Czech Technical University in Prague

Faculty of Mechanical Engineering – Department of Mechanics,
Biomechanics and Mechatronics

Doctoral Thesis

New advanced methods in side crash testing

Author: Ing. Jakub Jelínek
Supervisor: prof. Ing. Růžička Milan, CSc.
Field of study: Mechanics of rigid and flexible body and environment

Declaration on the word of honour

I, Jakub Jelínek, student of the Faculty of Mechanical Engineering of Czech Technical University in Prague, declare that I wrote my thesis on my own and all information sources I draw upon literature are stated at the end of this work.

In Prague on ……..……….. Signature: …………………….

Jakub Jelínek

Acknowledgments

I would like to thank my family for their support and encouragement they have given me through all the time I spent writing the thesis. I would like to thank my supervisor, prof. Ing. Milan Růžička, CSc. for his technical guidance, valuable advices and his professional approach.

I would also like to thank the TÜV SÜD Czech colleagues, namely Martin Škopek, Lukáš Rakosník and Michal Kalinský for their help, useful advices, tips and tricks and also a lot of work they have invested in ALIS physical testing, which was necessary for this thesis.

Furthermore, I would like to whole simulation team in TÜV SÜD Czech Jakub Prchal, Petr Záruba and Lucie Kotanová who has done the simulation work I used in this thesis and provided great insights.

Annotation

This work is focused on methodology used within the field of passive safety, ie. crash testing. The work is based on experience gained in the Active Lateral Impact Simulator (ALIS) project and describes complete process. The main focus has been the fine-tuning of the boundary conditions and loading of the system in order to ensure correct biomechanical loads. It has been decided that only pole strike is of interest and therefore the barrier strike will not be assessed and developed.

This work is to give an overview of current methodology and subsequently propose a new advanced approach of combined virtual and physical testing. The main idea is to reduce development time and associated costs by using sled testing which used to be used mainly for physical simulation of frontal crashes. Simulation of side crash in sled environment is not a brand-new topic, but certainly very complex one. This method is not really used on regular basis especially due to predictability issues and low accuracy. This work presents new approach of combination both virtual and physical testing. The whole process starts with full crash simulation, goes through conversion of virtual model to reduced sled model, sled testing and finally is wrapped up with full vehicle crash.

The new method uses mathematical-statistical method Design of Experiment, that offers many benefits for the physical test setup and furthermore the general overview of the sensitivity of system behaviour.

Anotace

Práce se zaměřuje na metodiku používanou na poli pasivní bezpečnosti a crash testování. Je založena na zkušenostech získaných v rámci projektů Active Lateral Impact Simulator (ALIS) popisuje celý proces. Hlavní zaměření je na finální a precizní nastavení počátečních podmínek a také zatížení celého systému tak, aby byla zajištěna dostatečná korelace biomechanických kritérií mezi saňovou zkouškou a zkouškou s celým automobilem. Na základě zkušeností bylo také rozhodnuto, že se bude vyvíjet pouze náraz na kůl. Náraz bariérou je díky nastavení zkoušky méně závažný.

Tato práce shrnuje a dává přehled o současném stavu užívaných metodik a následně navrhuje nový přístup v kombinaci virtuálního a fyzického testování. Základní myšlenka je snížit potřebný vývojový čas automobilu a tím snížit i náklady za použití saňových zkoušek, které se primárně používají na testování čelních nárazů. Simulace bočních nárazů v saňovém formátu není novinkou, ale dozajista je velice komplexní. Tato metoda není v praxi používaná zejména kvůli obtížné prediktabilitě a nízké přesnosti. Tato práce představuje nový přístup a vhodně využívá kombinaci virtuálního a fyzického testování. Celý proces začíná virtuální simulací celého vozu, vede skrze redukci modelu celého bočního nárazu na model saňové zkoušky, vlastní fyzickou saňovou zkoušku až na závěr se dostaneme k fyzické zkoušku celého vozidla.

Navržená metoda používá matematicko-statistickou metodu Design of Experiment, která poskytuje vhodný aparát a mnoho výhod pro účely fyzického testování a také lepší náhled do celkového chování systému, včetně citlivostní analýzy.

Keywords

crash test, finite element method, design of experiment, biomechanical loads, DYCOT, ALIS

Klíčová slova

Nárazová zkouška, metoda konečných prvků, design of experiment, biomechanická zatížení, DYCOT, ALIS

List of used symbols

ABS – anti-block system

ADAS – advanced driver assistance systems

AE-MDB – advanced moveable deformable barrier

ALIS – Active Lateral Impact Simulator

ANOVA – the analysis of variance

ASD_SY – scale factor of sled

ASD_OA – abscissa offset

ASIS – advanced side impact system

$A_{x,y,z}$ – linear acceleration in x-, y- and z-axis

BIW – body-in-white

CAD – computer aided design

CAE – computer aided engineering

DBB_SF – B-pillar bottom scale factor

DBB_OA – B-pillar bottom abscissa offset

DBU_SF – B-pillar upper scale factor

DBU_OA – B-pillar upper abscissa offset

DDD_SF – door scale factor

DDD_OA – door abscissa offset

DoE – design of experiment

DoF – degrees of freedom

$D_{x,y,z}$ – displacement in x-, y- and z-axis

DYCOT – Dynamic Component Testing

ENCAP – European New Car Assessment Programme

ESC – electronic stability system

FEA – finite element analysis

FEM – finite element method

FMVSS – Federal motor vehicle safety standard

$F_{x,y,z}$ – forces in x-, y- and z-axis

GUI – graphical user interface

HIC – head injury criterion

LHS – Latin hypercube sampling

LSTC – Livermore Software Technology Company

MBS – multi-body systems

MDB – moveable deformable barrier

$M_{x,y,z}$ – moments around x-, y- and z-axis

NCAP - New Car Assessment Programme

NIC – neck injury criterion

OEM – original equipment manufacturer

RBPD – robust parameter design

RSM – response surface methodology

$R_{x,y,z}$ – rotations around x-, y- and z-axis

SID – side impact dummy

SIPS – side impact protection system

SUV – support utility vehicle

t – actual time

t_0 – time of crash

Contents

List of figures

List of tables

1 Crash tests

This chapter is to give a general overview of the crash test problematics and it gives to reader reasonable introduction. Since the very beginning of the automotive era, the car has been mainly considered as a mean of a transport and as a scale of a social level. It has reached back as far as to the 17th century, to 1672 to be exact, when Ferdinand Verbiest [1] built the first steam-powered vehicle, however it has been intended to work as a toy. The first "real" vehicle was built in 1873, when Amédée Bollée built a self-propelled vehicle for transport of a group of people.

1.1 History of crash tests and safety components

As cars were becoming complex and faster, safety issues have become more important due to the increase of fatal injuries among drivers and people around cars – pedestrians and members of traffic.

The first barrier crash test [2] was performed by General Motors in USA in 1934. In 1949 the first crash dummy, Sierra Sam, was created and used for evaluation of aircraft ejection seats on rocket sleds.

The first safety component [2][3] has been introduced in 1959. Three-point seatbelts have been invented by Volvo and they are still one of the most effective safety systems. One year later came a padded dashboard reducing the face and chest injury ever since. In 1966 has been anti-blocking-system (ABS) introduced. It was inspired by aircraft technology. Year 1968 was the first one when Volvo created and implemented the first head restraint mounted on seat for rear crash events. Australia has been the first country in the world, where the mandatory seatbelt wearing has been put law in 1970. The New Car Assessment Program (NCAP) has been founded in USA in 1979. The NCAP has given impulse to many countries and regions to establish their own programs (EuroNCAP, Latin NCAP, AESAN NCAP, ANCAP…). The modern driver's airbag has been developed by Mercedes Benz in 1981, based on US simple airbags that have been introduced in 70s. In Europe wearing of the front seatbelts have been put in force in 1983 and rear in 1991 respectively and have been followed by immediate complaints. It has been Volvo again who has introduced Side Impact Protection System (SIPS) in 1991 with reinforced bars in door structure and transverse seat rails followed by side-airbags in 1994. Premium OEMs have started with implementing of advanced stability systems and so Electronic Stability Control (ESC) has seen daylight in 1995. One year later it was KIA who has added knee airbag. In 1997 has been established EuroNCAP. Saab has come up with Active Head Restraints in 1998. The first car with all five starts has been Renault Laguna in 2001. Two years later has been added the children safety assessment. Finally in 2005 Jaguar has developed a pop-up bonnet in order to reduce pedestrian injuries. At the beginning of the 21st century a pioneer advanced driver assistance systems (ADAS) started to be implemented. It has started with Citroën lane departure warning in 2005. Volvo has developed blind spot monitoring (mirrors) and autonomous braking in 2007, in 2008 respectively. The latest additions to the ADAS are Pedestrian detection in darkness, barrier detection and active cruise with steering (all Volvo) in 2015 and Car2Car + Car2Infrastucture planned in 2018. Generally, it can be said that companies plan to have fully autonomous car systems sometime around 2025.

Based on time of the crash, the safety can be divided into three categories: (t_0 – time of the crash)

- Active safety ($t<t_0$) – set of safety systems that aim to prevent accidents
    - Lights
    - Brakes
    - Steering
    - Vision
    - Electronic assistant systems
    - Visibility

- Passive safety ($t\geq t_0$) – set of precautions and tools which aim to minimize accident consequences on human health
    - Crash tests
    - Sled tests
    - Numerical modelling and simulations such as finite element method (FEM), multibody systems (MBS),…
    - Structural performance of primary structure - Body-in-White (BIW)
    - Interior energy absorption
    - Pedestrian safety

- Integrated safety ($t\geq 0$-100ms) – set of precautions and tools that aim to minimize accident consequences on human health by using active safety
    - Seatbelts
    - Airbags

1.2 Principle of crash tests

The principle of the crash test is to understand kinematics and dynamics of the impact itself. With first crash tests in the second half of the last century, they have assessed structural behaviour of the vehicle only with output parameters such as deceleration and intrusion. Later on, the effect of the crash on human body has been put forward and so the first dummies have been developed. Nowadays there are many types of dummies. Each of them represents different "human body" and allows different biomechanical parameters to be measured and they are intended for different crash event.

1.3 Mandatory and consumer crash tests

Mandatory tests have been established by governments to ensure minimal safety and all vehicles have to meet their criteria. Each country/region has its own tests (e.g. EU, USA, China,…), nevertheless they differ only in several cases. The base is pretty much the same everywhere and so is the occupant protection. Mandatory tests have two results – pass or fail. Overview of the crash tests around the world is shown on Figure 1.

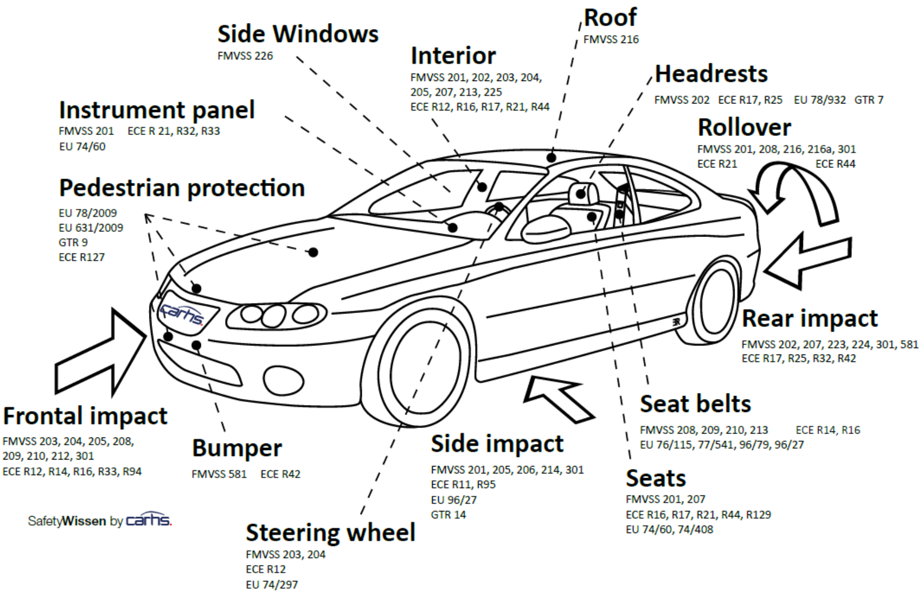


Figure 1: Overview of crash tests [4]

Consumer tests have been additionally established in order to compare cars among OEMs and so push them to the improved safety through better score. They are usually stricter than mandatory tests. The results scale is different to mandatory tests and it uses stars, when 5-star is a top score. The score is based on car safety performance during all types of crash tests, presence of safety features (e.g. seatbelt reminder) and others. Overview of mandatory and consumer tests is given on Figure 2.

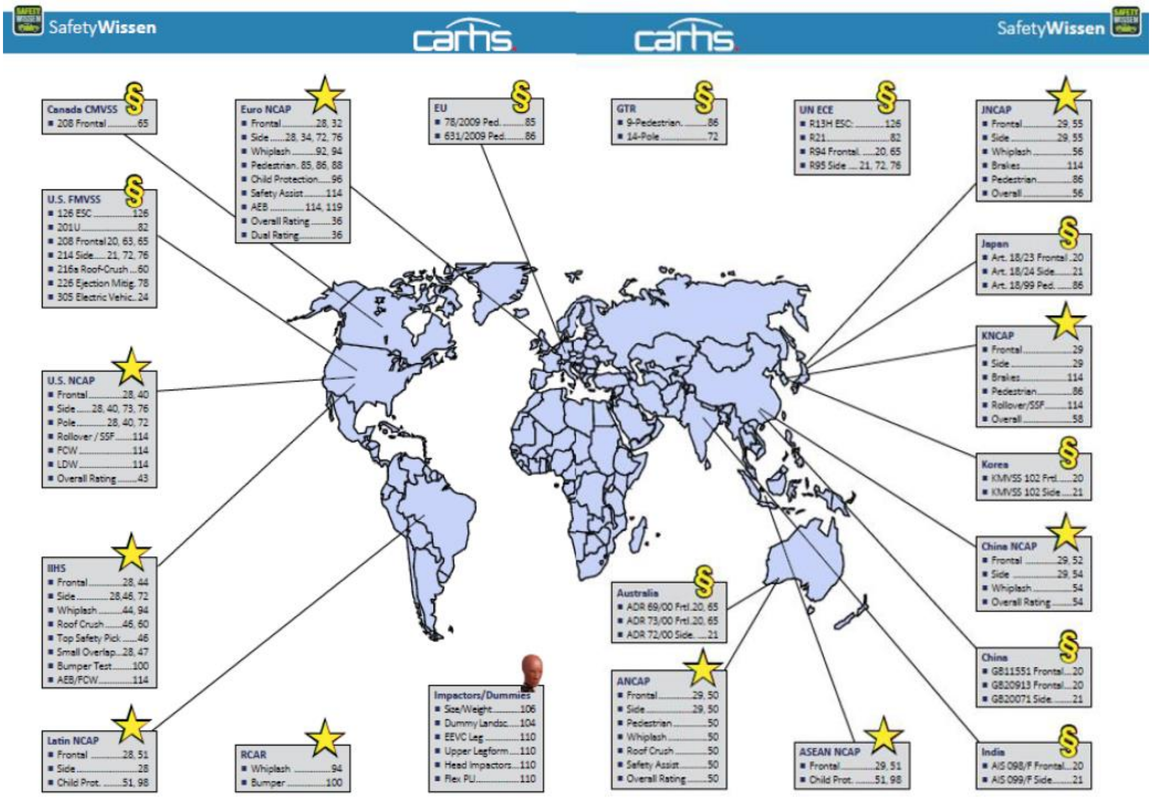


Figure 2: Mandatory and consumers’ tests around world [4]

The main objective of the crash tests is to assess car primary structure performance in terms of injury risk. Main criteria are biomechanical loads that apply to human during crash. The whole complexity of the system is assessed via parameters (biomechanical loads) measured on several parts of body. These parts are as follows (standard for ECE legislation and EuroNCAP):

- Head
- Face
- Neck
- Chest
- Abdomen + Pelvis
- Spine
- Lower extremities

Measured parameters are mainly

- Deceleration (in g)
- Force (in kN)
- Moment (in Nm)
- Compression (in mm)
- Velocity (in ms^{-1})
- Other specific parameters (HIC, NIC,…)

Crash tests are supposed to present a tool to improve car structural performance and increase occupant's survivability during crash event. They have been chosen to reflect the most probable cause of injuries and deaths based on large-scale statistics. The effect of the selected regulations (tests) is shown in Figure 3 with relative comparison given in Table 1.

