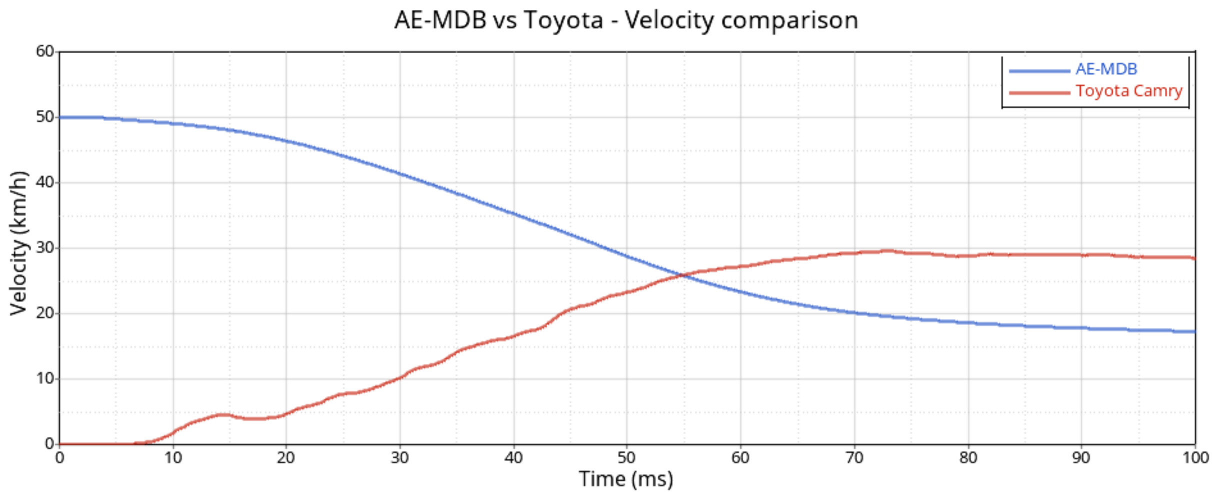


Figure 5. 9 - AE-MDB vs Toyota - Velocity comparison

As can be seen from the Figure 5.9 the trolley impacts the vehicle at 50km/h as indicated to the Euro NCAP normative.

5.4 THUMS sensors analysis

In this chapter the results of the THUMS accelerometers, described in the chapter 4.5, are presented. The results were all filtered using a SAE 180 filter [20]. The reference systems used for the results are defined as describe in the chapter 4.5, where the z axis is perpendicular to the cross section plane and the y axis is along the direction of impact. For the parts not specified in the chapter the reference system used is the global one of the simulation where the z axis is perpendicular to the ground and the y axis is along the direction of impact.

5.4.1 THUMS – Head

The acceleration of the head is an important parameter to understand the gravity of the accident. Following the Euro NCAP normative the acceleration along the x, y and z are plot in the following.

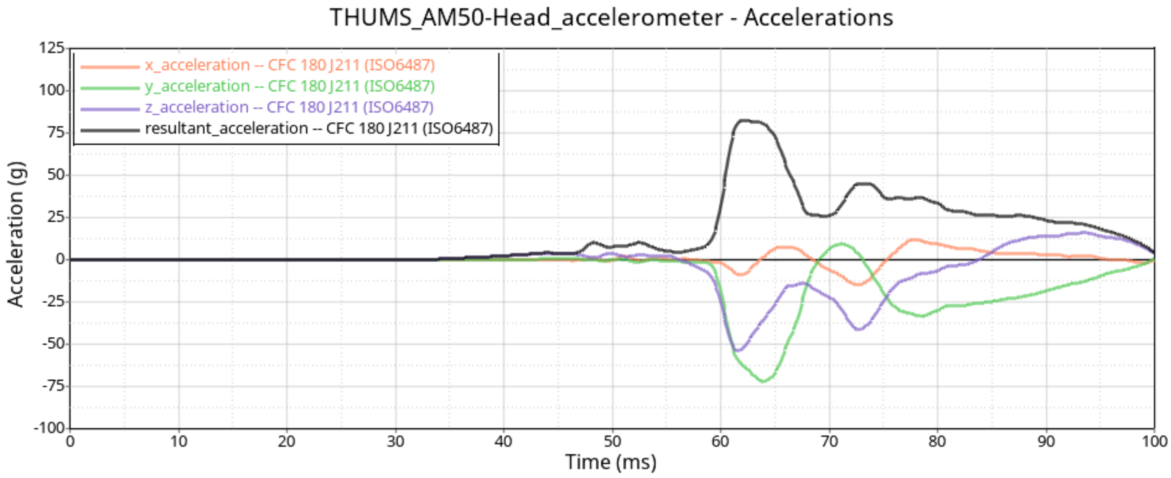


Figure 5.10 - Head acceleration

As can be seen from the Figure 5.10 the head undergoes a considerable acceleration on the y axis. The Euro NCAP standard set a lower limit of performance of 88g and a higher performance limit of 72g, for the resultant acceleration, in this case the peak value results 82g [22].

5.4.2 Head Injury Criteria (HIC)

The Head Injury Criteria is then calculated as describe in chapter 2.2.2. The window took in account is 36ms as suggest from the Euro NCAP standard. The HIC_{36} then calculated is equal to 314 in the window between 60ms and 89.5ms. This data results lower than the higher performance limit set by Euro NCAP of 650 [22]. Using the set of curves developed by Prasad-Mertz, Figure 5.11, it is

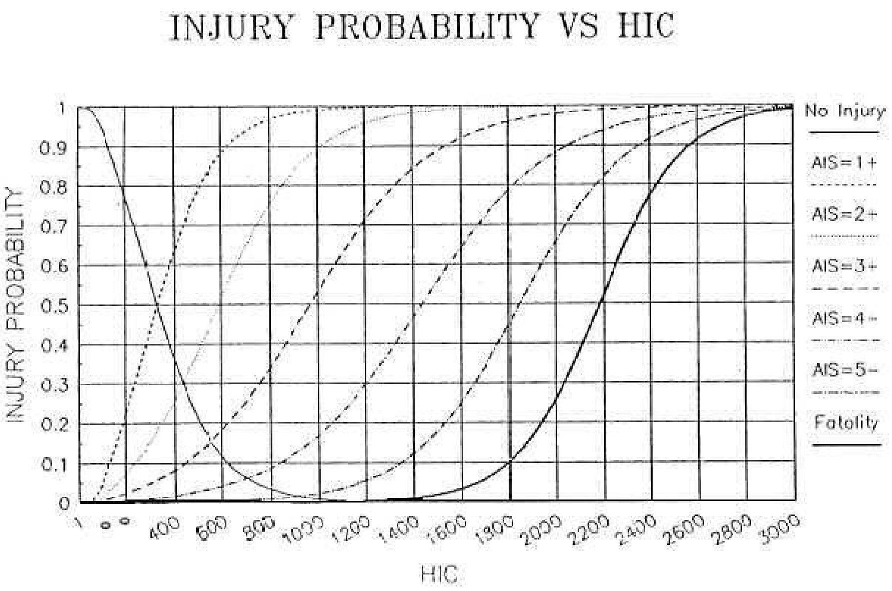


Figure 5.11 - Prasad-Mertz Injury probability vs HIC curve

possible to correlate the values of HIC with the probability of injury. In this case the probability of a serious injury (AISI 3) is close to 4.8% and the probability of a minor injury is close to 49% [23].

5.4.3 THUMS - Neck

The Euro NCAP normative does not need a signal from neck ,however, from the images of the impact, it seems that the neck undergoes an important deflection that should be indagate. For do so the forces and moments of the neck are plot below and a neck injury is provided in the next chapter.

