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FIMCAR
XV – Fleet Studies

frontal impact and compatibility assessment research

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EXECUTIVE SUMMARY

Subject of this study is the development of a generic method to evaluate the characteristics of future vehicle fleets, which assist in vehicle compatibility research. The ever increasing demands for occupant safety have led to improved crashworthiness of vehicles. However, vehicles have become increasingly stiff over the last decades. In combination with a trend of heavier and higher vehicles this results in more aggressive and incompatible vehicles. Also the trend of smaller and lighter vehicles results in a mismatch of vehicles. Compatibility research focuses on improvement of crashworthiness while taking the safety of a possible crash partner into account with the aim to reduce the injury risks off all crash partners. In this regard it is important to conduct research of behaviour on a fleet wide basis.

The generic vehicle modelling procedure developed in FIMCAR was used to generate a set of MADYMO models of various vehicles. Due to the limited available data, only three different car models could be made, the Supermini 2, Small Family Car 2 and SUV 4. The created models are tuned with the test data of Full Width Rigid Barrier (FWRB) and checked with test data of Offset Deformable Barrier (ODB) tests. To compensate the limited amount of vehicles additional simulations were ran with variable masses. The available models are used to run two large sets of simulations with various vehicle parameters, like longitudinal stiffness, overlap and speed. These simulations are used to evaluate the performance of the vehicle fleet. For crash severity evaluations the Vehicle Pulse Index (VPI) is used, in which higher VPI values represent a lower crash performance with higher risk of injury.

From the performed fleet studies it can be concluded that:

- A higher vehicle mass results in a lower VPI. For the opponent vehicle an impact with a vehicle with higher mass results in higher VPI.
- An impact with a vehicle that shows cross beam failure shows lower VPI values for both vehicles compared to an impact with a vehicle in which the cross beam stays connected, as this increases the overall stiffness of the vehicle.
- A higher longitudinal stiffness results in a higher VPI, for as well vehicle 1 with stiffer longitudinal and even more for the opponent vehicle 2.

It should be taken into account that due to the assumptions made in the used MADYMO models some phenomena are not represented that might have an effect on the occupant. Cross beam failure and/or lower longitudinal stiffness result in a vehicle with lower crash stiffness in frontal impacts. This lower stiffness gives a lower VPI value, but in reality it might result in intrusion of the occupant compartment which was not taken into account in the current vehicle models.

The results of the performed fleet studies show that it is possible to evaluate and predict the effect of various vehicle characteristics on the overall crash performance of the (future) vehicle fleet.

1 INTRODUCTION

1.1 FIMCAR Project

For the assessment of real life vehicle safety in frontal collisions the compatibility (described by the self-protection level and the structural interaction) between the opponents is crucial. Although compatibility has been analysed worldwide for years, no final assessment approach was defined. Taking into account the EEVC WG15 and the FP5 VC-COMPAT project activities, two test approaches are the most promising candidates for the assessment of compatibility. Both are composed of an off-set and a full overlap test procedure. However, no final decision was taken so far. In addition another procedure (tests with a moving deformable barrier) is getting more and more into the focus of today's research programmes.

Within this project different off-set, full overlap and moving deformable barrier (MDB) test procedures will be analysed to be able to propose a compatibility assessment approach, which will be accepted by a majority of the involved industry and research organisations.

The development work will be accompanied by harmonisation activities to include research results from outside the consortium and to early disseminate the project results taking into account recent GRSP activities on ECE R94, Euro NCAP etc.

The FIMCAR project is organised in six different RTD work packages (WP). WP1 (Accident and Cost Benefit Analysis) and WP5 (Numerical Simulation) are supporting activities for WP2 (Offset Test Procedure), WP3 (Full Overlap Test Procedure) and WP4 (MDB Test Procedure). Work Package 6 (Synthesis of the Assessment Methods) gathers the results of WP1 – WP5 and combines them with actual car-to-car testing results in order to define an approach for frontal impact and compatibility assessment.

1.2 Objective of this Deliverable

This deliverable describes a methodology for predicting future vehicle fleet characteristics. This based on performing various vehicle fleet studies with MADYMO models, in which a series of vehicle parameters were varied to evaluate the effect on crash severity. The MADYMO models were created with the generic vehicle modelling procedure created in FIMCAR.

1.3 Structure of this Deliverable

The deliverable starts with an introduction. The general model creation process is explained in Chapter 2. In Chapter 3 the creation of the used MAYDMO models used in the fleet studies is explained. Chapter 4 describes the actual fleet creation and evaluation of the results. In the last chapter a conclusion is presented.

2 VEHICLE MODEL CREATION PROCESS

The multi-body vehicle models shall help to perform several sensitivity analyses or investigate car-to-car crash behaviour. Furthermore, they will help to predict the effects of the desired changes in the future fleet. Within FIMCAR two other types of numerical car models are developed, the PCMs (*Parametric Car Models*) and the GCMs (*Generic Car Models*). These models are described in [Stein 2013]. However, these models are often case specific by their level of detail. A wider range of vehicle models is desired in order to research these compatibility determining factors, which will be possible by the generic vehicle modelling procedure.

This generic vehicle modelling procedure is used as a basis for designing different multi-body vehicle models in order to establish a vehicle fleet. The requirements for the vehicle models result from shortcomings of traditional vehicle models (like the PCMs and GCMs). This means computing time has to be as low as several minutes on a normal personal computer. A balance between accuracy and availability has to be found in order to guarantee reliability in combination with efficiency. Besides that, less complex models enable quick modifications on the structure of the vehicles. Prerequisite is that the vehicles need to be detailed enough to reflect the influence of distinct structural elements. In addition to that, development and validation of the vehicle models has to be done without additional real live testing.

Years of experience with multi-body vehicle models lead to the opinion at TNO that multi-body models with a simplified structure have potential for fleet wide compatibility research. Simplified models have a more stable behaviour and reduced CPU time. Based on these findings the generic vehicle modelling procedure uses the MADYMO multi-body package.

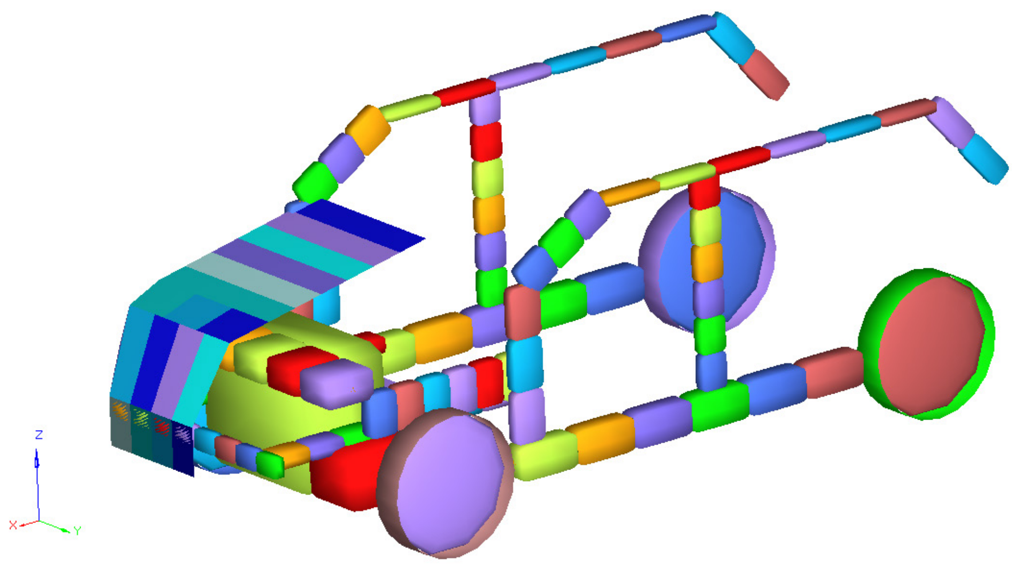


Figure 2.1: Multi-body vehicle model.

2.1 Basic Geometry

Existing MADYMO vehicle models were analysed to determine the main structural components of influence on the crash behaviour. The models were investigated to see where major deformations occur and to check if parts could be simplified to reduce computation time. The effectiveness of energy absorbing features was analysed by determination of the contribution of structures in energy transfer and dissipation. These studies resulted in a set of structural parts that are essential in a generic vehicle model.

It was concluded that the longitudinals, the shotguns, the bumper beam and the subframe suffer from large deformations. Analysis of the crush modes of these parts is essential for a correct choice of joints with optimal computing times. The longitudinals, the shotguns, the subframe and the bumper beam are also the major parts involved in energy management with regard to energy absorption, together with the engine and the wheels with regard to energy transfer. This means these parts are essential in a vehicle crash model.

In order to study frontal compatibility with the multi-body vehicle models it is important to have a realistic structural interaction and frontal stiffness. Realistic frontal stiffness is achieved by fitting the crash pulse to a real-life crash test. This is discussed separately in Chapter 2.3. Taking structural interaction into account, the geometries of the parts and their locations are of major importance. A geometrical database is used as a basis for the generic vehicle modelling procedure to obtain the geometrical data of the structural elements that have been identified as necessary for the crash models.

The part geometries can be obtained by completely disassemble the vehicle for measurements or through a numerical model supplied by an OEM. The French organisation for automotive and industrial testing, UTAC, started to set up a database with vehicle structural part measurements to facilitate compatibility research as a part of the VC-COMPAT project [Edwards 2007] . This database is used as a basis for a collection tool for the relevant data to construct the multi-body vehicle models. This collection tool can then be send to an OEM for filling in. The collection tool contains besides measurement data for wheelbase, vehicle mass, centre of gravity and H-point (for future dummy simulations) also detailed geometrical measurements for the longitudinals, shotguns, firewall, bumper and subframe. A complete set of measurement data for the frontal structure is included, together with a limited set of data for the side structure.

2.2 Model Geometry Generation

The measurement data from the geometrical collection tool are used to construct the geometries of structural elements for the MADYMO model. MATLAB is to process the measurements and to generate vehicle geometries automatically with the use of a script. The script converts all the measurement data to joint positions in the global coordinate system in a generic existing template xml file. For every body the body COG is calculated, followed by the joint position and the orientation of the joint leading to a local coordinate system. The angles are calculated with the joint positions in the global coordinate system. The size and location of the ellipsoids is determined together with the body masses and inertias. The mass and inertia of the ellipsoids are based on their size and the density of steel assuming tubular components with a defined wall thickness. However, for some parts such as engine and transmission, the mass is specified using vehicle specifications. The mass, COG and moments of inertia of the rear part (modelled as being undeformable) of the vehicle are computed to obtain the correct total vehicle mass properties. An initial stiffness function input for the structural parts is obtained from a similar situation in an existing multi-body vehicle model. This is only done to obtain the rough shape of the function; the correct values are found in the fitting phase as described in Chapter 2.3. The inter-system restraints positions and orientations are also calculated. The stiffness functions between the different systems are scaled according to a reference vehicle mass. Finally, all computed data is written to an xml-file which serves as an input file for MADYMO. It is important to bear in mind that the vehicle models are designed for frontal impact. This means that all choices made to build the structures are done to describe frontal impact as accurately as possible.

In the following paragraphs, a brief explanation is presented of every vehicle part that is used in the model. All choices made according to crush modes, number of bodies, joints and stiffness functions are explained.

2.2.1 Compartment and Firewall

The compartment offers a survival space for the occupants. Compartment collapse should therefore be avoided; thus the last decade showed a trend towards stiffer compartments [Ewens 2004] (Figure 2.2). This trend is shown in the majority of newly launched vehicle models. Because of this trend it is decided to model the compartment as undeformable. The compartment is mounted on the vehicle COG, which serves as a reference point for the whole vehicle. The A-pillar, B-pillar and C-pillar are also modelled with ellipsoids. A very important part of the compartment is the firewall. In a severe crash situation in which the engine is moved, the engine will hit the firewall, resulting in compartment intrusion. Measurement data of the location of the vertical part of the firewall are available. The firewall is thus modelled with a body and a single plate connected to the COG with a translational joint. The plate might be given a force penetration characteristic and the translational joint an initial stiffness characteristic. However, taking into account modern vehicle design this option was neglected.

Figure 2.2: Left: Model year 2000 Seat Ibiza which suffers from severe compartment deformation noticeable by the A-pillar collapse and the front wheel displacement. Right: Model year 2003 Seat Ibiza with minimal compartment deformation [Euro NCAP 2013].