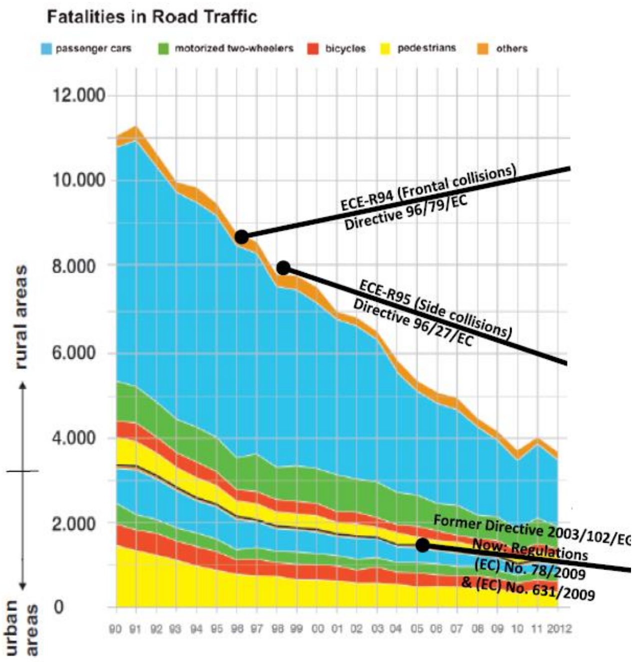


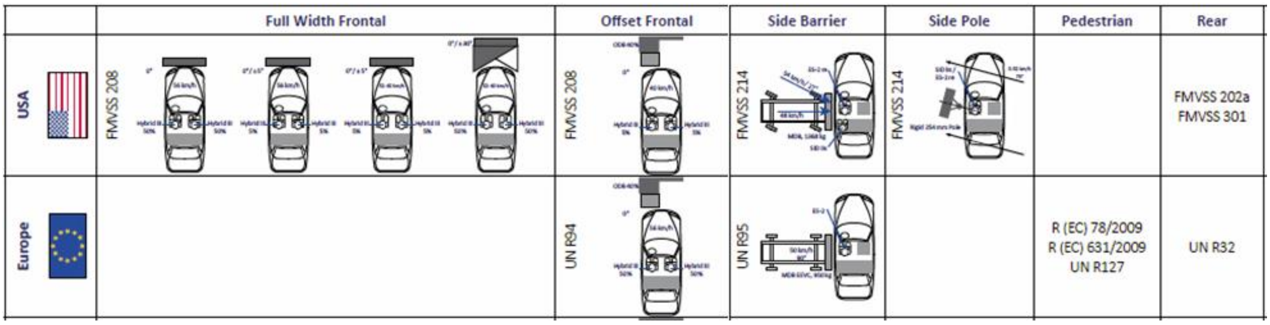
Figure 3: Effect of selected regulations on fatality rate

Effect of safety features (fatal injuries reduction)	Relatively	Compared to state in 60s
Safety Steering Column (60s)	-10%	-10%
Three point seatbelt (70s)	-40%	-50%
Driver's airbag (90s)	-25%	-60%

Table 1: Comparison of safety measures taken

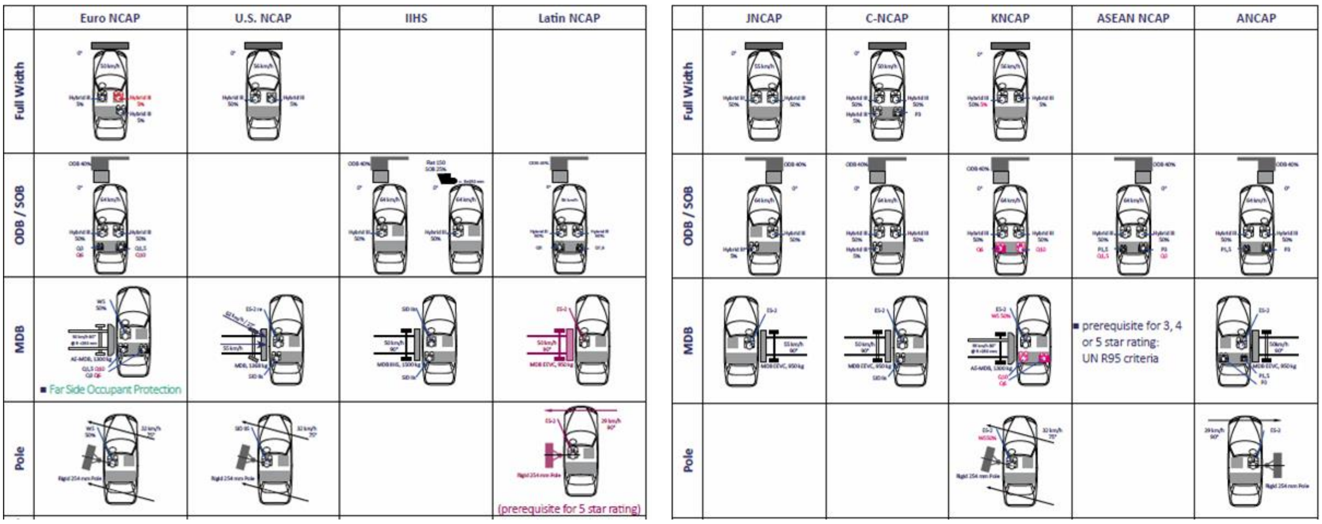
1.3.1 Test setup and conditions

As it has been already mentioned, tests do differ country from country. An overview of mandatory tests in EU and USA can be seen on Figure 4a., followed by consumers' tests on Figure 4b. It is clear that the base of all tests is fairly similar. In case of the consumers' tests, it can be seen that they include more variants of test setups and reflect more statistically fatal accidents.



	Full Width Frontal	Offset Frontal	Side Barrier	Side Pole	Pedestrian	Rear
USA	FMVSS 208	FMVSS 208	FMVSS 214	FMVSS 214		FMVSS 202a FMVSS 301
Europe		UN R94	UN R95		R (EC) 78/2009 R (EC) 631/2009 UN R127	UN R32

Figure 4a: EU and USA mandatory test setups [4]



	Euro NCAP	U.S. NCAP	IIHS	Latin NCAP
Full Width				
ODB / SOB				
MDB	Far Side Occupant Protection			
Pole				(prerequisite for 5 star rating)

	JNCAP	C-NCAP	KNCAP	ASEAN NCAP	ANCAP
Full Width					
ODB / SOB					
MDB				prerequisite for 3, 4 or 5 star rating: UN R95 criteria	
Pole					

Figure 4b: World consumers' test setups [4]

Nowadays the trend of the market has been set to decrease development time while larger volume of work is required. There is also high pressure on lower expenses/costs while maintaining the same quality, variability and customer demands. This altogether leads to use of a more predictive methods. At the very beginning, there has been only a knowledge, that the vehicle crash can turn into to a potential injury, ie. it has come from real accident. In further development crash tests have been subsequently introduced, followed by simulated sled tests and finally virtual simulations. Obviously, the crash tests are the most representative and only based on them, the legislative safety criteria can be met. However, in order to reduce development time, both sled tests (physical) and virtual simulations have been heavily used as proven methods with satisfactory predictivity and results. During development stage, the physical crash tests have been used as validation of both simulations and so improve the accuracy of results.

1.4 Crash safety not only in Europe

The main focus of this work has been set to Europe as it is continent where we live and main aim is to enhance knowledge and methodology that would set new trends in research and development as well as in testing. Europe has experienced significant increase in research and development within the automotive industry in last 50 years.

Let us compare front and side crash events from physical point of view. Driver is simply better protected during frontal one as the distance between struck object (barrier) and driver is larger than in case of side impact and hence the energy can be dissipated on longer distance, therefore the acceleration (deceleration) is lower. Generally, it can be said that the distance starts at around 1000mm in frontal test. On the other hand, side crash has very specific conditions and presents a challenge to nowadays engineers as between barrier or pole and driver, there is only door structure, trim and safety features (seatbelts, airbags, …). It is a very quick event compared to the front crash. To reduce injury the timing of airbags is of essence. The side crash peak intrusion and deceleration are around 40-70ms, whereas front crash is more like 80-120ms.

1.4.1 Barriers

From test conditions point of view the pole strike is much more severe than Moveable Deformable Barrier (MDB) or Advanced European MDB (AE-MDB). Pole is considered as rigid vertical cylinder with diameter of 254mm. Barrier is much wider and is supposed to engage more structural elements of the vehicle as displayed on Figure 5. Barriers/vehicles are always positioned with respect to the H-point of the driver. Due to its width it distributes loading into doors and both A- and B-pillars.

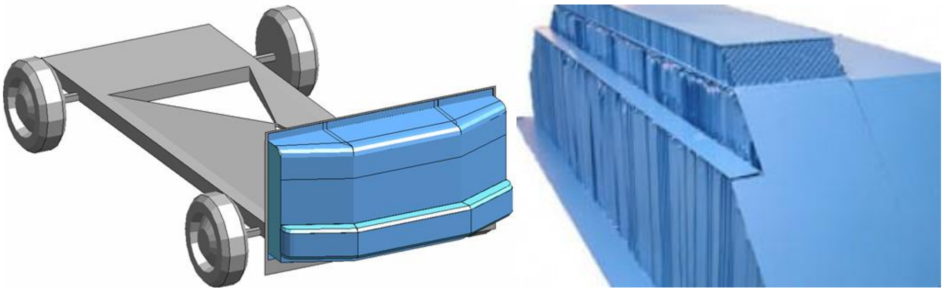


Figure 5: MDB (left) [6] and AE-MDB (right) [7]

The structural parts that have been designed as load paths are shown on Figure 6. Main function of these parts has been to delay the intrusion and so give enough time (up to 40ms) to engage the restraint system, ie. inflate airbags, fire pretensioners etc.

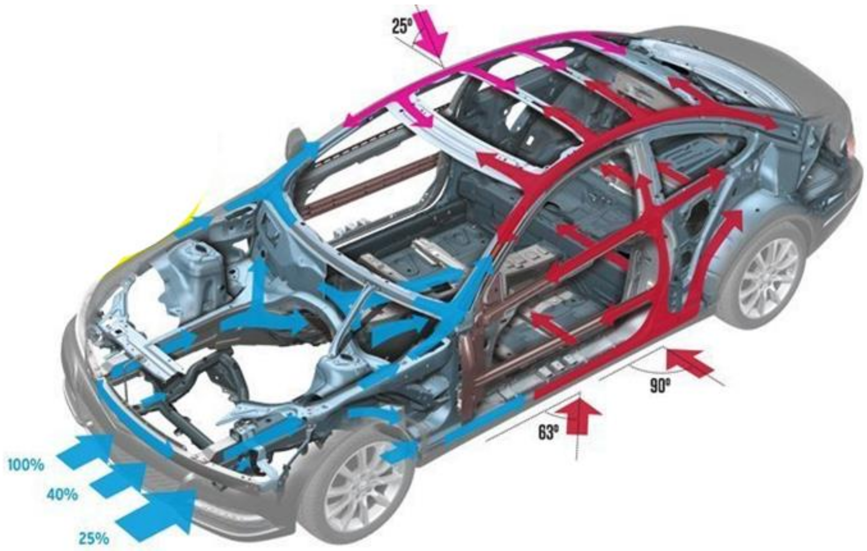


Figure 6: Side crash loadpaths (red) and also front crash (blue) and roof crash (purple) [8]

Now that the basic physics of the side crash is understood, it can be assumed that pole side crash is the most severe load case. Not only because of structural performance, but mainly due to the issues with airbags (side, curtain,…) timing and setup.

1.4.2 Dummies

In order to get correct (human-like) output responses, people have started using “testing humans” – dummies since 50’s. Dummies are representing human body. When used in crash scenario, many output parameters can be measured in real time. These are usually injuries associated with body parts as described in Chapter 1.3 and reflect body behaviour and its responses to loads during crash. While for front crash are usually required parameters such as acceleration and displacement of a head, torso and legs, for side impact, due to much shorter distance (barrier/pole to seat-dummy system) it is mainly head, chest and pelvis with their displacements and forces measured. There is an overview of dummies used in crash test shown in Table 2.

Crash	Hybrid III	THOR	BioRID	ES-2(re)	WorldSID	H-; P-; Q-dummies
Type	Adults female/male (5%/50%/95%)					Children (from 6mnths-10yrs)
Front	X	X				X
Side				X	X	X
Rear / Whiplash			X			

Table 2: Dummies selection for crash tests

Many sciences have been established based on the increasing knowledge associated with crash. The list is broad, however it would be good to emphasize biomechanics that is focused on human body and its kinematics, dynamics and injury tolerance. As shown on Figure 7, there are several areas of interest that are to be compared versus physical crash test and ENCAP score points according to the performance [4].

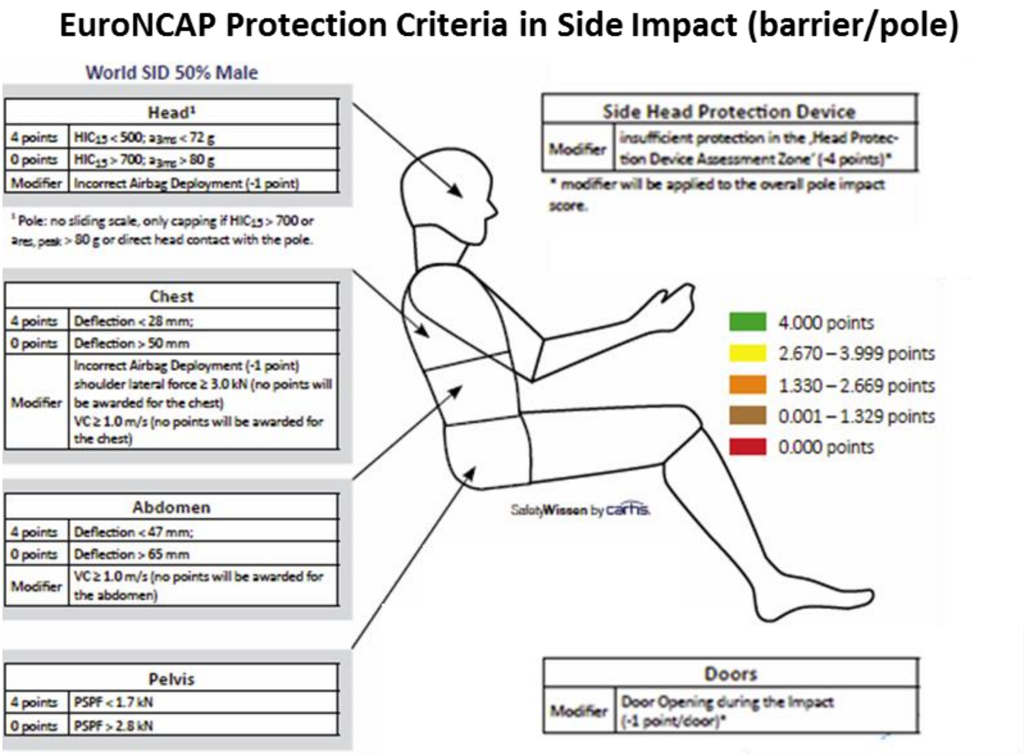


Figure 7: Biomechanical loads limit for ENCAP Side crash [4]

1.4.3 Restraint systems

Restraint system is a passive system in car that does not require any action from driver or passenger to get it work. There are two main sub-systems:

- Airbags
- Seatbelts

Airbag is a vehicle safety device that is based on rapidly quick inflation and deflation. It consists of flexible breathable bag from fabric, inflation module, sensor and soft cushion. When the vehicle crashes with sufficient severity, sensor will trigger inflation module and the cushion is inflated. This inflated cushion decreases head and body acceleration and generally softens the head impact pulse and absorb some head kinetic energy. It is important as it does not allow the head to come into the contact with steering wheel and dashboard (front crash) and other structural parts, including trim (side crash).

Seatbelt is a safety feature that “controls” movement of the pelvis and torso. There are many types of the seatbelts (2-points, 3-points, 6-points, etc.) but the common one is 3-points lap belt. It has got two additional features. Load-limiter triggers when the maximum load in seatbelt is reached, it slightly releases a seatbelt and engage again. One could call this principle as ABS for seatbelts. Pre-tensioner is triggered just like the airbag by a sensor, but this sensor can anticipate an accident even before it actually crashes. It measures pressure drop when closing to another object. It ensures that in the early stage of the crash the human body will be tightened to the seat via pre-tensed seatbelt. This reduces further injury risk due to excessive body motion.

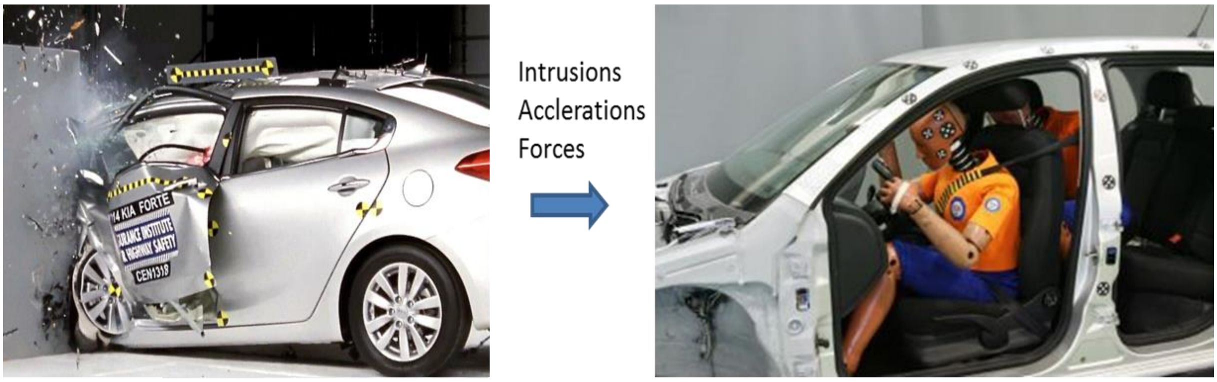
There are some others types as well but there are not that widely used compared to airbags and seatbelts.

All restraint systems are very important for minimizing the injury risk during crash and so they will be included in further simulations and testing.

1.5 Approach of car development cycle

1.5.1 Current status

At the moment, airbag settings have been found as very important, but difficult to determine. Simulations have shown certain level of accuracy, but for correct validation many expensive crash tests have to be carried out. In the whole world, the absolute majority of tests have been done with full vehicles. The procedure is sketched on Figure 8.



Crash test

Crash Target Data for Sled test

Figure 8: Reduction procedure from full car crash [9] to sled test [5]

With increasing testing requirements, people have tried to find an alternative approach that would offer a sufficient level of predictability and accuracy with time and money reduction. Physical testing of sub-systems has been on market for a while, but it has not been considered to be used for side crash in such scale. Development tools loop is shown on Figure 9.

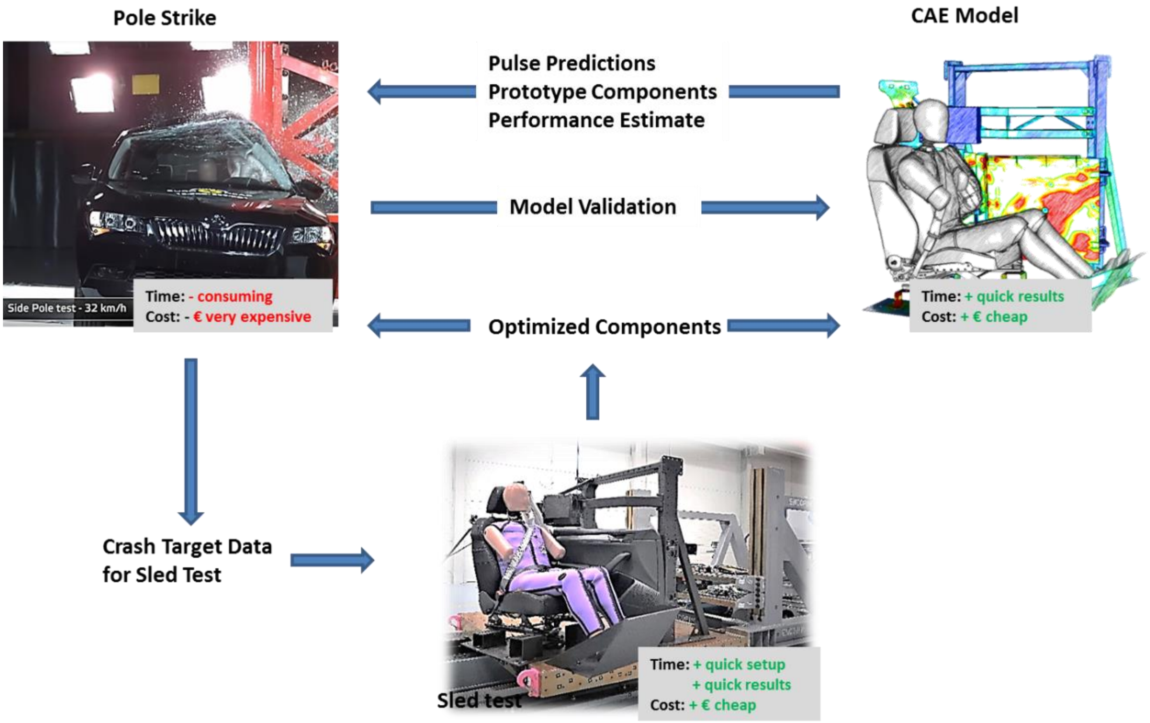


Figure 9: Complete loop of vehicle development life [10]

There has been a request on global market to develop such a testing device and method to incorporate all mentioned above. The device should be able to test sub-systems and also simulate side acceleration pulse. Usually catapult that is able to develop precise acceleration pulse that imitates side crash acceleration has been used. As it has been known, sled tests have been covering mostly front and rear crash scenarios. Usage of sled test for side impact is rather rare and it is not the main task of most of the sled systems and hence this work is focused on side sled testing.