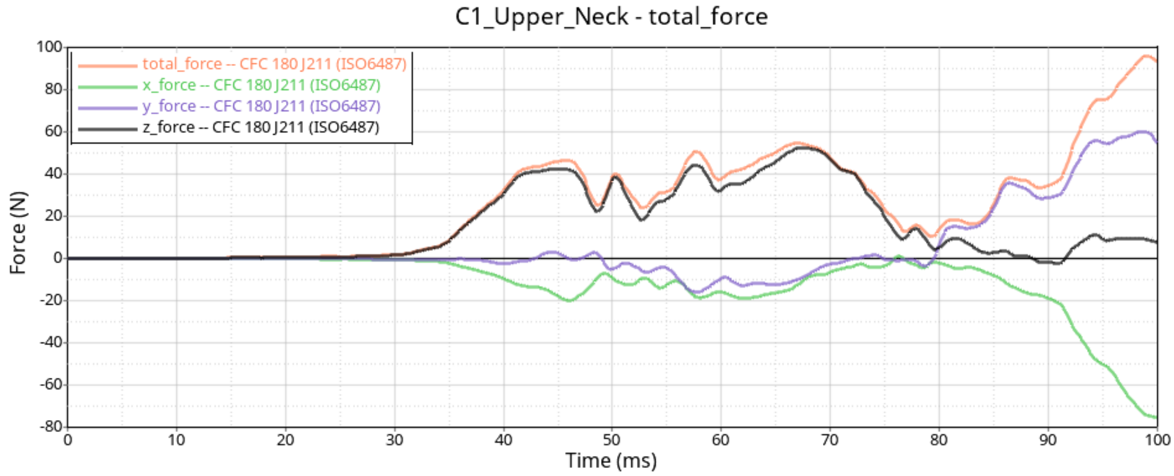


Figure 5.12 - Upper neck forces

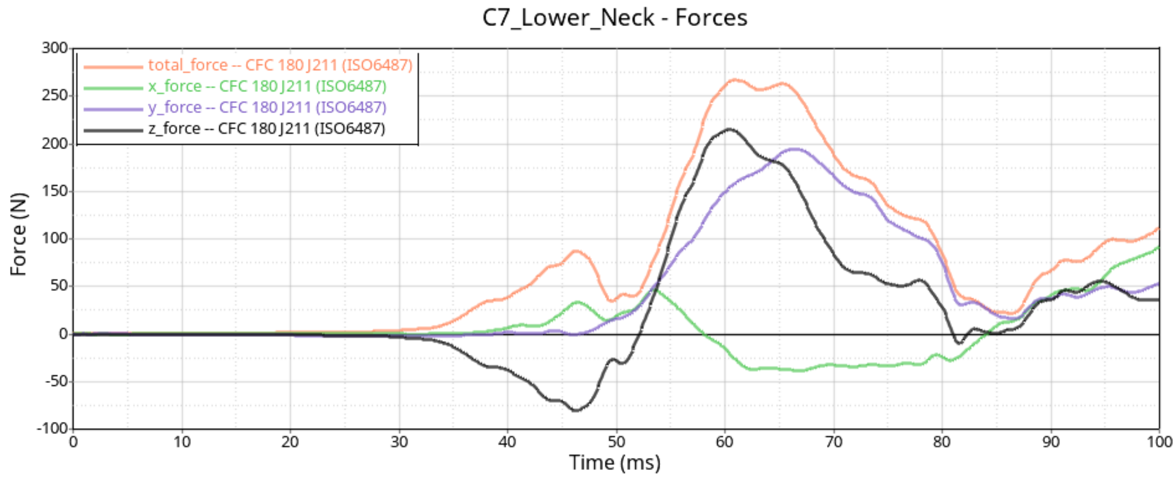


Figure 5.13 - Lower neck forces

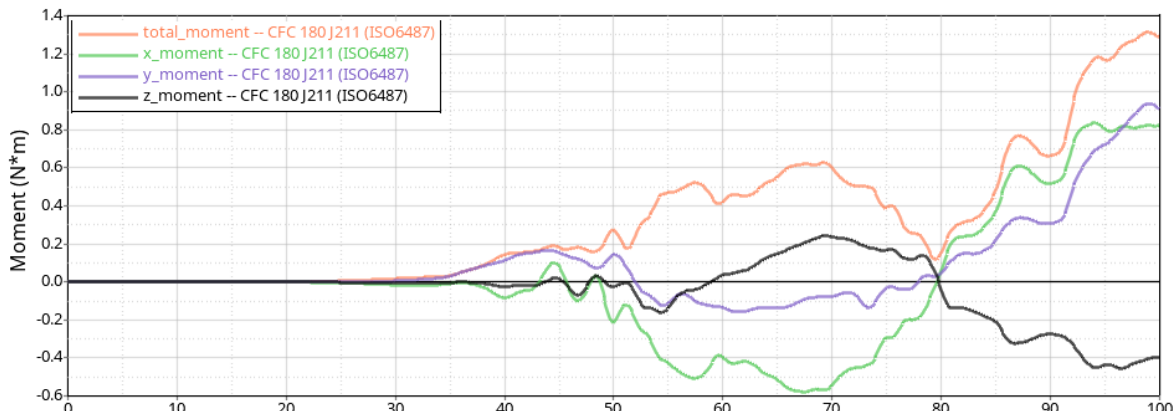


Figure 5.14 - Upper neck moments

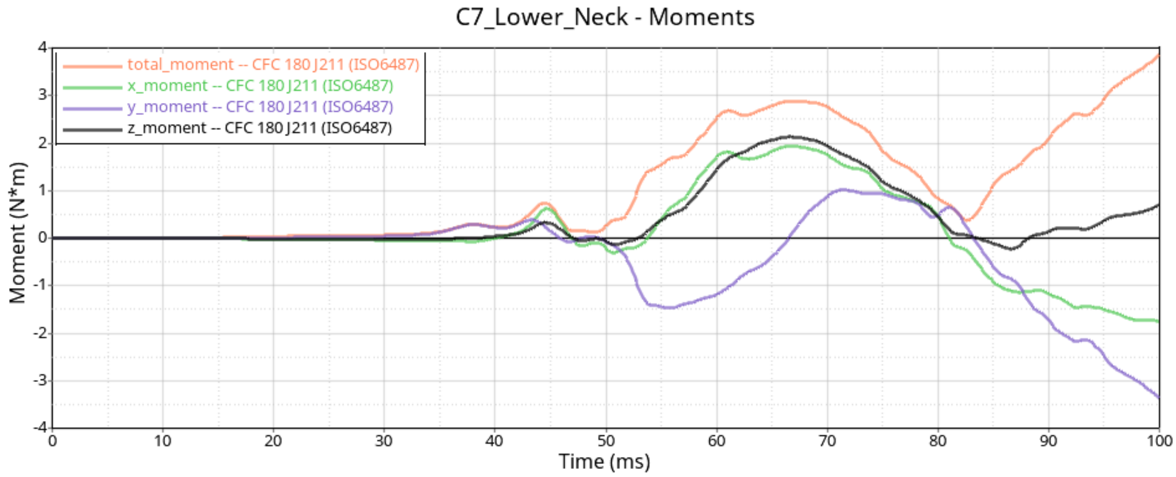


Figure 5.15 - Lower neck moments

From the results obtained it can be seen that the main component is the one on the z axis of the cross section plane defined. The peak values of the forces and moment are 0.27kN and 2.9Nm. From the results seems that the real peak value is outside the window of 100ms taked into account, anyway, comparing the values obtained with the literature, is accectable not proceed with further investigation since the values are 1 order of magnitude less then the corresponding limit [24].

5.4.4 Neck Injury Criteria (Nij)

The Neck Injury Criteria is then calculated as describe in chapter 2.2.3. The Nij obtained is equal to 0.04. The value of Nij confirm the evaluation made with the acceleration and moment plot.

5.4.5 THUMS – Thorax T1

Following the Euro NCAP normative the acceleration of the T1 sensor is plotted.

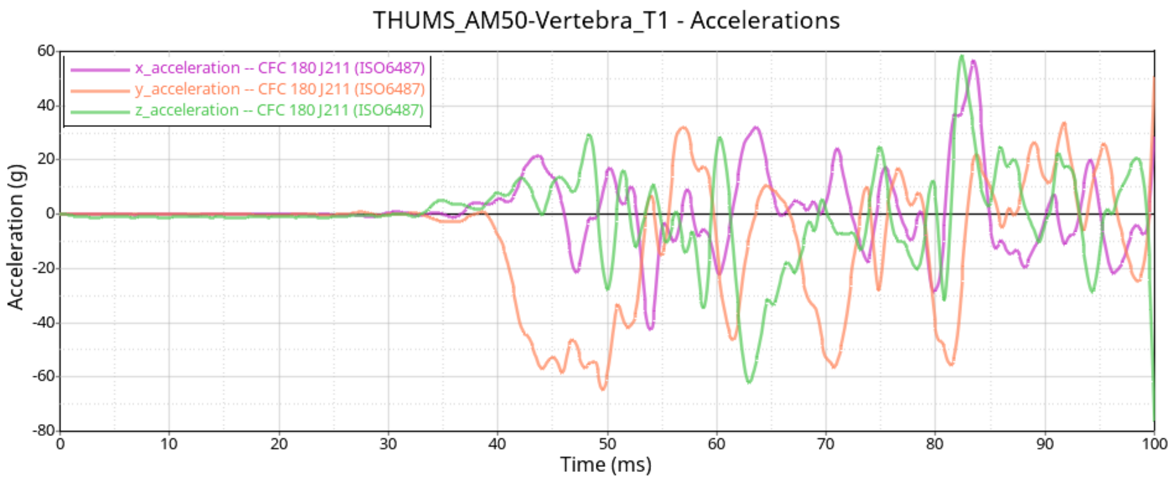


Figure 5.16 - T1 accelerations

5.4.6 THUMS – Thorax T4

The acceleration of the T4 is not request in the Euro NCAP normative but gives a better idea of the thorax behaviour of the THUMS.

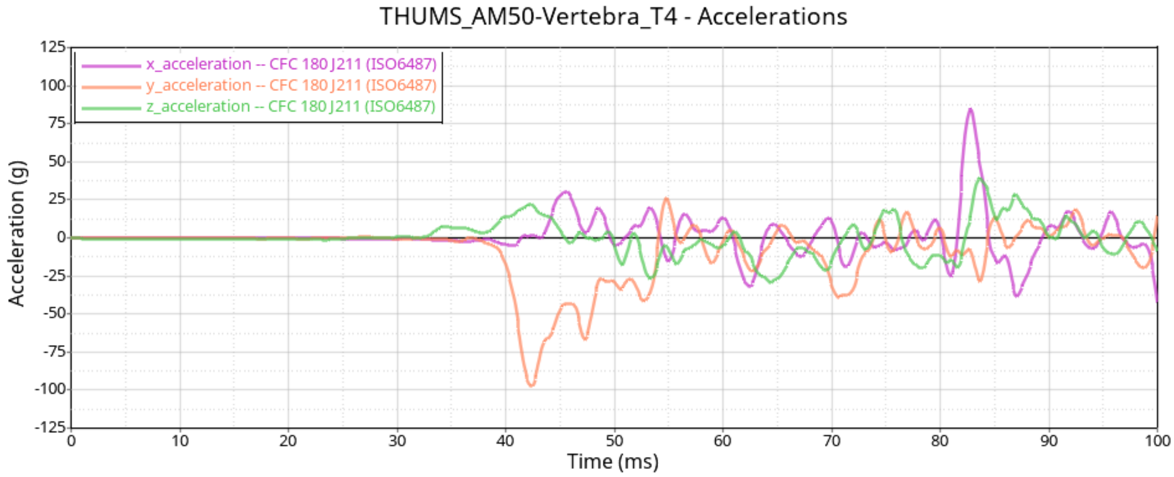


Figure 5.17 - T4 accelerations

5.4.7 THUMS - Thorax T12

Following the Euro NCAP normative the y acceleration, the force along the x and y axis and the moments on the x and y axis of the T12 vertebra are plot.

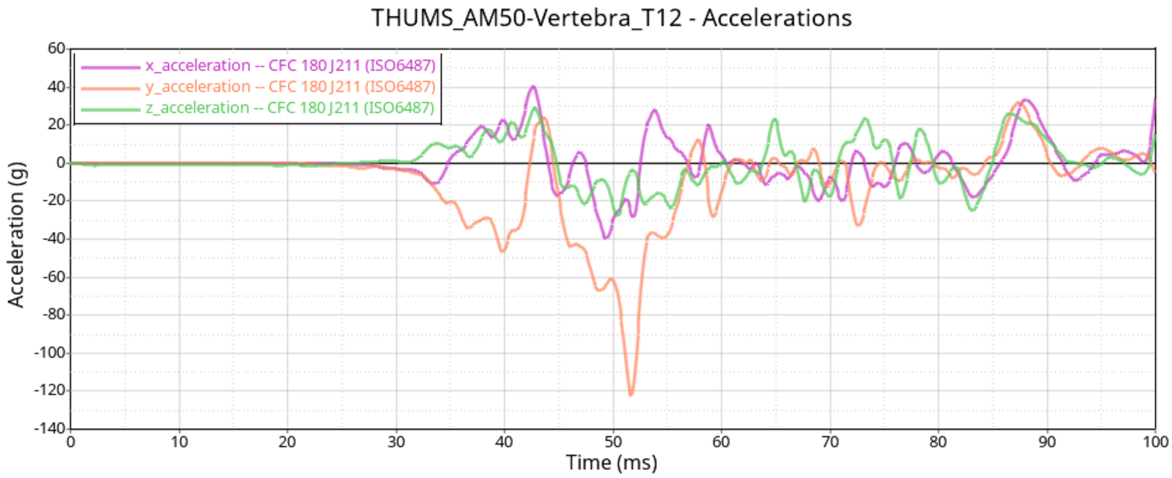


Figure 5.18 - T12 accelerations

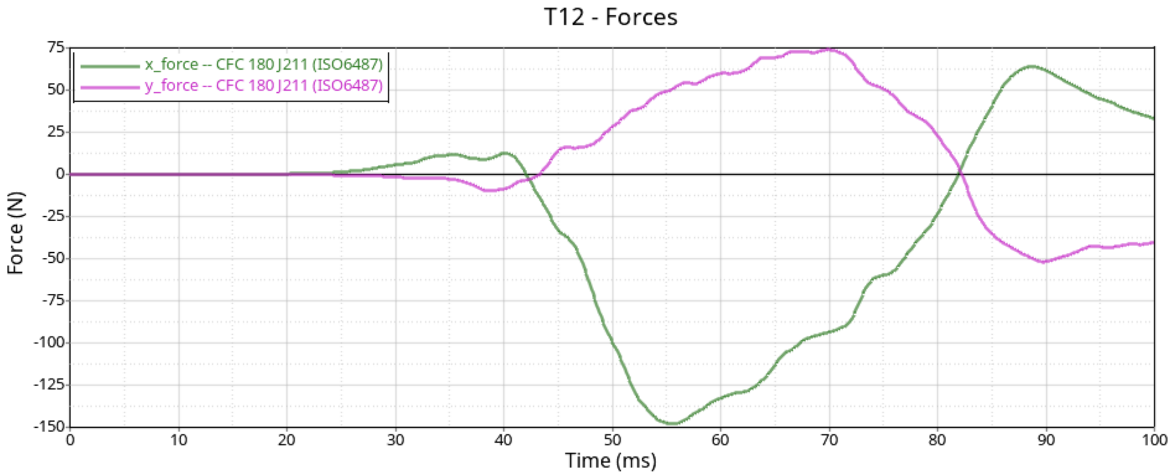


Figure 5.19 - T12 forces

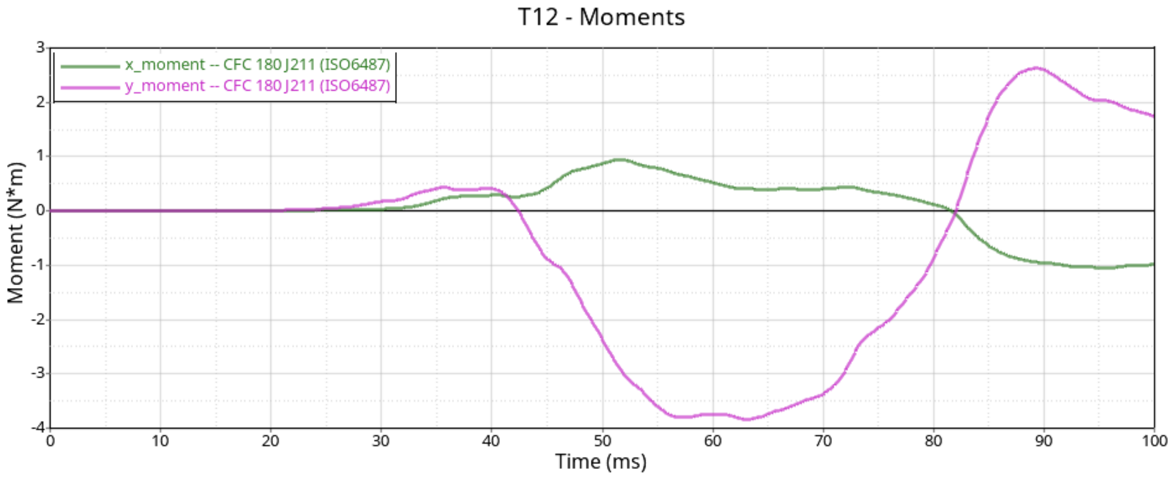


Figure 5.20 - T12 moments

Comparing the values of forces and moments of the T12 with the Euro NCAP performance it does not suffer a big stress from the impact [22].

5.4.8 THUMS – Ribs

Following the Euro NCAP normative the set of acceleration and deflection of the ribs (upper, middle, lower) are plot.