2.2.2 Longitudinals

The longitudinals are the most energy absorbing structures and therefore the most complex crush structures of the vehicles. Since these vehicles are a simplified model of the actual car, it is chosen to model the longitudinals as a straight beam. The main challenge for the longitudinals is that the combined crush and bend effect in the structures is complicated to describe accurately. The beam element is in most scenarios crushed first followed by a bending phase. This effect is difficult to model with the available joints in MADYMO because the bending stiffness actually depends on the amount of deformation. MADYMO is only able to adjust the stiffness characteristic during the calculation process in a complex manner and since these are simplistic models, this is not a desirable solution. A more practical solution in MADYMO is to use a translational joint and a universal joint in series which is able to combine crush (translational) and bending (universal), however, the decline in bending stiffness after crush cannot be described and it is therefore assumed to be constant. The longitudinal is constructed using a minimum of six bodies, where the maximum length of each body is 0.2 meter. They are geometrically described by their height, width, length and distance between each other (left and right)

2.2.3 Bumper Beam

In general, the bumper beam has the potential of playing an important role in the vehicle crash since it connects the two longitudinals and will be important in the fitting process. The bumper is modelled as a straight beam using eight bodies as a default value and is connected by spherical joints. The stiffness function is adapted to design very stiff or weaker bumper beams. Depending on the vehicle type this is an important parameter in the fitting procedure as will be explained in the next chapter. It is assumed that the bending stiffness around the y-axis is proportional to the bending stiffness around the z-axis. A beam's bending stiffness is considered to be:

$$S = \frac{1}{12} * b * h^3.$$

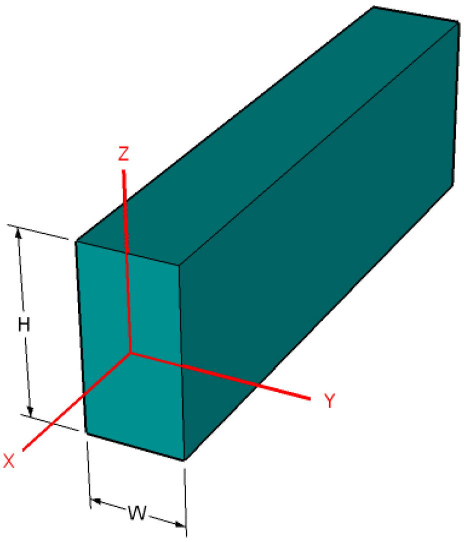


Figure 2.3: The bending stiffness for a beam around the y-axis is proportional to the stiffness around the z-axis.

This means if the height is twice the width of the beam, the stiffness around the y-axis is eight times the stiffness around the z-axis (Figure 2.3). The bumper is geometrically described by its height, width, length, distance to the floor and distance to the wheel axis.

2.2.4 Shotguns

For the shotguns, a similar approach is followed as is used in the longitudinals. They are constructed as a straight beam using six bodies as a default value and are connected with translational-universal joints. The shotguns are geometrically described by their height, width, length, distance between each other (left and right) distance to the floor and distance to the wheel axis.

2.2.5 Higher Crossbeam

For the higher crossbeam, a similar approach is used as in the bumper beam. The higher crossbeam is modelled as a straight beam using eight bodies as a default value and is connected by spherical joints. The higher crossbeam connects to the bumper and both the shotguns. The higher crossbeam is geometrically described by its height, width, length, distance to the floor and distance to the wheel axis.

2.2.6 Subframe

The short subframe is designed using six bodies (default, but customable) connected with spherical joints. It is connected with the longitudinals using point restraints. The wheels are connected to the arms of the subframe using spherical joints. The subframe is geometrically described by its width, length, height in the middle and distance to the floor in the middle.

2.2.7 Engine and Gearbox

Two types of engines are distinguished. Longitudinal engines are positioned in the axial direction, with the transmission located behind the engine. Transversal engines are positioned transversal to the vehicle axis and the gearbox is located next to the engine. The engine and gearbox are modelled with one distinct body each. They are connected to each other by bracket joints since the engine and gearbox system is regarded as being rigid. The engine is mounted to the subframe and longitudinals using point restraints. The engine and gearbox are geometrically described by their type, height, width, length, distance to wheel axis, distance to floor and distance from the centre.

2.3 Fitting the Vehicle Models Crash Response

The vehicle models created in the previous chapter have to be tuned to fit with a real live vehicle crash. The fitting procedure starts with fitting the multi-body vehicle model to the crash pulse from an FWRB impact. The stiffness functions of the different restraints and contact characteristics are used to fit the crash pulse from simulations onto the results obtained in real live FWRB test. This is done by combing matlab and MADYMO, where matlab determines the quality of the fit and adjusting the stiffnesses, whereas MADYMO is controlled by matlab to run the simulations.

2.3.1 Fitting Strategy

Fitting is done in three stages. The initial curve is fitted roughly onto the reference curve in the first stage whereby only the most influencing parameters are varied. Next the curve is split into several parts and fitting is done for the parts separately. Finally, fine tuning is done in a second stage in which fifty parameters are varied to obtain the best possible solution. These distinct stages are explained in this section

2.3.1.1 Initial Fit

It is found that the most important parameters of influence on the rough shape of the curve are stiffness functions regarding the longitudinals, engine, shotguns and subframe. In this stage it is only important to get the acceleration peak and timing in the same order as the reference crash pulse (Figure 2.4). This is done because it will substantially reduce the time needed in the next part of the fitting process. This is achieved by changing the stiffness functions mentioned above to get a decent enough fit.

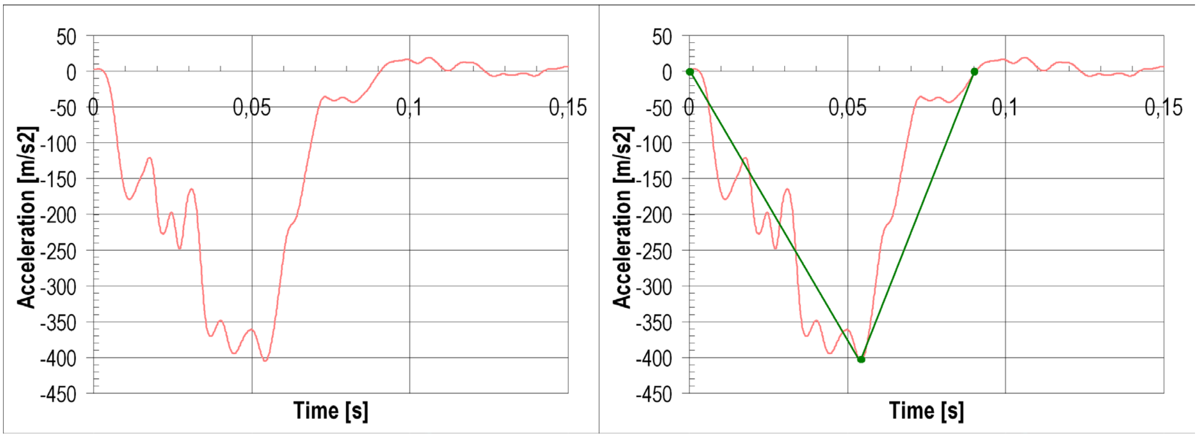


Figure 2.4: FWRB crash pulse (left) and the initial shape fitting points (right).

2.3.1.2 Second Stage

In the second stage the separate sections of the crash are fitted. First, the separate sections are detected by a simple peak detection algorithm, where each section between the peaks represents a unique combination of energy absorbing crash structures (Figure 2.5). A standard order of these crash structures is assumed in order to fit the shape of the deceleration crash pulse. When a different order is expected, a video analysis is done to find the correct crash structures for the corresponding sections during the crash.

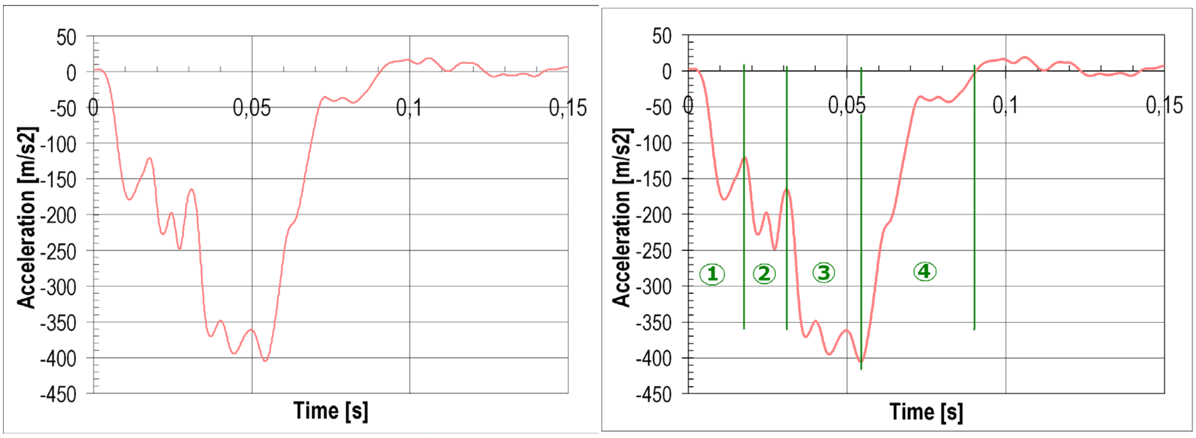


Figure 2.5: FWRB crash pulse (left) and different crash sections during the crash (right).

The iterative fitting process is done with the crash structures active in the corresponding section. A least square method is used to find the closest shape in that separate section. It is computed considering every data point. The outcome of the least squares solution approaches to zero when the solution improves. The least squares solution is given by:

$$ls = \frac{\sqrt{\sum_{i=1}^{N} da_i^{\,2}}}{N} \qquad (3.1)$$

In which ls is the least squares solution, da_i is the distance between the reference signal and the solution, and N is the number of data points. Furthermore a 90 percentile corridor is used to make sure that for each point a certain close enough value is reached. After each section the effect is also measured and controlled in the section before. This is done in order to keep the entire shape as close as possible.

2.3.1.3 Fine Tuning

Aim of the second fitting stage is to fine-tune the result of the second stage. For fine-tuning it is desired to vary all parameters that influence each other at the same moment. It is desired to evaluate every possible combination of parameters. Since this will result in a too large number of simulations, it is chosen to limit to the parameters used in the second stage and closely vary around the values found.

3 ACTUAL VEHICLE MODEL CREATION

The generic vehicle modelling procedure, which has been developed in FIMCAR, was used as a basis for designing different MADYMO vehicle models to establish a vehicle fleet.

Due to limited amount of available geometric data sets only a limited amount of models could be built. A MADYMO model of the vehicles below was generated:

1. Supermini referred to as Supermini 2
2. Small family car referred to as Small Family Car 2
3. SUV referred to as SUV 4

3.1 General

Chapter 2 showed that it is possible to construct and fit simple vehicle crash models in a generic manner. Based on geometrical data a base MADYMO model was generated. This base model was used to tune the model characteristics to match a Full Width Rigid Barrier test (FWRB). Fitting of vehicle models was done by an iterative process of the adaptation of the stiffness functions with focus on matching the velocity and displacement profile. Once the model reaches an acceptable level of correlation those models are used to verify the performance with the Euro NCAP Offset Deformable Barrier (ODB) configuration.

It should be taken into account that the created models have some limitations due to the assumptions made:

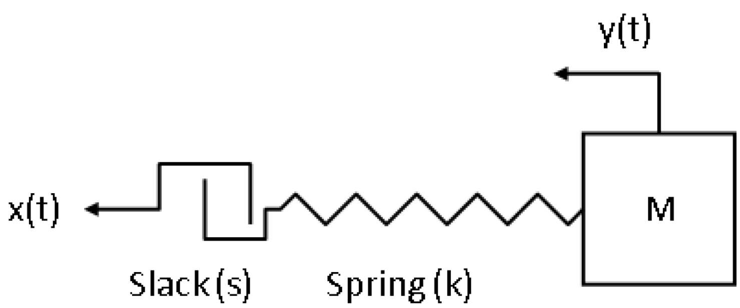
- The occupant compartment of the model is rigid, therefore no intrusion of the occupant compartment has been assumed.
- Vertical misalignment has not been evaluated as current vehicle models are not suited for this.
- No dummy injury assessment, as dummy injury assessment is not feasible, since there is:
    - No interior available
    - No restraint system information
    - No trigger information
    - No seat and floor structural information
    - No steering wheel, steering column, knee bolster information

For the crash severity evaluations the Vehicle Pulse Index (VPI) [ISO 2013] is used, in which higher values represent a lower crash performance with higher risk of occupant injury.

$$M\ddot{y} + ky = P(t)$$

where

$$P(t) = \begin{cases} 0, & x < s \\ k(x-s), & x \ge s \end{cases}$$



$$VPI = \max(\ddot{y})$$

Figure 3.1: Vehicle Pulse Index (VPI).