1.6 Overview of side sled testing

1.6.1 Literature survey

The literature survey has been done in order to find out what kind of side sled testing is currently available and whether any virtual simulations or mathematical methods approach have been used. There are many papers that have mentioned just physical testing. Side sled principle mentioned in 1997 Chung et al.[11] has been one of the first reactions on the new regulation in USA - FMVSS 214. This paper describes physical subsystem of two sleds in mutual interaction. When the first sled is accelerated in the side crash pulse and hits the second, static, sled with the Side Impact Dummy (SID) and complete door structure, including trim that due to the impact deforms. This paper covers barrier strike.

Another paper published by Stein [12] dated back to 1997 describes the same methodology, however this time the stuck sled is using honeycomb instead of the solid metal blocks at previous article. The whole test setup is shown below on Figure 10.

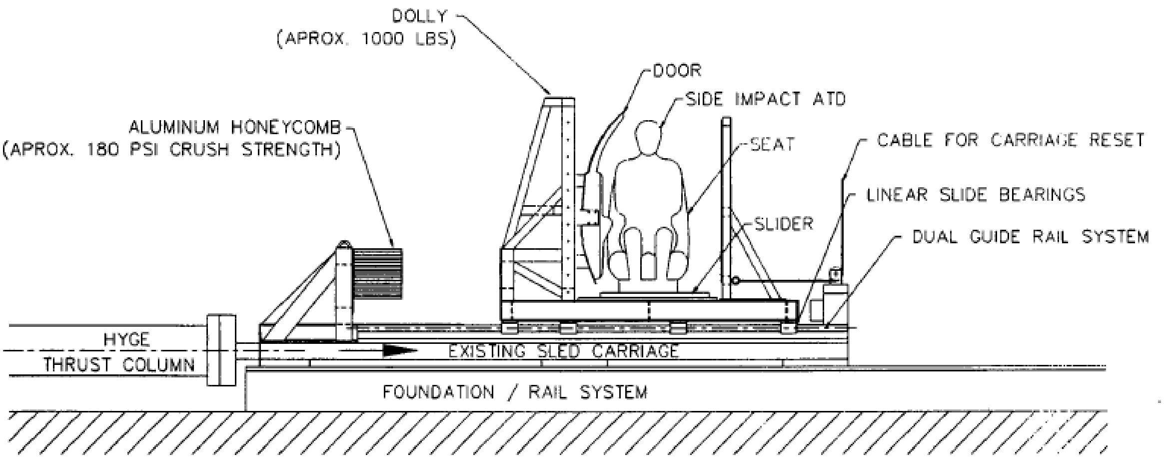


Figure 10: Side test setup as discussed in [12]

The trim deformation is controlled only via combination of honeycomb and door stiffnesses. This paper covers barrier strike and is dedicated to physical experiments only.

In 1999 Aekbote et al. [13] wrote a paper where They have come up with the first virtual simulations of the experiment (side barrier). They have used MADYMO software that has been based on MBS approach. It has offered a certain level of accuracy. The development has been done for NHTSA side impact, using DOT-SID dummy. The experimental setup is fairly similar to those mentioned already as shown on Figure 11.

The objective is to correctly reflect the door intrusion velocity and also imitate the right moment when the trim separates from the dummy. The kinetic energy of the door-sled and applies forces to the dummy, while the Hexcel decreases the velocity and also controls the deformation. Many tests have to be carried out to clarify either door sled pulse and also the Hexcel structure and dimensions.

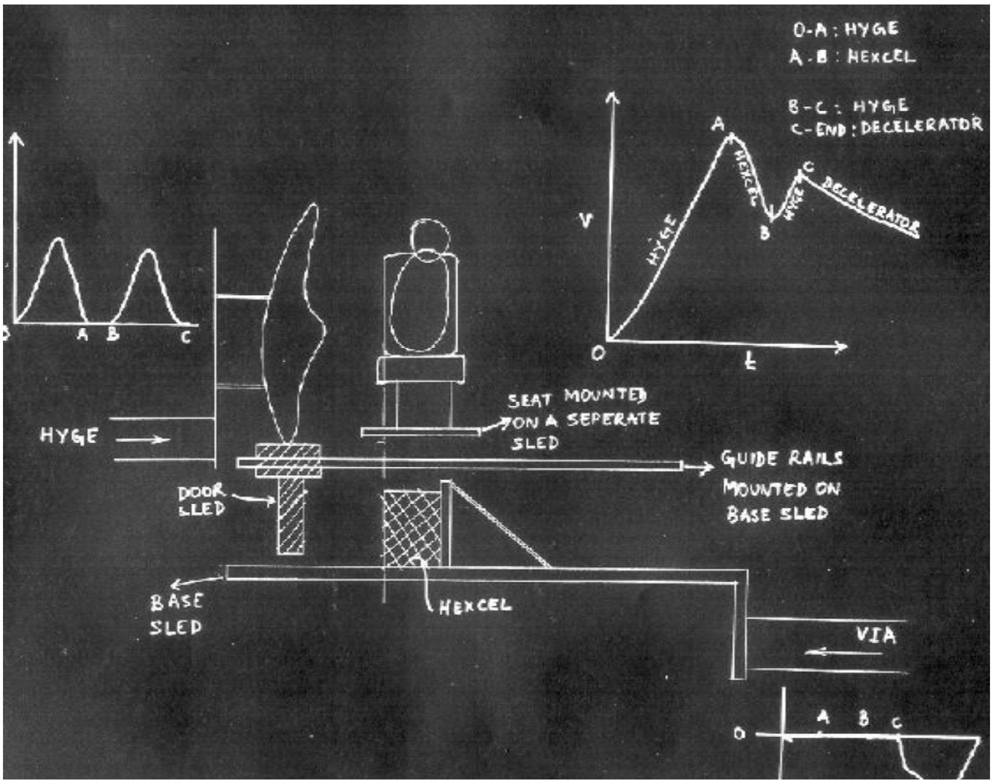


Figure 11: Sketch of side test setup as discussed in [13]

The virtual simulations have been validated to physical tests using SID accelerations (ribs, pelvis and spine). The feasibility of the proposed test method has been confirmed.

Several years later in 2002 the first pole strike approach has shown up. The author Miller II et al. [14] used already known principle (2 sleds hitting each other) for barrier strike. The paper proposes additional approach for pole strike using a “two carriage” system as shown on Figure 12. The upper carriage simulates the door response, while the lower carriage mimics the unstruck side of the vehicle. The mutual interaction of the upper and lower sleds is controlled via onboard pneumatic cylinder. The door trim is mounted to the upper sled, while the dummy sits on the lower sled. When the force of the upper sled (via catapult) overcomes the pneumatic piston, the upper sled moves towards the dummy and hits it, generated desired biomechanical responses. No virtual simulation, nor mathematical approach has been mentioned.

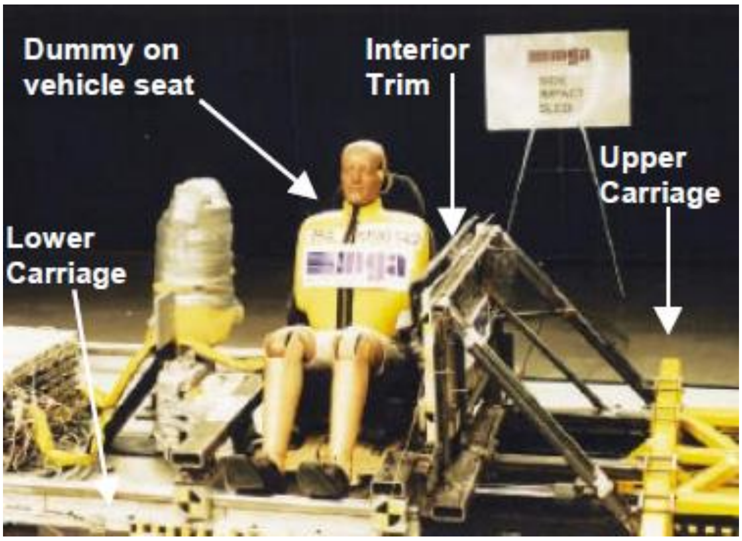


Figure 12: Pole strike test setup as discussed in [14]

In 2006, Owen [15] has presented study of definition of maximum load and kinematics of the different dummies (SID-IIs; ES-2 and US-SID). It is a broad study of the restraint systems, their settings in virtual simulations. This paper is dedicated to the virtual environment of the LS-DYNA and complex mechanisms of the side crash in general.

A few papers have been published in 2007. Aekbote et al. [16] has presented new methodology for barrier strike, where there are two sleds/carriages. The first one with “bumper” shaped to the barrier has been accelerated and has got kinetic energy (Figure 13 left). It hits the second sled/carriage where the door is mounted (Figure 13 right). The impact generates deformation of the trim and hence biomechanical loads. Again, the paper is solely focused on physical experiment.

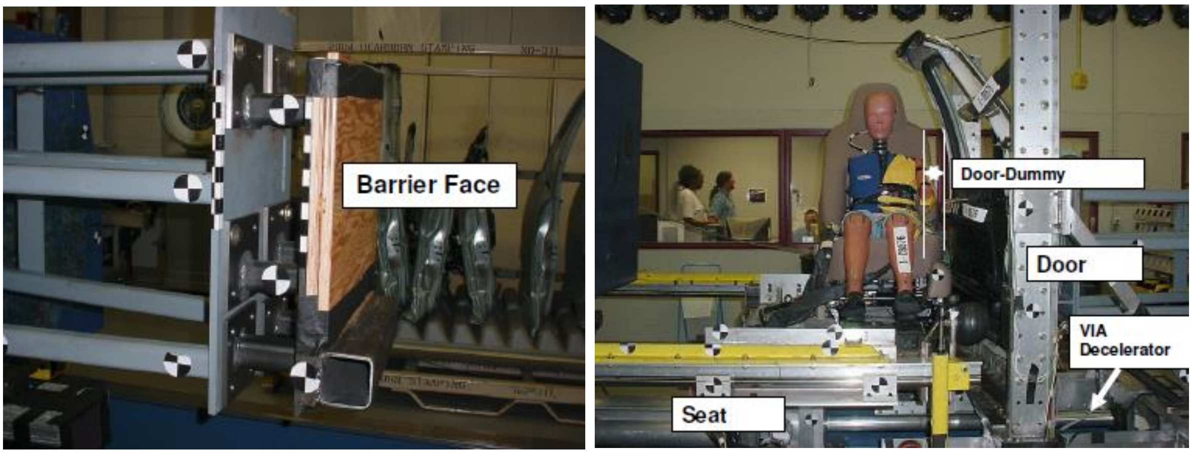


Figure 13: Barrier strike test setup as discussed in [16] – left: barrier face carriage; right – door and dummy carriage

Another paper written by Chou et al. [17] does not have any new ideas, but it offers a broad overview and state-of-art of the side crash testing methodology. Many of other papers have been referenced here. For more information regarding the overview I would suggest this one as a very good start.

Lee et al. [18] has come up with a methodology of semi-controlled door intrusion. It lays basics of nowadays approach. The test setup is shown on Figure 14.

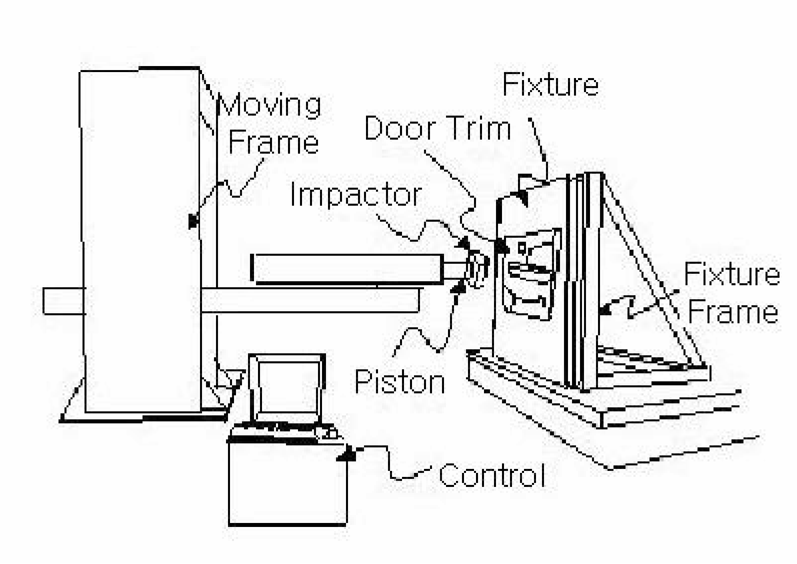


Figure 14: Sketch of pole strike test setup as discussed in [18]

The impactor is shot at the door trim in certain point (aligned with abdomen). It has got an initial velocity and cannot control the intrusion. The main objective is to find out the right initial velocity that would result in the appropriate abdomen force. The virtual simulations are used to determine the door intrusion and maximum stress levels to the respective initial velocity.

Two years later, in 2009 Dix et al.[19] comes up with a new methodology for oblique pole impact according to the FMVSS 214. The setup sketch is displayed below on Figure 15.

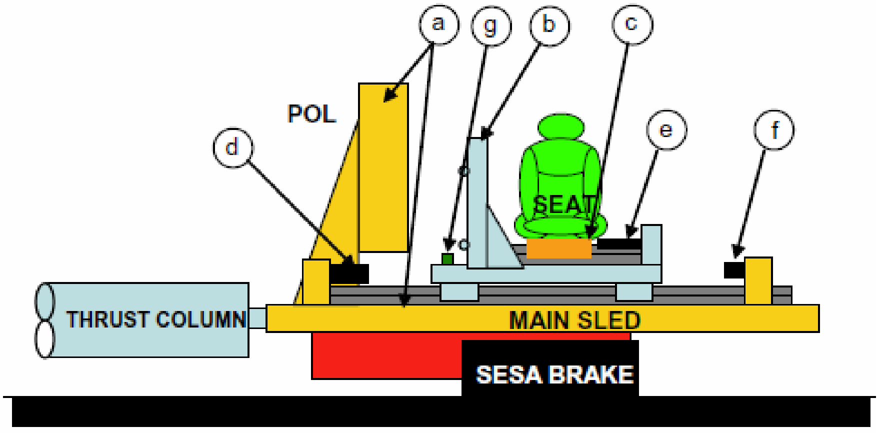


Figure 15: Setup of pole strike test as discussed in [19]

Where (a) – is main frame with rigid pole; (b) – is sliding carriage to which the door structure, dummy and seat are mounted; (c) is seat slider; (d), (e) and (f) – are various crush elements.

In principle, the main sled is accelerated, while the carriage (b) is nearly static and sees only small displacement until the pole hits the door trim, leading to the biomechanical responses.

The paper focuses on the physical experiments for both USNCAP and FMVSS standards. Two types of dummies ES-2re and SID-IIs are used. Paper also covers comparison of sedan and SUV car types.

Another very useful paper that has great overview of the body biomechanics during side impact is written in 2010 by Lessley et al.[20]. Even though there is not much test methodology, it offers very thorough insight into the biomechanics and body mechanisms during side impact.

In 2011 Kinoshita et al. [21] have presented the first paper regarding Advanced Side Impact System^{TM} (ASIS) and the methodology using multiple pistons that are able to control the stroke (i.e. displacement) in real-time. This method is practically nowadays state-of-art in terms of side crash testing and it is shown on Figure 16.

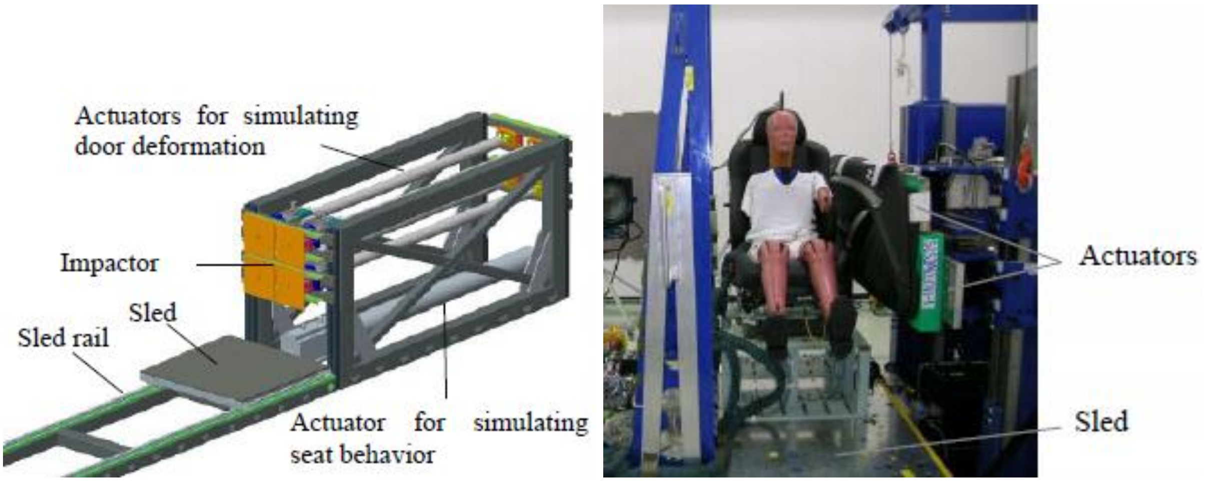


Figure 16: ASIS pole strike test setup as discussed in [21]

As this has been the first study using such a methodology, it was rather simple. It focuses on the body and door only. Curtain airbag, seat belts and B-pillar trim have been neglected. It is also important to note that the impactor is very simple (flat sheet) and split into several areas as shown on Figure 17.