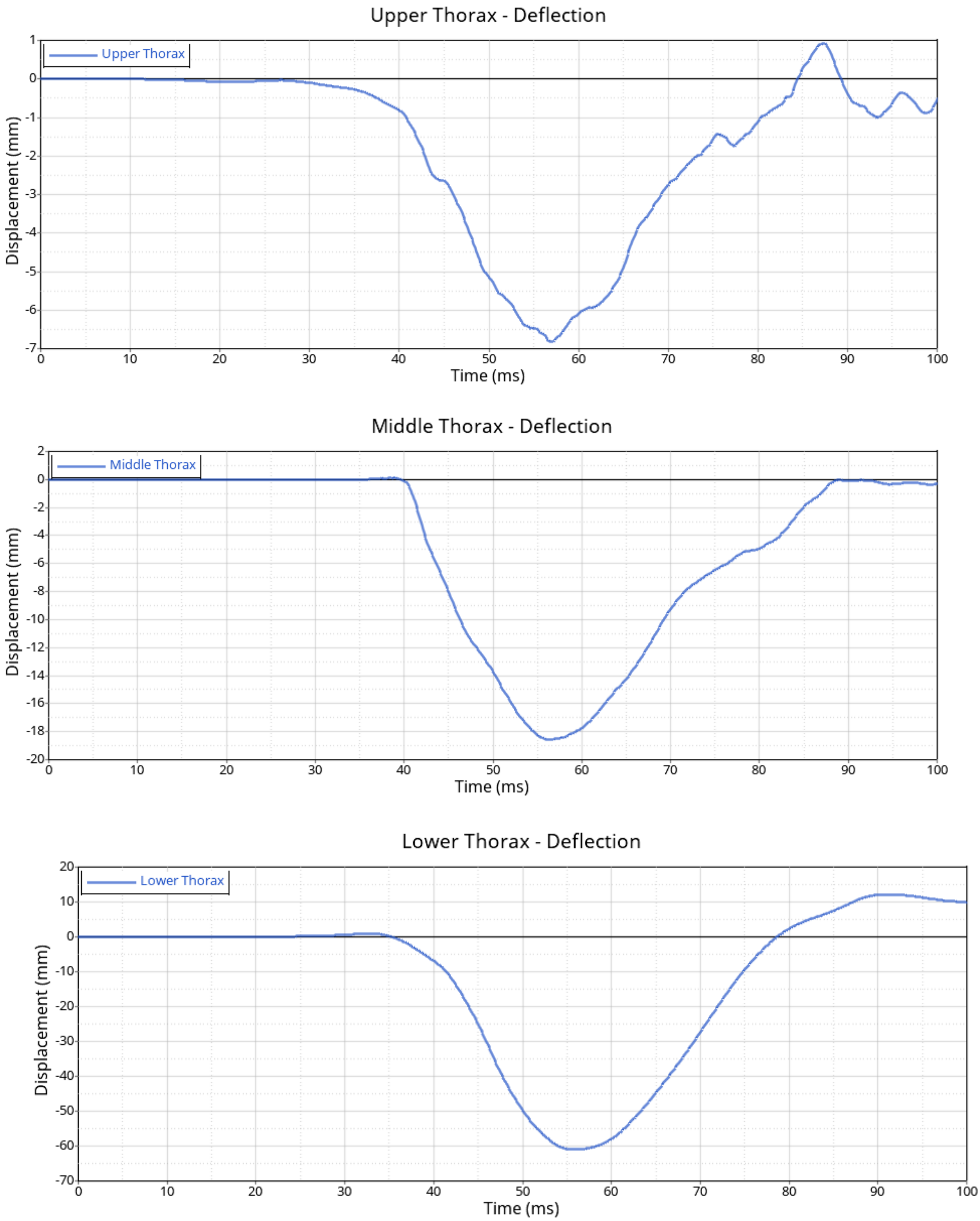


Figure 5.21 - Upper, middle and lower thorax deflection

As can be seen from the Figure 5.21, the lower thorax, corresponding to the 9th rib, suffer an important deformation. This result is expected since the thorax is one of the human parts that suffer the most during side impact crashes.

5.4.9 THUMS – Backplate

Following the Euro NCAP normative, the forces along the x and y axis and the moments along the y and z axis are plot.

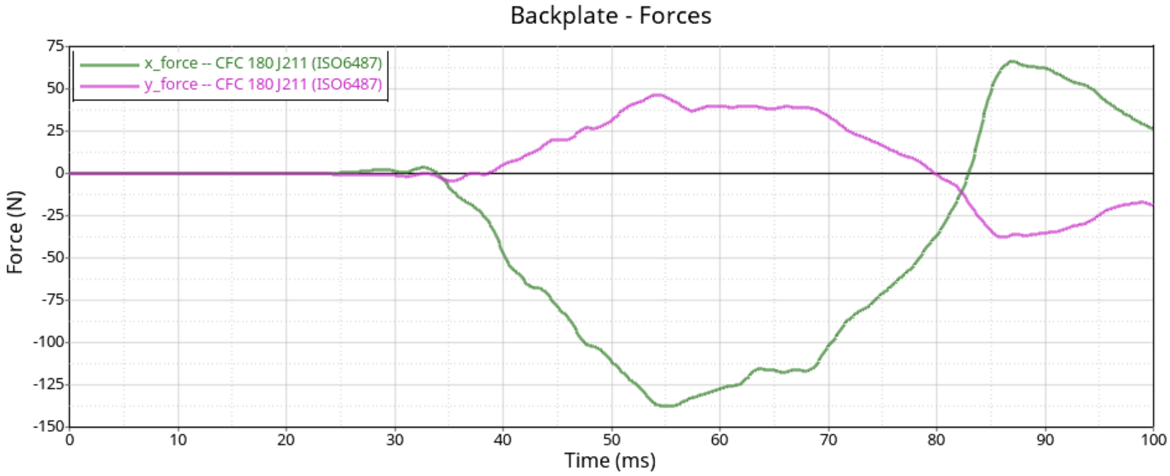


Figure 5.22 - Backplate forces

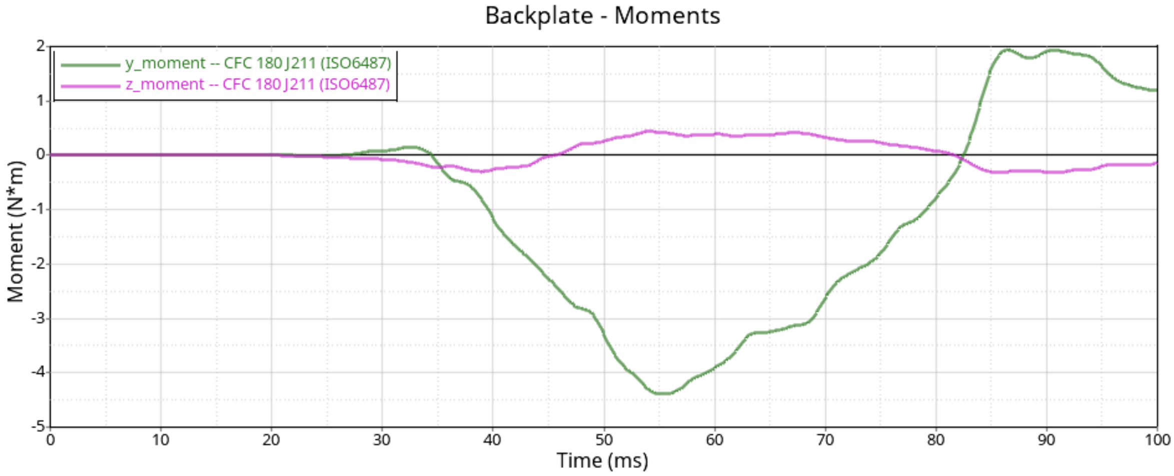


Figure 5.23 - Backplate moments

Comparing the values of forces and moments of the backplate with the Euro NCAP performance it does not suffer a big stress from the impact [22].

5.4.10 THUMS - Pelvis

Following the Euro NCAP normative, the full set of acceleration of the Pelvis are plot.

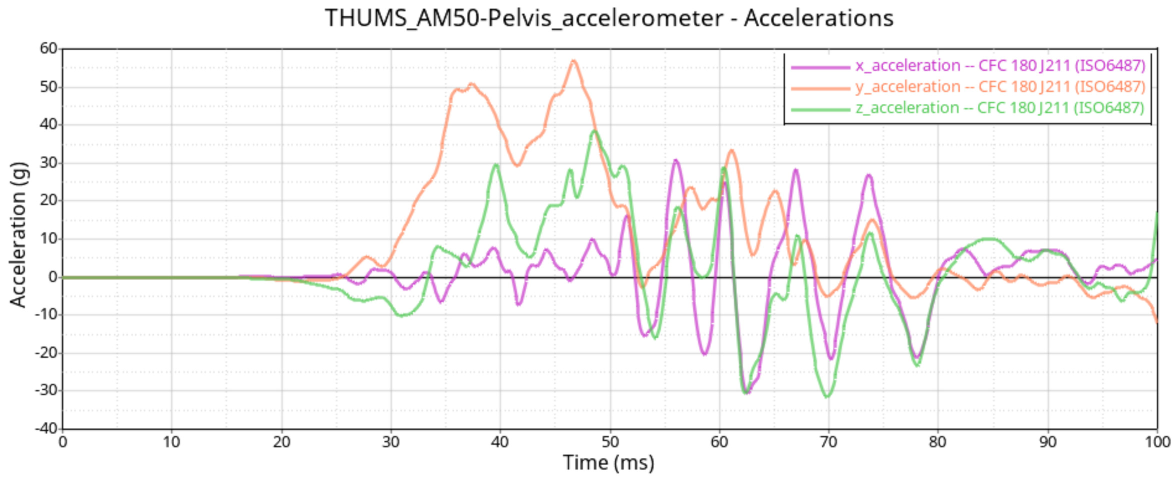


Figure 5.24 - Pelvis accelerations

5.4.11 THUMS – Pubic Symphysis

Following the Euro NCAP normative the Pubic Symphysis the y force is computed.

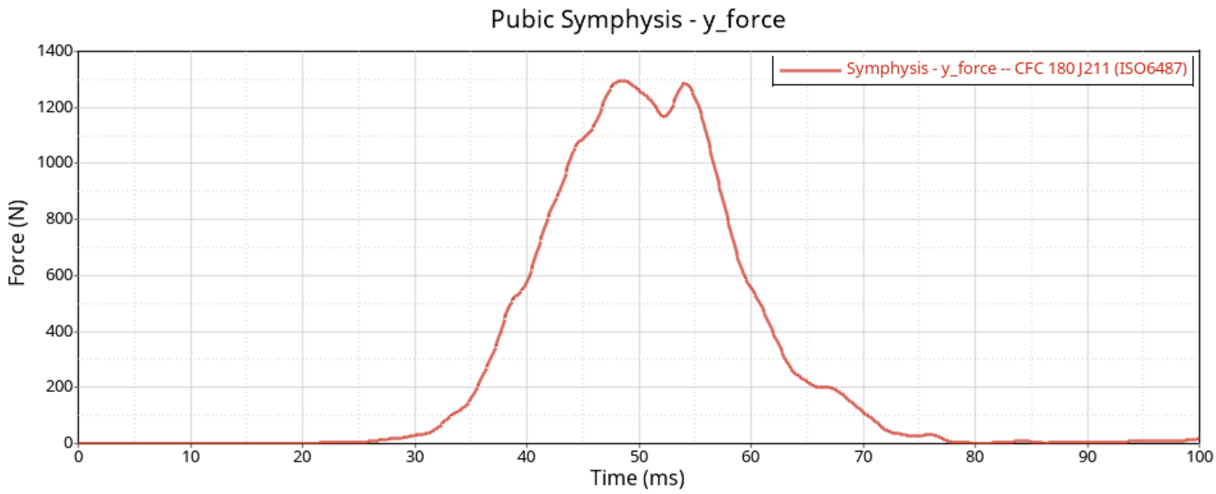


Figure 5.225 - Pubic Symphysis y force

5.4.12 THUMS - Femur (L&R)

Following the Euro NCAP normative the full set of forces and moments are plot below.

