Unified parametric car model – A simplified model for frontal crash safety

Mathias Stein[1], Pit Schwanitz[1], Hariharan Sankarasubramanian[2,1]

[1] Technical University, Berlin, Germany
[2] Indian Institute of Technology, Delhi, India

Abstract

In addressing crash protection of car front ends, three different energy levels are encountered in the form of pedestrian crashes, low and high speed crashes against obstacles and other vehicles. The aim is to approach vehicle front design problem as three separate formulations at the initial phase of the product development process instead of one complex model. Therefore three highly parametric complex models are established to identify the variables with high impact on the self and partner protection as well as pedestrian safety.

The long term objective will be to merge the three simplified models into one common full implicit parametric vehicle model. This model can be used in the early stage of the product development process to predict the impact of structural modifications for typical crash configurations.

This paper shall give an overview about the simplifications and the process of verification and validation of the three model approaches leading to one single effective simplified vehicle-front model. A detailed description of the implicit parametric CAD models will be presented along with different interfaces and tools to create an automated optimisation loop, effectively leading to a comprehensive design methodology.

Keywords: *simplified vehicle models, insurance classification, pedestrian safety, car-to-car frontal impact compatibility, front end optimization, implicit parameterization, SFE CONCEPT, crashworthiness, automotive front structures, MADYMO coupling,*

1 Introduction

By reducing the period of the early phase of the product development process (PDP) the development costs can be reduced significantly. Thereby the length of the PDP is controlled by the length of the concept phase and the realisation phase. To ensure that a concept fulfils all requirements, CAD tools help to predict the basic characteristics like crashworthiness of a vehicle. Especially, the requirements for passive vehicle safety are manifold and require specific knowledge of the most important parameters which influence the crash behaviour. Conventional methods adopted include usage of separate models to simulate the crash responses in fields like insurance classification, self and partner protection and pedestrian safety. This modelling process consumed a lot of time and was implemented relatively late in the PDP while, a lot of details of the concept remain unknown at early stages. The FEM models used for engineering analyses did not permit easy changes in terms of geometry and topology of the vehicle structures. Therefore, the usage of a flexible tool to directly work on CAD model to generate FE model offered the potential to modify the topology as well as the shape of the structures that were already defined in the early stage of the PDP. The software SFE CONCEPT ensured easy modification of the CAD data with implicit parametric design capability. The connectivity of the structures was assured during the modification and neighbouring structures followed the modified ones. Included auto-mesh algorithms created computable FE meshes as well as welding definitions and other FE constraints applied to the model. This solution offers the potential to reduce the length of the PDP in combination with a simplified model that is able to address the most relevant crash requirements.

2 Objective

In addressing crash protection of car front ends, three different energy levels are encountered in the form of pedestrian crashes, low and high energy crashes against obstacles and other vehicles. The main objective is to approach vehicle front design problems as three separate formulations at the initial phase of the product development process instead of one complex model. Therefore three highly parametric simplified models were established to identify the variables with high impact on the self and partner protection, pedestrian safety and insurance classification tests. The results were to be transferred back to the complex models which will be available at the end of the PDP. A special emphasis was placed on the simplification process. Finally the three models can be merged together into on unified parametric car model.

3 Process of model development

3.1 Development Method

Basically the methodology used for this study consists of three parts, see Figure 1. The first part is the identification of the most important load cases in frontal crash scenarios which shall be addressed. Within this study the following crash configurations were considered:

1. Offset:
    a. RCAR structure test (15 km/h, 40 % overlap, 10° wall inclination)
    b. ODB_56 (acc. to ECE R94, 56 km/h, 40 % overlap)
    c. ODB_64 (acc. to Euro NCAP, 64 km/h, 40 % overlap)
2. Full Width:
    a. RCAR bumper test (10 km/h)
    b. FWRB_56 (acc. to US NCAP, 56 km/h)

Depending on the load cases the crash management systems can be defined by specifying the important front end structures of the vehicles. The third part of the methodology is crucial for the development process of the simplified models. By simplifying detailed vehicle models (FORD Taurus and TOYOTA Yaris [1]) crash relevant structures have to be isolated. Within the verification process the limitations of the models will be defined and finally the models will be validated with typical crash configurations to ensure the correct response of the simplified models. A special emphasis was placed on the whole simplification process to guarantee that the results obtained with the simplified models can be transferred back to the detailed models. The model depended simplification process is described in the following chapters. Thus three independent models were created allowing investigations of the most relevant frontal impact crashes. Due to the common modelling approach the three models can be merged into on simplified parametric full vehicle model.