With a mass of 1 kg and the by Volvo recommended values of; k = 2500 N/m and s = 0.03m.

3.2 Supermini 2

The created model for the Supermini 2 based on the provided geometrical data can be seen below in Figure 3.2.

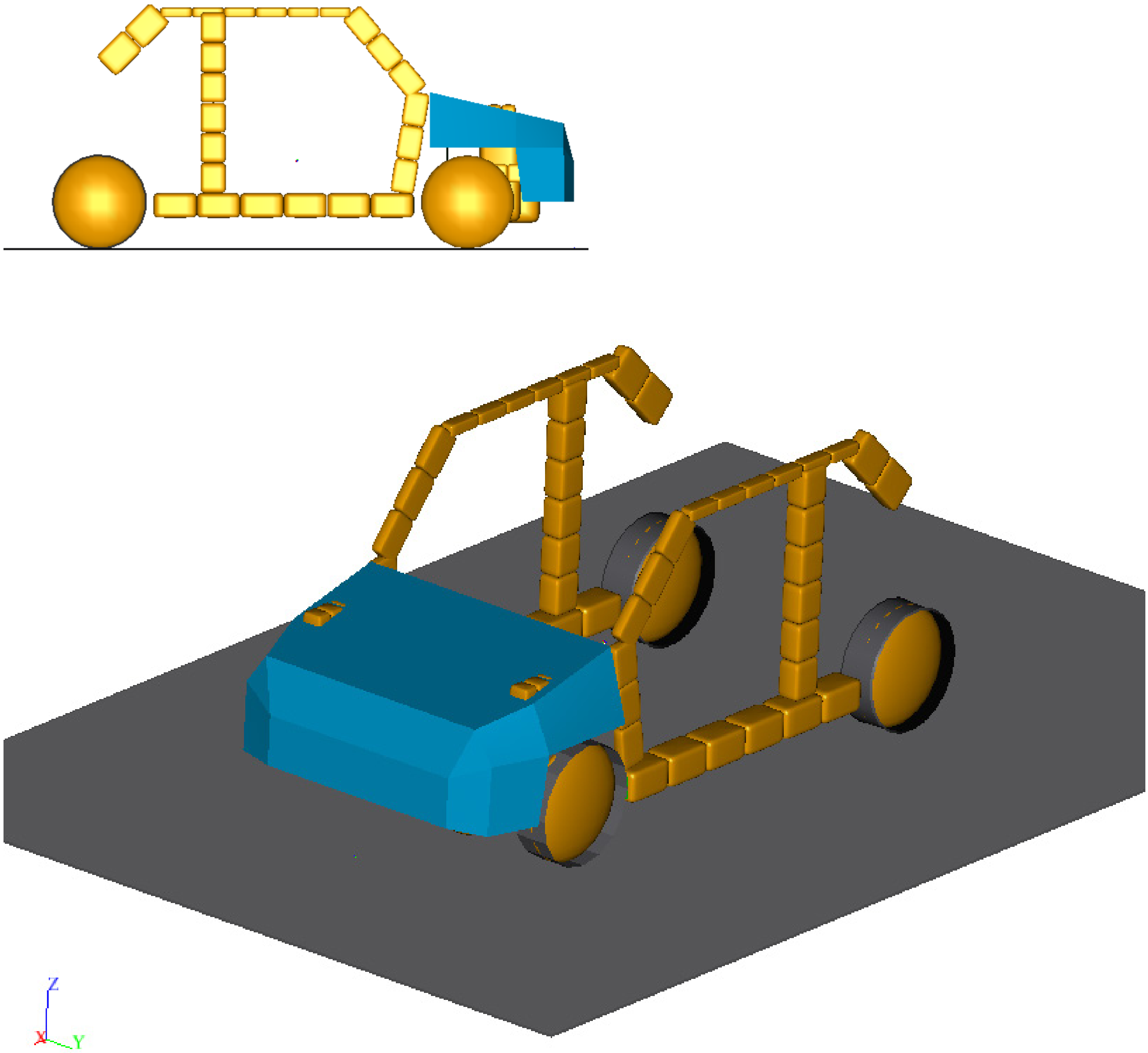


Figure 3.2: Model set-up of Supermini 2.

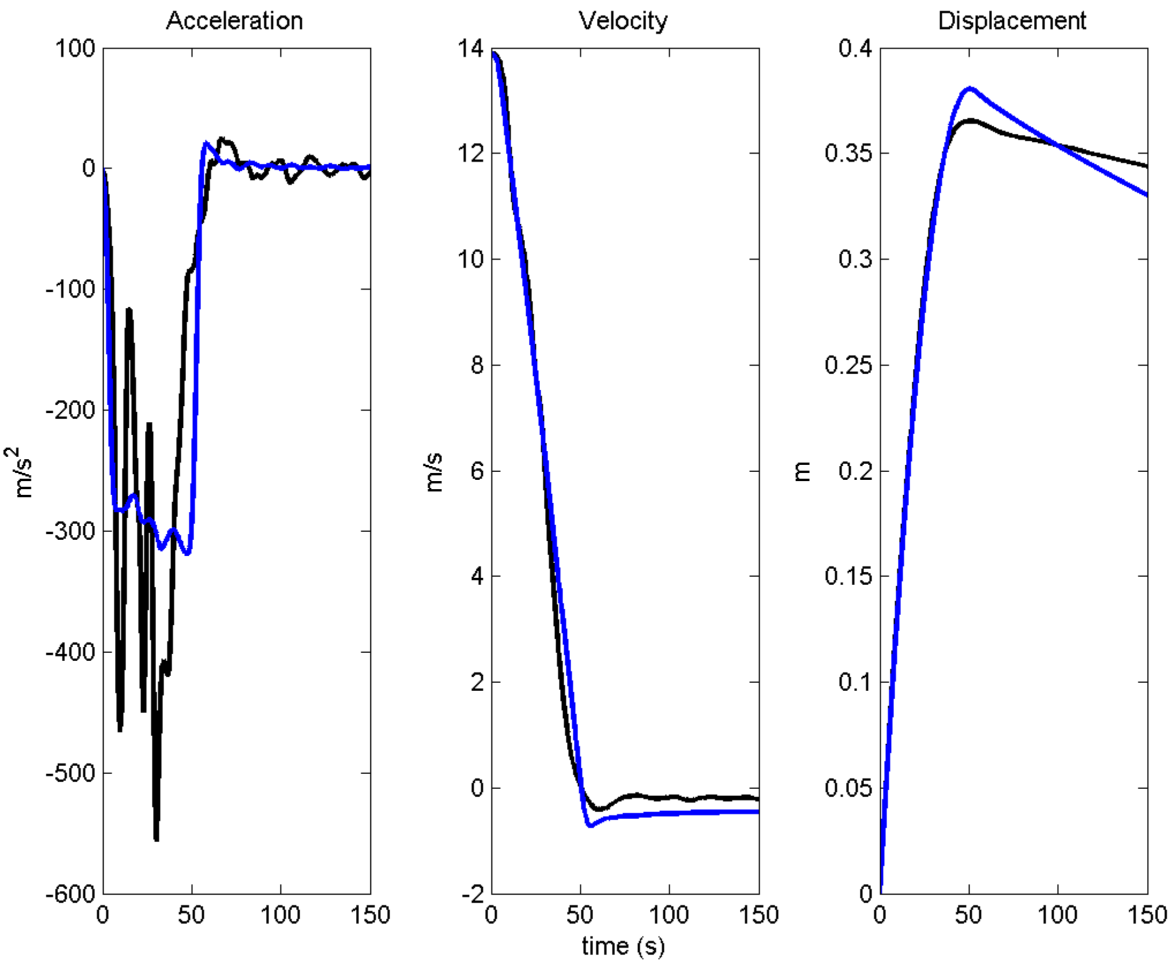


Figure 3.3: Correlation FWRB test (black) vs. simulation (blue) left lower B-pillar Supermini 2.

The base model of the Supermini 2 was tuned with the test data of the Full Width Rigid Barrier (FWRB) test. Figure 3.3 shows the acceleration, velocity and displacement over time for the FWRB test (black) as the simulation (blue) of the final Supermini 2 model. During the tuning the focus was directed towards the velocity profile of the left lower B-pillar. The final Supermini 2 simulation model shows a similar velocity curve as observed in the FWRB test.

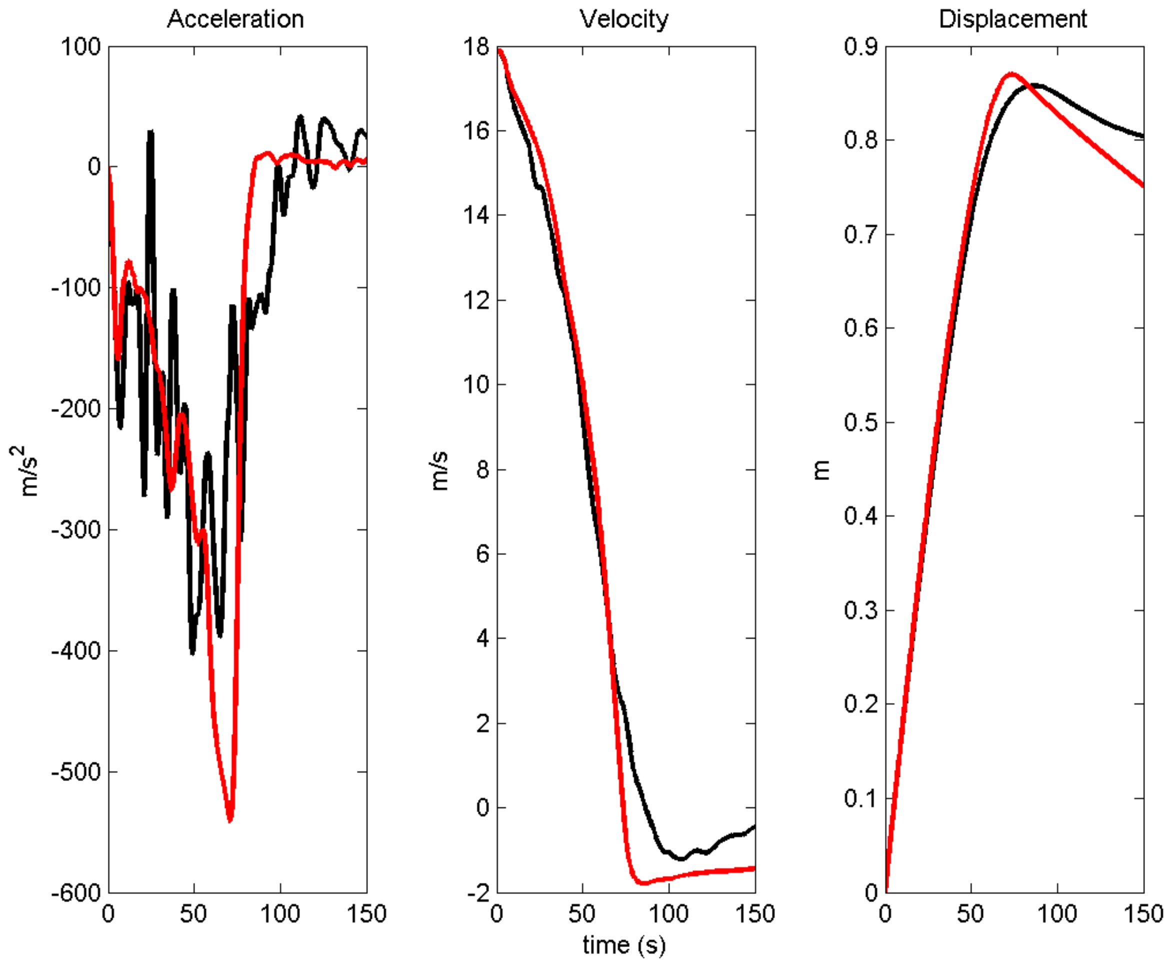


Figure 3.4: Correlation ODB test (black) vs. simulation (red) left lower B-pillar Supermini 2.

To check model performance a simulation of Offset Deformable Barrier (ODB) was performed, which has been compared to the ODB test data. Figure 3.4 shows the ODB test (black) and simulation (red) results for the Supermini 2.

3.3 Small Family Car 2

The created model for the Small Family Car 2 based on the provided geometrical data is shown in Figure 3.5.