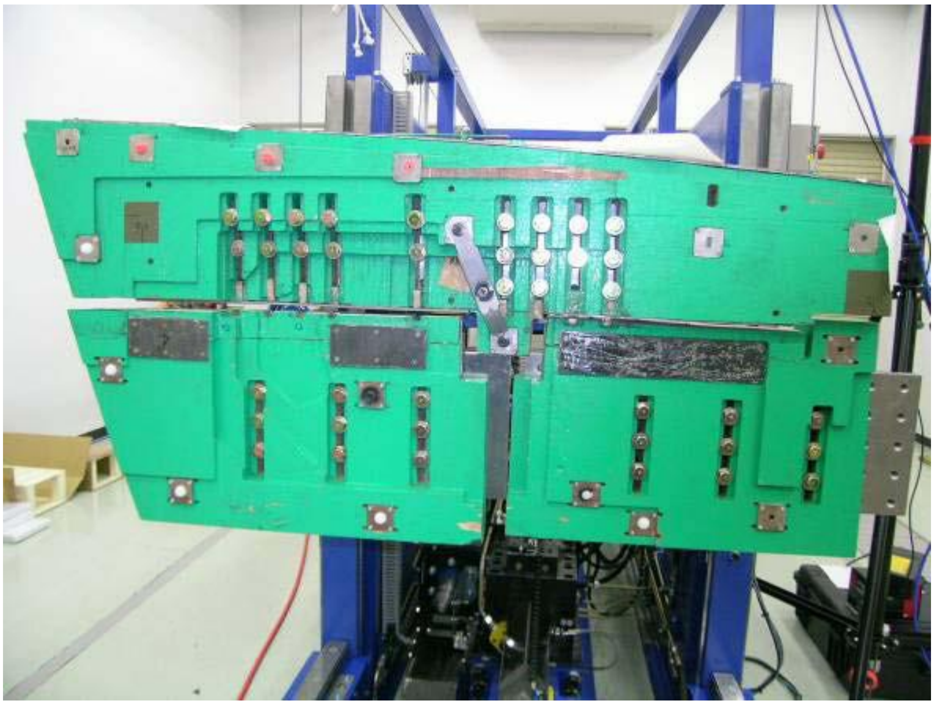


Figure 17: Impactor split [21]

Virtual simulations have been used to identify suitable pulses to ensure correct door trim velocity and airbag deployment space. It is also important to note, that following validation has confirmed that such approach can provide reasonable results. No biomechanical loads have been validated in this paper. Given the simplicity of the setup, it would not even make a sense to do so.

Also in 2011, Liu et al.[22] has presented similar method to the one discussed at [13] as shown on Figure 18. The paper is focused solely on the physical experiment and hence no details have been given.

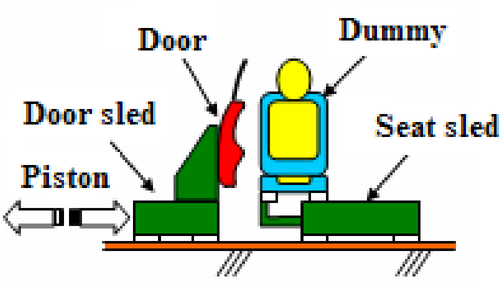


Figure 18: Side test setup as discussed in [22]

Kinoshita et al.[23] has also presented another paper in 2012, which has extended his previous work [21] on barrier strike. The paper is dedicated to the pole strike. The very simple model has been upgraded by adding the seat belt as displayed on Figure 19.

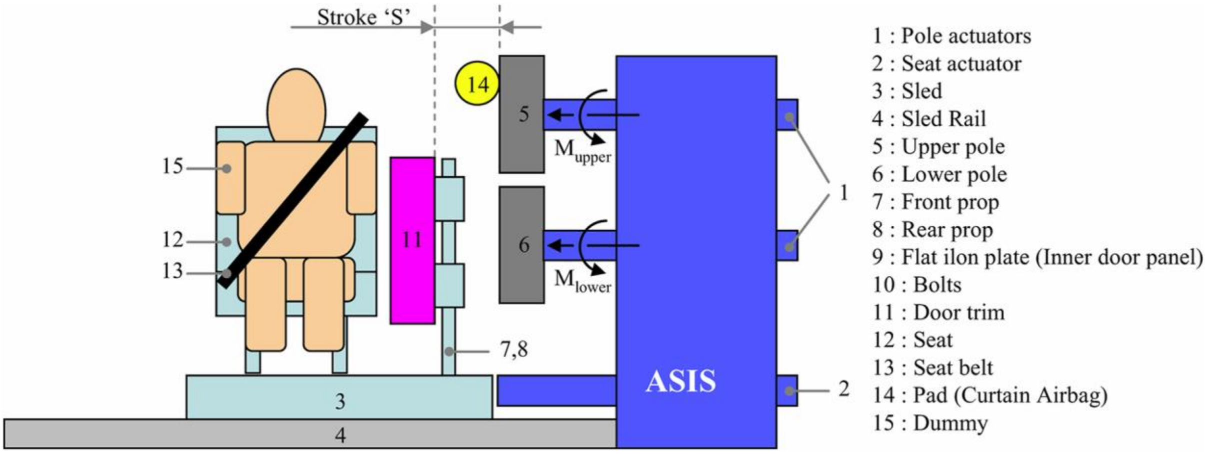


Figure 19: Side test setup as discussed in [23]

However, the methodology is the same, including the simplified barrier and missing curtain airbag and B-pillar trim. No virtual assessment has been presented. Complete validation is presented between ASIS and full vehicle crash.

Janca et al.[24] in 2014 has presented different modification of already discussed methods as shown on Figure 20.

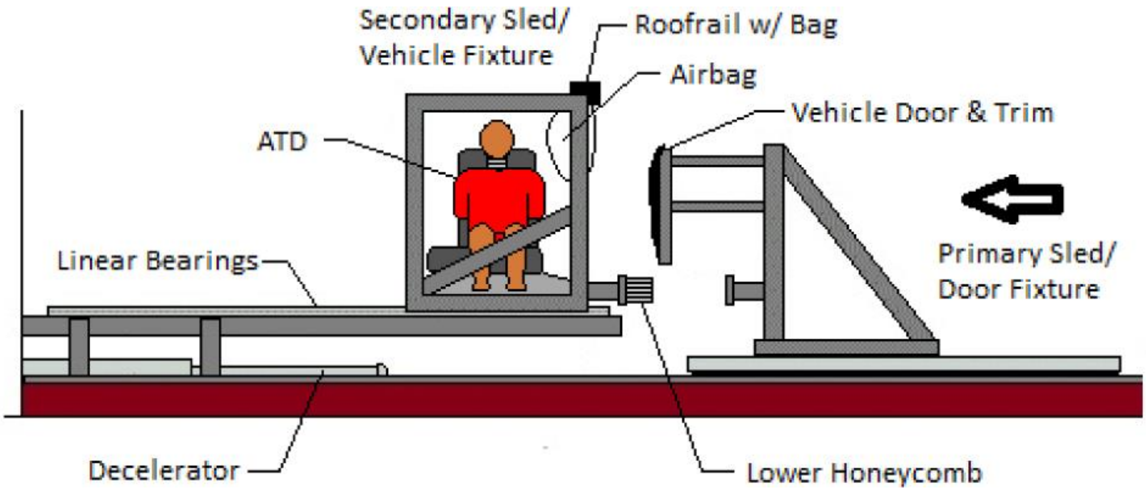


Figure 20: Side test setup as discussed in [24]

Even this paper is focused on the physical experiment and there is no mention of virtual simulations and/or approach by mathematical methods.

To sum those up. There are several papers available on the topic of side sled impact. Majority is focused solely on physical experiment and only several of them mention virtual simulations. Even of them are using FEM for the dummy responses.

No mention of using FEM for estimation of the dummy biomechanical loads and criteria followed by validation to the physical experiment has been found. In general majority of surveyed papers that have mentioned FEM have a single step approach and no mathematical and/or statistical approach has been identified.

1.6.2 Test facilities around the world

This chapter is to give a brief overview of current test labs around the world that actively use sled systems for side crash simulations. All labs have been using principles that are mentioned in Chapter Literature survey [20]. In Seattle USA, Seattle safety uses system as described by Dix et al. [19] and their sled device is shown on Figure 21 below.

Figure 21: Seattle safety [25]

Another lab that is situated in USA belongs to Instron. It is not only manufacturer of the side crash sled system, but it is also manufacturer of the complete sled solution. The system is shown on Figure 22.

Figure 22: Instron test facility [26]

Other labs are based in Europe. Continental in Germany uses exactly the same principle and adds the modification of the side door when it may deform in certain way via hinges and links as displayed below on Figure 23.

Figure 23: Contintenal sled setup safety [27]

There is another lab in Germany that offers side crash sled testing. It is ACTS GmbH, that is connected to the MAGNA Group. They use the principle as proposed Aekbote [13] with single hydraulic cylinder fixed to the door. Cylinder has got controlled displacement.

Finally, Austria houses DSD lab. DSD has developed known ASIS with principle proposed by Kinoshita [21] and also Kinoshita [23]. ASIS can use up to 9 cylinders and can be mounted on the sled as shown on Figure 24. It is the closest device to the one TÜV SÜD Czech and ENCOPIM are developing.

Figure 24: ASIS [21][23][28]

To sum all previously mentioned up, it is clear that this kind of side testing with controlled intrusion of the door trim is very demanding and no papers are currently presenting such complex approach that joins both virtual and physical testing. This work is to fill such a gap in publications and methodology. It is very important to quicken and to get cheaper the complete car development cycle while the restraint system tuning would be more accurate and convenient.

2 Aims of the Thesis

Due to large amount of physical crash tests there is a high demand on reducing the problem size. That would allow quicker and more accurate finite element correlation, restraint system tuning (airbags, seatbelts) and more convenient dummy positioning.

The main objective of the thesis is to develop virtual method of real side impact sled test with corresponding biomechanical loads that would reflect the full vehicle crash test. It should also shorten necessary development time and improve predictability and accuracy of both physical and virtual testing and hence significantly reduce costs associated with vehicle development. Finally, the output would enable complex tuning of restraint systems which are currently difficult.

Outcome of this work will be ALIS test setup and sensitivity study of the whole system behaviour.

2.1 Objectives

In order to reach main objectives, a new approach that uses virtual method and mathematical apparatus that would determine complex system setup has to be suitably implemented. It may use an advanced mathematical model for results evaluation and sensitivity and robustness studies. Following partial objectives are necessary to fulfil to reach the main objective (also shown on Figure 31):

1. Take over initial complete side crash simulation of virtual car
2. Evaluation of objectives and model size reduction
3. Creation of ALIS virtual model and setup
4. Initial determination of physical setup input parameters of ALIS via Design of Experiment (DoE)
5. Successful physical test
6. Comparison of sled test and full vehicle crash

Design of Experiment will be used for sensitivity study of the experimental design. The question is if we apply DoE to the virtual simulations, we expect to get rather detailed insight of the system behaviour and response sensitivities. The idea is to tune ALIS and sled control pulses so well that we will get the biomechanical results very similar to the simulation results of full vehicle.

3 Method and experimental devices

3.1 DYCOT

TÜV SÜD Czech has recently invested a large sum to test lab equipped with sled system (catapult) – DYnamic COmponent Testing (DYCOT) [5]. Sled test system consists of sled with grid holes and pusher sled, where all electronics and measurement equipment is mounted as also shown on Figure 25. The pusher sled is being pushed by CSA catapult, equipped with hydraulic piston that can accelerate the sled by up to 90G to total velocity of 100kph with payload of 1000kg. When fully loaded (payload of 5000kg), the piston is capable of accelerating the sled up to 35G. Maximum force is equal to 2.5MN. Maximum acceleration gradient is 14G/ms.

Figure 25: DYCOT sled test lab

It is usually used for frontal crash test where the occupant safety is being tested. It can also be used for testing of crash-landing of any small airplane that would fit in the lab. Latest addition to the service portfolio is battery pack testing for any battery packs up to 1000kg.

3.2 ALIS

The capabilities of DYCOT sled system have been significantly increased by adding ALIS into serie, right next to the sled platform see Figure 26. It uses up to 6 hydraulic cylinders in order to correctly simulate the door intrusion kinematics during the side crash. It enables one to use only small part of the car together with dummies and restraint systems and carry out simulation of the side crash with focus on restraint system and biomechanical loads.

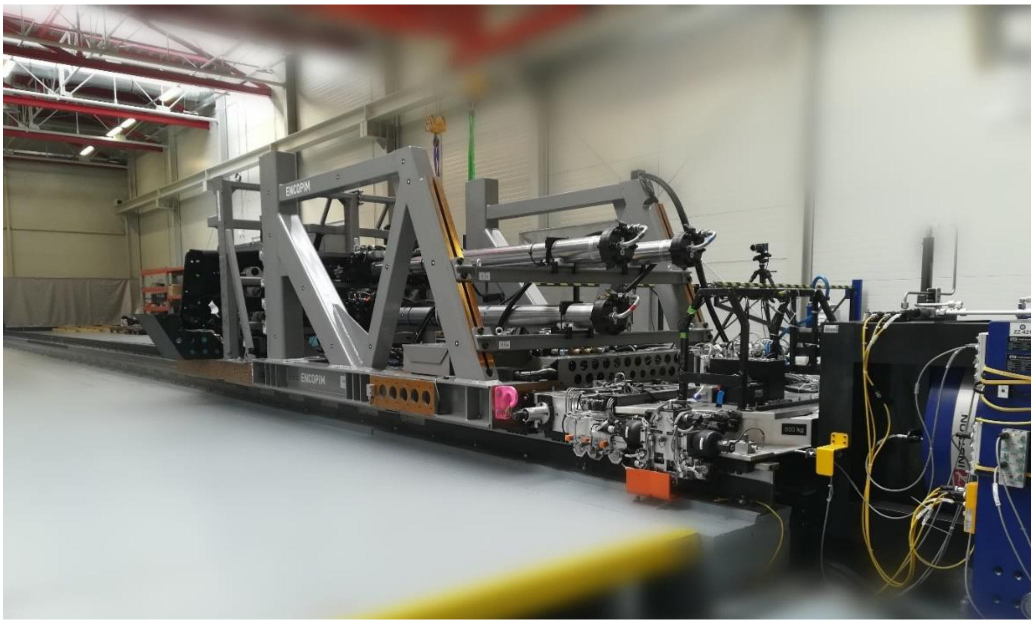


Figure 26: Active Lateral Intrusion Simulator (ALIS)

The system may seem as a "train of trolleys". The driven sled trolley is mounted to the main hydraulic system that generates the main acceleration pulse. ALIS is mounted on the separate trolley, attached to the sled. The whole structure is shown on Figure 27, where main components are identified. The lateral system consists of additional pneumatic system directly attached to several pneumatic cylinders, ALIS primary structure and control system, linear guiding system and "impact break-in structure".

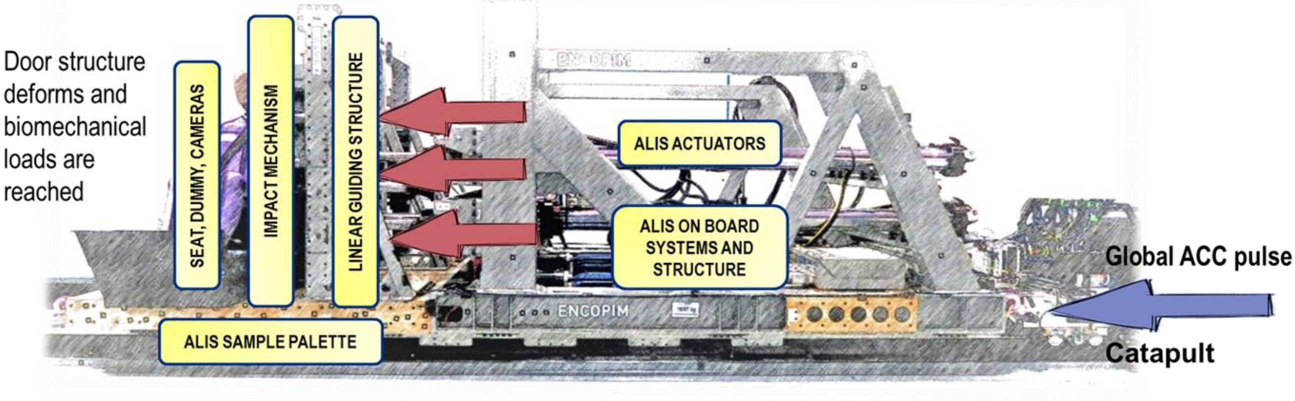


Figure 27: DYCOT + ALIS concept [A01]

ALIS control system is based on predictive control, learning algorithms and feed-forward control. The simplified scheme is shown on Figure 28.

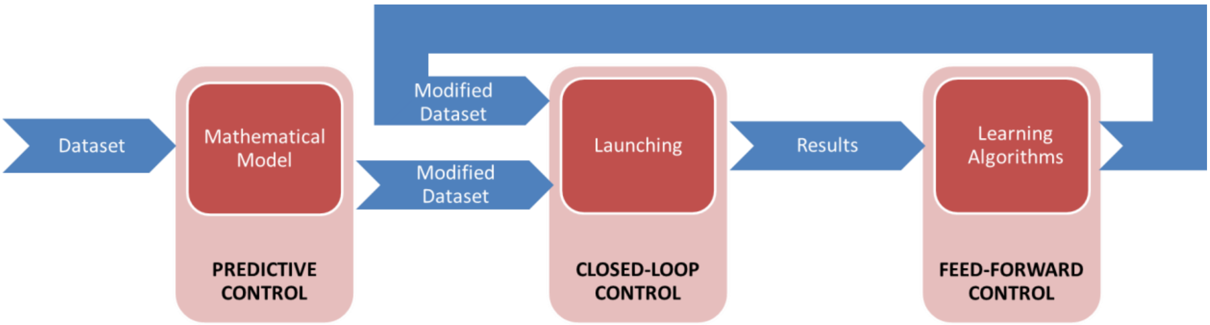


Figure 28: ALIS control scheme

The ALIS can house up to 6 pneumatic cylinders that may have force of either 60kN or 120kN. Currently the system is equipped with three cylinders, one 120kN and 2 per 60kN. Such setup is sufficient for both main loadcases (barrier and pole), but it may have difficulties when new EuroNCAP 2020 requirements will come into force. The barrier will increase its weight to 1400kg (from 1300kg) and also the initial velocity will rise to 60kph (was 50kph). Altogether this is an increase of kinetic energy by more than 50% and hence all additional energy has to be transferred to the car structure and occupants.

Due to the spacing limitations of the cylinders (central axes) the minimum mutual distances are

- minimal distance of 210 mm in transversal direction
- minimal distance of 270 mm in vertical direction

As this equipment is supposed to cover and be useable for most of the typical cars, it has the ability to move all cylinders within a working space. This forms a boundary box with dimensions 1250 x 700 mm (axes positions); where minimal height above floor (ALIS palette) is 319 mm as shown on Figure 29.