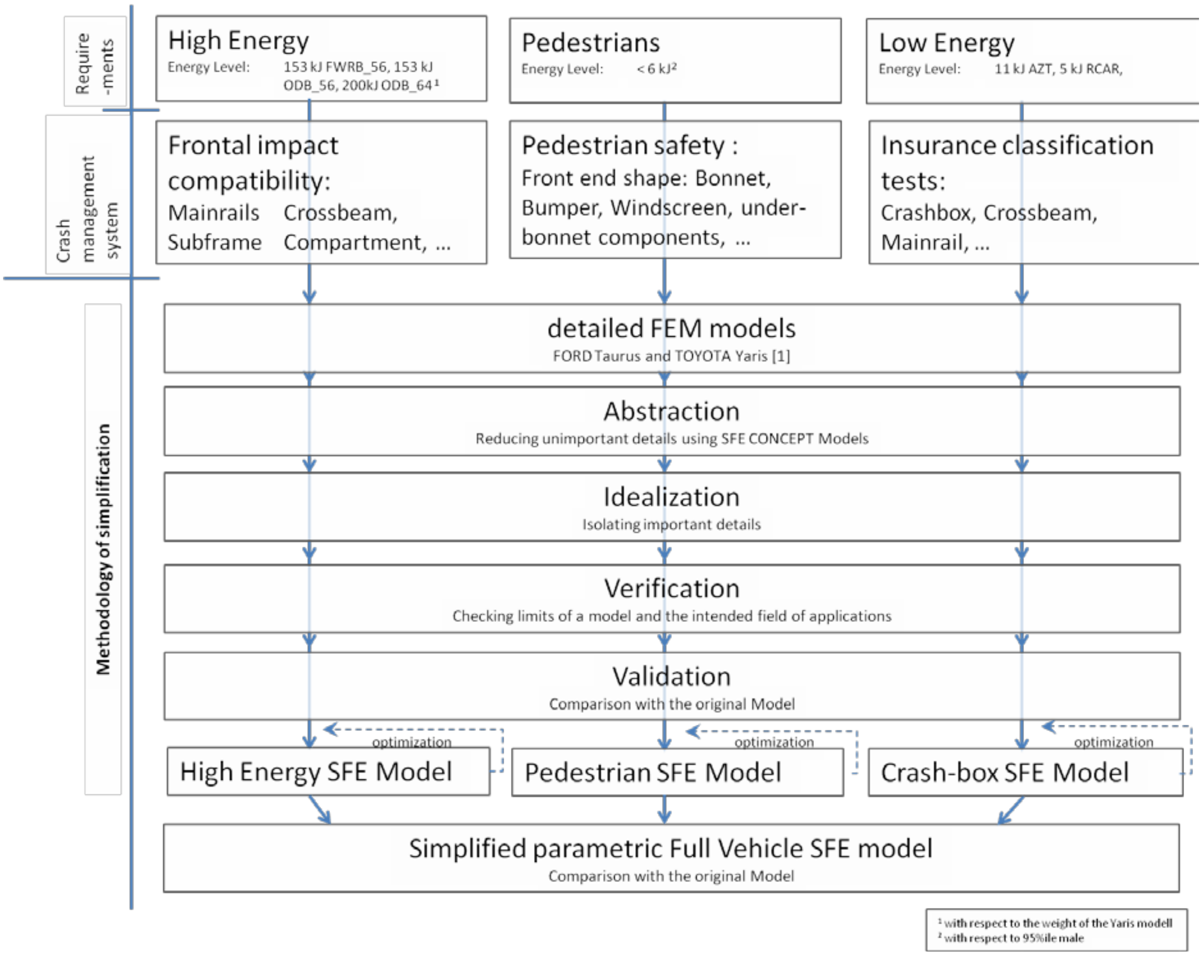


Figure 1: General overview of the unified model development methodology

3.2 Optimization loop

Figure 2 shows a simplified representation of the optimization loop which was used to improve the efficiency of the single models.
At first stage, an implicitly parametric CAD model was created using SFE CONCEPT. The mentioned CAD package has powerful auto-mesh functionality with welding and multi-flange definitions to handle relatively complex actual vehicle FE models. A FE mesh of the geometry was exported from SFE CONCEPT in the format to suit LS-Dyna input deck.
With boundary conditions, material properties and other inputs prepared and ready for LS-Dyna input deck, the FE mesh exported with SFE CONCEPT was added an include file to it. Calculations were performed using LS-Dyna solver or a combination of LS-Dyna and MADYMO.
With critical output parameters of the calculations known, the output files were processed using MATALB or combination of LS-Prepost with MATLAB.
The whole process was controlled using OptiSlang, a commercially available optimization tool. It was capable of performing design of experiments, sensitivity analysis, robustness analysis and single and multi-parameter optimizations which were required for the development proposed methodology to develop simplified vehicle models.

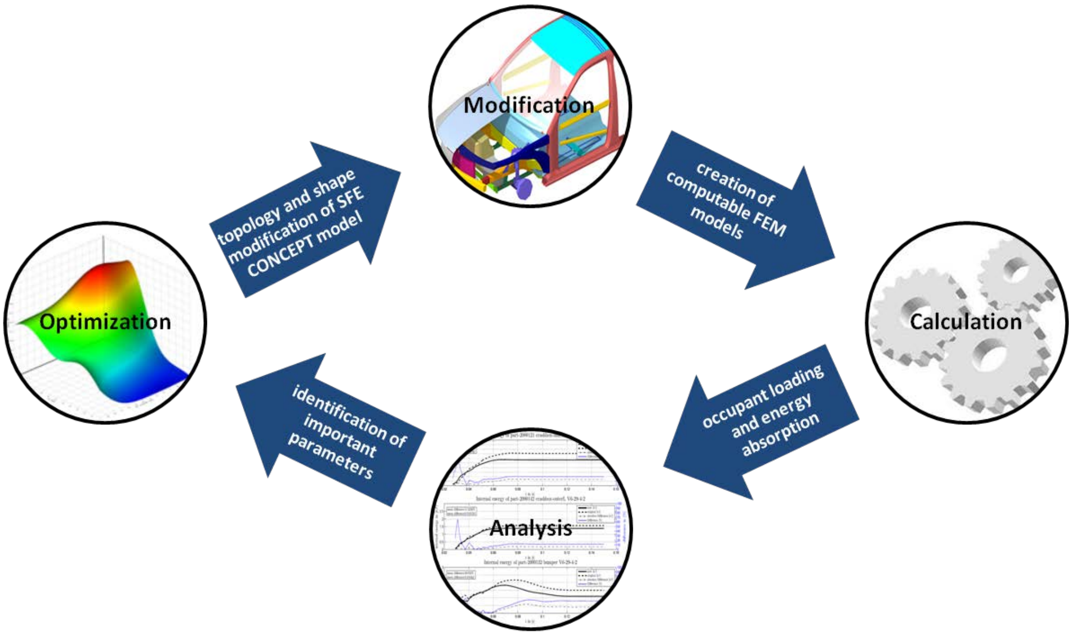


Figure 2: Optimization loop

3.3 Low Energy Model

3.3.1 Introduction in low Energy Vehicle Car crashes

The aim is to optimize front end structures in particular the crash-box to absorb the energy of low speed crashes with a velocity of maximal 15 km/h. This type of crash usually happens during the rush hour in urban areas. The aim of the crash-box is to absorb major parts of the excess energy thereby that other parts ideally experience force within elastic limit. The deformation and energy absorption of the crash-box is very useful especially in terms of repair costs reduction and therefore minimizing the insurance contribution [2].
Past activities have covered various optimizations of different crash boxes. Usually with a very specific goal in terms of shape and cross-sections [3] [5], weight reduction, crash behavior [6], to prove the functionality of a optimization methodology, influences of the meshing quality [4] as well as foam filled structures [7] has been covered.
The most recent trend goes towards combined shape and topology optimizations, which seems promising [8]. Nevertheless a comprehensive study regarding different types of crash-boxes has not been carried out. Therefore a reduced model with a highly parametric crash-box is necessary. As Multi-parameter optimizations involve higher number of combination of inputs simulations for effective search within the design space. Reduced models which replicate the critical output parameters effectively are therefore crucial to establish a development process within a desired time range.

3.3.2 Simplified Model and Validation

As reference car the TOYOTA Yaris [1] has been used. The model was validated by NCAC for US regulatory frontal impact load conditions.
The internal energy over time distribution of the bumper and the crash-box (inner and outer) was used as reference value, see Figure 3. The Research Council for Automobile Repairs (RCAR) structure test barrier was used as obstacle and the vehicle has a speed of 15 km/h [2].