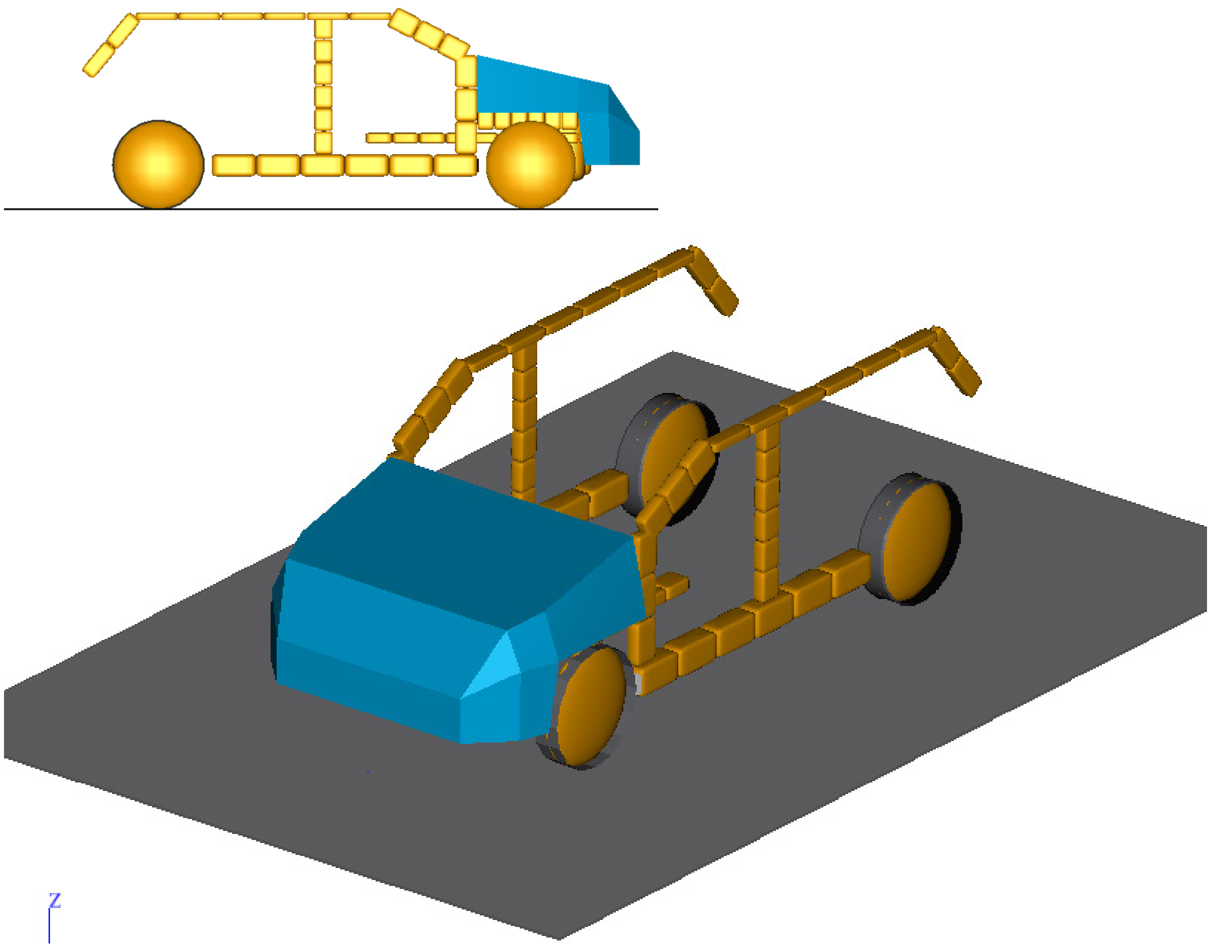


Figure 3.5: Model set-up of Small Family Car 2.

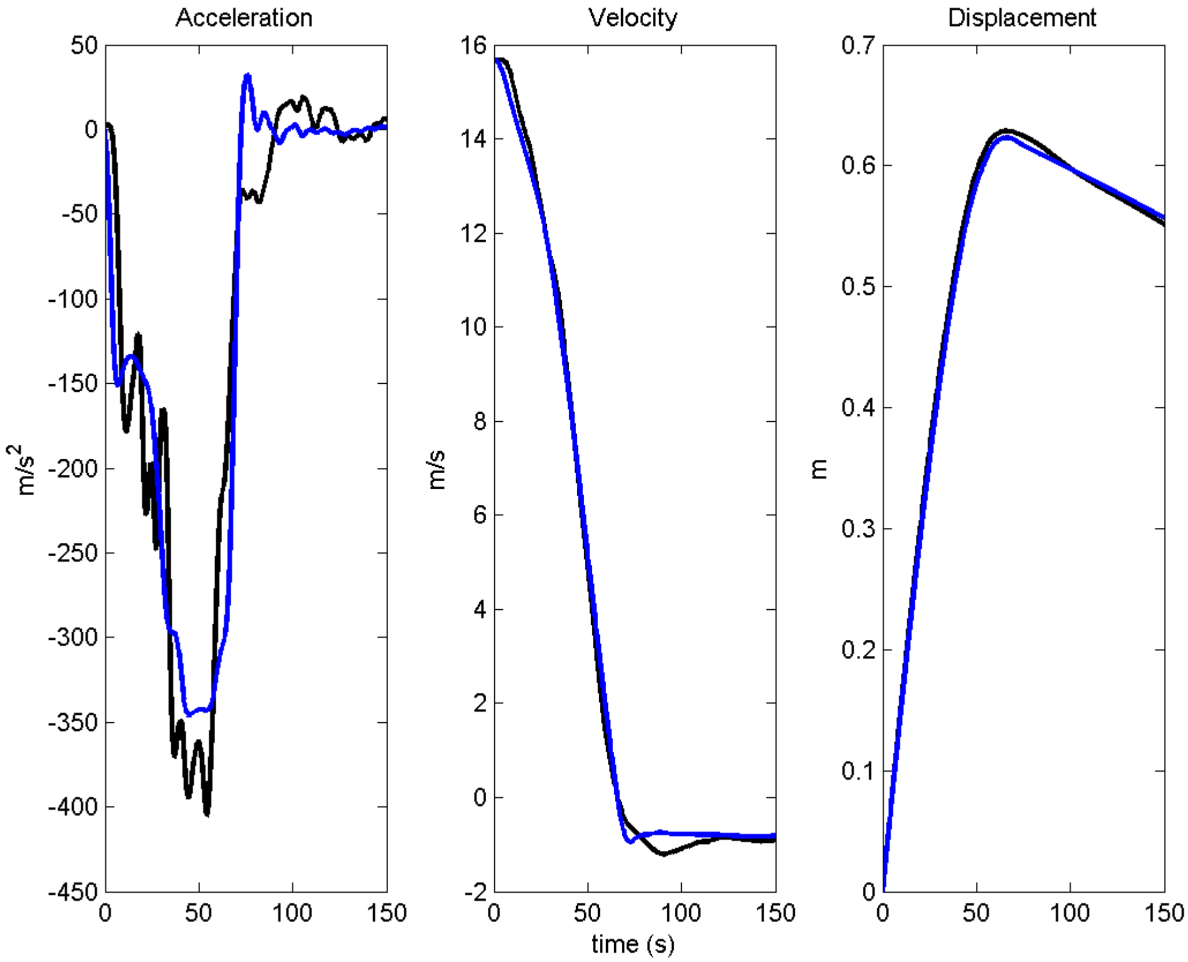


Figure 3.6: Correlation FWRB test (black) vs. simulation (blue) left lower B-pillar Small Family Car 2.

Figure 3.6 shows the acceleration, velocity and displacement over time for the Full Width Rigid Barrier (FWRB) test (black) as the simulation (blue) of the final Small Family Car 2 model. The model was created by tuning the simulation with test of the FWRB. The tuning focuses on the velocity profile of the left lower B-pillar. The final model of the Small Family Car 2 has a similar velocity profile compared to the FWRB test.

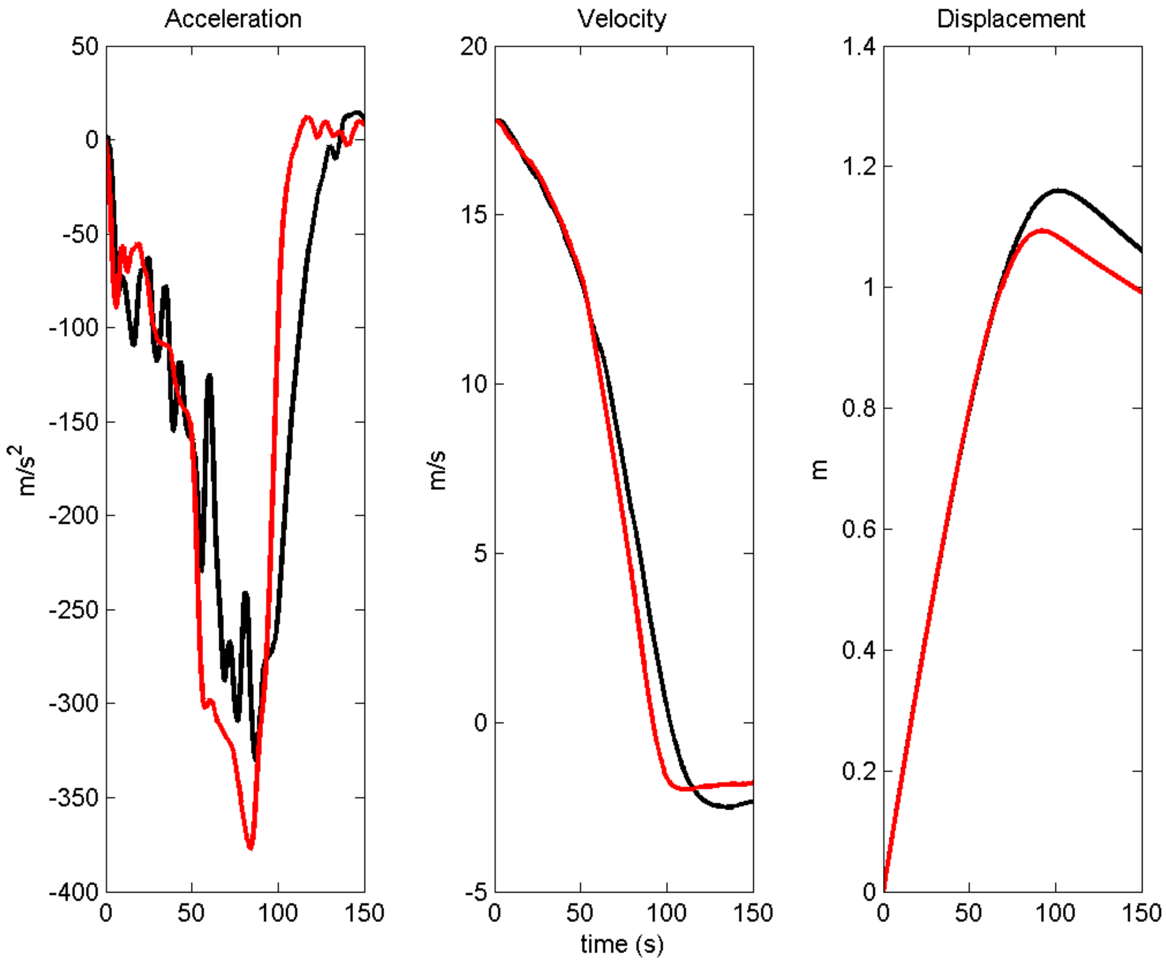


Figure 3.7: Correlation ODB test (black) vs. simulation (red) left lower B-pillar Small Family Car 2.

To check model quality also test and simulation of Offset Deformable Barrier (ODB) test have been compared. Figure 3.7 shows the ODB test (black) and simulation (red) for the Small Family Car 2.

3.4 SUV 4

The model of the SUV 4, which was created based on the provided geometrical data, can be observed in Figure 3.8.