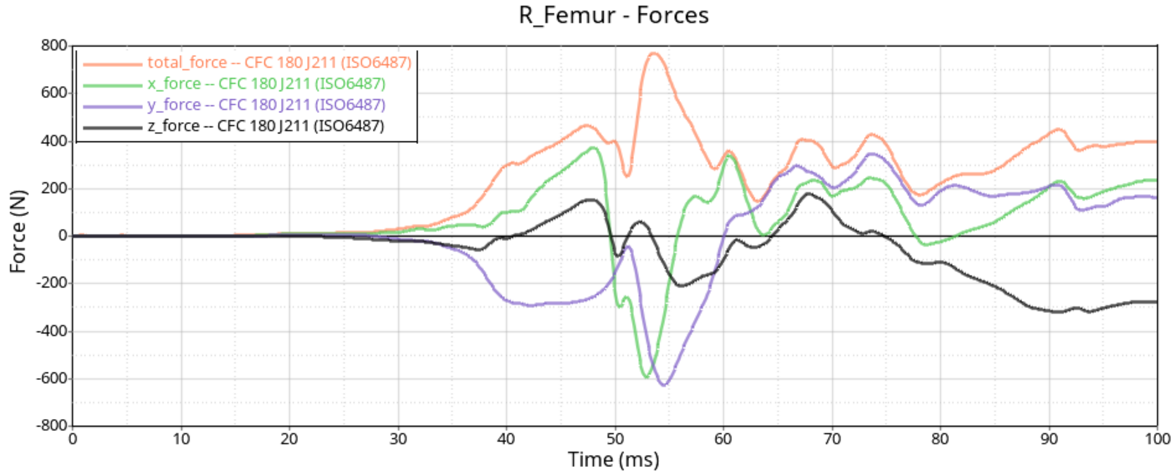


Figure 5.26 - Right femur forces

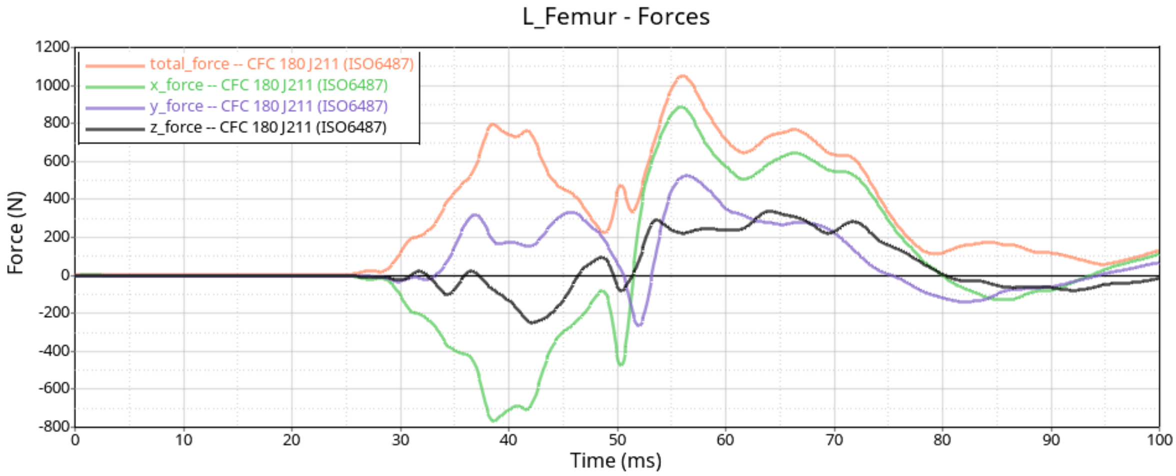


Figure 5.27 - Left femur forces

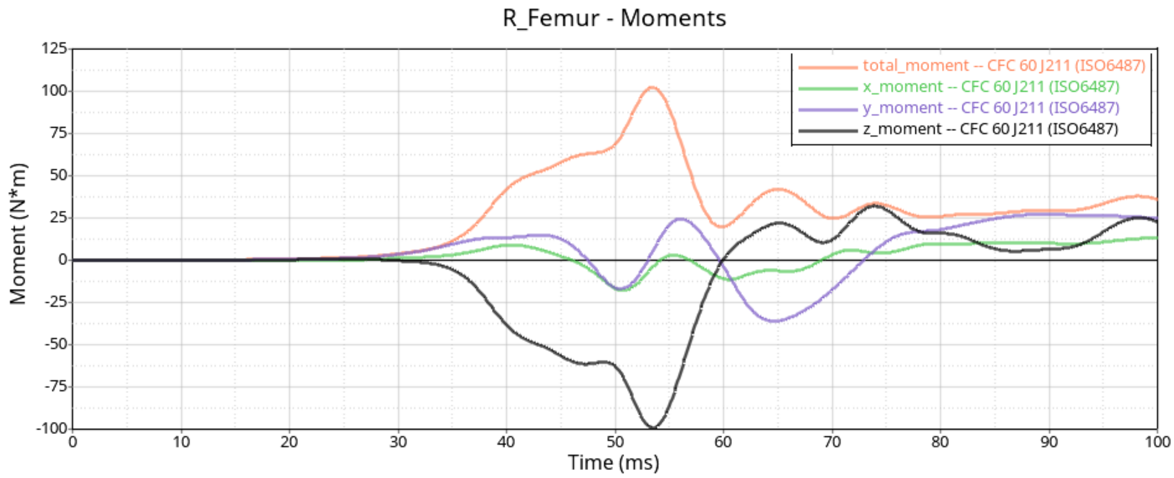


Figure 5.28 – Right femur moments

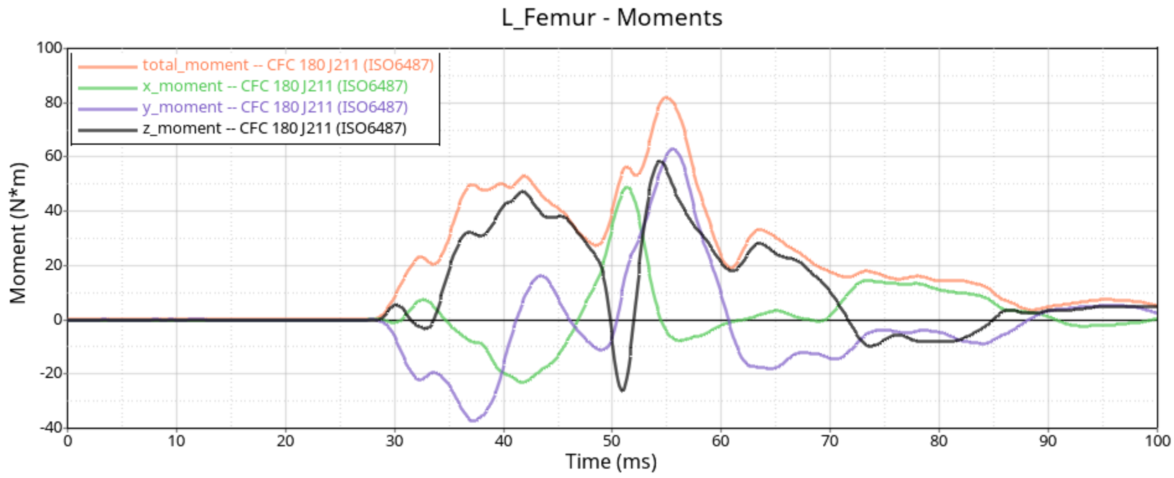


Figure 5.29 - Left femur moments

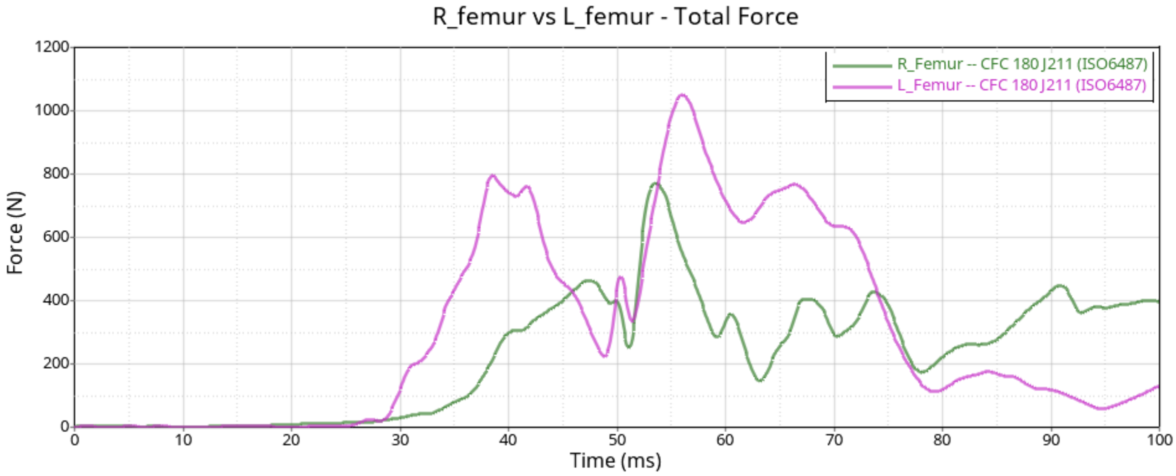


Figure 5.30 - Right vs Left femur - Forces

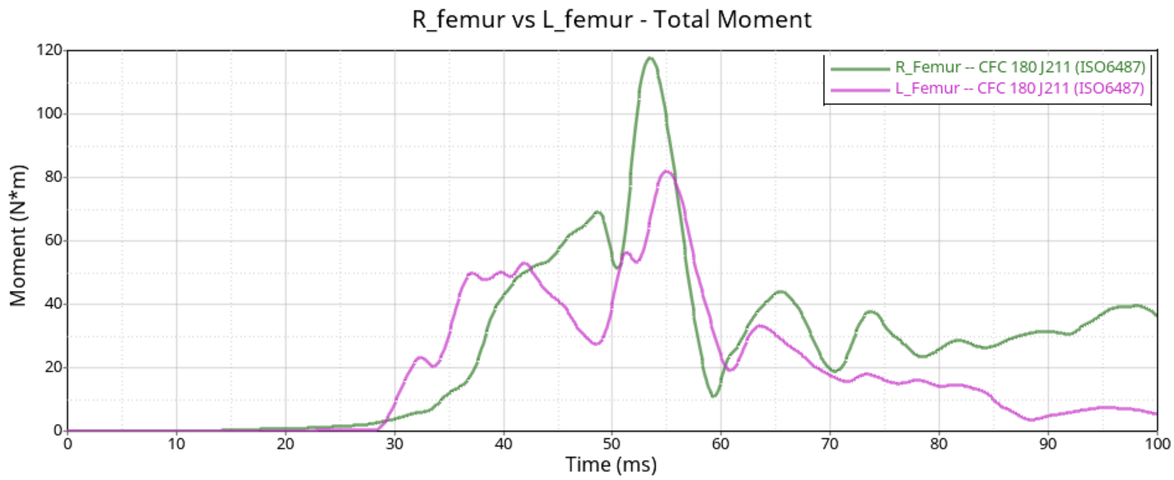


Figure 5.31 – Right vs Left femur - Moments

5.4.13 Tibia Index (TI)

The Tibia Index is then calculated as describe in chapter 2.2.4. The critical bending moment result equal to 225Nm, instead the critical force 39kN. The tibia index is then obtained, and, in the worst case, it results equal to 0.107.

5.4.14 THUMS – Internal Organs Volume and Surface Area

The THUMS sensor set allowed to obtain the volume and the surface area of define organs through the keyword *AIRBAG_SIMPLE_PRESSURE_VOLUME as describe in chapter 4.5. The organs analysed in this thesis are lungs, the heart, the pancreas, the spleen, the liver, the stomach, the intestine and two larger regions such as the ribcage and the whole abdomen that enclose all the previous organs. The complete results are provided in Appendix A. In Figure 5.32 and 5.33 the Ribcage results are plotted as soon as the thorax, according to the literature, is one of the most injured part in a side impact crash scenario.

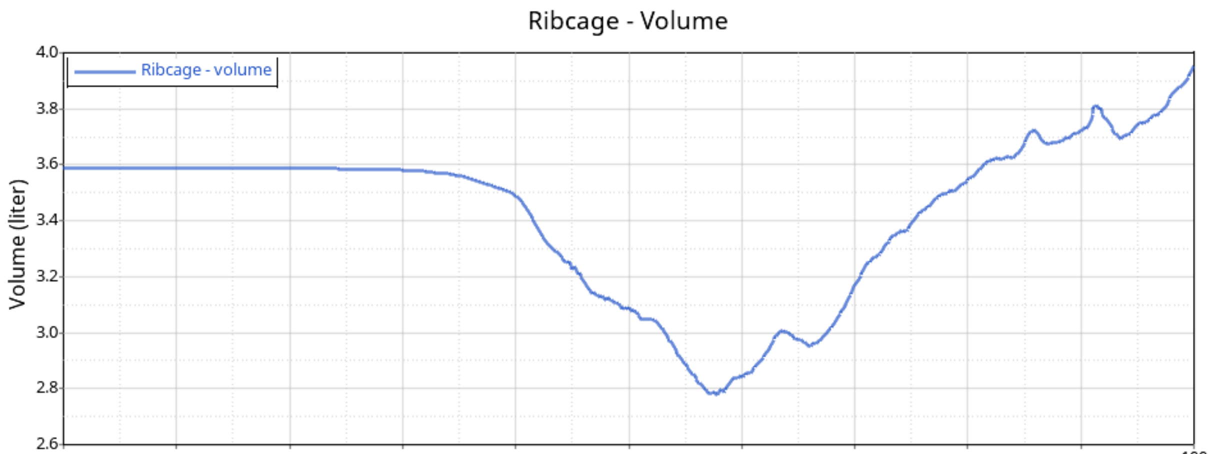


Figure 5.32 - Ribcage volume

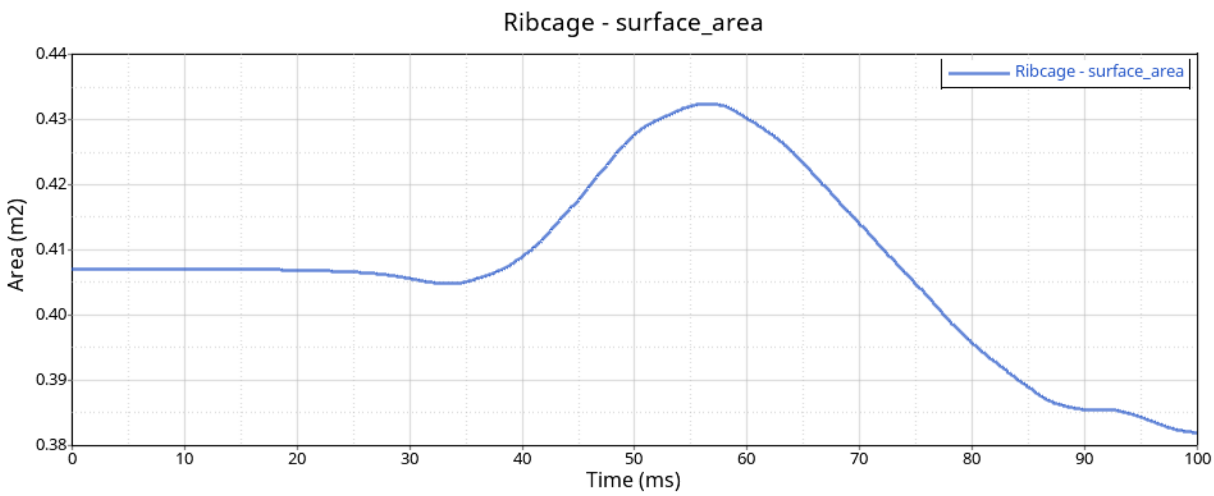


Figure 5.33 - Ribcage surface area

5.4.15 THUMS – Spine Deformation

Through the keyword *DATABASE_NODOUT and markers it was possible to track the x, y, z coordinate of every bone of the human spine. In Figure 5.34 the initial spine projected along the plane XZ and YZ is presented. In the Figure 5.35 and 5.36 are presented the spine projections on the XZ and YZ plane in these samples of time: 0ms, 20ms, 40ms, 60ms, 80ms and 100ms.