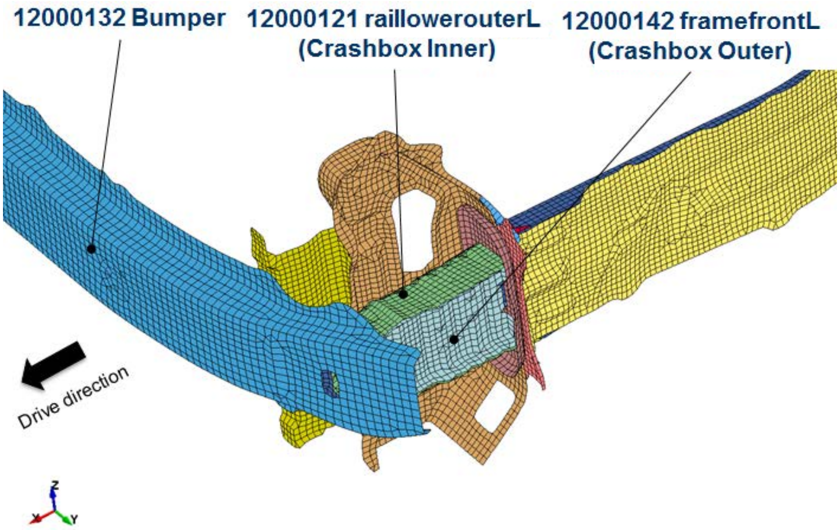
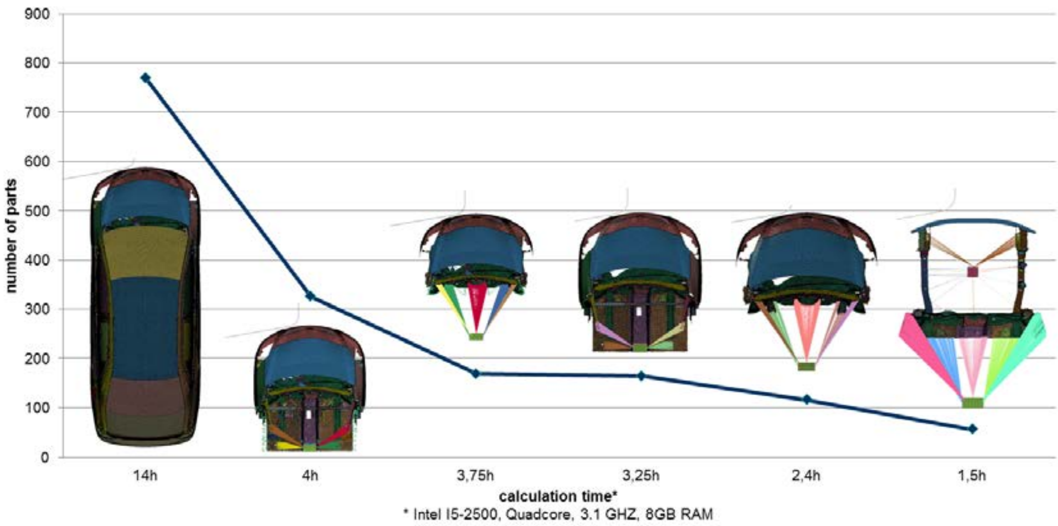


Figure 3 Important TOYOTA Yaris front end parts



* Intel I5-2500, Quadcore, 3.1 GHZ, 8GB RAM

Figure 4: Simplified model simulation time

The number of parts in the Yaris model has been reduced step by step and the crash-box performance of the original Yaris crash-box has been checked regarding their crash performance in terms of absorbed energy.
Figure 4 shows the different simplified models with the calculation time on one workstation. With a decreasing number of nodes and parts the calculation time was reduced significant. For comparison of the results, the internal energy of the three parts (bumper, crash-box inner, crash-box outer) has been plotted, Figure 5. Each plot shows the result of the internal energy of the part in the full vehicle calculation and for comparison the reduced vehicle calculation. Furthermore, the absolute difference of the internal energy between the original vehicle and the reduced vehicle was plotted as well as the absolute difference on the second ordinate. Additionally, every plot shows a box with the mean difference of the original Yaris model and the reduced model in terms of the percentile deviation and mean energy deviation.

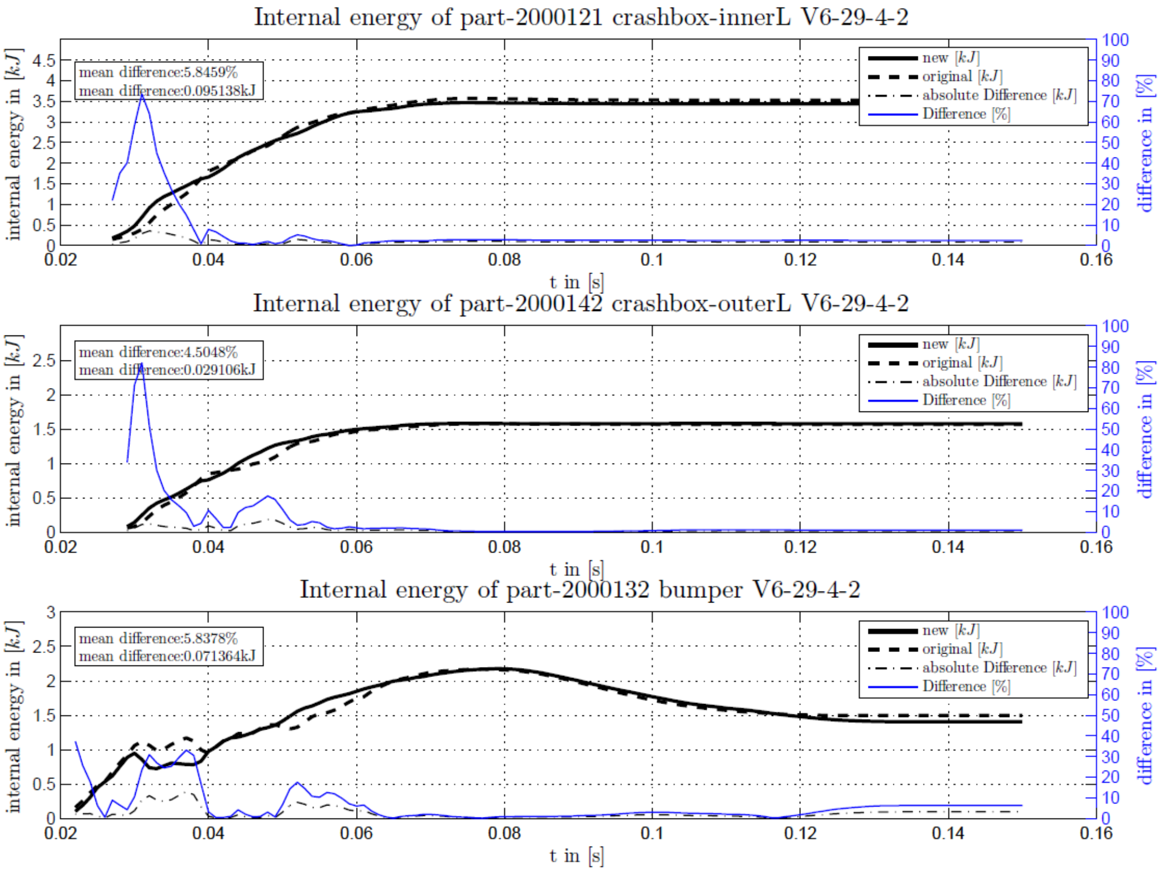


Figure 5: Final design, mass and inertia optimization (27 parameters), 15h Model (limited boundaries)

The simplified model had an overall calculation time of 1.5 h and has been used for an initial optimization. The deviations from original model indicated the need for optimization process to fine tune parameters of the simplified model to achieve similar prediction capability as the original model.
Therefore an optimization has been started to modify the three different weights and the appending inertias, 27 variables in total.
After 183 calculations a significant improvement was achieved. The average deviation of the internal energy of the three parts has been reduced from 17 % to 6%. This result was within desired limits of accuracy to permit the simplified model to run further simulations with highly parametric crash-boxes.
The simplified Yaris Model was used and in the first step the Yaris crash-box was substituted with an implicitly parametric crash-box modelled to an equivalent geometrical shape of Yaris crash-box created with SFE CONCEPT. This implicit crash-box shows an equivalent behaviour compared to the original model.