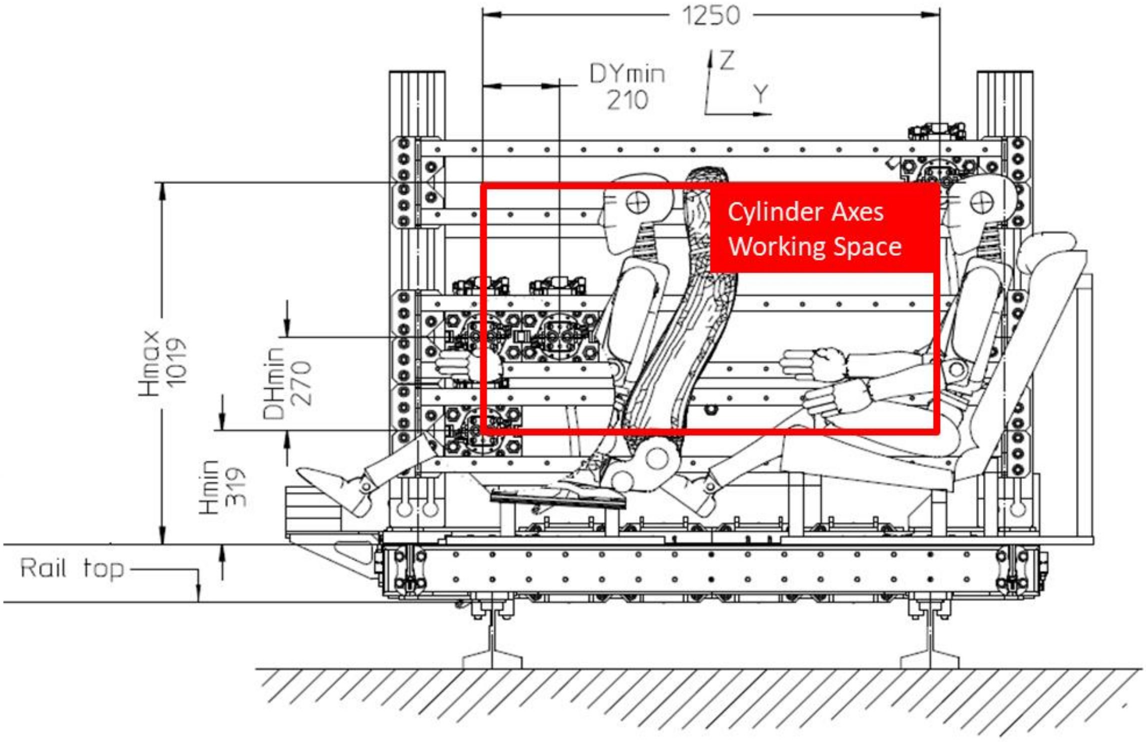


Figure 29: Side view of ALIS working space

This box has been overlaid by typical car sketches as displayed on Figure 30. Note that the space covers area between front driver and rear passenger.

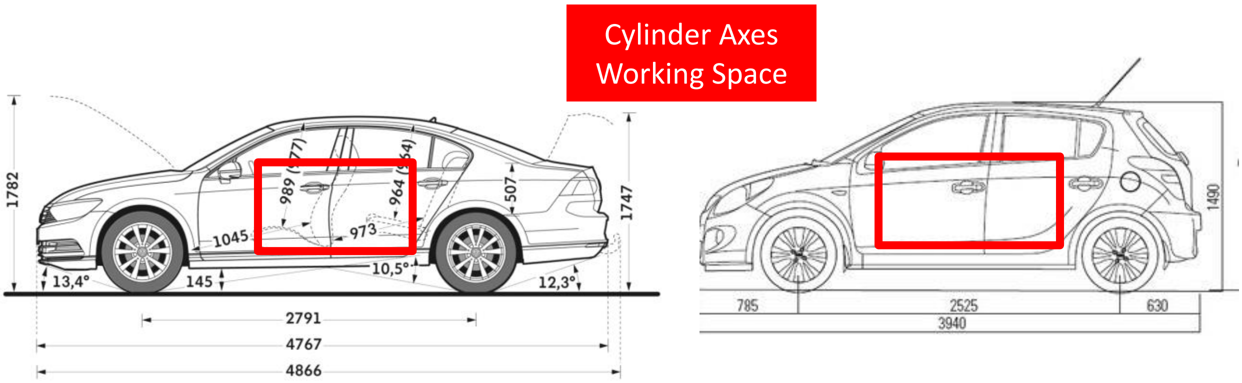


Figure 30: Typical car vs ALIS and MDB (sketch) [29][30]

This is very important as according to the latest ECE and EuroNCAP standards, the rear passenger will be evaluated as well. So far, all test methods and systems have been focused only on the single passenger, mainly driver. ALIS presents a unique opportunity to capture also interaction between driver and front passenger and also between rear seat passengers. It has not been assessed so far and offers a great way to evaluate a lot of new data, biomechanical loads and mechanisms within one test run or simulation.

3.2.1 Principle of ALIS [31]

The basic principle is to accelerate the sled with ALIS attached according to the real side crash pulse while the cylinders push forward through linear guide into the “impact structure”. It should then cause exactly the same intrusion and kinematics of the door system, ie. biomechanical loads (=replication of the physical test). The source data will be extracted from full vehicle crash test and sled test simulations via FEM.

The main idea is to perform simulations before the physical testing loop to ensure the correct kinematics and structural behaviour reflect physical test. The simulation would determine parameters such as amount and position of cylinders used; timing, shape and magnitude of the pulses. These will be then used for the physical test of reduced model. The method is unique due to its limitless options of simulations. It will save time, money and help engineers with restraint systems tuning. Currently the process of tuning of side and curtain airbags is extremely time-consuming and expensive (painful). The approach is based on using only part of a car and it is a combination of physical and virtual methods. It is clear that every vehicle will require unique set of input parameters as well as impact structure.

3.2.2 Methodology

The whole process starts with FE simulation of full vehicle crash and is shown on Figure 31. Output is to be biomechanical loads, intrusion and kinematics of important structural parts such as doors, A- and B-pillars.

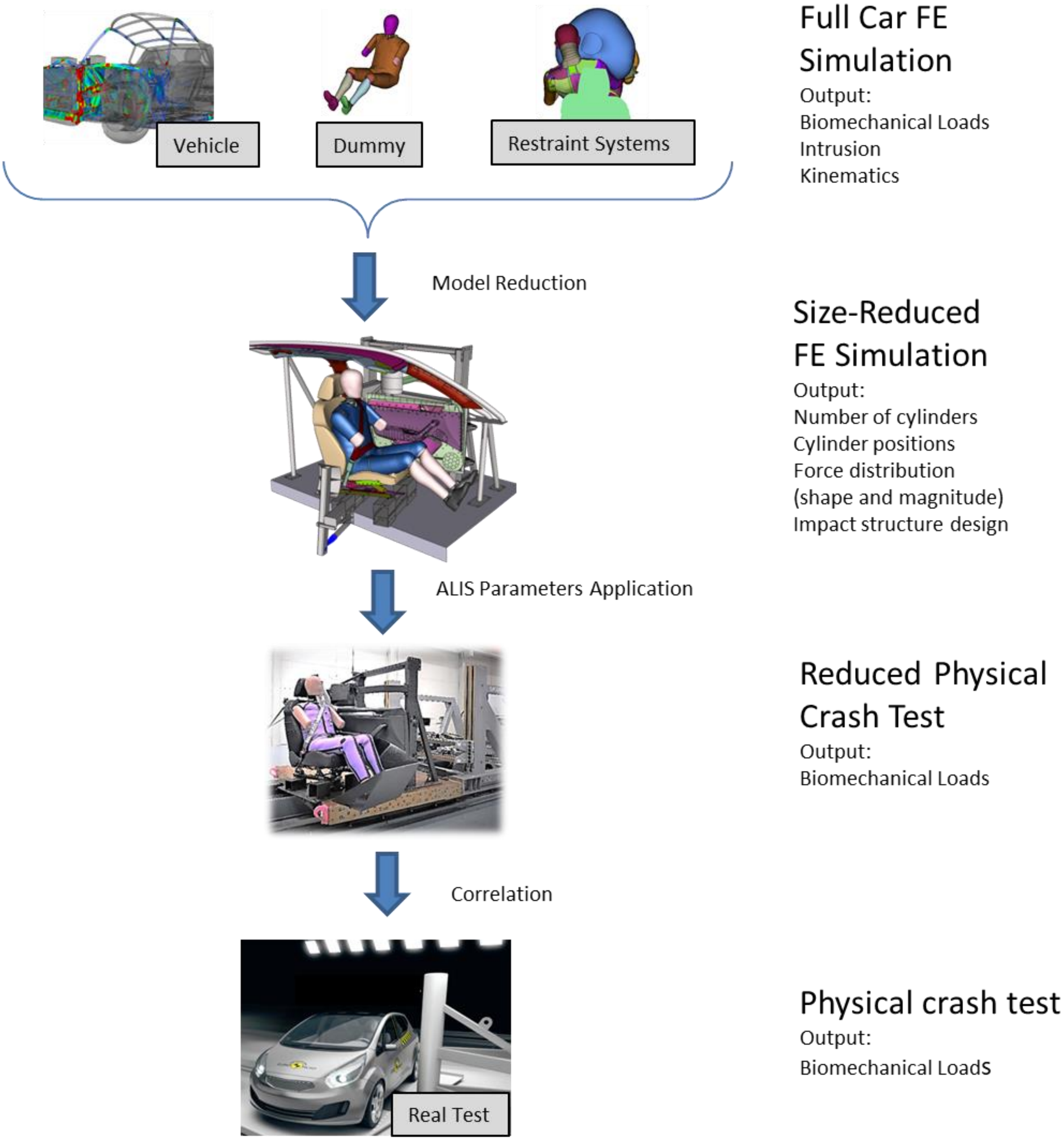


Figure 31: Real crash to ALIS reduction procedure [31] (Courtesy of Škoda Auto)

Size reduction of FE model comes next. The most important outcome of this phase is determination of the ALIS settings. This includes number of cylinders used, their timing and also design of the impact structure. Amount of input parameters is countless. Other two phases are related to the physical testing.

3.3 Stages and partial objectives

There are several necessary milestones, that have to be fulfilled as the project evolves. This complex problem has been split into several partial objectives as follows:

- Stage 1: Take over initial complete side crash simulation of virtual car – pole strike (from OEM)
- Stage 2: Evaluation of objectives and model size reduction
- Stage 3: Creation of ALIS virtual model and setup (kinematics, interactions,…)
- Stage 4: Initial determination of physical setup input parameters of ALIS (@biomechanical loads + kinematics) via Design of Experiment (DoE)
- Stage 5: Successful physical test
- Stage 6: Comparison of sled test and full vehicle crash

Complete process covers many intermediate steps that need to be met in predefined sequence. Example of project plan is shown on Figure 32a and 32b, where both 1st and 2nd iteration loops are shown. They are very same in all activities, however the what changes is source of input data. In the 1st iteration loop, the design and pulses are based on virtual simulation only, whereas in the 2nd iteration loop, the data are based on the prototype crash test.

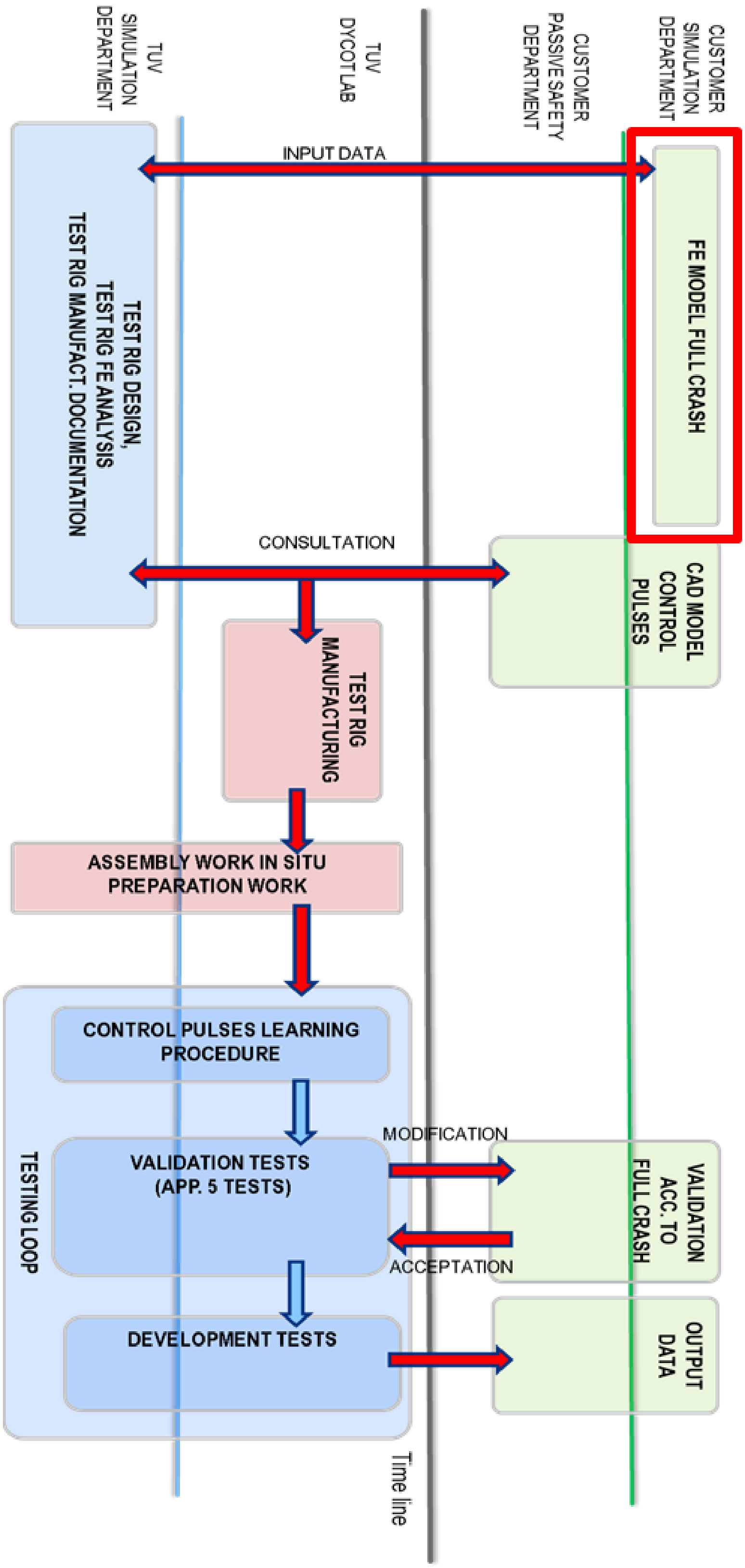


Figure 32a: Complete ALIS project process – 1st loop

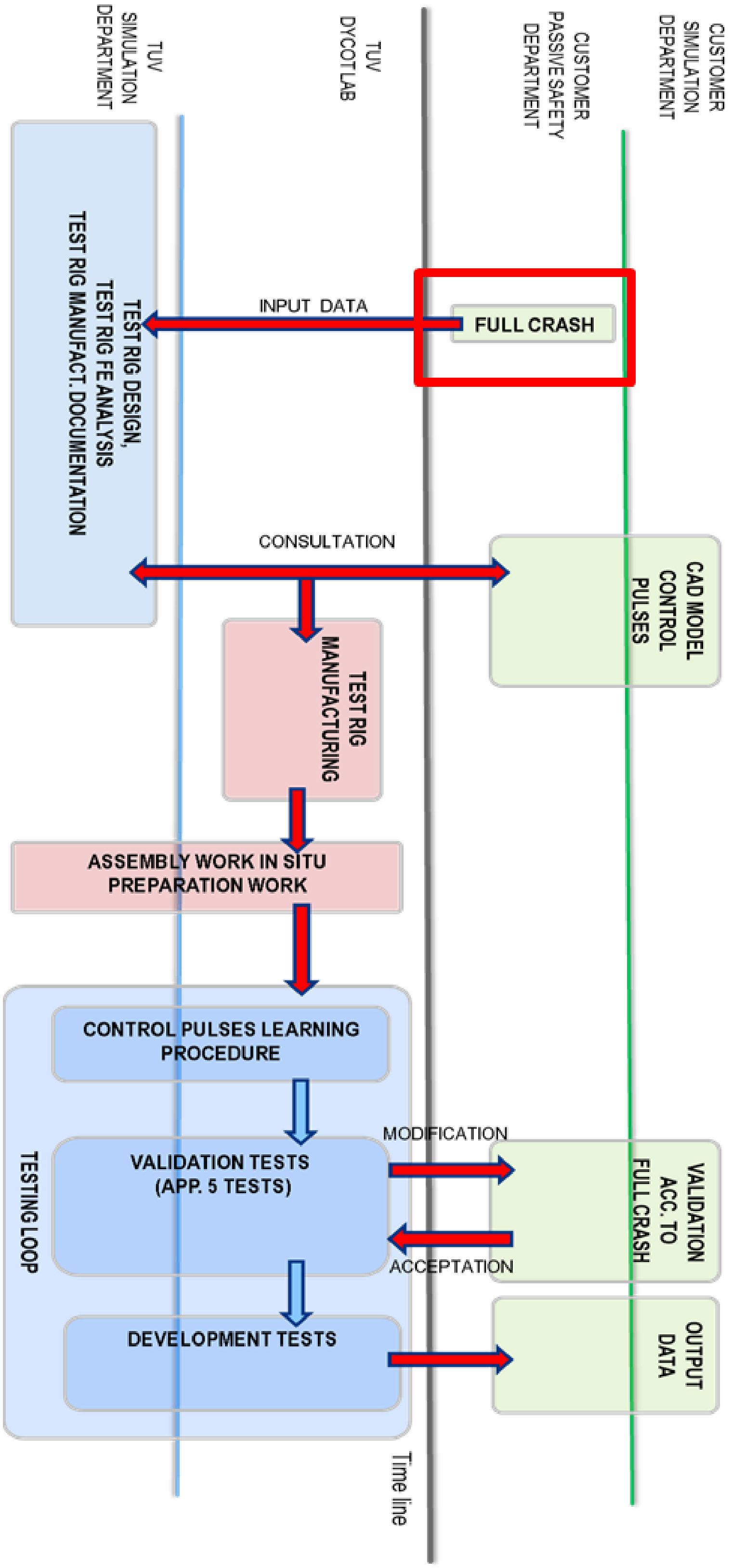


Figure 32b: Complete ALIS project process – 2nd loop

3.4 ALIS project requirements

3.4.1 Objectives

There is a brief summary of tasks below (also see Chapter 3.2.1):

- To create impact structure in terms of kinematics based on customers input data
- To determine ideal cylinder axis positions within ALIS working space
- To determine suitable shapes and timing of cylinders and/or of the whole sled system pulses. The most important is the correlation of dummy behaviour during the physical test and simulations (kinematics, biomechanical loads and intrusion). Besides that, several other parameters are to be monitored such as behaviour of airbag deployment, seat and seat rails (movement/slide away from barrier).