Figure 5.34 - FE spine - plane XZ and YZ

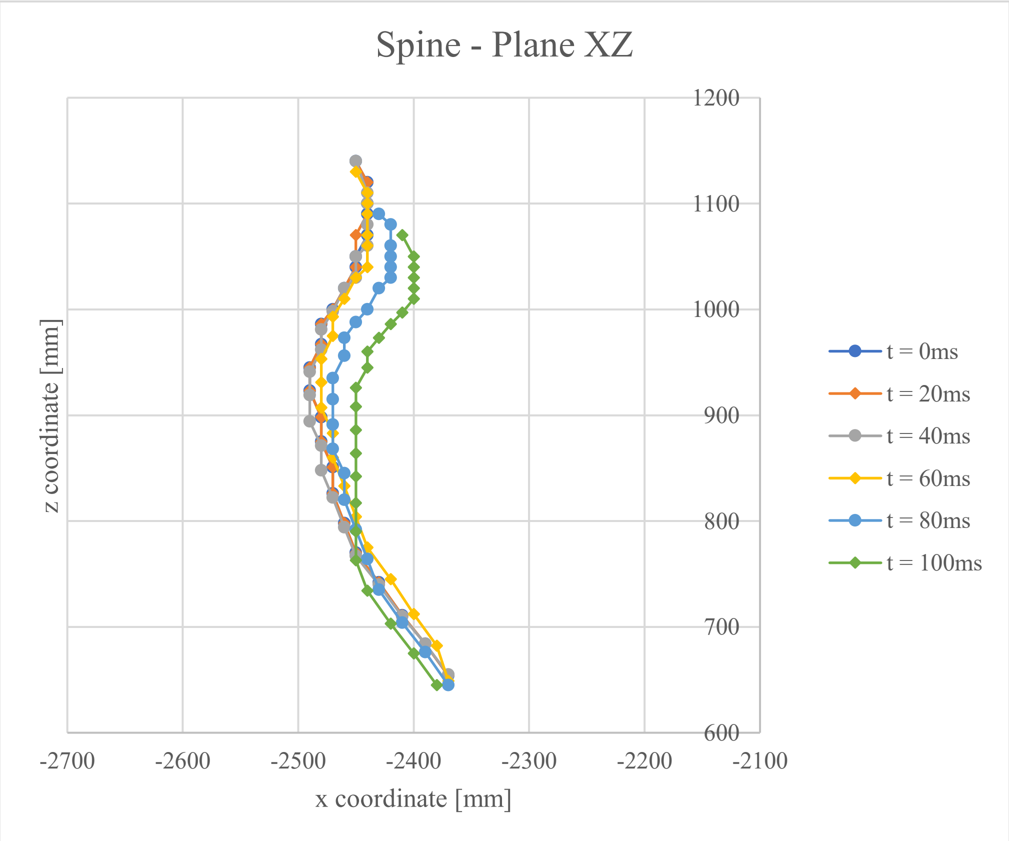


Figure 5.35 - Spine deformation on plane XZ at 0ms, 20ms, 40ms, 60ms, 80ms and 100ms

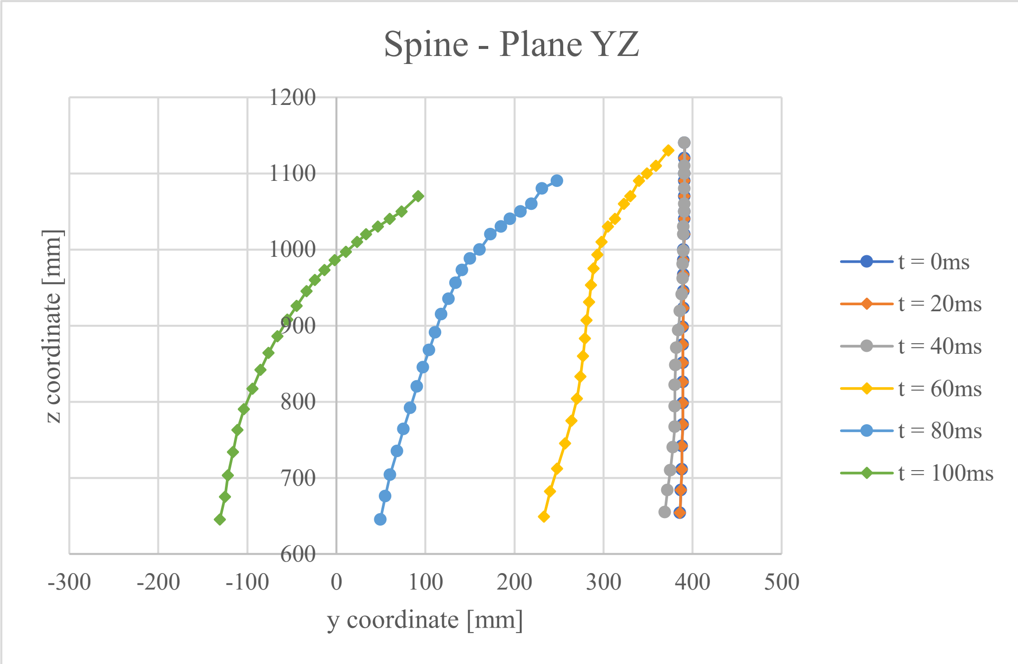


Figure 5.36 - Spine deformation on plane YZ at 0ms, 20ms, 40ms, 60ms, 80ms and 100ms

As can be seen from the figures the first vertebrae, associated with the neck, does not suffer an important deformation. This confirms the results obtained with the comparison of the neck moments and forces and of the Nij, in the chapter 5.4.3 and 5.4.4.

5.4.16 Euro NCAP score evaluation [22]

Euro NCAP have a score system to evaluate the injury during the impact. This score consider if some parameters are above or below certain limits. Some modifiers, defined by the Euro NCAP normative, are added in order to correct the final score. One of them is related to the partial ejection of some defined body. Since the head end up outside of the vehicle, a -1 assessment is applied. A final score of 10 out of 16 is evaluated for the side impact crash simulation with the Toyota Camry 2012. The breakdowns of the points can be seen in the table 4.1 [22].

Dummy parameters				**THUMS output**	**Score**
Part	*Parameter*	*Higher performance*	*Lower performance*		
Head	Hic_36	650	1000	314	3/4
	Resultant Acc. 3 msec exceedence	72 g	88 g	82 g	
Chest	Lateral Compression	22 mm	42 mm	61 mm	0/4
	Viscous Criterion (VC)	0,32 m/s	1 m/s	1,143 m/s	
Abdomen	Total Force	1 kN	2,5 kN	0,03 kN	4/4
Pelvis	Force	3 kN	6 kN	1,3 kN	4/4
Backplate	Fy	1 kN	4 kN	0,05 kN	-0/2
T12	Fy	1,5 kN	2 kN	0,08 kN	-0/2
	Mx	150 Nm	200 Nm	3 Nm	
Partial ejection modifier					-1
Euro NCAP score					10

Table 5.1 - Euro NCAP dummy score

Chapter 6: Conclusion

In this thesis a side impact was studied with a FE simulation and Human Body Model, according to the Euro NCAP side impact standard. The Euro NCAP side impact test consist in the side impact of a movable deformable barrier thrown against the car tested, at 50km/h. The direction of impact of the barrier is perpendicular to the car along the R-point of the car, given from the manufacturer. In this thesis, since the R-point was unknown, the H-point of the HBM was chosen. All the simulations were ran using LS-DYNA version R9.

The FE simulation was composed by the following FE models:

- Advance European Movable Deformable Barrier (AE-MDB)
- 2012 Toyota Camry mid sedan
- Total Human Model for Safety (THUMS)

First the AE-MDB was validated according to the documentation provided by LSTC, then a fully simulation without the HBM was set and run. The results were completed and showed a correct and satisfying behaviour.

After this step the Human Body Model was positioned, through the PIPER software and a seatbelt model was created and fit along the THUMS to ensure the driver to the seat, previously deformed with a sitting simulation of the HBM. A set of accelerometers and load sensors was implemented in the human model to track the behaviour of critical part of the human body during the impact. Head, neck, thorax, pelvis, and lower limbs were tracked, according to the Euro NCAP standard and not, sensors were added to track the volume and surface area of defined internal organs and the ribcage, lastly some markers were positioned along the spine of the HBM, in order to track the deformation of it during the impact. This allows to have a complete idea of the severity of the impact and fully use the potential of the THUMS. The FE simulation was then run for a considered time interval of 100ms, where, according to the literature, there is the peak value of acceleration. The simulation was completed after 40 hours and 35 minutes with 64 cores.

The results were then analysed comparing them with the Euro NCAP protocol and with Injury Criteria (IC), described in chapter 2.2.

The results show a satisfying behaviour of the vehicle and the MDB, this is also confirmed by the energy analysis and by the energy ratio, tending towards unity.

The THUMS showed a first important slide of the entire body against the driver door and a considerable movement of the head against the lateral window. The impact of the head against the window does not happen, however, because the window breaks before.

Analysing the sensor's output, an important acceleration of the head was detected, with a peak value between the lower and the higher performance limit set by Euro NCAP. The severity of the head injury was analysed also with the Head Injury Criteria (HIC) were the values obtained were way under the higher performance limit set by Euro NCAP. Using the Prasad-Mertz set of curves to have a better idea of the injury level, it was obtained a probability of severe injury close to 4.8% and a probability of minor injury of 49%. However, this criterion has been highly criticised and is not entirely reliable, although it continues to be used.

Continuing the analysis, an important deflection of the neck was noticed and indagated analysing the moments and the forces of the upper and lower neck, i.e., C1 and C7 vertebrae, and through the Neck Injury Criteria (Nij). Both the results, unexpectedly, did not give a significative sign of injuries on the neck.

The literature review shows how the thorax injury is one of the main causes of injury and death due to a side impact crash. This evidence was found through the thorax deflection, in particular on the 9^{th} rib, and the Viscous Criterion (VC), both over the worst performance limit according to the Euro NCAP normative, and the accelerations of the upper set of thorax vertebrae implemented (T1, T4), all relatively high.

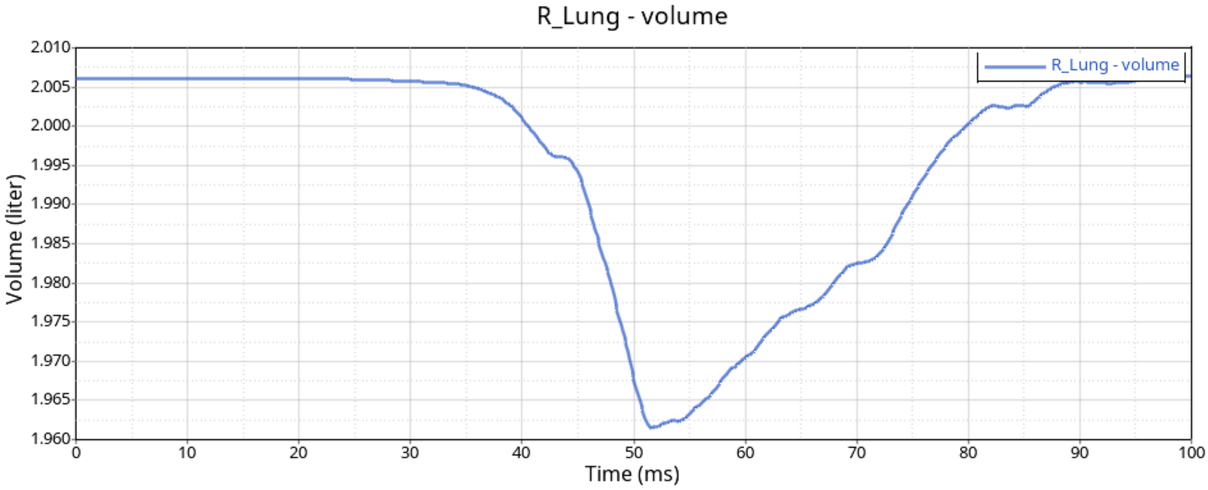
Analysing the sensors of the lower part of the body (backplate, pelvis, lower limbs) and the computation of the Tibia Index (TI), the results did not show any evidence of a particular severe injury.