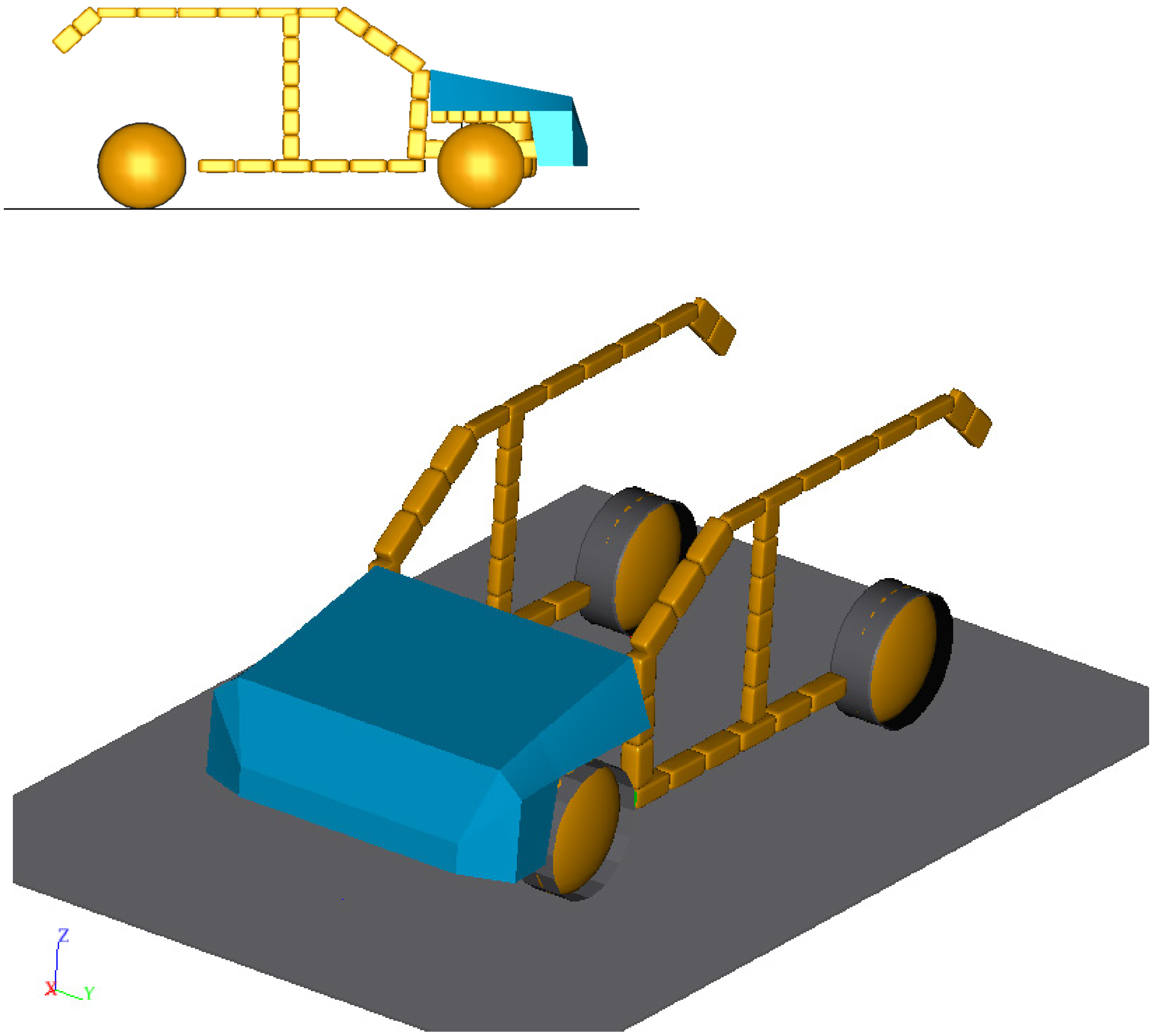


Figure 3.8: Model set-up of SUV 4.

Also the base model of the SUV 4 was tuned with Full Width Rigid Barrier (FWRB) test data. Figure 3.9 shows the acceleration, velocity and displacement of the left lower B-pillar over time for the FWRB test (black) as the simulation (blue) of the final SUV 4 model. A similar velocity profile can be observed in FWRB test and simulation.

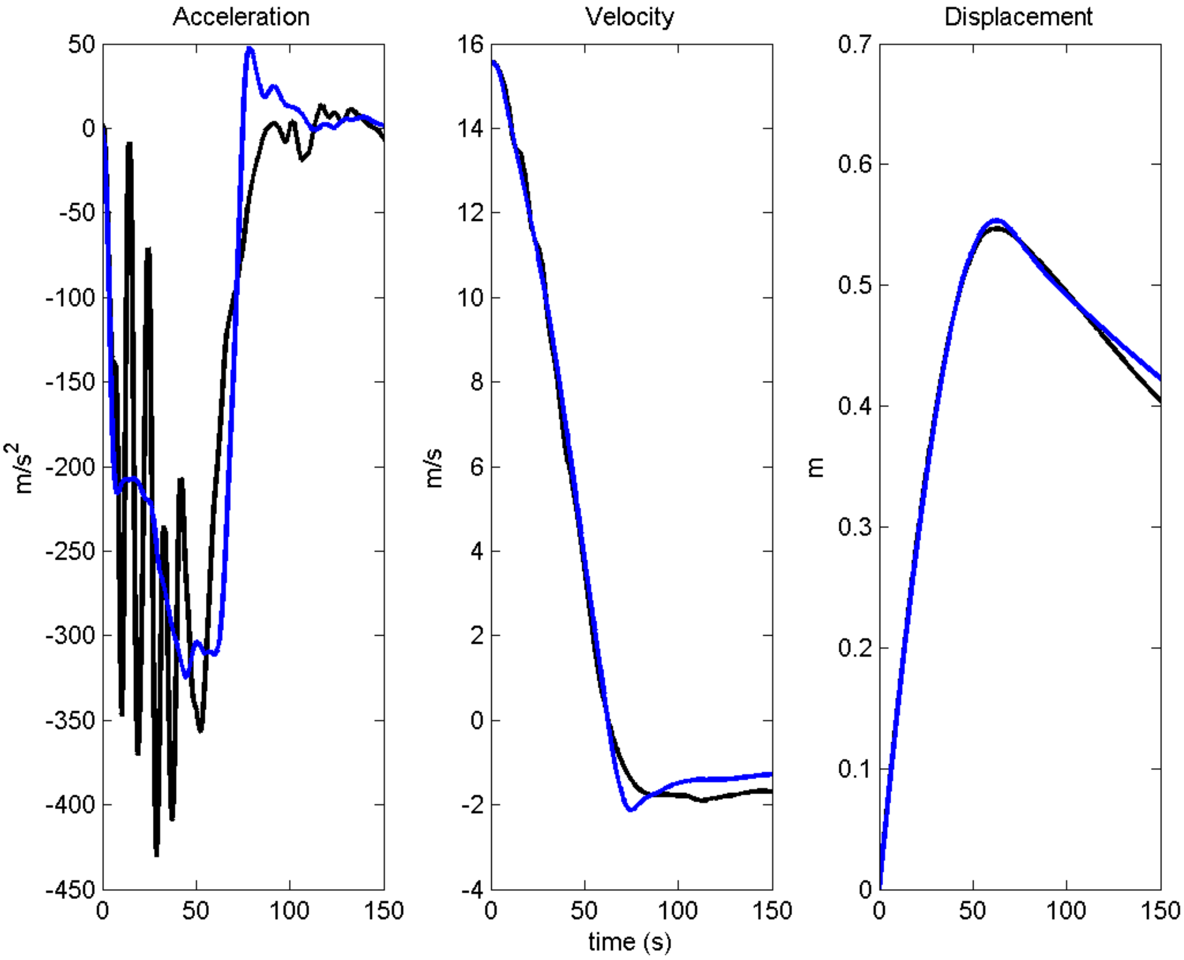


Figure 3.9: Correlation FWRB test (black) vs. simulation (blue) left lower B-pillar SUV 4.

Also for the SUV 4 the Offset Deformable Barrier (ODB) check was performed. Figure 3.10 shows the ODB test (black) and simulation (red) for the SUV 4.

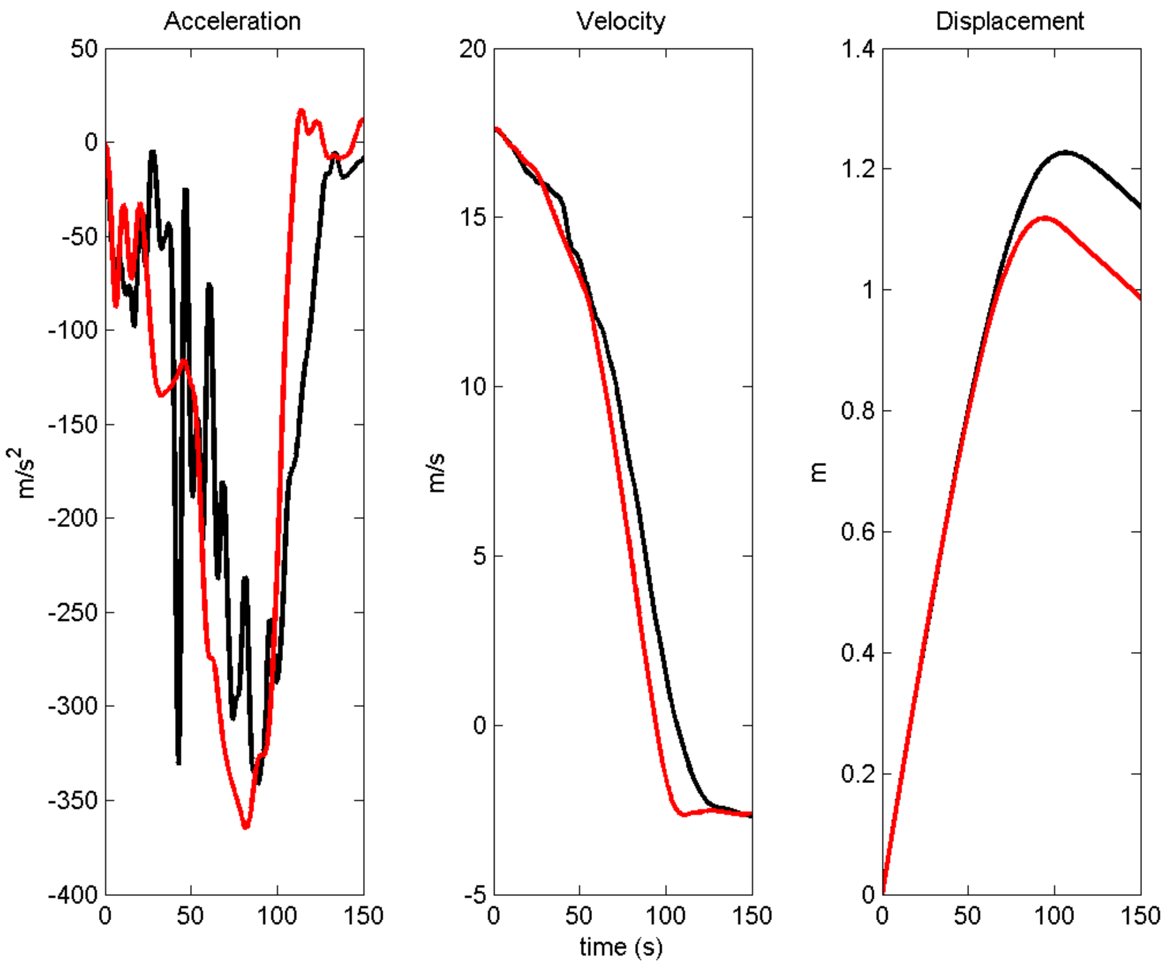


Figure 3.10: Correlation ODB test (black) vs. simulation (red) left lower B-pillar SUV 4.

4 FLEET STUDY ANALYSIS

Two separate fleet studies were performed, the initial one with all available models to evaluate a large set of variables with a largest possible set of vehicles. The second fleet study focussed on the evaluation of the specific phenomena of longitudinal stiffness and cross beam failure and is performed with a selection of vehicles.

4.1 Fleet Study I

4.1.1 Set-up I

4.1.1.1 Vehicles I

For the initial study a large spread of vehicle configurations was used to have the largest possible representation of the actual vehicle fleet. All available vehicle models were used, so the Supermini 2, the Small Family Car 2 and the SUV 4. In order to compensate for the limited amount of evaluated vehicle masses an extra parameter was added in which the vehicle mass was adjusted. In this way also the gaps between the evaluated vehicles were covered.

4.1.1.2 Input Variables I

- **Mass of vehicle 1** — 3 settings per vehicle
  - Supermini 2 — -75kg — test mass (1159 kg) — +150 kg (2 occupants)
  - Small Family Car 2 — -75kg — test mass (1309 kg) — +225 kg (3 occupants)
  - SUV 4 — -75kg — test mass (2255 kg) — +375 kg (5 occupants)
- **Speed**
  - 40 km/h for both vehicles
  - 56 km/h for both vehicles
- **Misalignment**
  - 50% overlap of vehicle 1
  - 100%
- **Strength longitudinal of vehicle 1**
  - x1 — (represents longitudinal standard vehicle)
  - x1.5 — (represents stiffness x1.5 of longitudinal standard vehicle)
- **Strength cross beam of vehicle 1**
  - x1 — (represents connected cross beam)
  - x0.001 — (represents cross beam failure)

4.1.1.3 Output Parameter I

Various output parameters were available.