3.4.2 Model Assumptions

The whole ALIS is not to be modelled in full scale.

Main interior frame and hydraulic equipment are considered to be rigid, while main external frame, cylinders, linear guide and impact structure will be modelled explicitly. The main objective is to capture adequate stiffness of the structure. This will be very important when whole ALIS will be accelerated with car crash pulse (around 35 - 40g).

The necessary customer input data includes side structure of the vehicle and contains at least:

- Door trim
- B-pillar
- Sills
- Part of roof
- Cantrail
- Part of floor
- Seats including rails
- Seatbelts
- Airbag modules

and others such as

- Exterior side impact structure (substituted by simple geometry)
- Pillars – anchor point reinforcements
- Hinges and other coupled parts of the mechanism

will be confirmed based on magnitude of forces and accelerations.

Structural model will be enhanced by following safety features:

- WorldSID or Euro SID II
- Side and curtain airbags
- Seatbelt load limiters, pre-tensioners etc.

Ideally the input data will be complete crash model where all necessary parts are carried over.

3.5 Biomechanical loads

3.5.1 Introduction

To be able to evaluate the biomechanical results, basic theory is to be presented. Since the beginning of the automotive industry, man has been trying to understand mechanics of crash and biomechanics of the human body. In the middle of 20th century, when the first FE solvers have been created, they have enabled man to simulate such events and study their mechanics into detail. The first attempts have covered only structural impact and only structural responses have been measured and assessed (deceleration, intrusion,…). Later on, the focus has been shifted to study the effect of crash event on the human. This is how the dummies have been invented. Nowadays there is wide range of dummies, each of them is intended for different types of crashes, while different biomechanical responses are measured and evaluated. The range starts with 6 months, through 3, 6 and 10 years old dummies up to adult dummies for both women and men (5th;50th a 95th dummies determine percentage population coverage).

For more details see Chapter 1.4.2.

3.5.2 Current trends

Nowadays cars are assessed based on results in crash tests and resulting biomechanical loading. The main criteria are a loading that dummy is exposed during simulated crash, respectively human during real crash event. The whole complexity is considered via evaluation of the responses at several human body parts and extremities (head, neck, thorax, abdomen, spine, lower extremities).

Various responses are measured at different dummies at different crash tests. Most of time there are mainly deceleration (in G), force (in kN), body part compression (in %/mm) and velocity. The measurement is done in both directions in line of impact (longitudinal) as well as normal (transversal) direction to the impact.

3.5.3 Thorax and abdomen

3.5.3.1 Mechanism of abdomen and thorax injury

Basic mechanism of abdomen and thorax loading is compressive at higher velocities. It leads to extension and deformation of internal organs and viscera. In case of the extensive compression above rib cage limit, the fracture occurs and that leads to damage/failure of viscera. Sometimes the failure of viscera can occur even when the rib cage remains intact and it is so due to high-velocity loading. This happens due to viscous or sensitive high-speed loading basis of soft tissue as a biomechanical response that is different for low-speed and high-speed impact.

When organs are loaded slowly, the energy is continuously absorbed via deformations that are resisting through elastic properties and pressure generation in tissues. In case of high-speed loading the reaction forces are proportional (F=kx) to deformation velocity of tissues as well as to viscous properties of body that resists deformations and provides natural defence of the body during impact. The inertial effects all body parts related to the reaction forces have to be taken into consideration. In such case the body creates high internal pressure and the injury can occur before the damage of rib cage. The ability of organs and other biological systems to absorb energy without their damaging is called tolerance. Organs and viscera can be loaded in many ways leading to different injuries. During the thorax compression, the heart movement extends aorta along its axis. It may cause transversal rupture if the ultimate strength is exceeded. If the internal pressure in tissues/organs exceeds the strength limit they end in the rupture. In severe cases the internal pressure in aorta can be up to 1000mmHg (valid only for longer exposure). When the aorta has partial tear, the predominant damage mode is axial and combination of extension and internal pressure increases the injury. During the crash the rib cage is compressed and so the rib upper fibres are tensed. When the limit loading is reached, rupture occurs. It is injury via deformation mechanism.

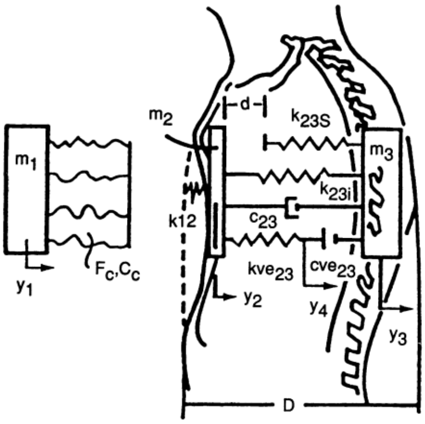
The abdomen is more injury sensitive than thorax because there is less bone support underneath the rib cage, which protects organs during all crashes. Impacts into the upper abdomen can compress and injure liver and spleen even before the whole gets in the motion. Compression in liver can lead to internal pressure increase and also to tensional and/or shear loading. If the liver tissue is sufficiently loaded, it can result in internal bleeding.

The restraint system (seat belts, airbags) and also structural optimization help to dissipate the kinetic energy during the crash into the BIW and also more robust body parts. The contact velocity between body and impacting object can be also decreased in the same manner. Quantification of the human body tolerance, understanding of the injury mechanism and also the numerical methods development help the design of restrain system and also BIW. Virtual simulations are able to identify mutual relationship between injuries and measurable engineering parameters (force, velocity, acceleration, intrusion,…). These relationships are called injury criteria.

3.5.3.2 Biomechanical responses during crash

Basic mechanical model of the human body can be described via group of responses force vs. displacement. Basically, it is a mechanical system with several springs and damper. Dynamic compliance is related to viscous, inertial and elastic body properties. The force increases first due to inertial effects and then the viscous deformation occurs (while maintain constant forces) followed by increase of force and deformation due to elastic stiffness. The system tends to keep hysteresis behaviour during unloading that represents absorbed energy caused by body deformation.

Basic mechanical model of thorax with discrete masses has been developed in 1973 by Lobdell [32] and is shown on Figure 33. Impacting object has got mass m_1 and skin stiffness k_{12}. Viano [33] has added interface that allows energy absorption and is used for evaluation of protective lining. The thorax structure consists of parallel springs with damper that connects thorax m_2 and spinal m_3 masses. Such a biomechanical model describes compressive and viscous thorax responses.



Model Parameters	AP Thorax Hybrid III
Masses (kg)	
m_2	0.45
m_3	27.20
Springs (kN/cm)	
k_{12}	2.81
k_{23i}	0.263
k_{23S}	0.526
kve_{23}	0.132
Dashpots (kN/m/s)	
C_{23} compression	0.525
C_{23} tension	1.230
cve_{23}	0.180
Distances (cm)	
d	3.8
D	22.2

Figure 33 : Hybrid III thorax model with discrete masses. Biomechanical parameters such mass, spring and damper stiffness are characteristic for blunt head crash [33]

Dummy Hybrid III developed by Foster [34] has been the first one that trustworthily represented behaviour of the human thorax so typical for front crashes. Later on the dummies have been upgraded in order to assess injuries caused by seatbelts Rouhanna [35].

The first side crash dummies (EuroSID a BioSID) have been developed by Mertz [36]. Today are the Hybrid III family, family Q, WorldSID, EuroSID and Crabies used in world-large scale and therefore set reasonable standard. More dummies such as BioRID or THOR are in development and/or validation.

Just for illustration, in Table 3 are shown maximum values of biomechanical criteria that are required by European legislation ECE R95 (side impact). These values are not limit values, but they ensure high probability of survival.

Side crash		
Description	Requirement	Measuremt location
HIC (3-axes accelerometer)	HIC ≤ 1000	head
Viscous criterion	VC ≤ 1 m/s	thorax
Ribs compression	RDC ≤ 42mm	thorax
Max pelvis force	PSPF ≤ 5kN	pelvis
Max abdomen force	APF 2,5kN	abdomen

Table 3: Biomechanical criteria according to the ECE R95

More information can be found in [37][38][39][40][41][42][43]

This whole chapter is intended to give a brief overview of the essential biomechanics as some of the signals as some of the responses will be later used in the simulation. Both physical and virtual dummies data/signals are compared and are used for tuning of pulses.

4 Design of Experiment theory

This chapter introduces methods used in this thesis for sensitivity study. It considers application of mathematical and statistical tools in right order and highlights the chosen options that are used latter in the thesis.

4.1 Introduction

Design of Experiment is a systematic process of understanding the effect between inputs and outputs, ie. parameters, variables and responses (results). It is a method that uses mathematical statistical-optimization apparatus to identify level of contribution of variables to responses. It is very common in many industry fields, where processes, design or simply anything that can be mathematically described are used. DoE enables one to study calculated and predicted responses based on variables within certain limits – design domain. It also allows one to understand mutual effect of any variable to any parameter and hence to understand the complete system behaviour.

The classical DoE has been developed by Sir Ronald Fisher in early 1920s, who was an agricultural engineer who conducted many experiments with various fertilizers on different lands. He has started to use DoE to differentiate effect of fertilizers and of other factors. Even though the DoE was developed almost a century ago, it has not been widely spread as one would anticipate. Nowadays it is not common to use DoE during development regarding products from a mass-production.

Many use DoE to understand very complex systems and their behaviour with wide range of input variables and responses. That leads to reduction of price and time as well as higher effectiveness of such processes, eg. quality of products.

Design of experiment consists of five main actions:

- Hypothesis – an idea that is to be either confirmed/rejected
- Experiment - set of tests can are to analyse the hypothesis
- Analysis – analysis of the experimental data and understanding of the system behaviour
- Interpretation – clarification of the analysis results
- Conclusion – confirms or rejects the original hypothesis

4.2 Basic principles

The key of the design of experiment lies in understanding of the whole process. The better the knowledge, the more efficient it may turn. Process of planning, designing and statistical data analysis are essential for design of experiment. During the whole design of experiment, one comes across two types of factors – quantitative and qualitative. Qualitative factors are mostly discrete for example type of material, type of spring and others. Quantitative are more complex as they often use range of values or settings.

Experimental design has got three principle as follows:

- Randomization
- Replication
- Blocking

These principles are used for problem size reduction up to removal of the experimenter bias. It is also common that large experiments are complex and often lead to wrong results.

4.2.1 Randomization

Real life is a set of constantly changing situations and circumstances. Even though, there are processes that are precisely defined, they will never have the conditions. Generally, processes that involve people and machine will never be same as people are not able to perform always the same and also machine will slightly change over time due to fatigue or wear of material. Therefore, one has to use randomization in order to predictively model yet unclear conditions that may occur in future.

Usually during any process there are almost always some sort of noise. There are also factors that cannot be controlled such as weather, ambient temperature or electrical current fluctuation or material batches with different mechanical properties. These factors can also affect the overall results of the experiment. The main idea of randomization is to give all factors the same or at least fairly similar chance of affecting by the noise factors. Complete randomization is used in classical DoE.

4.2.2 Replication

Replication is method, when a set of experimental trials is run in random order. It means that the results are not dependent on the order, in which the experiment ran. Replication covers both the complete experiment or part of it. Replication has got two main properties. First, it allows one to study the effect of factors or interactions. The second property is an opportunity to estimate experimental error via runs under different conditions. Should one have only one experiment, neither of these two properties can be evaluated and hence one could not make satisfactory conclusions of the factor or interaction effect. Experimental error could not be evaluated due to insufficient data. Replication requires a lot of time and costs, should they be applied (material,…).

4.2.3 Blocking

Blocking is approach that eliminates the noise and/or external irrelevant factors from the experiment. It takes away factors such as variability of batch or driver operation. Usually the similar conditions and their effects are grouped together such as material batches or acceleration pulses. Recorded results within these groups are then compared. Significant variations between these groups are to be eliminated in order to improve the precision of the DoE.

4.2.4 Degrees of Freedom (DoF)

Simply said, number of statistical DoFs is number of variables that may vary during the experimental analysis and design. It is often minimal number of independent variables within pre-defined constraints that describes dynamic system. The more variables, the more complex system and the more DoFs.

4.2.5 Metrics

In order to understand chapters where the procedure of DoE is described, several characteristics/metrics should be defined:

- Accuracy – defines a level of proximity between referenced/measured value and computed/calculated value from DoE
- Precision – defines range of scattered results. It is not related to any exact value, but helps to determine random error from experiments that are repeated with the same conditions (inputs)
- Capability – any studied system is capable, when it is robust, sensitive and accurate. It has often small error (accuracy) and tight scatter of results.
- Stability – the system is stable when there is a adequate change in response to a small change in input parameter (e.g. small change in intrusion, when applied slightly higher force)

4.2.6 Practical application of DoE

Since the DoE method is neither extensively taught on academic ground nor extensively used in industry due to time constraints, it is not very well established among the engineers and scientists although it may bring significant benefits both to the engineers and to the industry sector as well. The DoE methodology has got four stages as follows:

- Planning
- Design
- Conducting
- Analysis

4.2.6.1 Planning

Planning stage consists of 3 tasks:

1. Problem identification and description – the first is one of the most important. The deep survey of the problem is advised as it may save many attempts that are irrelevant for given assignment. This task ensures that one well understands the context of process and overall objective and hence helps to specify exact input parameters and constraints.
2. Design variables – these are the input parameters, that can be controlled and quantified. Usually the whole process it just a way how to find the best combination of these variables to satisfy given constraints and achieve the optimal function (minimize/maximize).

3. Metrics and response definition – in general the response is crucial for the experimental design. The response is in effect an output parameter and it is metrics how to measure effect of respective variable on the intended system behaviour. Response can be velocity, length, stress or any other quantity

The planning phase ends here, where the problem is formulated and given mathematical description.

4.2.6.2 Design

This stage is about designing of the response surface and its mathematical modelling. It will be described more in detail later, when the sampling and metamodeling will take place.

In order to bring down the size of experiment, which is dependent on umber of variables and//or interactions that are studied, one should think the strategy through as it highly affects budget, time and also accuracy. It is always better to go slightly over the edge while specifying the constraints and design points as it is usually unclear whether the values on limits are still continuous.

4.2.6.3 Conduction

This stage mostly captures the execution of the experiments. There can be physical, but also virtual. Even though the majority uses the physical experiment, this work is dedicated to the virtual simulation = experiments.

4.2.6.4 Analysis

This stage is very important but also very difficult. It takes results from experiments and interpret them in means of the desire design. Firstly, the response surface has to be created based on experiments, ie. matrix of variables per experiment and recorded response. Response surface then mathematically represents not just calculated, but also predicted variable combinations and their predicted responses. This is mainly used for sensitivity studies and tracking the effect of variable change on the response values.

It may go even further, when optimization takes place. Based on data from this DoE, optimization algorithm can be introduced and find minimum/maximum, if it is feasible within the response surface.

4.2.7 Results of DoE

As DoE is a multipurpose tool that identifies mutual effect of input variables/parameters and related responses. Durakovic [44] has presented a very good overview. It is regression analysis used for following tasks:

- Comparison – multiple comparisons for the best option selection that uses t-test, F-test or Z-test
- Variable investigation – defines and determines which variable has an (in)significant effect on overall performance and/or behaviour of the respective system

- Transfer function identification – it is not necessary to completely understand the complete process; the transfer function can be determined based only on input and output data. One does not have to get a complete overview and the “black box” is simply defined by a mathematical function
- Optimization – optimization of the system behaviour/performance via either ideal variable combination or optimized transfer function
- Robust design

5 Process

As already mentioned, several subsequent stages have to be followed in exact order. This chapter covers complete process with detail description of each of stages. There are two iteration loops – 1st loop (Figure 32a) is based purely on virtual data as no prototype or its crash data exists. The 2nd loop (Figure 32b) is upgrade of the 1st loop where the data from physical test are fed into the simulation and improves the accuracy. This work is dedicated to the 1st loop as the DoE approach has got significant benefits there. That means there is an objective to reflect what has been virtually simulated in the real test. Should this method prove feasible in the first loop, the second loop can be realized subsequently.

5.1 1st Iteration loop

This chapter is closely focused on the activities mentioned in Chapter 3.3 and describes complete process within the first iteration loop.

At the beginning of each project it has to be clearly stated what will be ultimate result of the physical testing. The goal of the first iteration loop is to tune the ALIS to get very good match with full crash FE simulation. When the correlation is satisfactory, several development tests are carried out in order to get at the moment the best possible restraint system setup into full crash of prototype.

5.1.1 Stage 1: Take over complete side crash simulation of virtual car

In the initial phase of the project, only virtual simulation data of the full vehicle crash is available. All necessary data in both formats 3D CAD and FE models are required. It should contain complete model suitable for further reduction. For purposes of model reduction the FE model is taken, however the 3D CAD data has been considered as a master data should there be any mismatches. CAD data are also used for design of impact structure as it is not very suitable to use FE model as master in CAD software.

Currently the EuroNCAP test for side crash consists of 2 load cases (barrier and pole strike). The pole strike has been considered for some time more severe and hence the design was tuned mainly on this case and regularly tested for barrier. The pole strike setup is shown on Figure 34.

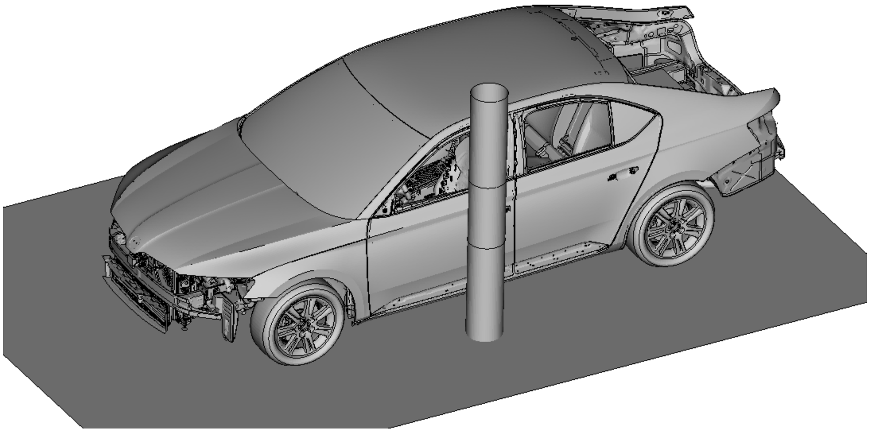


Figure 34: Pole strike virtual setup (Courtesy of Škoda Auto)

As mentioned in Chapter 3.2, EuroNCAP has recently announced changes in side crash setup that increases barrier mass, velocity and hence kinetic energy. Therefore, there will be even larger volume of simulation effort of barrier tests in future as both of the load cases will require equal attention. Our goal is pole strike, which is much severe in terms of structural intrusion as well as biomechanical loading on occupants.