These results shows that the severity of the injury is higher in the upper part of the body and then it slightly decreases as soon as the lower part of the body is considered. This result confirms the statistics found on the literature, were the upper part of the body (head and thorax) are the most injured during side impact crashes. It is important to remember that the car model used in this thesis was not provided with any passive safety system, like the side airbag.

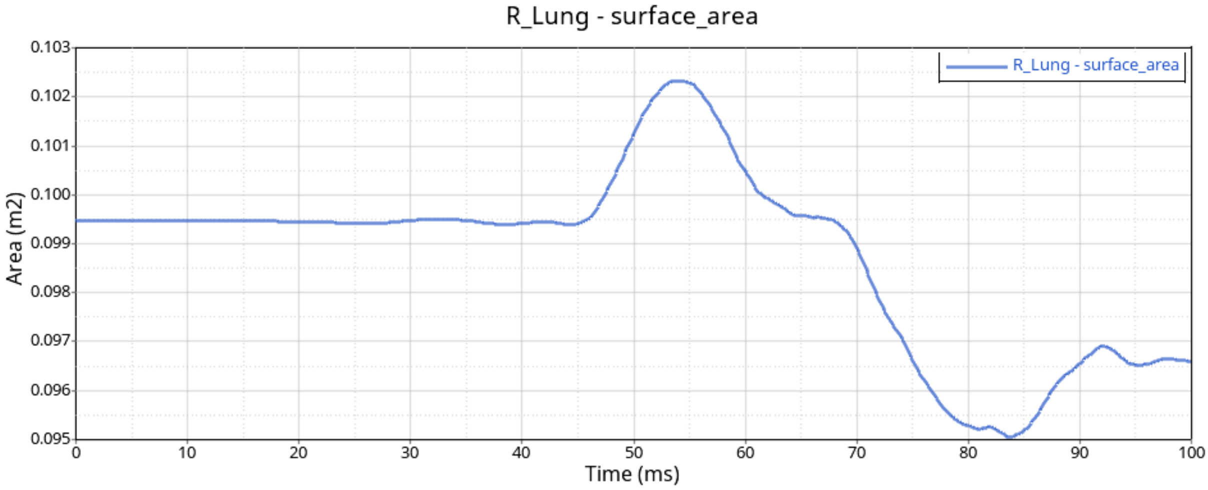
The use of an HBM in this thesis allow to have a complete idea of the body behaviour during the impact and give to the user the possibility of analysed more data, compare to the real dummy used in the NCAP test, like the internal organs volume, the surface area of them and the spine deformation. The advantages of the HBM results clear, with a low budget analysis and a potential complete understanding of the body behaviour. The implementation of this type of analysis in the automotive industry can give a preliminary view of a crash scenario and will be a fundamental tool for the passive safety systems design and beyond.