- Acceleration of B-pillar bottom left and right
- Velocity of B-pillar bottom left and right
- Displacement of B-pillar bottom left and right
- Max ΔV of B-pillar bottom left
- Max mean acceleration (= max ΔV / time to max ΔV) of B-pillar bottom left
- ASI (Acceleration Severity Index) of B-pillar bottom left [ECS 1995], see Figure 4.1
- VPI (Vehicle Pulse Index) of B-pillar bottom left [ISO 2013], see Figure 4.2

$$ASI(t) = [(\bar{a}_x / \hat{a}_x)^2 + (\bar{a}_y / \hat{a}_y)^2 + (\bar{a}_z / \hat{a}_z)^2]^{1/2}$$

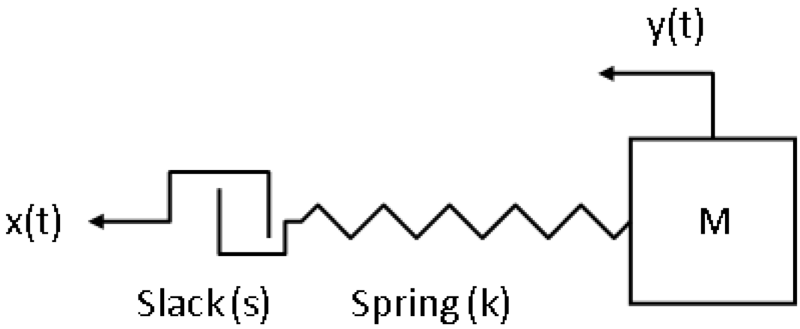
$$\hat{a}_x = 12\ g \qquad \hat{a}_y = 9\ g \qquad \hat{a}_z = 10\ g$$

Figure 4.1: ASI calculation.

$$M\ddot{y} + ky = P(t)$$

where

$$P(t) = \begin{cases} 0, & x < s \\ k(x - s), & x \geq s \end{cases}$$



$$VPI = \max(\ddot{y})$$

Figure 4.2: Vehicle Pulse Index (VPI).

With a mass of 1 kg and the by Volvo recommended values of; k = 2500 N/m and s = 0.03 m.

For the crash severity evaluations the Vehicle Pulse Index (VPI) is used, in which higher values represent a lower crash performance with higher risk of occupant injury.

4.1.1.4 Simulation Matrix I

A reduced matrix was evaluated based on selection below resulting in 162 simulations, see Table 1.

Equal vehicles	3 masses of vehicle 1
	2 equal speeds
	2 overlaps
	2 longitudinal strengths of vehicle 1 (long strengths)
	2 cross beam strengths of vehicle 1 (c-b strengths)
Different vehicles	both original test mass
	1 speed
	2 overlaps
	2 cross beam strengths (only for 50% overlap) (c-b strengths)

Table 1: Simulation matrix I

		Vehicle 2		
		Supermini 2	**Small Family Car 2**	**SUV 4**
Vehicle 1	**Supermini 2**	3 masses 2 speeds 2 overlap 2 long strengths 2 c-b strengths	40 km/h 50% 100% 2 c-b strengths	40 km/h 50% 100% 2 c-b strengths
	Small Family Car 2	40 km/h 50% 100% 2 c-b strengths	3 masses 2 speeds 2 overlap 2 long strengths 2 c-b strengths	40 km/h 50% 100% 2 c-b strengths
	SUV 4	40 km/h 50% 100% 2 c-b strengths	40 km/h 50% 100% 2 c-b strengths	3 masses 2 speeds 2 overlap 2 long strengths 2 c-b strengths

4.1.2 Results I

4.1.2.1 Mass Dependency

In Figure 4.3 below an overview can be found of the VPI values of the various vehicle weights. The first 3 pictures show the results with equal vehicles, respectively Supermini 2, Small Family Car 2 and SUV 4. The last picture shows all simulations, i.e. as well the simulations with equal vehicles as with different vehicles. For each vehicle, the 3 mass variations are shown as described under input variables.

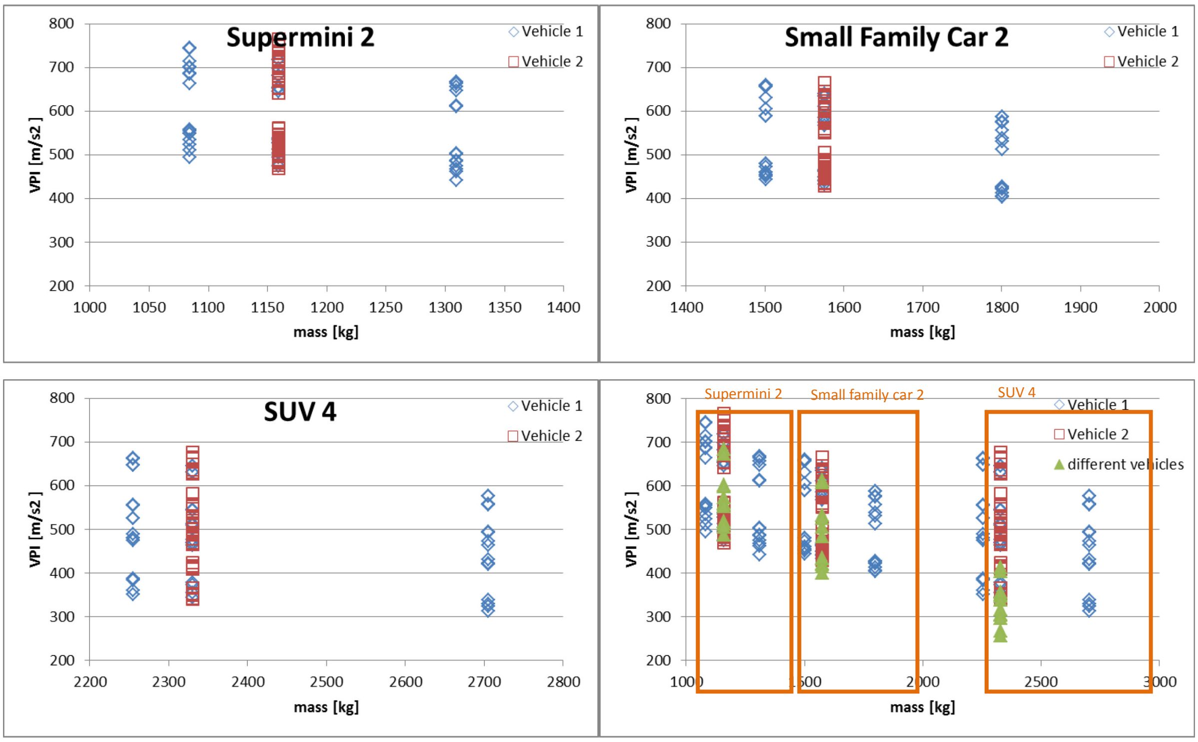


Figure 4.3: VPI of vehicle 1 and 2 in simulations with variable mass.

A clear difference can be observed in VPI for the difference between low (40km/h) and high (56km/h) impact speed. The pictures also demonstrate clearly that a higher mass of vehicle 1 results in lower VPI values for vehicle 1 and a higher VPI value for vehicle 2, where vehicle 1 and 2 are the same type.

The data of impacts with different vehicles (green triangles in right bottom corner picture) show average VPI's from high to low:

- Supermini 2 with SUV 4
- Small Family Car 2 with SUV 4
- Supermini 2 with Small Family Car 2
- Small Family Car 2 with Supermini 2
- SUV 4 with Small Family Car 2
- SUV 4 with Supermini 2

The much heavier SUV 4 compared to the Supermini 2 and Small Family Car 2 gives much higher VPI values for the opponent (Supermini 2 and Small Family Car 2), but lower VPI values for the SUV 4.

Overall, it can be stated that a higher vehicle mass results in lower VPI for that vehicle. For the opponent vehicle an impact with a vehicle with higher mass results in higher VPI.

4.1.2.2 Longitudinal Stiffness

Figure 4.4 shows the 72 configurations (total 144 simulations) that were evaluated with default (x1) longitudinal and cases in which the longitudinals of vehicle 1 have an increased stiffness (x1.5). The left picture shows the VPI values of vehicle 1, with default (x1, blue) and higher (x1.5, red) longitudinal stiffness per configuration. In the right picture also the VPI of vehicle 2 is added.

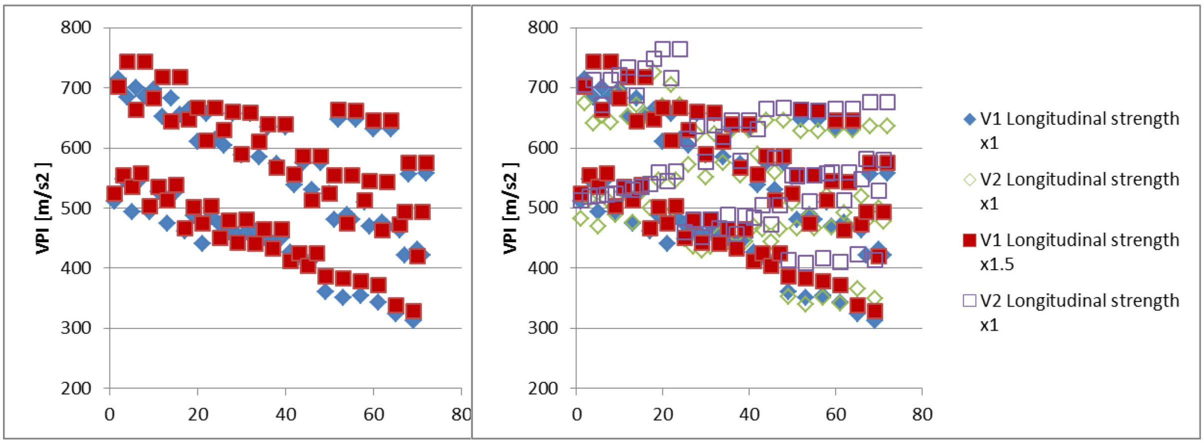


Figure 4.4: VPI of vehicle 1 and 2 in various longitudinal stiffness simulations.

Figure 4.4 shows that overall the stiffer (x1.5) longitudinals of vehicle 1 result in a higher VPI of vehicle 1 compared to vehicle 1 with the default (x1) stiffness. The effect on vehicle 2 however is overall larger. The VPI values of vehicle 2 for impact with opponent with stiffer (x1.5) longitudinal are significantly higher compared to opponent with default (x1) longitudinal stiffness.

Figure 4.5 shows a simulation of SUV 4 against SUV 4 with 100% overlap at 40 km/h, with green the default longitudinal stiffness (x1) and red the highest stiffness (x1.5), with connected cross beam.

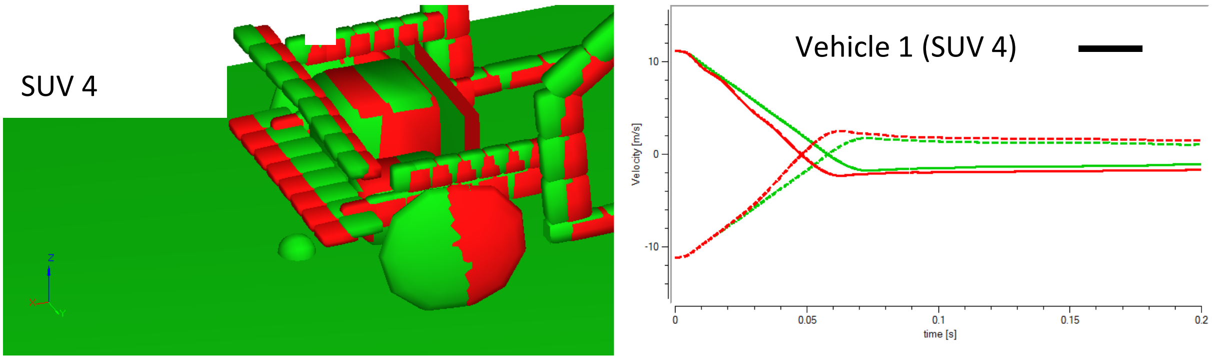


Figure 4.5: Default (x1) (green) and high (x1.5) (red) longitudinal stiffness simulation of SUV 4 - SUV 4.

Overall, it can be stated that a higher longitudinal stiffness results in higher VPI, for as well vehicle 1 with stiffer longitudinal, but even more for the opponent vehicle 2.

4.1.2.3 Cross Beam Failure

Figure 4.6 shows the 42 configurations (total 84 simulations) that were evaluated with cross beam connected and with cross beam failure in vehicle 1. Only 50% overlap configurations are taken into account. The left picture shows the VPI values of vehicle 1, with cross beam connected (blue) and failed per configuration (red). In the right picture also the VPI of vehicle 2 is added.