There is no contribution of the author at this stage. CAE simulation team of TÜV SÜD Czech takes care of it.

5.1.2 Stage 2: Evaluation of objectives and model size reduction

When a complete CAD and FE model is received, full crash simulation has to be carried out. Results determine the preliminary inputs for reduced model of ALIS and a part of car interior.

5.1.2.1 Evaluation of objectives

Virtual dummies are fully instrumented, and they reflect biomechanical loads with good correlation with physical buddies. For both side crash load cases is used WorldSID 50% that is shown on Figure 35. It has been developed in parallel with front crash dummies, but with different focus area. In side crash the most important loading is on the head and torso (thorax, chest, pelvis, spine, etc.). Upper and lower extremities are not in the usual focus are and hence are not by default instrumented (lower legs) and also fully “modelled” (lower arms).

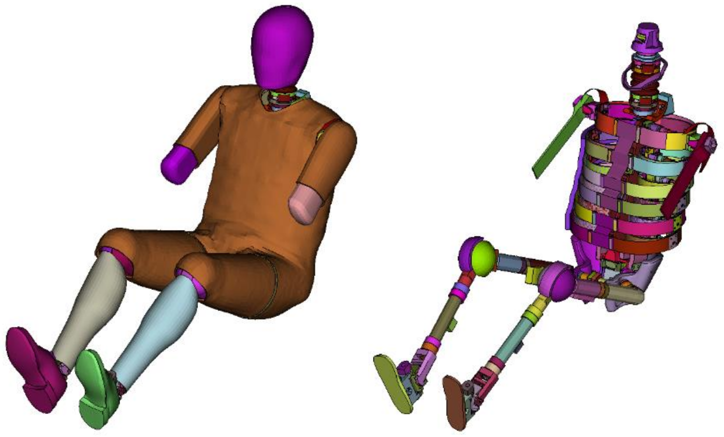
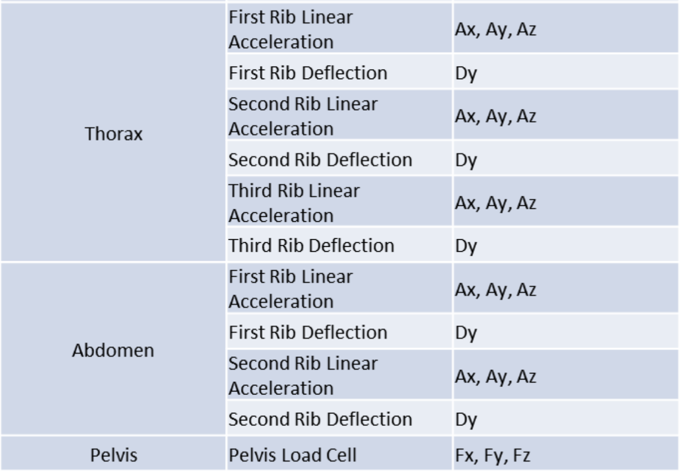


Figure 35: WorldSID 50% with skin (left) and without skin (right) (Courtesy of ESI Group)

Dummies can be delivered with full arms and completely instrumented legs, but this is optional with associated additional costs. Complete instrumentation that is available for these dummies can be seen in Table 4.

The objective is purely dependent on customer requests, but usually it is in line with EuroNCAP requirements and hence the main focus is put on the biomechanical loads measured in dummies. Optionally some may want to ensure kinematics of certain body parts and/or behaviour of airbags or other components of the restraint systems during the development stage. Then the focus is shifted to the structural behaviour of BIW and trim parts that come into direct contact with body.

Location	Description	Components
Head	CG Linear Acceleration	Ax, Ay, Az
	Rotational Acceleration	Ax, Ay, Az
	Tilt Rotation	Rx, Ry
Neck	Upper Neck Load Cell	Fx, Fy, Fz, Mx, My, Mz
	Lower Neck Load Cell	Fx, Fy, Fz, Mx, My, Mz
Shoulder	Rib Linear Acceleration	Ax, Ay, Az
	Rib Displacement	Dy
	Joint Forces	Fx, Fy, Fz
Full Arm (half arm standard)	Upper Arm Load Cell	Fx, Fy, Fz, Mx, My, Mz
	Lower Arm Load Cell	Fx, Fy, Fz, Mx, My, Mz
	Elbow Moments	Mx, My
	Elbow Angular Displacement	Dy
	Elbow Linear Acceleration	Ax, Ay, Az
	Wrist Linear Acceleration	Ax, Ay, Az



Thorax	First Rib Linear Acceleration	Ax, Ay, Az
	First Rib Deflection	Dy
	Second Rib Linear Acceleration	Ax, Ay, Az
	Second Rib Deflection	Dy
	Third Rib Linear Acceleration	Ax, Ay, Az
	Third Rib Deflection	Dy
Abdomen	First Rib Linear Acceleration	Ax, Ay, Az
	First Rib Deflection	Dy
	Second Rib Linear Acceleration	Ax, Ay, Az
	Second Rib Deflection	Dy
Pelvis	Pelvis Load Cell	Fx, Fy, Fz

Table 4: Overview of WorldSID 50% available responses [45]

Evaluation of the results is in case of side crash rather tricky as simple “sinking” of the dummy or its incorrect seat-positioning may lead to significantly different results. It is very important to build a robust model that is not vulnerable to a minor change in parameter setting such as minor change in material model (e.g. change of Youngus Modulus) or minor change in initial crash velocity (in range of units of percent, e.g. 32±1kph).

In this case the major focus has been set to kinematics of extremities and airbag inflation (early phase of crash) and secondly to biomechanical loads during the second phase of crash. Evaluation has been therefore split in two phases in each with different recorded responses.

5.1.2.2 Early phase (up to 20ms)

This phase usually captures airbag fire-up and engagement of seatbelt pretension. The side crash suffers from very small initial distance between barrier/pole and driver. In addition to that as the pole intrusion increases, the gap between driver and door trim closes rapidly. That gives very limited time and space for airbag to inflate and protect the driver. During this phase there is high ratio of intrusion to deceleration due to the lack of structural parts.

5.1.2.3 Second phase (above 20ms)

In the early phase the dummy kinematics and airbag inflation has been determined. During the second phase the main focus is transferred purely on biomechanical loads acting on the dummy. The main intrusion during the pole strike occurs in this phase. Hence following dummy responses are required to be as accurate as possible:

- Thorax compression of three ribs
- Abdomen compression of two ribs

These responses are based on evaluation criteria of EuroNCAP and its most important “items”.

More information regarding the biomechanical loads and assessed responses is given in Chapter 3.5

5.1.2.4 Model size reduction

Main task during this phase is to reduce the model size in order to fit it to current needs and to reflect ALIS physical setup. In order to decrease running time and increase amount of analyses that can be run, the model of whole vehicle has to be reduced to compact and equivalent reflection of the complete one. From experience it can be generalized that several structural components and most of the trim has to be carry over. Reduced model after several iterations is shown on Figure 36. Usually the complete model is stripped off complete front and rear parts so only cabin interior is left. Then based on customer demands the important structural and trim parts will remain. For each project there are mandatory parts that are necessary for the sufficiently predictable virtual model:

- Seats
- Restraint system (seatbelts, airbags)
- Door trim
- B-pillar trim
- Cantrail and roof (if curtain airbag is present)

And some are optional – based on individual requirements:

- Instrumentation panel
- Steering wheel
- Central console

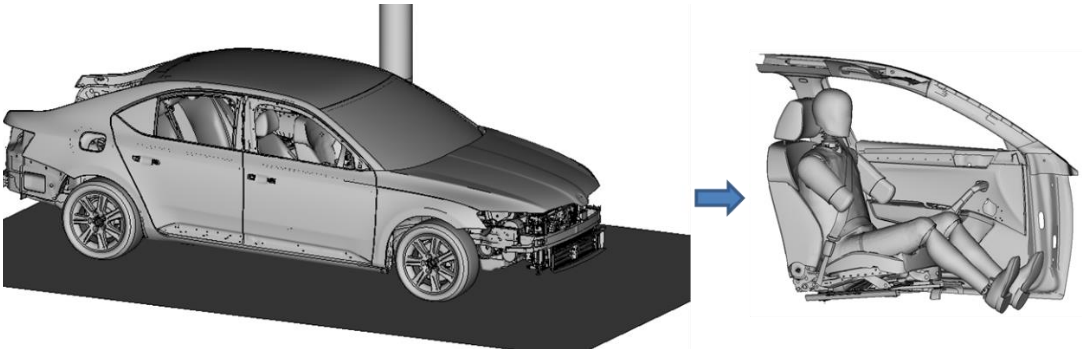


Figure 36: Size of model reduction from full crash model (left) vs. ALIS reduced (right) (Courtesy of Škoda Auto)

Every unused element saves a lot of computational effort. In this case it has been saved over 4.3m elements – from 4.9m to 0.6m elements (over 87%). This represents a significant reduction and offers much more efficient approach for upcoming iteration loops, where hundreds of hours or even maybe tens of days computational time will be saved.

As the model is usually include-based there are many debug simulations that have to be run. Main issue presents the fact that each OEM is using different software package and has got their own FE model-built process and hence CAE engineers have to adopt every one of them. Due to reference issues this step takes even up to several weeks.

There is a little contribution of the author at this stage, where the reduction of FE model has been joint task of CAE simulation team of TÜV SÜD Czech and me.

5.1.3 Stage 3: Creation of ALIS virtual model and setup

As mentioned in chapter Model Assumptions (Chapter 3.4.1), ALIS itself is not be modelled completely. It is assumed that the main frame has much higher stiffness compared to the impact structure and therefore there is no real contribution of its compliance to the resultant kinematics of impact structure..

At this stage the test rig has to be designed. It contains joints, dampers and springs. Such mechanical system represents the stiffness of the whole car and yet could be used repeatably. Therefore we reduce costs and time as this test rig can be used more than once. This is also a partial objective of the thesis, however it is not my task.

Several steps have to be carried out to determine desired properties as follows:

- Definition of the kinematics
- Impact structure splitting
- Basic stiffness assessment
- Determination of necessary mounting and acting points (joints, etc.)

Each loadcase requires unique design. Usually there are pole strike and barrier strike which means 2 designs.

5.1.3.1 Definition of the kinematics and impact structure splitting

In order to understand the impact structure intended behaviour, the full crash model has to be analysed, frame by frame. When using constraint towards suitable plane, the car side structure (sills, B-pillar, etc.) exhibits simply described deformation mechanism that can be converted into fundamental kinematic loops. The key is to find these loops and convert them from full scale model to simplified model as shown on the Figure 37.

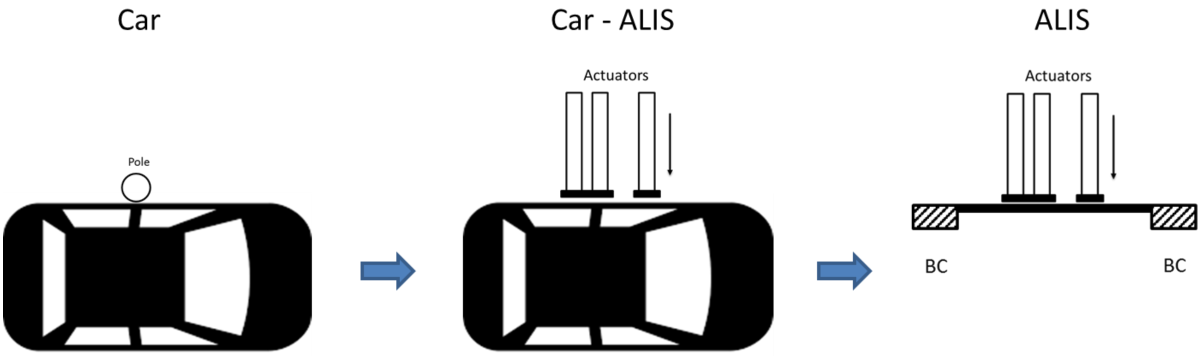


Figure 37: Mechanism reduction diagram

It is necessary to determine appropriate boundary conditions as well as stiffness of individual parts, including their mutual joint stiffness. The basic mechanical scheme can be visualized as displayed on Figure 38.

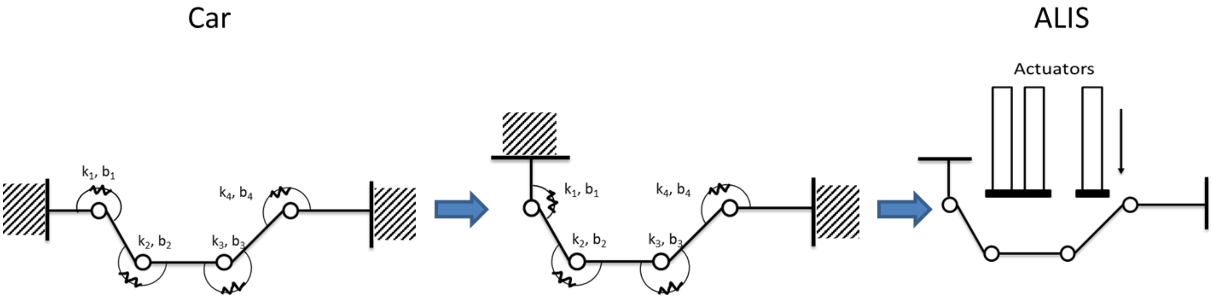


Figure 38: Mechanism reduction diagram

It is rather complex problem that requires experience and time to get reasonable kinematic design, including appropriate boundary conditions. On the left side of the Figure 38, there is a simplified version in the end of the kinematics identification process.. The right hand side then illustrates generally the ALIS scheme. Its real design is displayed on Figure 39.

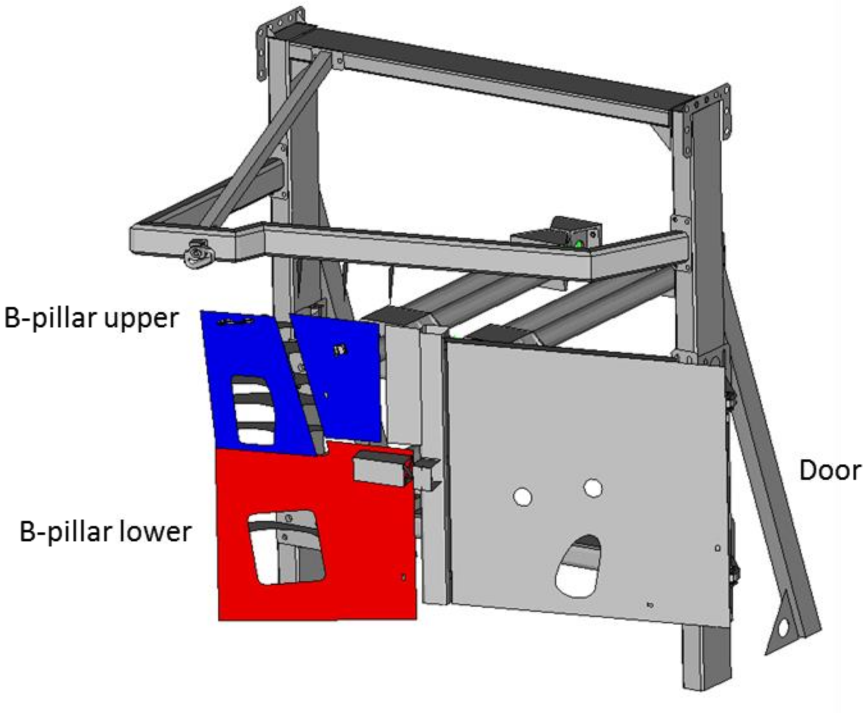


Figure 39: Example of horizontal split of the impact structure

It is important to note, that each loadcase (barrier and pole strike) has got unique setup and design.

It is also necessary to determine where to position the actuators. This comes out of the kinematics study and structure split (Figure 38) is also unique for each project. On Figure 40 can be seen the position of actuators relative to the dummy and structure.

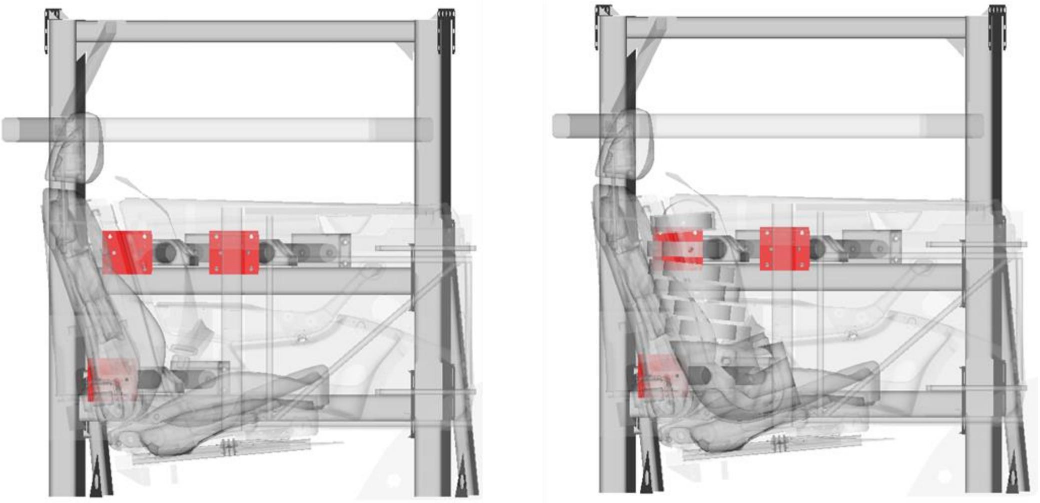


Figure 40: Actuators position (red) with respect to seat and dummy (Courtesy of Škoda Auto)

5.1.3.2 Basic stiffness assumption

Following assumptions are based mainly on engineering expertise and experience. During the test it is assumed that impacting structure is much stiffer than trim and dummy. It is also important to ensure that this is the case. Should the structure that is directly attached to the actuators be compliant it may affect the controlled pulse and lead to the inaccurate test results. The trim and dummy reactions may lead to additional loading of the structure and it should already be taken into the consideration.

5.1.3.3 Determination of necessary mounting and acting points

It is also important to define trim attachment points as well as loading points – points that will be for load transfer used during the loadcase, these usually are:

- seatbelt anchorage points
- D-loop
- Retractor attachment point

All these points are design based on provided 3D CAD data as in FE model they are often neglected.

5.1.3.4 Initial structural analysis of ALIS setup

While design is being tuned in order to ensure proper kinematics, it is necessary to simultaneously analyse the structure under the anticipated loading that may occur. As the pulses are not known yet and hence the first assumption is to take pulses from the full vehicle crash as shown on Figure 41.