Appendix A: Appendix

Right Lung

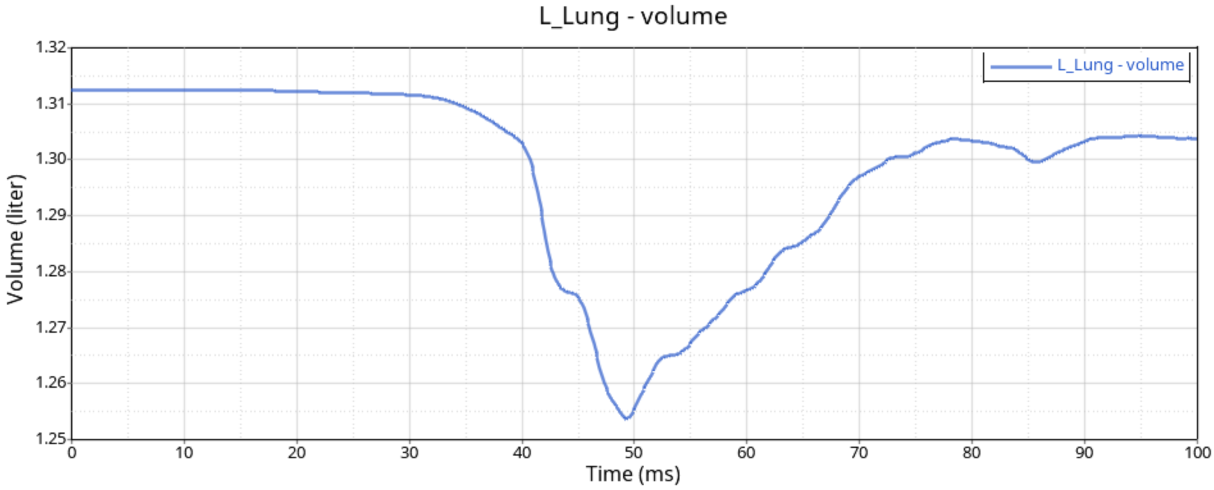


Appendix A 1 - Right lung volume

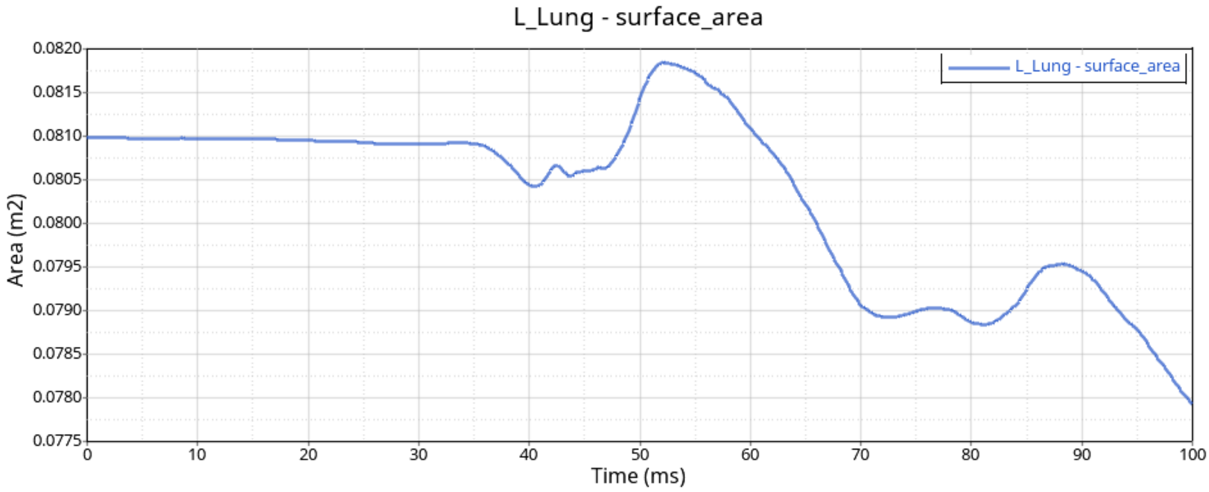


Appendix A 2 - Right lung surface area

Left Lung

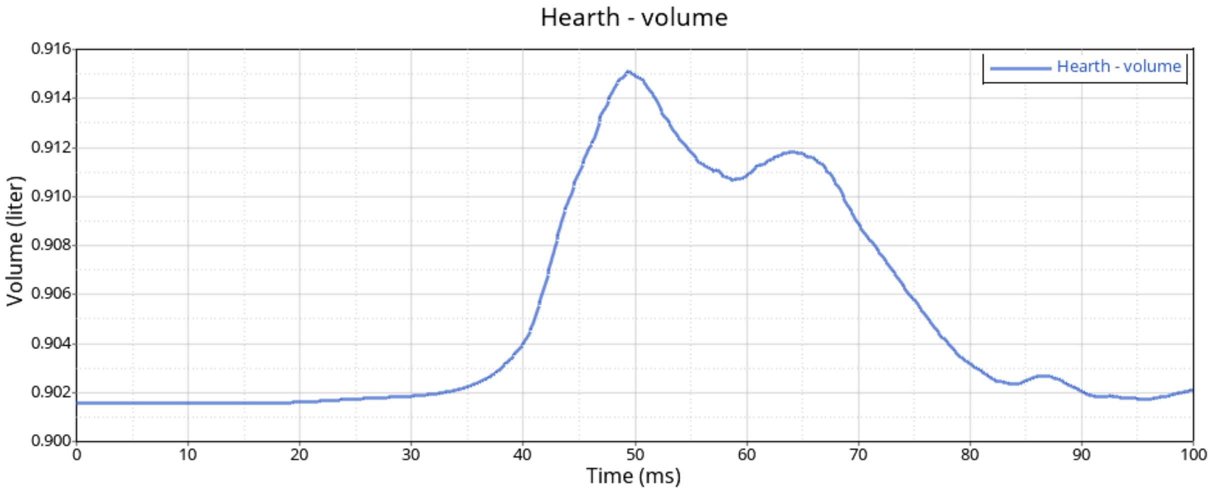


Appendix A 3 - Left lung volume

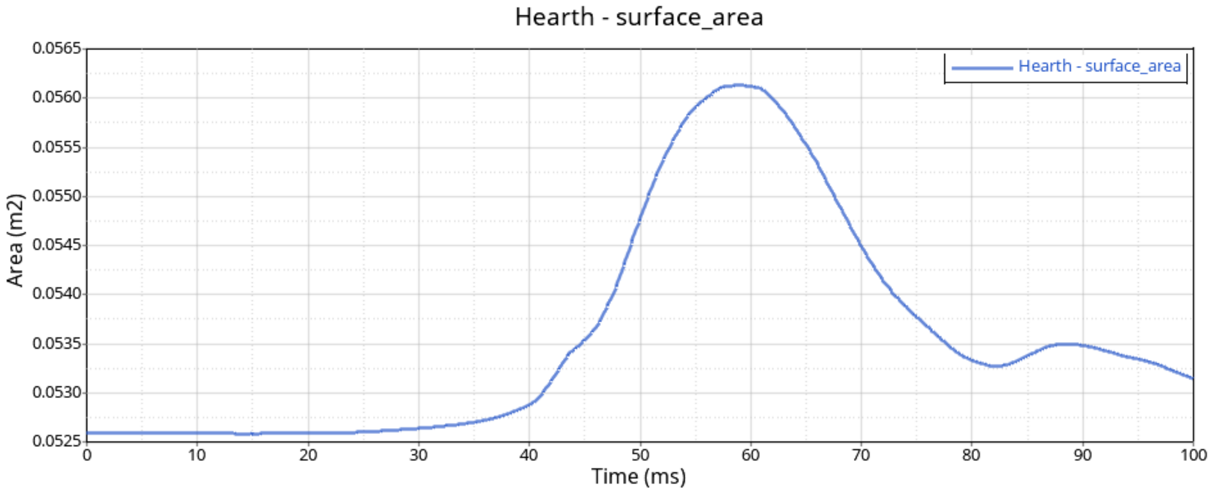


Appendix A 4 - Left lung surface area

Heart

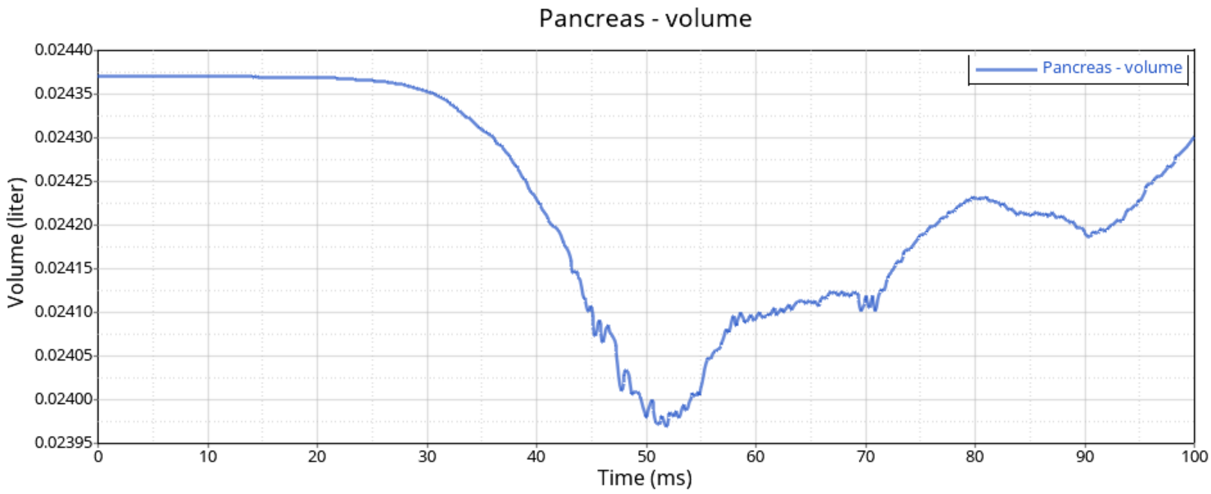


Appendix A 3 Heart volume

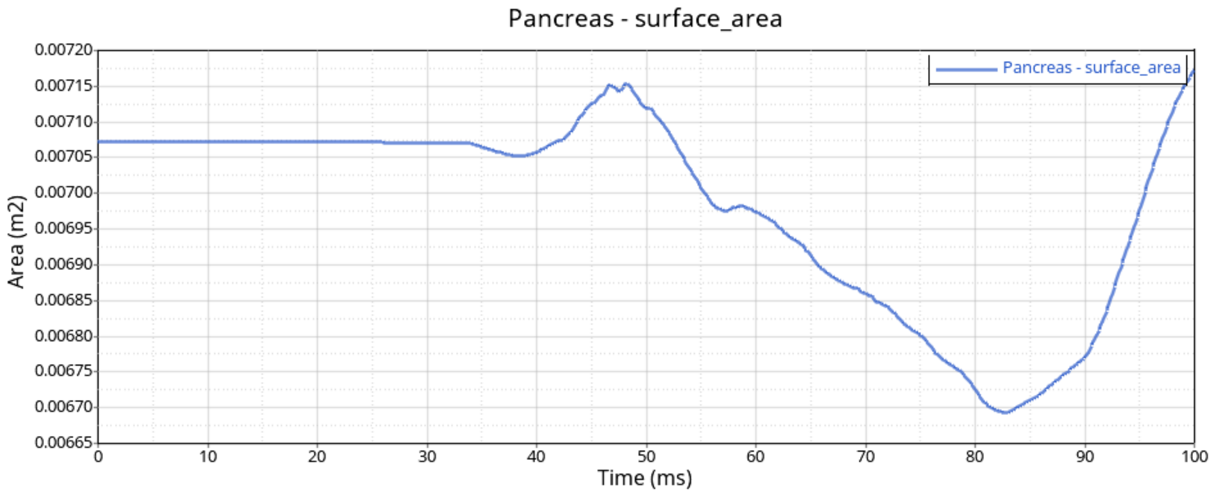


Appendix A 4 - Heart surface area

Pancreas

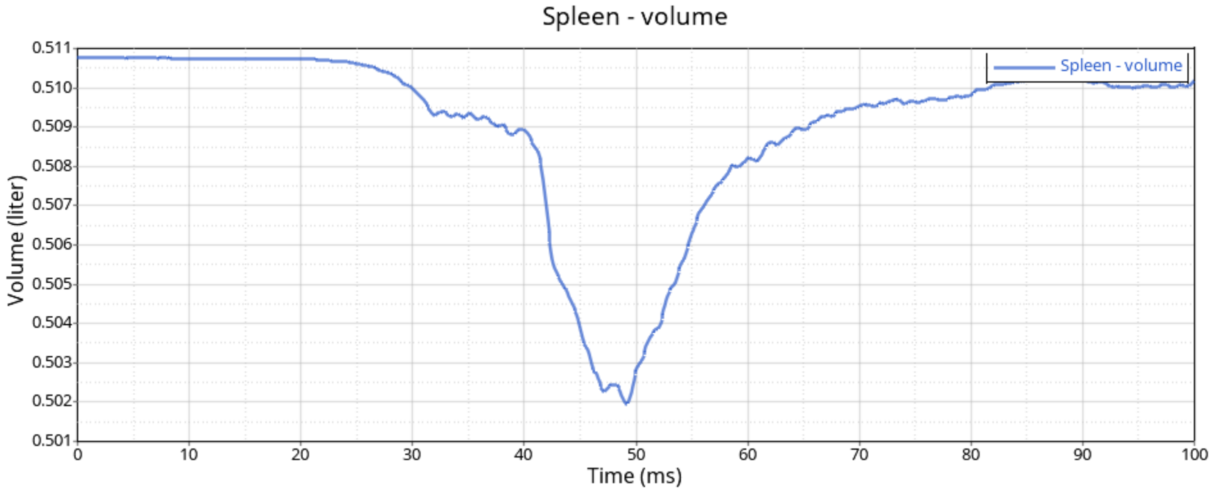


Appendix A 7 - Pancreas volume

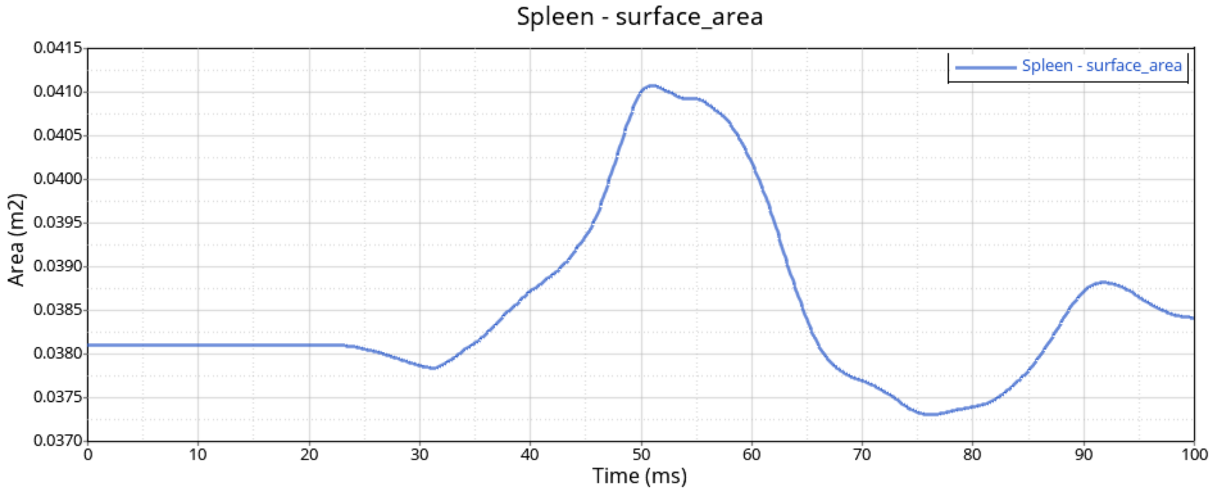


Appendix A 8 - Pancreas surface area

Spleen

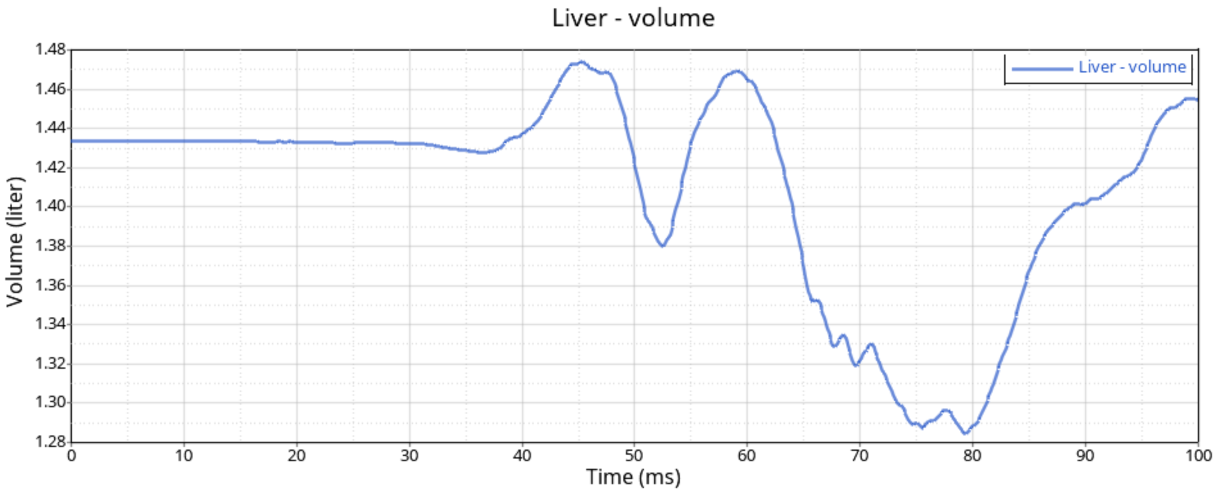


Appendix A 9 - Spleen volume

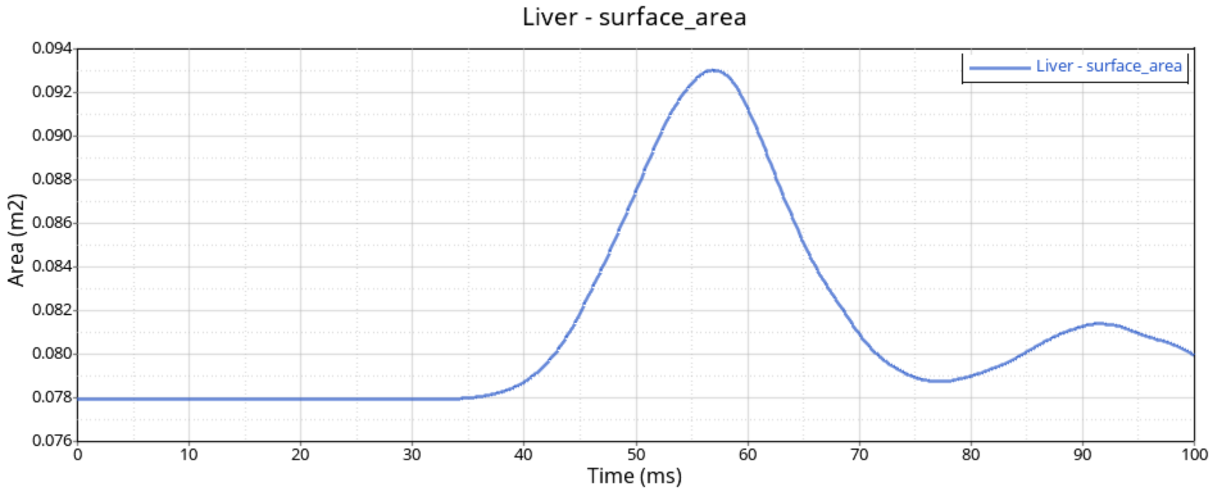


Appendix A 5 - Spleen surface area