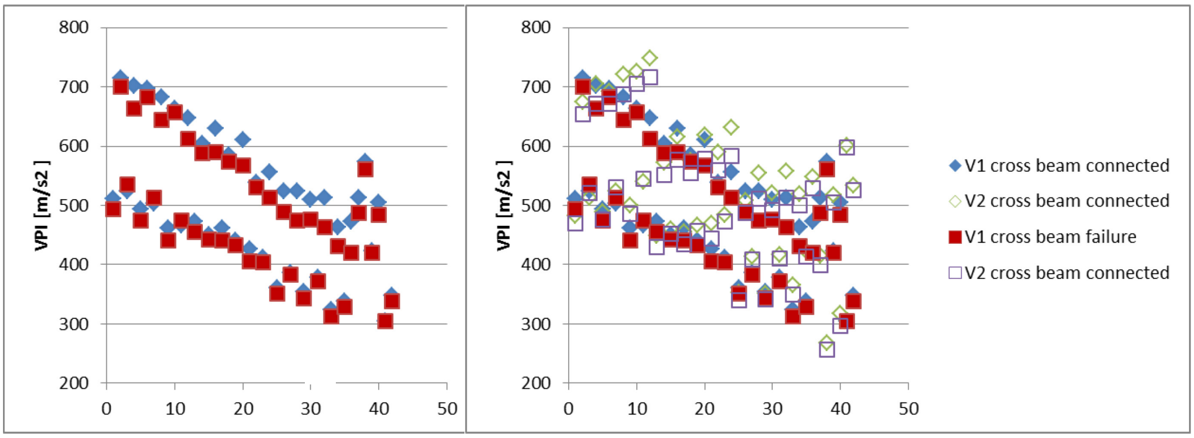


Figure 4.6: VPI of vehicle 1 and 2 in cross beam connected and failed simulations.

Figure 4.6 shows that overall the VPI is lower in case the cross beam fails (red) of vehicle 1 compared to vehicle 1 in which the cross beam does not fail (blue). This holds for as well vehicle 1 as vehicle 2. The overall stiffness of the vehicle increases if the cross beam does not fail, as also the longitudinal of the non-impacted side will be deformed.

A simulation of SUV 4 against SUV 4 with 50% overlap at 56km/h, with green the connected cross beam and red the failed cross beam simulation is shown in Figure 4.7.

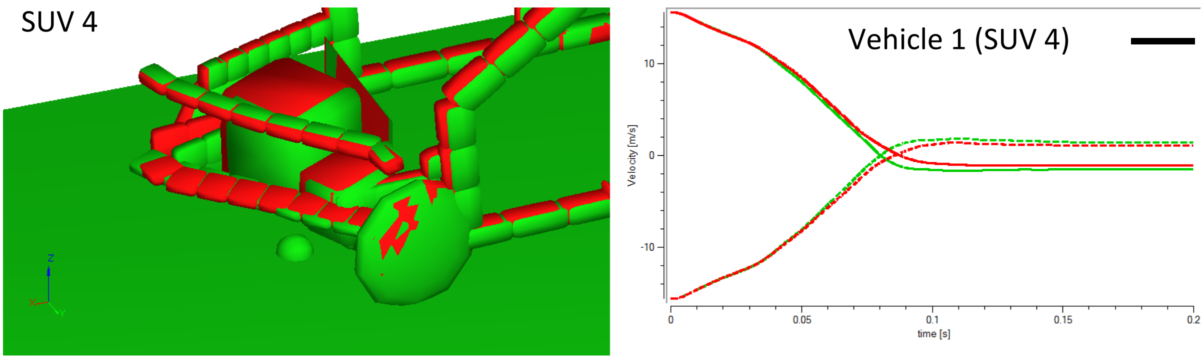


Figure 4.7: Cross beam connected (green) and cross beam failed (red) simulation of SUV 4 - SUV 4.

Overall, it can be stated that an impact with a vehicle that has cross beam failure shows lower VPI values for both vehicles compared to an impact with a vehicle in which the cross beam stays connected, as this increases the overall stiffness of the vehicle. However, it needs to be noted that phenomena like intrusion resulting from the cross beam failure are not considered in the simulation. Therefore the VPI might give a wrong estimation of the dummy loadings.

4.2 Fleet Study II

4.2.1 Set-up II

4.2.1.1 Vehicles II

The focus of the second part of the fleet study was to evaluate the longitudinal stiffness and the failure of the cross beam. This was done with the Supermini 2 and SUV 4. The possible failure of the cross beam has been implemented for the Supermini 2.

4.2.1.2 Input Variables II

Fixed variables:

- **Mass**
  - Supermini 2 test mass (1159 kg)
  - SUV 4 test mass (2255 kg)
- **Misalignment**
  - 50% overlap of vehicle 1 (Supermini 2)
- **Speed**
  - 56 km/h for both vehicles

Variables:

- **Strength longitudinal**
  - Supermini 2 150% - 50% (10% steps, 11 levels)
  - SUV 4 100% - 50% (10% steps, 6 levels)
- **Strength cross beam of vehicle 1 (Supermini 2)**
  - x1 (represents connected cross beam)
  - x0.001 (represents cross beam failure)

4.2.1.3 Output Parameter II

Various output parameters were available.

- Acceleration of B-pillar bottom left and right
- Velocity of B-pillar bottom left and right
- Displacement of B-pillar bottom left and right
- Max ΔV of B-pillar bottom left
- Max mean acceleration (= max ΔV / time to max ΔV) of B-pillar bottom left
- ASI (Acceleration Severity Index) of B-pillar bottom left [ECS 1995], see Figure 4.1
- VPI (Vehicle Pulse Index) of B-pillar bottom left [ISO 2013], see Figure 4.2

4.2.1.4 Simulation Matrix II

A full matrix has been evaluated, resulting in 132 simulations, see also Table 2.

Different vehicles both original test mass
1 speed

1 overlap
11 longitudinal strengths of vehicle 1 (long strengths)
6 longitudinal strengths of vehicle 2 (long strengths)
2 cross beam strengths of vehicle 1 (c-b strengths)

Table 2: Simulation matrix II.

		Vehicle 2
		SUV 4
Vehicle 1	**Supermini 2**	test masses 56 km/h 50% overlap 11 x 6 long strengths 2 c-b strengths

4.2.2 Results II

4.2.2.1 Longitudinal Stiffness

Two sets of each 66 simulations (11x6) were performed, one in which the cross beam stays connected and one in which the cross beam fails for vehicle 1. First the effect of the stiffness variation of the longitudinal will be discussed. The longitudinal stiffness of vehicle 1 (Supermini 2) various between low stiffness (x0.5) and high stiffness (x1.5), for vehicle 2 (SUV 4) between low stiffness (x0.5) and default stiffness (x1).

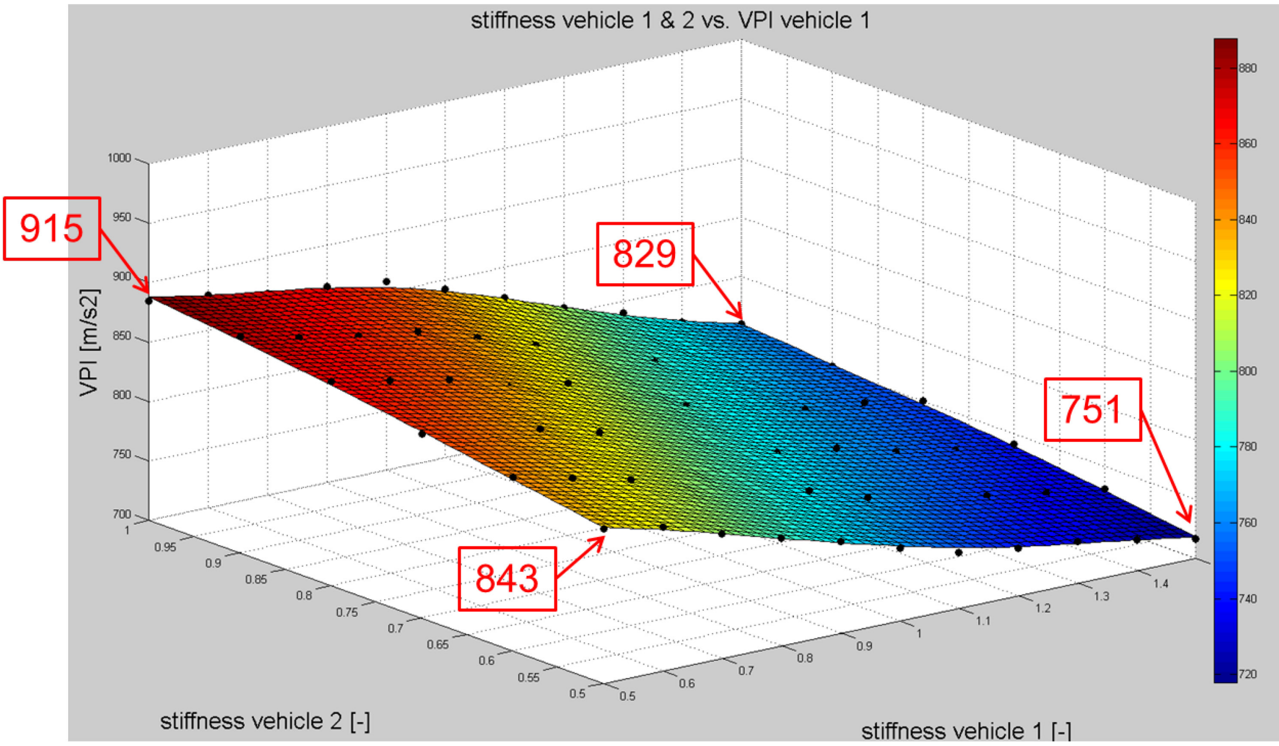


Figure 4.8: VPI of Supermini 2 for simulations with connected cross beam.

Figure 4.8 shows the fitted surface of the VPI of vehicle 1 (Supermini 2) to the simulations (black dots) with the connected cross beam, showing the highest VPI (915m/s^2) for the impact of the Supermini 2 with lowest longitudinal stiffness (x0.5) and SUV 4 with default (highest) longitudinal stiffness (x1). The lowest VPI (751m/s^2) occurs with the Supermini 2 with highest longitudinal stiffness (x1.5) and SUV 4 with lowest longitudinal stiffness (x0.5).

The VPI of vehicle 1 (Supermini 2, purple) and vehicle 2 (SUV 4, green), both with connected cross beam is shown in Figure 4.9. This clearly shows that the VPI values of the Supermini 2 (min.: 751m/s^2) are always well above the VPI values of the SUV 4 (max.: 429m/s^2), even with the increased longitudinal stiffness of the Supermini 2 (x1.5) and the reduced longitudinal stiffness of the SUV 4 (x0.5).

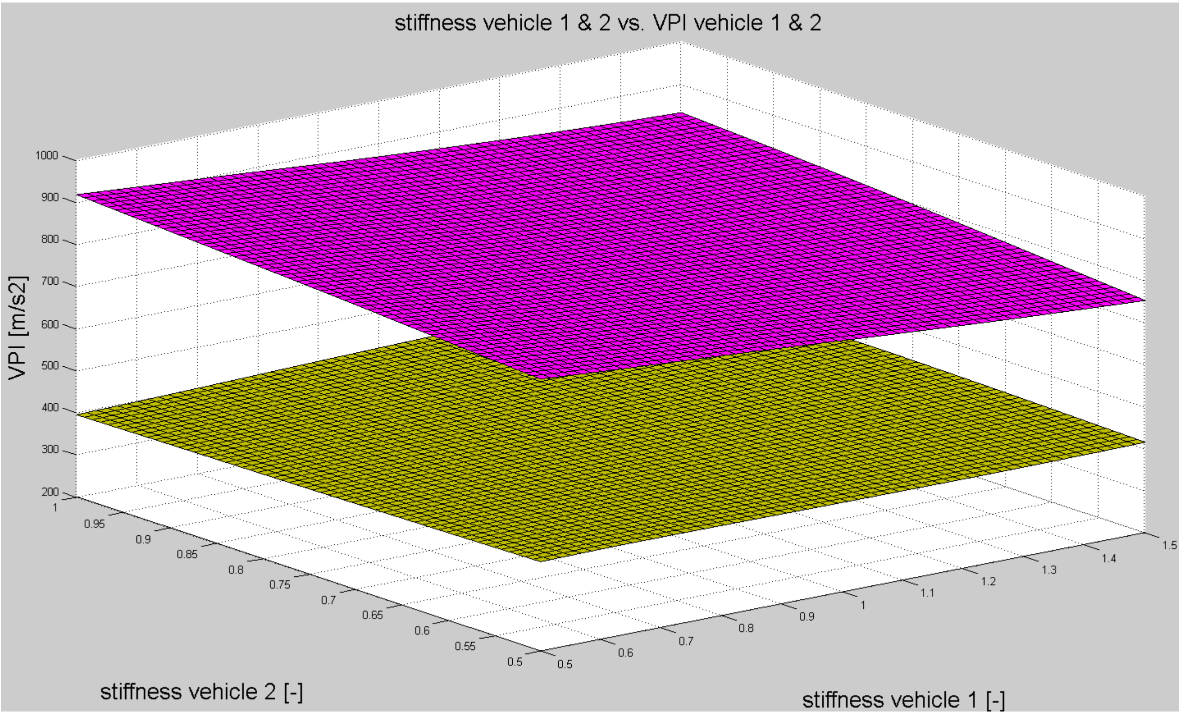


Figure 4.9: VPI of Supermini 2 (purple) and SUV 4 (green) for simulations with connected cross beam.