3.3.3 Discussion

The simplified front end model was found suitable to be used for Crash-Box optimizations. The calculation time reduced significantly with a deviation of 5% compared to the original Model. Further investigations with respect to other important parameters such as accelerations and others have to be carried out. The impact of different materials, the mass distribution, the number and type of welding as well as the influence of the rigid body elements does have to be checked. The found optimum has to be reviewed regarding their robustness. The model itself is verified for this specific load case, other load cases have to be verified.

3.4 Pedestrian Safety Model

3.4.1 Introduction to Pedestrian Safety and vehicle front-end design

Pedestrians represent one of the vulnerable road users and their safety on-roads need attention in developing as well as developed countries [9], [10]. According to the analysis of data from crash databases, the most frequent pedestrian-to-vehicle crash scenario was the vehicle-front striking the pedestrian laterally. The studies relating speed of vehicles to the probability of survival of pedestrians by [11] suggested a speed of 40 km/h for safety of pedestrians.

For a typical sedan shape, the pedestrian crash kinematics was observed as leg to bumper, pelvis to bonnet leading edge, torso to bonnet and or head to windscreen type of crash for adults and in children, it was leg to bumper, torso or head to bonnet leading edge [12]. In case of flat front vehicles, the secondary crash injuries were found to be more severe than the primary injuries.

With such a unique requirement for safety of pedestrians, a simplified vehicle front model would serve as a good starting point for a pedestrian friendly design at preliminary stages to minimize injuries based on kinematics involved in pedestrian crash

3.4.2 Vehicle-pedestrian crash

Why vehicle-pedestrian crash is unique?

Unlike the crash tests involving the low velocity impact or the rigid wall impact, pedestrian crash energy levels are governed by size and weight variations in humans. Considering a large human size, 95%^{ile} Male with a relative velocity of 40 km/h crashing against the vehicle front would involve a total kinetic energy around 6 kJ. In ideal conditions, the whole energy of the pedestrians needs to be absorbed to save the pedestrian from any blunt impact injuries. At the lower end of size and weight variation is a 6 year old child having one third of the weight and less than half the height.

With such a wide variation in energy involved, passive safety countermeasures like location and design of energy absorbers remain dependent on the predicted potential impact points during a crash (kinematics).

Measurement of Injury severity to pedestrians

To understand the injury risk to a pedestrian by a vehicle profile, Injury to whole body would need to be considered. Rating and regulatory tests use linear acceleration based criteria for head, acceleration and displacement based criteria for chest, penetration based criteria (peak force) for abdomen, peak force for pelvis, combination of bending and compression force factors to long bones of lower extremity and displacement based criteria for knees.

For studies related to optimization for pedestrian safety, it was found that a single objective function was more effective to address the relationship between injuries. An injury cost based measure was a representative number involving hospitalization and medical expense with provision of high penalty for potential impairment or death [13]. Injury cost calculation is shown in *Figure 6*.

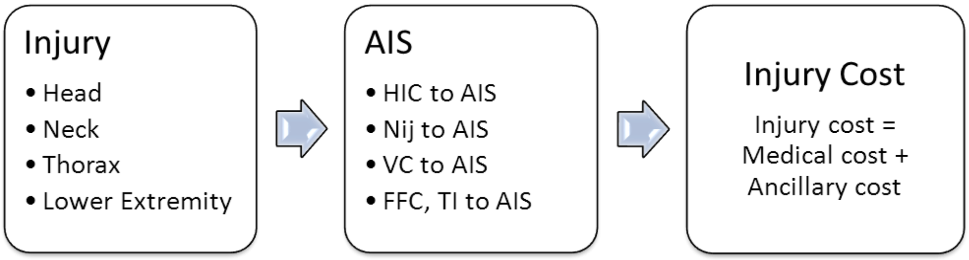


Figure 6: Calculation of injury cost

3.4.3 Methodology of development of the simplified Pedestrian Model (PedMo)

Abstraction

The first stage involves identification of the components relevant to pedestrian safety. All major components within 200 mm of the body outer surface of the vehicle front end involve a potential to influence pedestrian primary (blunt) injuries on impact. Major components shortlisted were Radiator front surface, bonnet inner reinforcement, bumper cross beam, bumper foam, grill plastic, bonnet locks, radiator mountings on top, engine top surface, brake fluid tank, suspension cover, exhaust manifold, firewall top surface linkages. Figure 7: Development process for PedMo (top left) shows the isolated parts in exterior from the LS-DYNA FE model.