Liver

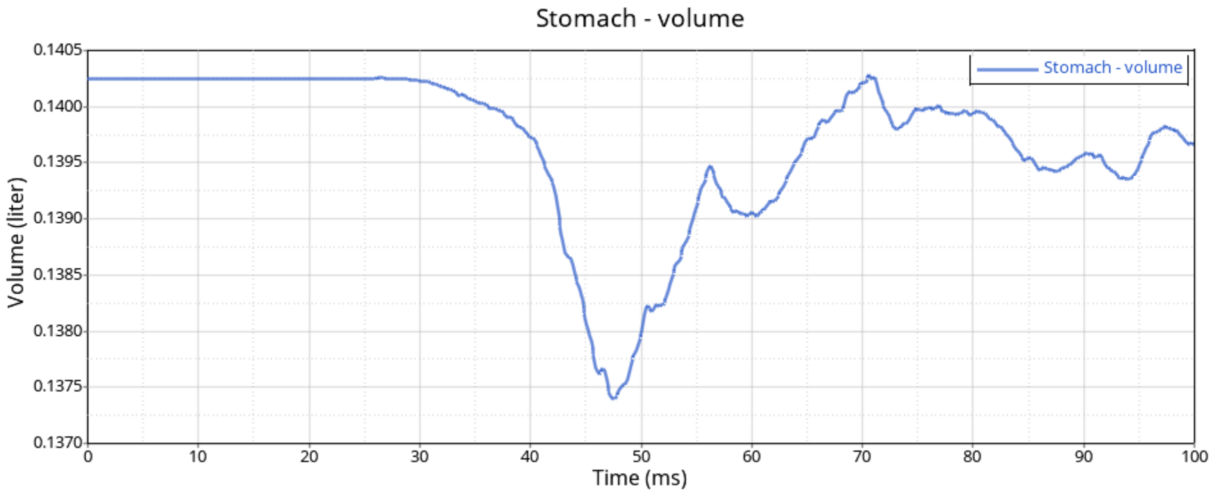


Appendix A 11 - Liver volume

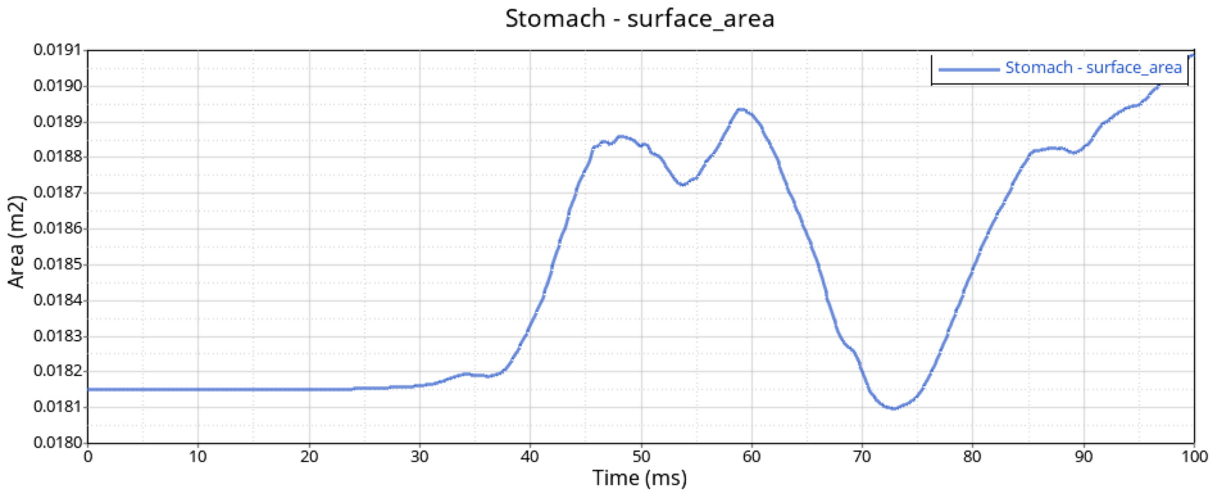


Appendix A 6 - Liver surface area

Stomach

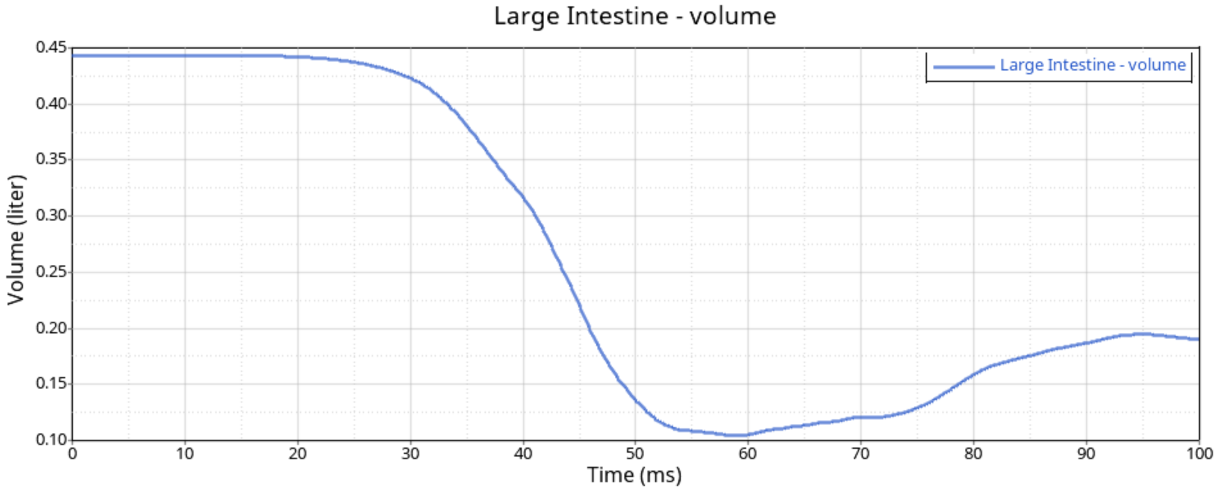


Appendix A 13 - Stomach volume

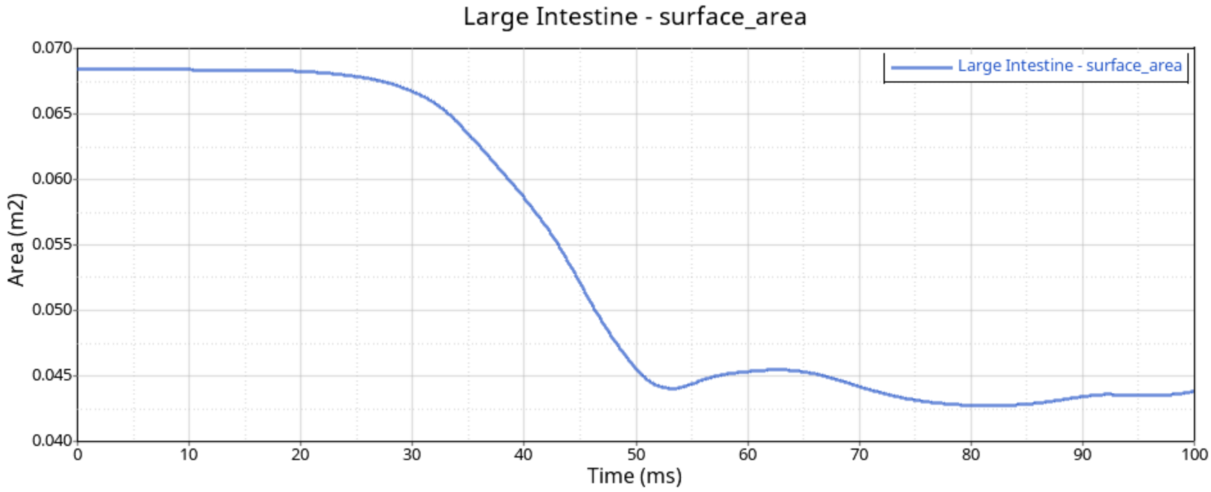


Appendix A 14 - Stomach surface area

Large intestine

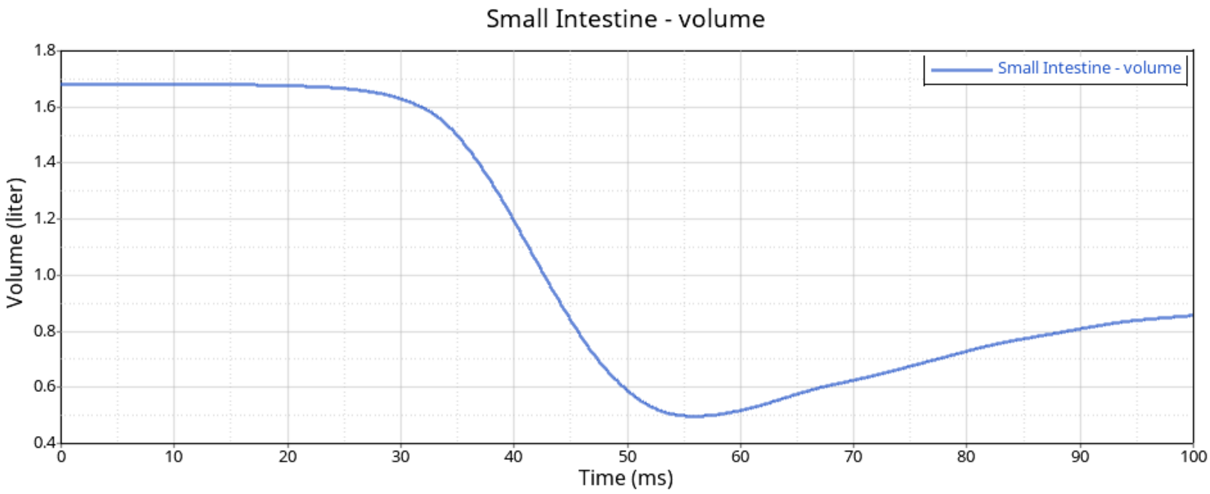


Appendix A 85 - Large intestine volume

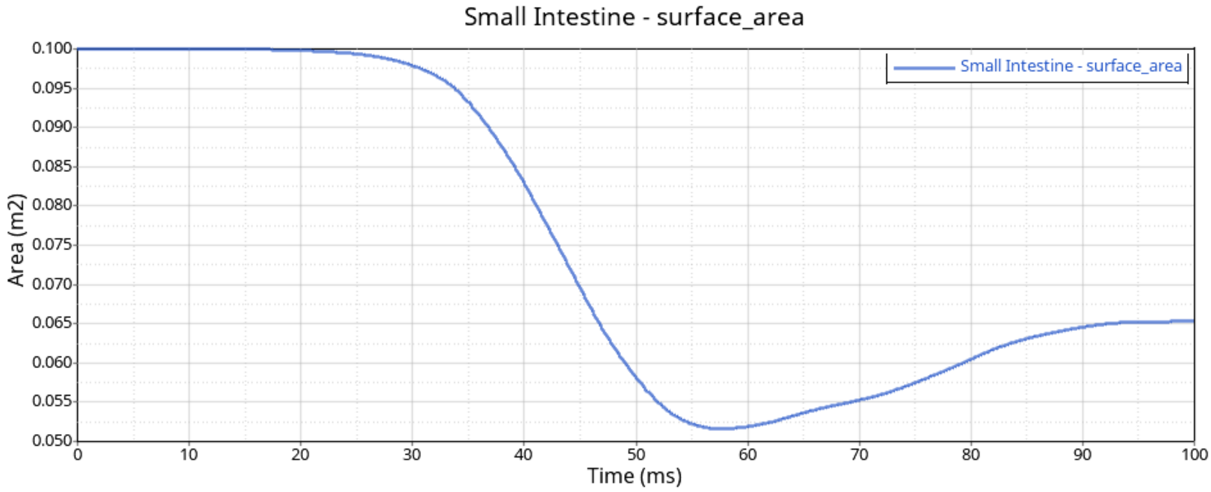


Appendix A 7 - Large intestine surface area

Small intestine

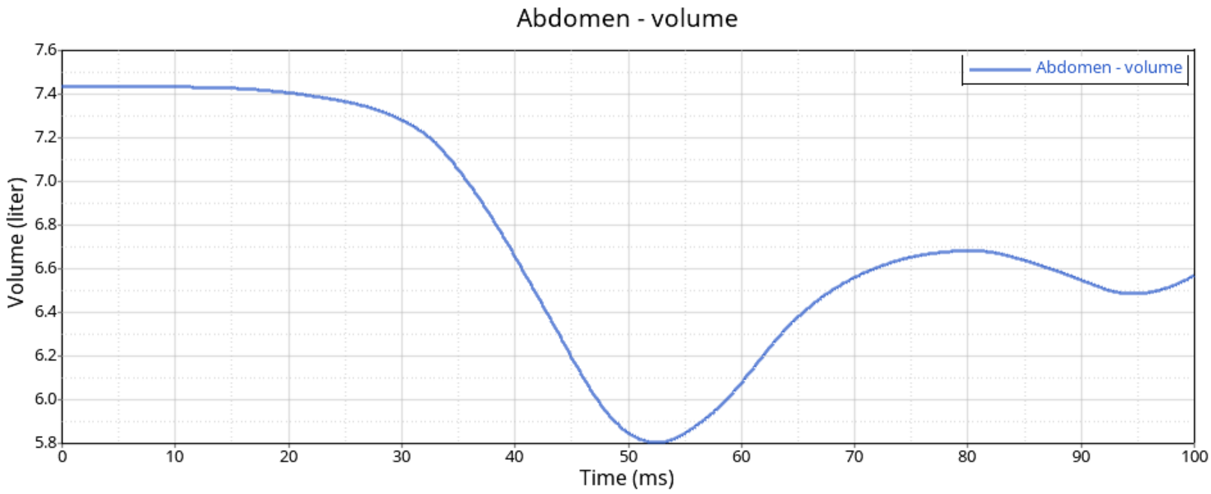


Appendix A 17 - Small intestine volume

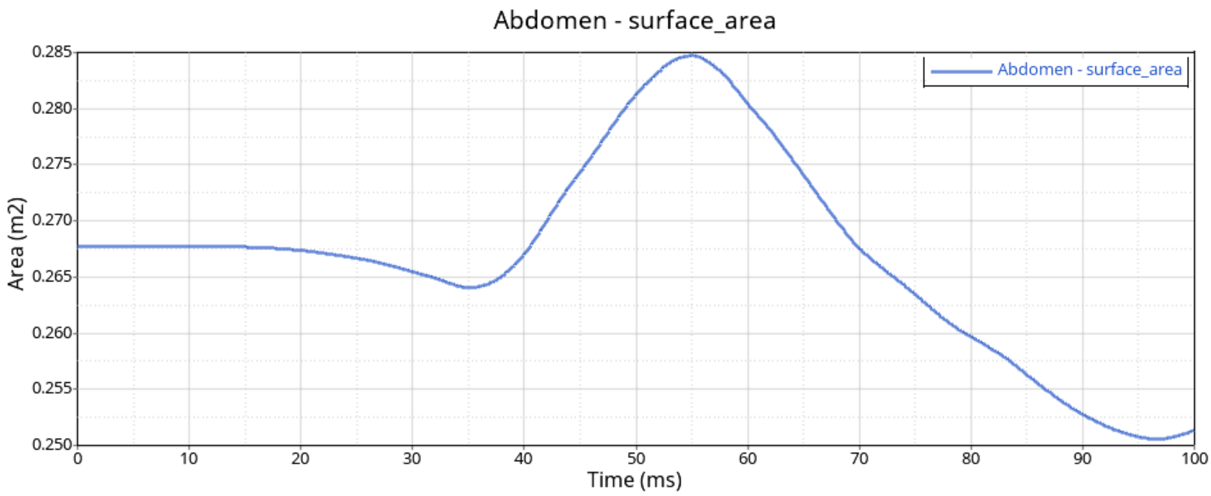


Appendix A 9 - Small intestine surface area

Abdomen



Appendix A 19 - Abdomen volume



Appendix A 20 - Abdomen surface area

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