Figure 4.10 shows a simulation of Supermini 2 against default SUV 4 with 50% overlap at 56 km/h, with green the lowest longitudinal stiffness (x0.5) and red the highest stiffness (x1.5) for the Supermini 2.

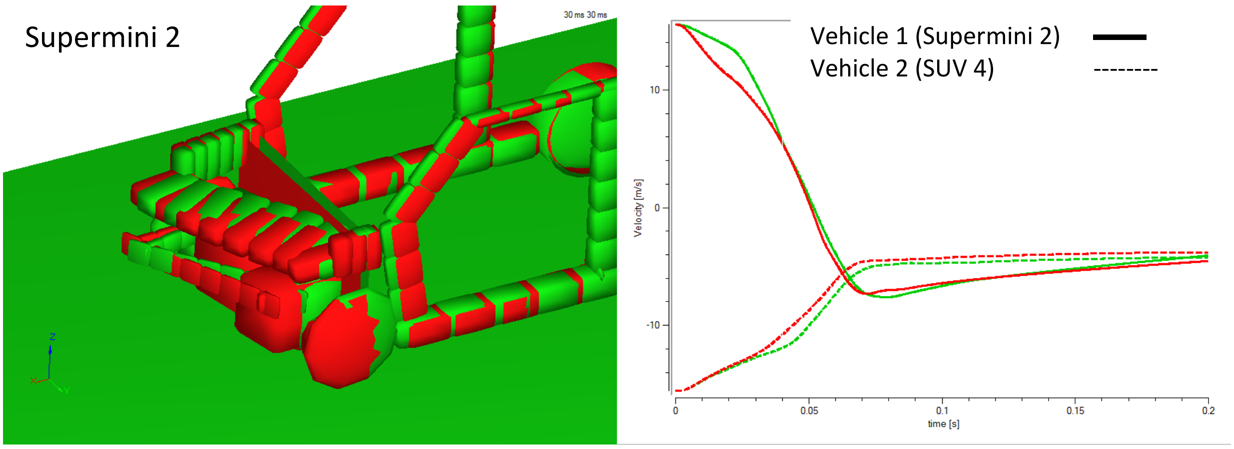


Figure 4.10: Low (x0.5, green) and high (x1.5, red) longitudinal stiffness simulation of Supermini 2 - SUV 4.

Fleet study II shows:

- Significant difference (close to 100m/s2) in VPI of vehicle 1 (Supermini 2) between decreased (x0.5) and increased (x1.5) longitudinal strength for vehicle 1 (Supermini 2).
- Significant difference (close to 100m/s2) in VPI of vehicle 1 (Supermini 2) between decreased (x0.5) and standard (x1) longitudinal strength for vehicle 2 (SUV 4).

Similar to fleet study I, this fleet study demonstrates that a higher longitudinal stiffness results in higher VPI for vehicle 1 (Supermini 2) with stiffer longitudinal.

4.2.2.2 Cross Beam Failure

Two sets of each 66 simulations (11x6) have been performed, one in which the cross beam stays connected and one in which the cross beam fails for vehicle 1 (Supermini 2).

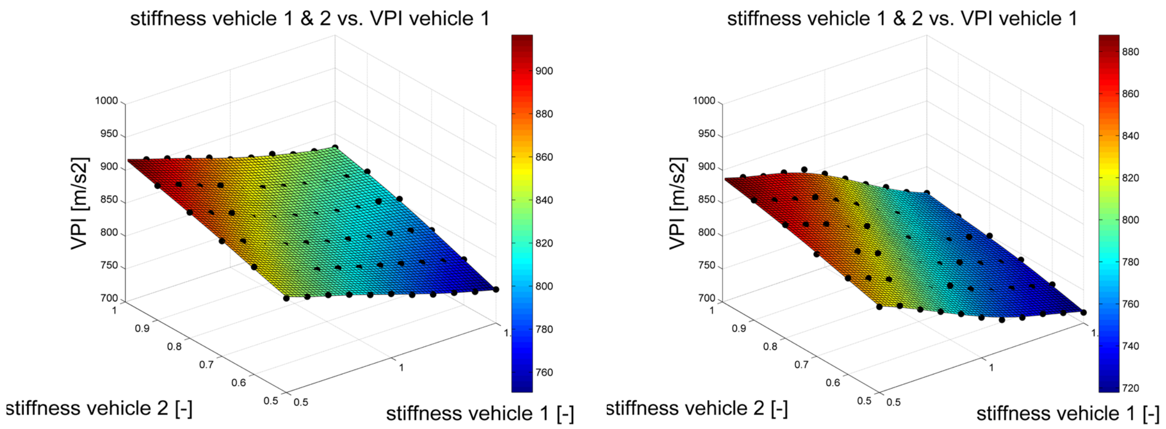


Figure 4.11: VPI of Supermini 2 with connected cross beam (left) and cross beam failure (right).

Figure 4.11 demonstrates the fitted surface of the VPI of vehicle 1 (Supermini 2) to the simulations (black dots) with the connected cross beam (left) and cross beam failure (right).

Figure 4.12 shows that the VPI of vehicle 1 (Supermini 2) with connected cross beam (green) exceeds the VPI values of vehicle 1 (Supermini 2) with cross beam failure over the entire evaluated area.

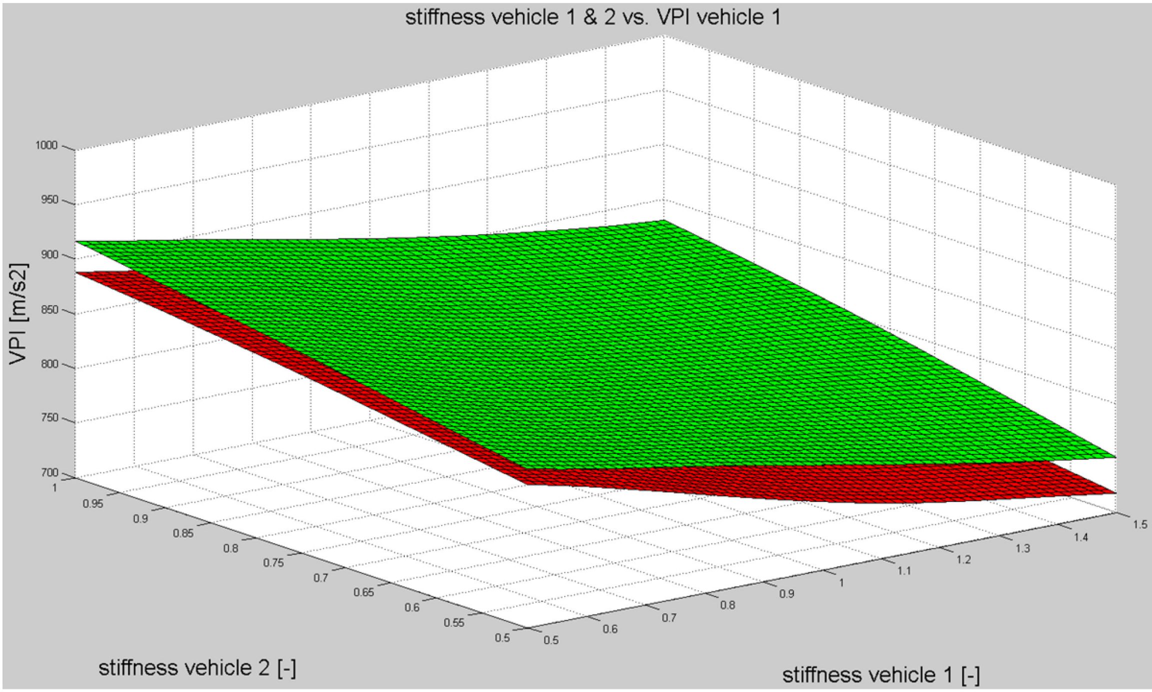


Figure 4.12: VPI of Supermini 2 with connected cross beam (green) and cross beam failure (red).

The simulation of Supermini 2 against default SUV 4 with 50% overlap at 56km/h, with green the connected cross beam and red the failed cross beam with default longitudinal stiffness for both vehicles is shown in Figure 4.13.

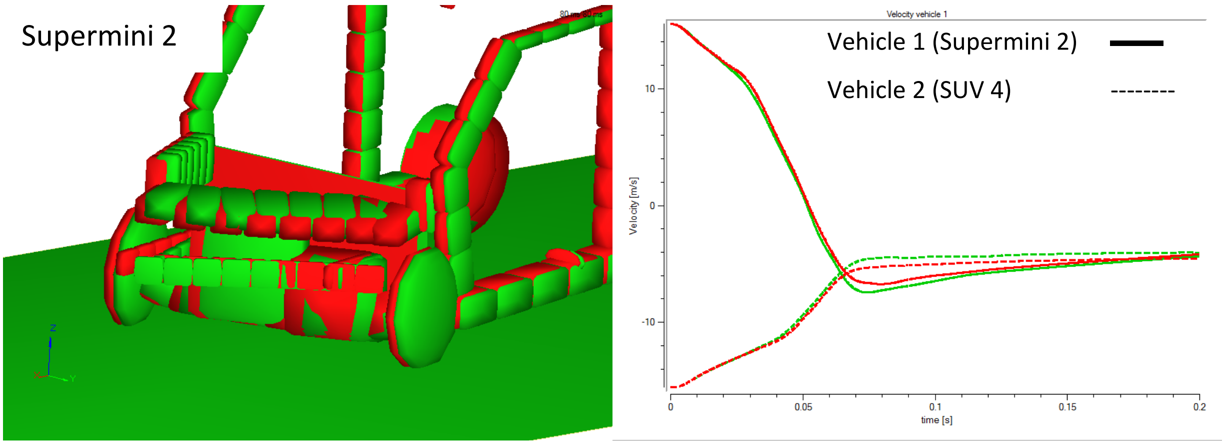


Figure 4.13: Cross beam connected (green) and cross beam failed (red) Supermini 2 - SUV 4.

As observed in fleet study I also fleet study II demonstrates that an impact with a vehicle with cross beam failure gives lower VPI values for both vehicles compared to an impact with a vehicle in which the cross beam stays connected. However, it needs to be noted that phenomena like intrusion resulting from the cross beam failure are not considered in the simulation. Therefore the VPI might give a wrong estimation of the dummy loadings.

5 CONCLUSION

The objective of this deliverable is to describe a methodology for predicting future vehicle fleet characteristics. The results of the performed fleet studies show that it is possible to evaluate and predict the effect of various vehicle characteristics on the overall crash performance, represented by VPI (Vehicle Pulse Index), of the (future) vehicle fleet.

From the performed fleet studies it can be concluded that:

- A higher vehicle mass results in a lower VPI. For the opponent vehicle an impact with a vehicle with higher mass results in higher VPI.
- An impact with a vehicle that shows cross beam failure shows lower VPI values for both vehicles compared to an impact with a vehicle in which the cross beam stays connected, as this increases the overall stiffness of the vehicle.
- A higher longitudinal stiffness results in a higher VPI, for as well vehicle 1 with stiffer longitudinal, but even more for the opponent vehicle 2.

It should be taken into account that due to the assumptions made in the used MADYMO models some phenomena are not represented that might have an effect on the occupant. Cross beam failure and/or lower longitudinal stiffness result in a vehicle with lower crash stiffness in frontal impacts. This lower stiffness gives a lower VPI value, but in reality it might result in intrusion of the occupant compartment, which was not taken into account in the current vehicle models.

6 GLOSSARY

ASI:	Acceleration Severity Index
Euro NCAP:	European New Car Assessment Programme
FWDB:	Full Width Deformable Barrier
MDB:	Moving Deformable Barrier
ODB:	Off-set Deformable Barrier
SUV:	Sports Utility Vehicle
VC-Compat:	EC funded project (FP5) Vehicle Crash Compatibility
VPI:	Vehicle Pulse Index

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