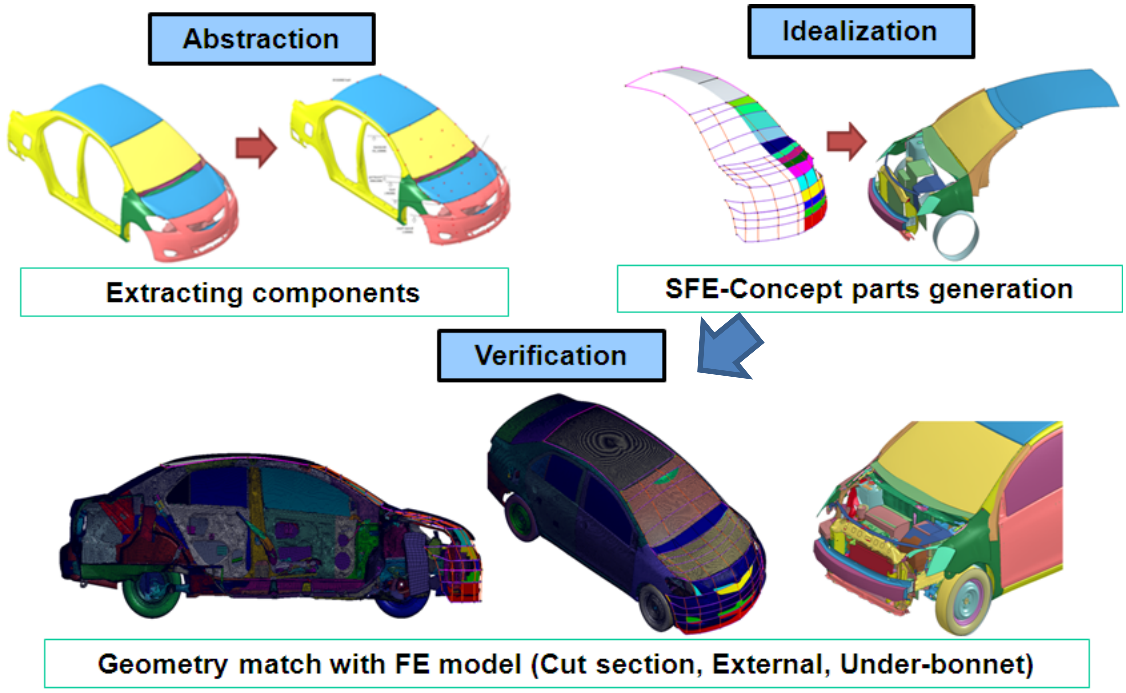


Figure 7: Development process for PedMo

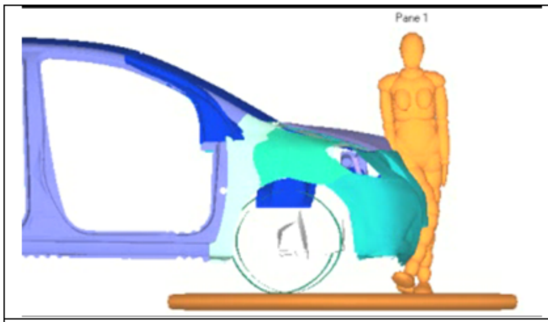
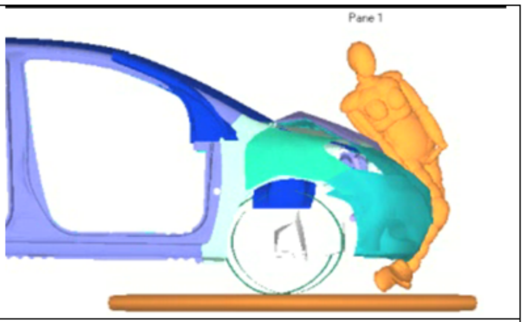
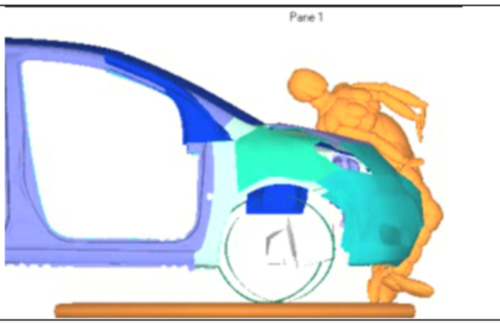
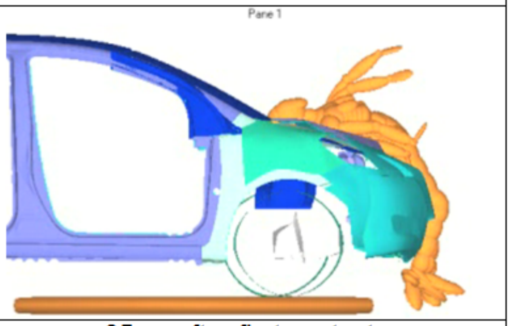
Idealization
The shortlisted components were modelled using SFE-CONCPET. Figure 7: Development process for PedMo (top right) shows the stages of development of surfaces of this model. Geometric profiles were created using FE model of TOYOTA Yaris as reference, [1]. Vehicle front profile was constructed as approximated curve using 4 to 5 control points along the lateral direction of the vehicle. Bonnet had 4 'base sections' to cover geometry in relatively good accuracy. Similar constructions were provided for the windscreen, bumper, roof and cowl region components. The provisions of SFE-CONCEPT macros were used to control the shape of the curves and also the location of the base sections. It also allowed having spot welds definitions, but for the initial models, rigid bodies were modelled for linkages.

Verification of the Model
The modelled generic parametric vehicle front was verified for its geometrical representation of Yaris model shape by comparing with the shape of the FE model in LS-PREPOST. Bottom left two figures in Figure 7: Development process for PedMo show a similar match of the outer profiles of both models. The figure on the bottom right shows match of the planes representing the under-bonnet components matching in geometry with the FE model. The importance of these hard points location was critical for replicating potential injury to pedestrian during a crash.

Validation of the Model - Vehicle-Pedestrian crash scenario simulation
A 40 km/h crash between vehicle front and pedestrian during a lateral impact was simulated. Pedestrian was represented using a MADYMO multi-body pedestrian model. These pedestrian models were validated for three dimensional velocity and kinematics by [14]. Vehicle model was represented by LS-DYNA model of the car developed in the previous step.
An extended coupled LS-DYNA (SMP) / MADYMO simulation was performed. Contact was defined between the pedestrian models and the whole car front surface and the shortlisted components.

Validation of the Model - Comparison of the kinematics
Impacts simulated between the detailed Yaris model and the new SFE CONCEPT simplified PedMo is compiled in Table 1. Kinematics of the MADYMO pedestrian model shows a good overall match from first contact to about 70 ms after impact. The location of the head impact observed at 95 ms after first contact. The kinematics in terms of body rotation showed a minor variation but the head impact time and locations remained the same.
The acceleration peaks of head impact were also observed in the same time but values were higher in the PedMo.

Table 1: Comparison of kinematics against a 5%^{ile} female during PedMo and original TOYOTA Yaris coupled simulations

	
20ms after first contact	45ms after first contact
	
70ms after first contact	95ms after first contact

3.4.4 Discussion

With PedMo, the simulation times reduced to one tenth of the whole FE model. PedMo was approximated in shape and mass properties to obtain these results. The process of adding rigid body masses to compensate mass and centre of gravity of car resulted in isolated hard points leading to random increase in the head acceleration values. Despite the isolated peaks, the location of impact and pedestrian kinematics in terms of displacement and velocity to other parts of the body remained consistent with Yaris model.

3.5 High Energy Crash Model

3.5.1 Background

Regarding the current activities in the field of vehicle compatibility for frontal impact, structural interaction of the front end structures of the colliding vehicles was identified as one of the major issues in car to car crashes [15]. The conducted accident analyses detected three mechanisms of crash mainly responsible for fatal casualties and MAIS2+ (maximum abbreviated injury scale) injuries: fork effect, under/overriding and small overlap. Amongst dynamic effects which can influence the position of the EAS (energy absorbing structures), the large number of different structure concepts lead to misaligned structures in crashes. To investigate the interaction of cars in frontal impacts, a vehicle fleet model was needed that suitable represented the different structural concepts in an appropriate manner.

3.5.2 Modelling Approach

Fleet Modelling

Numerical vehicle models offer the potential for in-depth investigations. Thus the analysis of mechanisms occurring in frontal car to car crashes is possible as well as the estimation of the variation in injury numbers and injury severity levels resulting from modifications of the vehicles, like stiffness or topology modifications of the front end

Different approaches to model vehicle fleets can be found in the literature. On one hand, generic models which represent average cars of a corresponding vehicle class in terms of mass, dimensions and other pre-defined characteristics (e.g. stiffness of the front end) and on the other hand FEM models of existing cars. The second approach was often used to investigate the level of passive safety of one specific vehicle fleet, e.g. of one manufacturer [16], [17]. However, due to different solver types and confidentiality issues, detailed models of one manufacturer were not capable to represent the whole European vehicle fleet. Furthermore, the large numbers of different front end structure concepts made it practically impossible to investigate all cars in all car to car crash configurations.

To eliminate these limitations the following requirements were defined for the modelling process of an appropriate vehicle fleet:

1. To represent the European vehicle fleet in terms of
    a. mass and dimensions
    b. topology of front end structures
    c. crash characteristics (crash pulse, intrusions)
2. To allow fast design changes of front end structures
3. To have low computational effort

These requirements demanded that the vehicle models be simplified. Thereby, simplification meant that all crash relevant structures be taken into account but the geometry to be simplified to allow fast modifications and to reduce the computational effort [18]. Furthermore, under bonnet components like battery, generator, etc., were removed to allow greater degree of freedom for the design changes. However, the model had to address the typical folding mechanisms (Euler buckling) and generate corresponding crash behaviours with typical deformation characteristics.

3.5.3 Generic Vehicle Models

To address the first requirement, generic car models of four different vehicle classes were modelled. For this purpose geometrical data of a database established within VC COMPAT and extended within IMPROVER and FIMCAR was used [19]. This database provides information about the position of crash relevant structures of 71 vehicles. A set of locations was defined to make the measurements comparable. For the modelling process the data were classified into four groups (super mini, family car, executive car and off road vehicles) and outlier (e.g. body on frame cars, rear engine cars, etc.) were removed. Figure 8 shows the average and max/min values for vehicle mass and dimensions of the chosen sample.

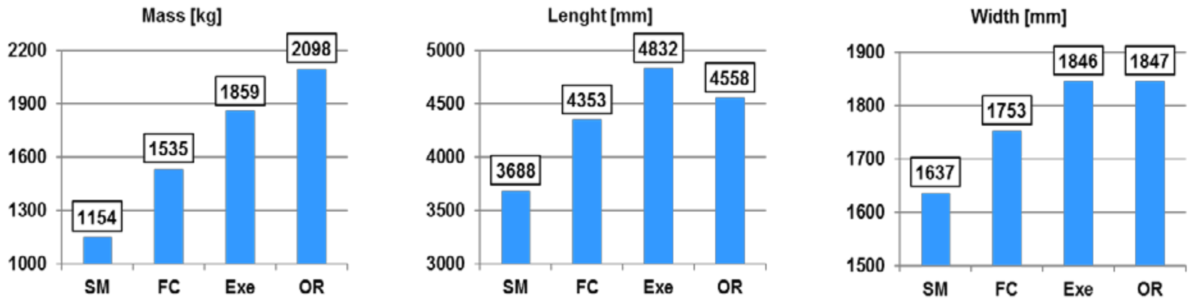
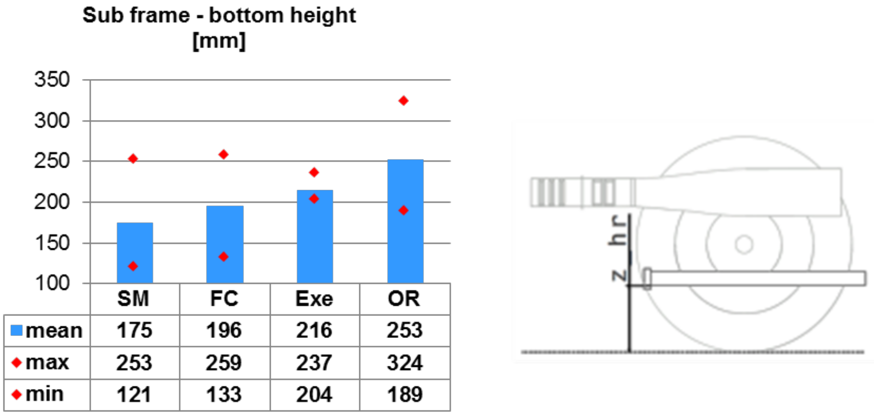


Figure 8: Mass and dimensions of the four vehicle classes

After that average values were calculated to define the position of the corresponding structures. Exemplarily Figure 9 gives an overview about the average and max/min values of the sub frame height.



	SM	FC	Exe	OR
■ mean	175	196	216	253
◆ max	253	259	237	324
◆ min	121	133	204	189

Figure 9: Modeling parameter – sub frame height zHR

In total 48 parameter were defined describing the generic topology of four vehicle classes. Amongst the average values the max/min values were used to define the upper and lower boundaries of positions which are possible for the corresponding structures. The topology models shall be able to create structure variants of all cars used for the calculation of the thresholds for the CAD modelling process.

Topology Model

To address the second requirement a full implicit parametric SFE CONCEPT model was created. In addition to the front end structures a compartment was designed to support all components of the front end. Furthermore, this gave the possibility to analyse compartment loading in terms of accelerations and intrusions (fire wall, a- and b-pillar) which was also important for the validation process, see Figure 10. All 48 parameters were defined as influence points. Thus the modification of the corresponding structures was done in an efficient manner. Further design parameter (e.g. tangents to control the shape, beads to improve buckling) helped to create realistic geometries and can also be controlled easily.

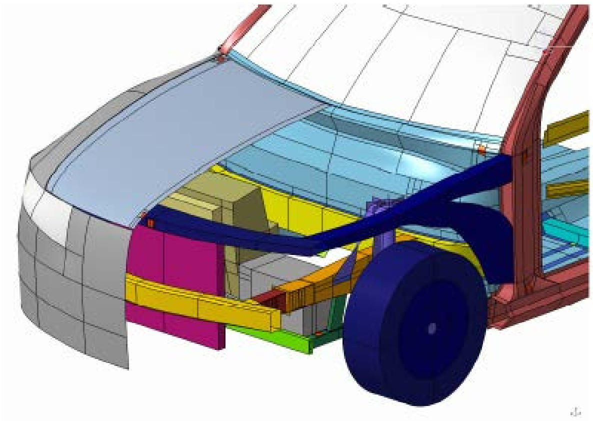


Figure 10: Topology model – Large Family Car (LFC)

In addition to the CAD data FE definitions like welding points and nodal sets for joints and constraints were defined. These definitions are taken into account during the auto-mesh process which is controlled by SFE CONCEPT. Depending on the crash solver the software exports the FE data automatically in separate files that can be included into a pre-defined simulation environment to ich calculate the models without further pre-processing.

To reduce the computational effort but nevertheless to ensure numerical stability in simulations with barrier models the mesh size was set to 15 mm. Therefore the LFC model consists of around 130,000 nodes and elements.

Analysis of Energies

The second step of the verification process is to design the energy absorption capabilities of the structures. This process involved adjusting the parameters which the energy absorption mechanisms. With respect to the simplification process relative simple structures were modelled in combination with disposable material models. Therefore the main (and simplest) parameter to adjust the energy absorption capability is to modify the wall thickness.

Different approaches provided information of the total amount of absorbed energy. One approach was to analyse crash pulses of real vehicles of the corresponding vehicle class. Acceleration- (force) displacement curves provide data about the total absorbed energy as well as the estimation of typical force levels. Another approach was to estimate the absorbed energy with tools normally used by accident re-constructing engineers. Different restitution coefficients for different crash configurations allow the estimation of the absorbed energy and therefore a calculation of the collision velocity [20]. But, both approaches only offer the estimation of the total amount of absorbed energy. To get information about the distribution of the absorbed energy two detailed FEM vehicle models (FORD Taurus and TOYOTA Yaris [1] were crashed in typical low and high speed as well as offset and full width crash configurations, see Chapter 3.1

The results of this analysis are given in Figure 11 and Figure 12. The diagrams show the distribution of the internal energy of different components. For the analysis the parts of the FEM models were grouped into nine groups (cross beam (blue), crash-box (red), longitudinal (green), sub frame (purple), shotgun (light blue), frontend (orange), firewall (light purple), others (pink) and barrier (grey)). The internal energy of the corresponding parts were summed up and compared with the total internal energy of each crash configuration.

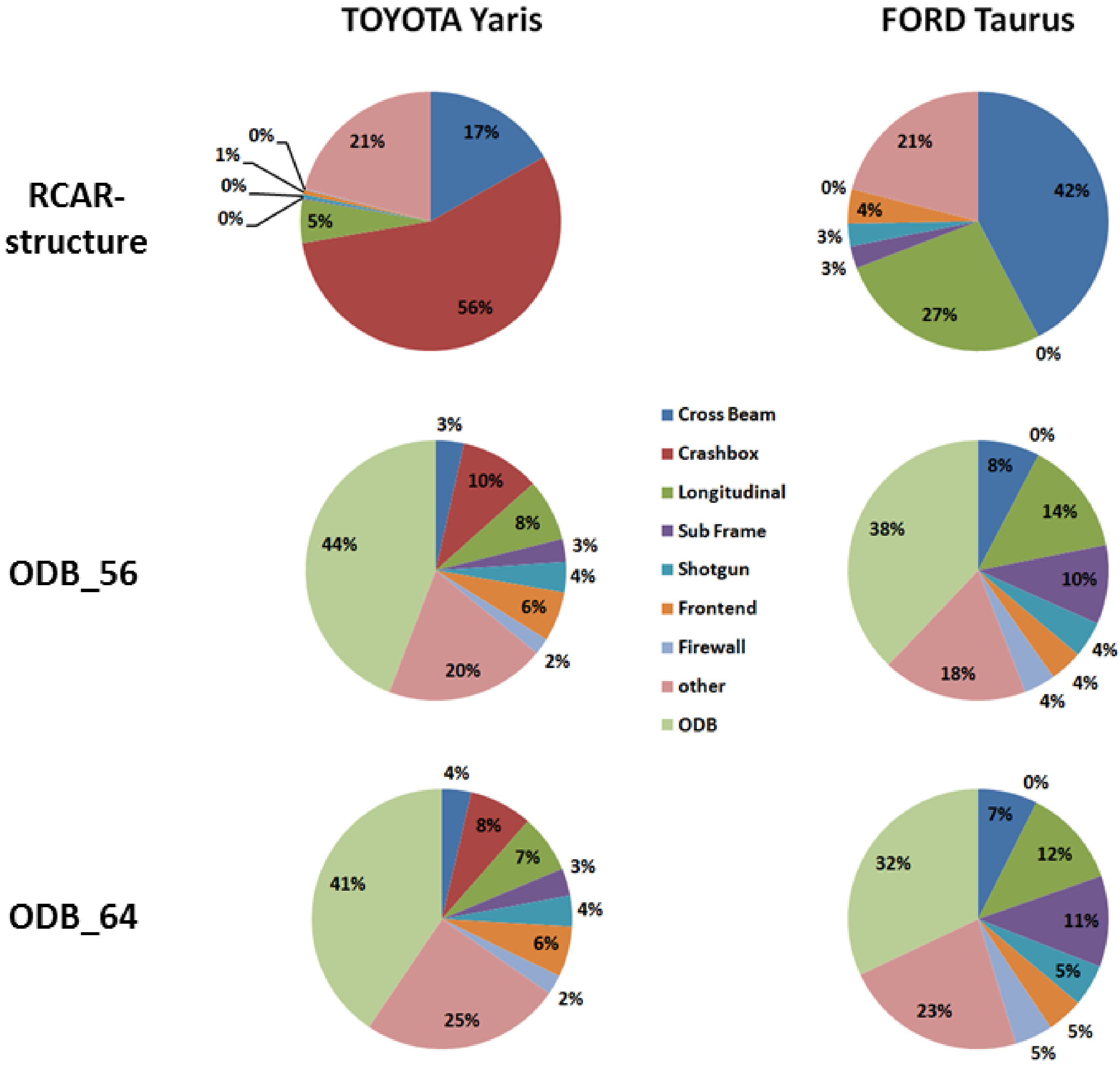


Figure 11: Proportion of total absorbed energy in offset crashes

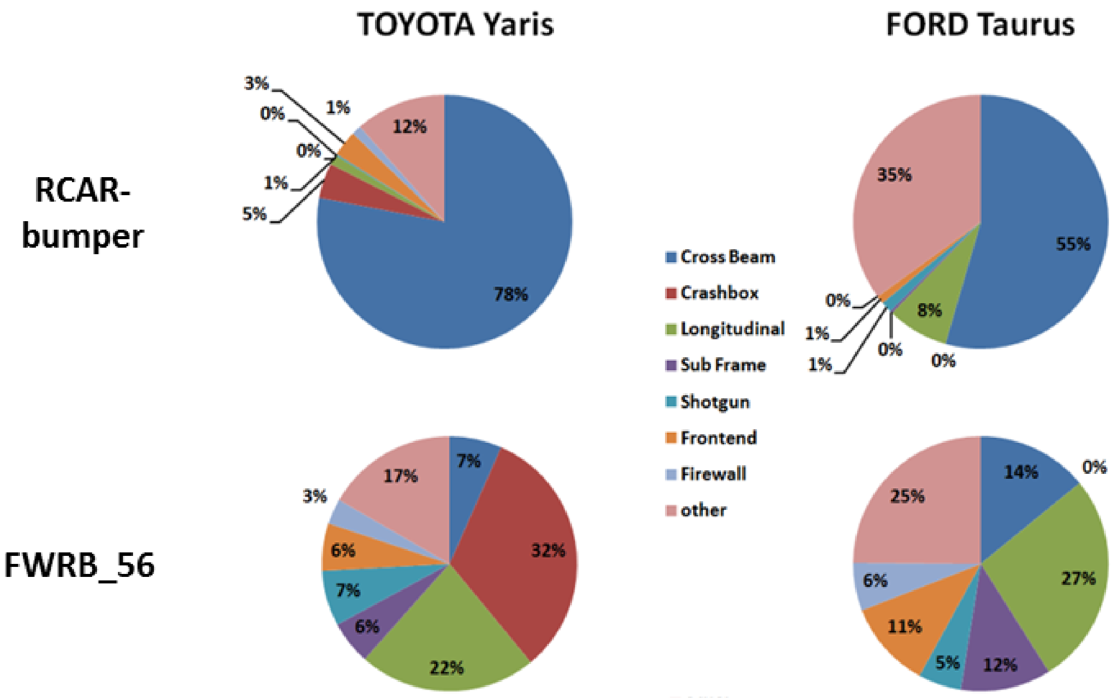


Figure 12: Proportion of total absorbed energy in full width crashes

The results indicated partially complete different energy absorption proportions in both configurations, low and high speed crashes. The main difference was that the FORD Taurus did not have a crash box. In addition the Taurus was equipped with a relatively far forward sub frame as well as a vertical connection to the longitudinal, which was activated during the high speed crashes. However, the Taurus was a relative old car compared to the Yaris. Even though there were big differences between the designs of the cars there were similarities in the energy distributions. The energy absorbed by the ODB decreases with increasing impact speed while the energy absorbed by the main crash structures is almost on the same level and other parts absorb the energy.
With respect to the intended models the TOYOTA Yaris provided representative data of the absorbed energy distribution for different crash configuration. With regard to other vehicle classes like executive cars, the Taurus provides information about the distribution of the absorbed energy if there is an additional energy absorbing structure. Thus the level of stiffness of the longitudinal can be adjusted.

4 Summary and Conclusions

A methodology was presented which describes the simplification and verification process to create simplified vehicle models addressing different passive safety requirements. All three models based on the same modelling approach to define a full implicit parametric vehicle model that is able to modify easily all relevant structures for frontal impacts.

The low energy model was designed to optimize the crash management systems for insurance ratings. The simplified model shows a good correlation with the original model. This offers the potential to investigate different crash-box designs as well as to optimize existing designs.

The main objective of the PedMo was to create a vehicle model which allows shape modifications of the front end to analyse the interaction between vehicle and pedestrian. Especially in the early stage of the PDP the pedestrian safety can be addressed with the PedMo without specific knowledge of the final front end design.

The third model was created to investigate the self and partner protection of vehicles. Based on the experiences made within the FIMCAR research project the modelling approach is very promising. The simplified model ensures to analyse the structural interaction in car to car crashes due to the generic design of the crash relevant structures. In combination with the parametric design different front end topologies can be created and optimised.

The identical modelling approach assures to merge the models into one unified parametric car model. This model will be suitable to reduce the length of the PDP and therefore to reduce development costs. Due to the parametric design structural modifications can be analysed and the impact on passive vehicle safety of these modifications can be estimated. This will help to support the decision process whether or not a new concept is capable to full regulatory and consumer requirements.

5 Perspective

The topology model has to be validated regarding typical crash characteristics like generic crash pules and intrusion behaviour. An assessment regarding the crash performance with self and partner protections indicators (e.g. simplified occupant load criteria or the Volvo pulse index) and intrusions has to be carried out.
The pedestrian model (PedMo) needs fine tuning to predict the injury related measures more accurately so that it becomes suitable for early stage pedestrian safety evaluations of a vehicle profile.
The Crash box model has to be extended with various types of crash boxes and optimized regarding the crash characteristics, weight goals, manufacturing costs etc.
The major goal is to merge the three different models into one, which is capable to address the manifold requirements of the front end structures during the early stage of the product development process.

6 Acknowledgement

The paper is based partially on research results of the FIMCAR project. The FIMCAR project is co-funded by the European Commission under the 7th Framework Programme (Grant Agreement no. 234216). The members of the FIMCAR consortium are: Technische Universität Berlin, Bundesanstalt für Straßenwesen. Chalmers tekniska hoegskola AB, Centro Ricerche Fiat S.C.p.A., Daimler AG, FIAT Group Automobiles Spa, Humanetics GmbH, IAT Ingenieurgesellschaft für Automobiltechnik mbH, IDIADA Automotive Technology SA, Adam Opel AG, Peugeot Citroën Automobiles SA, Renault s.a.s, TNO, TRL Limited, UTAC, Volvo Car Corporation, Volkswagen AG, TÜV Rheinland TNO Automotive International BV.
Further information is available at the FIMCAR web site www.fimcar.eu.

Furthermore, the authors appreciate the support of the chairman of SFE GmbH and their support team for sponsoring and providing valuable assistance in software usage during the entire time of this research project.

The authors also would like to extend sincere appreciation for DAAD for providing financial support during the research work.

7 Literature

[1] National Crash Analysis Center. Downloaded from: http://www.ncac.gwu.edu/vml/models.html

[2] Allianz Zentrum für Technik- Automotive GmbH, https://azt.allianz.de/azt-allianz-zentrum-technik/azt_automotive_gmbh.html ,accessed 18.10.2012

[3] Se-Jung Lee, Hyun-Ah Lee, Sang-Il Yi, Dae-Seung Kim, Heui Won Yang and Gyung-Jin Park, “Design flow for the crash box in a vehicle to maximize energy absorption”, Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering published online 30

[4] Ramon-Villalonga, Enderich Th, “Advanced Simulations Techniques for Low Speed Vehicle Impacts”, 6. LS-Dyna Anwenderforum 2007

[5] S. B. Kim, H. Huh, G. H. Lee, J. S. Yoo, M. Y. Lee, „DESIGN OF THE CROSS SECTION SHAPE OF AN ALUMINUM CRASH BOX FOR CRASHWORTHINESS ENHANCEMENT OF A CAR”, International Journal of Modern Physics B, World Scientific

[6] Y. NAKAZAWA, K. TAMURA, M. YOSHIDA, K. TAKAGI, M. KANO, “DEVELOPMENT OF CRASH-BOX FOR PASSENGER CAR WITH HIGH CAPABILITY FOR ENERGY ABSORPTION“, VIII International Conference on Computational Plasticity, COMPLAS VIII, CIMNE, Barcelona, 2005

[7] Cymat Technologies Ltd., www.cymat.com, “ALUMINUM FOAM TECHNOLOGY APPLIED TO AUTOMOTIVE DESIGN”

[8] F. Duddeck, H. Zimmer, “New Achievements on Implicit Parameterization Techniques for Combined Shape and Topology Optimization for Crashworthiness based on SFE CONCEPT”, ICRASH2012

[9] D. Otte, M. Jänsch, and C. Haasper, “Injury protection and accident causation parameters for vulnerable road users based on German In-Depth Accident Study GIDAS.,” Accident; analysis and prevention, vol. 44, no. 1, pp. 149-53, Jan. 2012.

[10] D. Mohan, “Traffic safety: International status and strategies for the future,” in 12th WCTRS, 2010.

[11] Y. Peng, Y. Chen, J. Yang, D. Otte, and R. Willinger, “A study of pedestrian and bicyclist exposure to head injury in passenger car collisions based on accident data and simulations,” Safety Science, vol. 50, no. 9, pp. 1749-1759, Nov. 2012.

[12] R. Fredriksson, E. Rosén, and A. Kullgren, “Priorities of pedestrian protection--a real-life study of severe injuries and car sources.,” Accident; analysis and prevention, vol. 42, no. 6, pp. 1672-81, Nov. 2010.

[13] H. Sankara subramanian, D. Göhlich, S. Mukherjee, and A. Chawla, “A bio-mechanics based methodology to optimize vehicle front profile for pedestrian safety,” in CMBBE 2012, 2012.

[14] J. Elliott, M. Lyons, J. Kerrigan, D. Wood, and C. Simms, “Predictive capabilities of the MADYMO multibody pedestrian model: Three-dimensional head translation and rotation, head impact time and head impact velocity,” Proceedings of the Institution of Mechanical Engineers, Part K: Journal of Multi-body Dynamics, vol. 226, no. 3, pp. 266-277, Jan. 2012.

[15] Johannsen, H., Adolph, T., Thomson, R.,Edwards, M., Lázaro, I., Versmissen, T. (2011). “FIMCAR - Frontal Impact and Comppatibility Assessment Research - Strategy and first results for future frontal impact assessment”. ESV Conference 2011, paper number 11-0286

[16] QIN, Y.: „A Concept to Design Fleet Compatible Vehicles for Real Accident Environments”, Fortschritt-Bericht VDI, Reihe 12, Nr. 737, ISBN 978-3-18-373712-3, Düsseldorf, Deutschland, 2011.

[17] APROSYS Deliverable D7.1.4. “A - Generic car (FE) models for categories super minis, small family cars, large family / executive cars, MPV, heavy vehicle” – Document AP-SP71-0029-C

[18] Stein, M., Friedemann, D., Eisenach, A., Zimmer, H, Johannsen, H. 2010. “Parametric Modelling of Simplified Car Models for Assessment of Frontal Impact Compatibility”. 8th LS Dyna User Conference 2010.

[19] VC COMPAT Deliverable D9. “Car geometry/structural database and analysis of car to car geometry compatibility”.

[20] Appel, H., Krabbel, G., Vetter, D. 2002. Unfallforschung, Unfallmechanik Und Unfallrekonstruktion. Verlag INFORMATION Ambs GmbH, Kippheim 2002. ISBN 3-88550-030-2