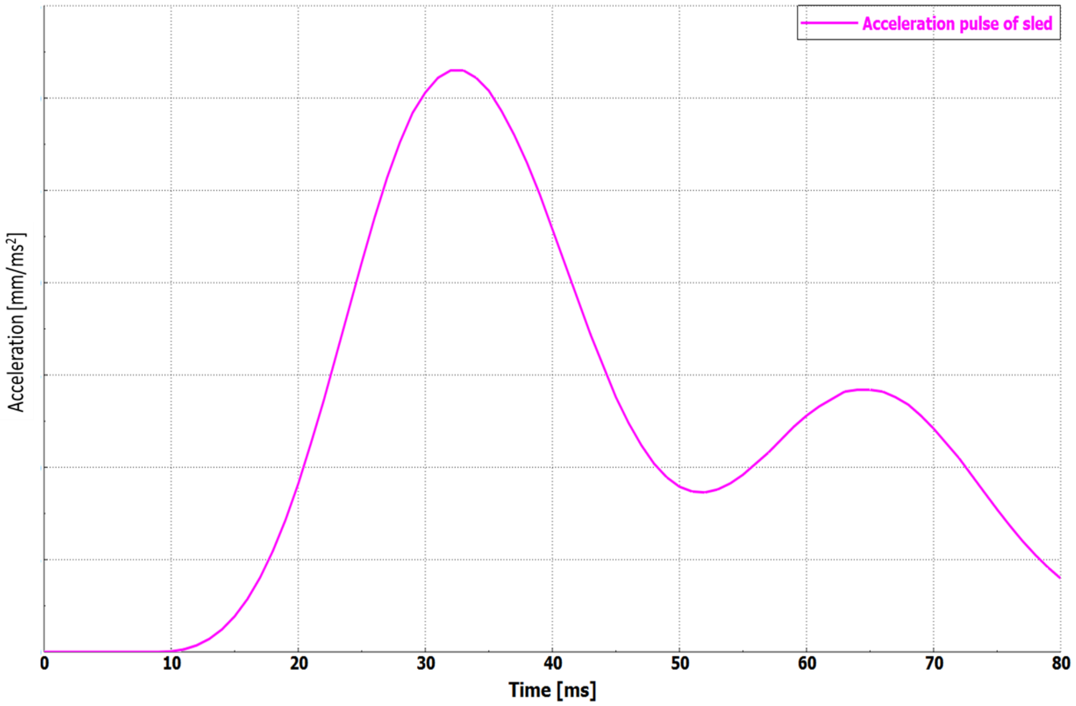


Figure 41: Acceleration pulse for sled

Actuator initial pulses have been taken from acceleration derived from displacement of trim points in vicinity of points as shown on Figure 42. The initial pulses related to these points are displayed on Figure 43. These four pulses will be used later for input variables definition.

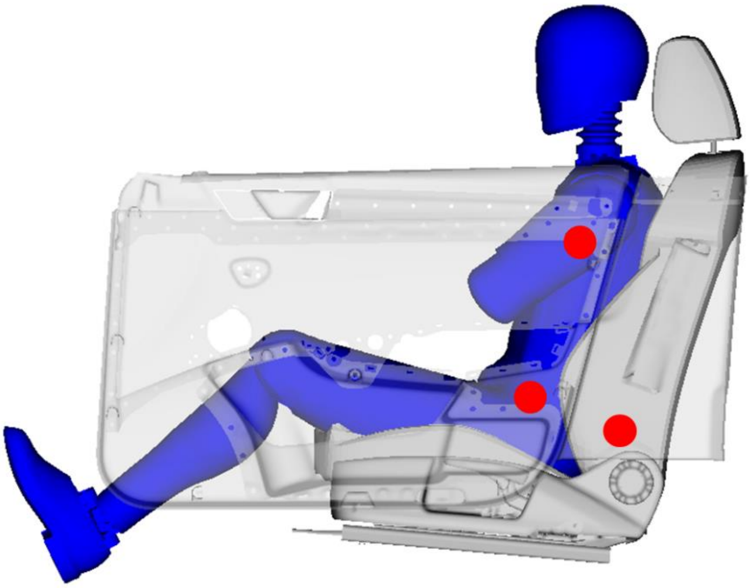


Figure 42: Position from the trim displacement is determined (Courtesy of Škoda Auto)

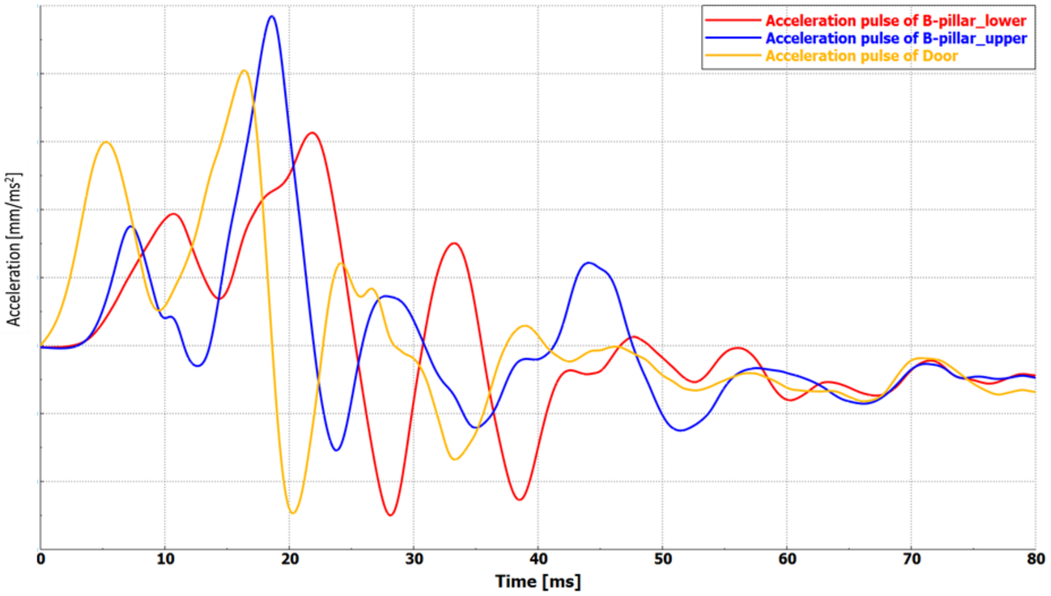


Figure 43: Acceleration pulses for all actuators

The structure is analysed with these pulses and updated if necessary. These iteration loops go until the structure is completely defined and behaves within the limits. No plasticity is allowed as design is repeatedly used during physical testing.

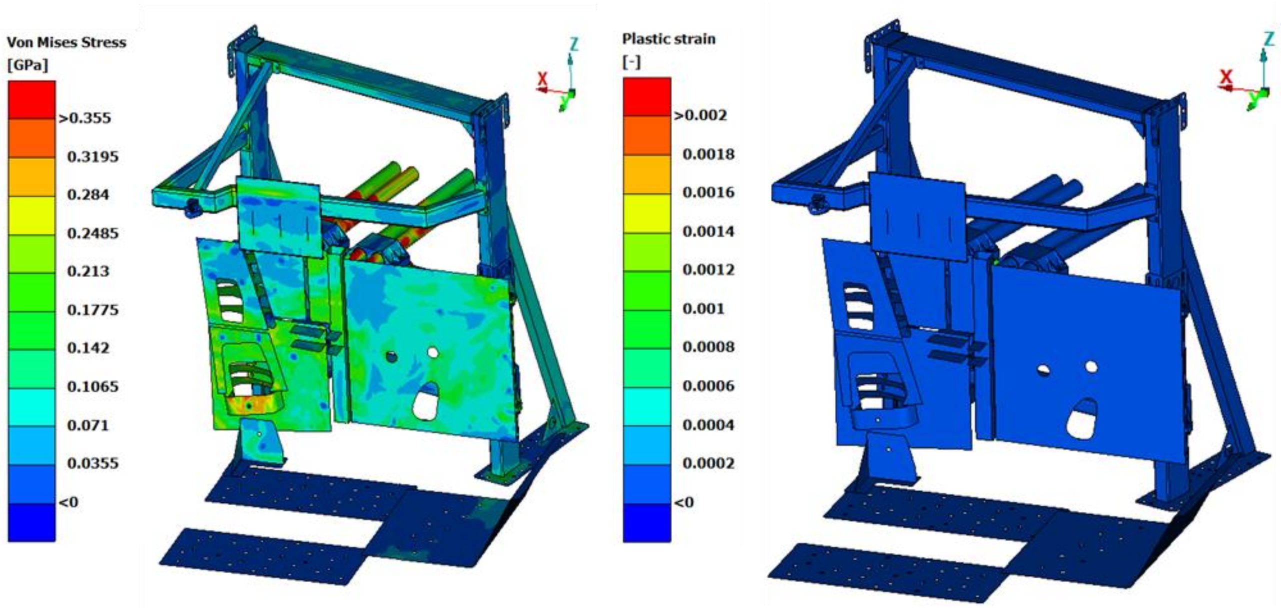


Figure 44: Von Mises stress (left) and corresponding plastic strain (right)

On Figure 44 are Von Mises resultant stresses shown (left) and corresponding plastic strains (right) with limit value of 0.002, which represents the yield point $R_{p0.2}$. The plastic strain evaluation is usually used due to independency of material variation as opposed to Von-Mises stress.

5.1.4 Stage 4: Determination of physical setup and input variables of ALIS via DoE

When the structural analysis is done, one can proceed to another step. At this stage the impact structure design is complete and fulfils all criteria (stiffness, strength and kinematics). Next step is to identify ideal combination of pulses that would then be the input into physical testing system. This stage has got two main objectives:

- To identify ideal combination of pulses
- To get a good knowledge of the system and its behaviour for future use during validation loop for support of physical testing (knowing trends)

As this system is a prototype in a fact and has not been used yet, there are no experience and/or knowledge regarding its behaviour and parameters sensitivity. There are several available approaches, but main two methods have been selected Step-by-Step iteration with subsequent physical correlation and design of experiment (see Chapter 5.1.4.1).

Step-by-step iteration presents traditional approach where every change of parameter is being investigated and therefore know-how base is built. The complete process, including iteration loop, is shown on Figure 45. This approach is not suitable for higher amount of input variables and sensitivity studies.

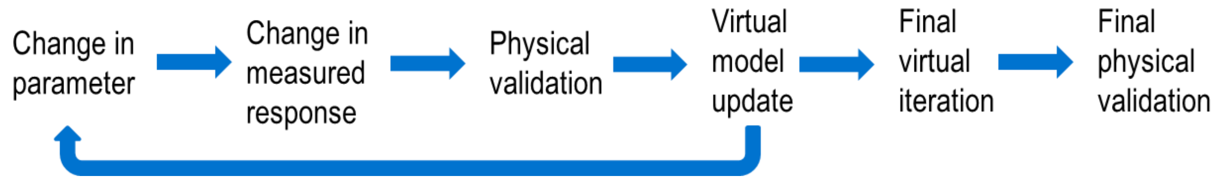


Figure 45: Step-by-Step iteration scheme [A02]

It has been decided to use a Design of Experiment approach that is able to map and predict the system behaviour based on suitable input parameter combinations and their responses. Design of experiment is one of the methods that are used for optimization. Next chapter will get into detail regarding its application to the ALIS problem.

Ultimate idea of both methods is to be able virtually reflect and simulate real physical behaviour of the system. Due to many unknown variables this task represents very complex problem that needs to be understood and patiently tuned.

Until now, all tasks and process have been handled by team of 3 engineers. Implementation of DoE has been assigned to me. There is lack of experience with DoE within crash-safety sector across the industry and hence such a task is supposed to identify new suitable methods and approaches to improve the development.

5.1.4.1 Application of DoE on the ALIS (LS-OPT)

As it was already mentioned, DoE approach is not very common in automotive industry and that is also the case in of TÜV SÜD Czech. After reviewing the ALIS process workflow I suggested to use this approach and use the LS-OPT tool. The reason was simple. LS-OPT is known to me for some time and I needed to solve statistical mechanics problem. It took only few moments to figure out solution as I am aware of LS-OPT capabilities.

5.1.4.1.1 History and tools

As the DoE is a method, many software companies offer their product to perform statistical modelling. One can choose to either write the algorithm by himself or buy commercial solution. In this case, the choice has been set to LS-OPT, developed by Livermore Software Technology Company (LSTC). It offers a design optimization and probabilistic analysis tool for the engineering analyst. LS-OPT is dated back to 1995 from research that has been done in University of Pretoria (South Africa). Since then the industry has been steering development and nowadays there is version 6.0 out.

It enables user to implement the systematic approach of design his own criteria and determine the best combination of variables and additionally use more advanced statistical tools and methods.

5.1.4.1.2 Capabilities of LS-OPT

Even though LS-OPT offers huge functionality it always follows the same process as in Chapter 4.2.6 – planning, design, execution and analysis. By default, it uses the response surface methodology (RSM), which based on input variables and output responses LS-OPT creates n-dimensional response surface as shown on Figure 46 left. Additionally, it may provide one with sensitivity studies as shown on Figure 46 right. More is to be explained on specific case. Only those methods, tools and mathematical apparatus, which have been used are mentioned and explained in this work, for further info please refer to LS-OPT User's Manual [46].

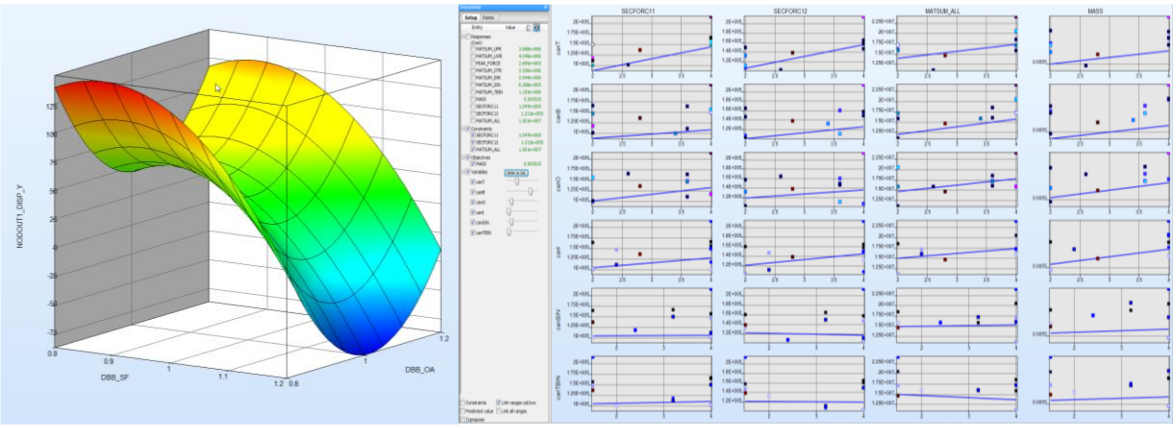


Figure 46: "DoE" Response surface (left) and sensitivity study (right)

5.1.4.1.3 Pre-processing

Firstly, one has to decide which task is to be done. It can be metamodel based:

- Optimization
- DoE Study
- Monte Carlo analysis
- Robust parameter design (RBPD)

In our case it is DoE study as the main focus is on unknown system behaviour and its sensitivity analysis.

The RSM is a method that collects "statistical and mathematical techniques" [46,p.42] for development, study and optimization of any processes. This method requires the analysis of predetermined set of designs. In this case, design means variable combination. Response surface is then fitted to response values using regression analysis and least squares approximations [46; p.34]. The design of experiment has to be well chosen to get appropriate response surface. When the design is chosen poorly, it may cause inaccurate or even incorrect response surface. There are several experimental design criteria available such as

- Factorial design
- Koshal design
- Central composite design
- D-optimal design
- Latin Hypercube Sampling (LHS)
- Space-filling design

5.1.4.1.4 Space-filling desing

For this work has been Space-filling design selected. The main reason is that it offers the best identification approach for unknown non-linear system and/or relationships. It is also often use as basis design, where D-optimal or other design are constructed based on it. The main goal is to create a random set of design points, while it covers evenly the whole design space and hence offers high amount of levels for each variable while maintain medium amount of experimental points. Such designs are very useful in conjunction with neural networks [47].

Probabilistic search techniques, genetic algorithms and adaptative simulated annealing are often used heuristics for approximating the solution to a wide range of the complex problem.

They are frequently used to solve combinatorial optimization problems. LS-OPT uses space-filling designs for these purposes:

- To generate a basis for D-optimal design, without having the full factorial design; having 20 variables and 3 points per variable, then number of points n=320
- To generate a basis for any other approximation types. It is however most suitable for Kriging and neural network

There are six space-filling algorithms available in the LS-OPT as shown on Figure 47.

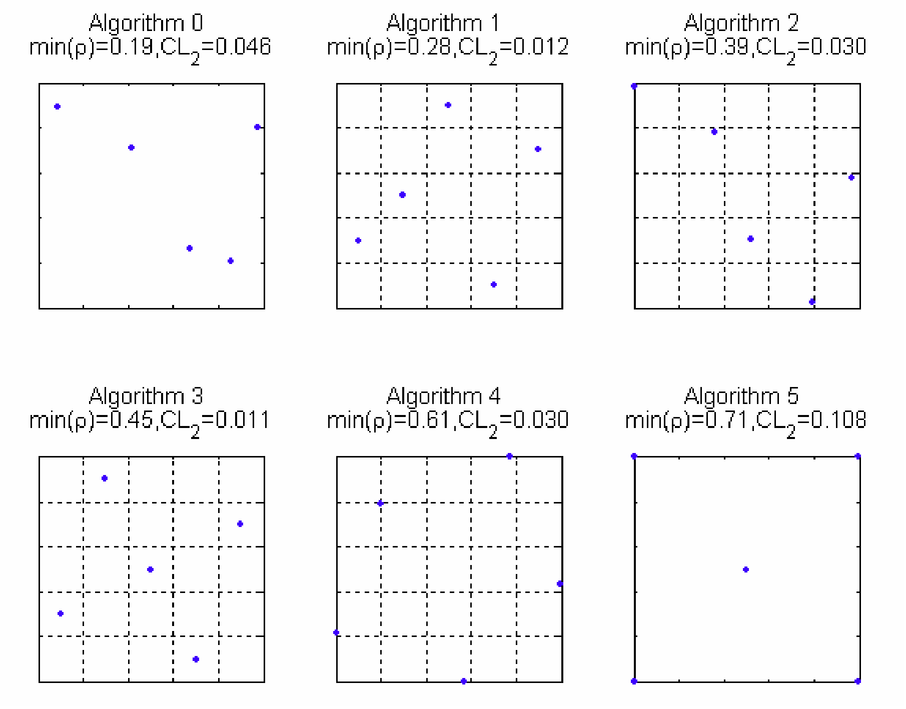


Figure 47: Six space-filling algorithms, 5 points in 2D region

Description of the algorithms is available in the Table 5. [46]

Algorithm Number	Description
0	Random
1	Central point Latin Hypercube Sampling (LHS) design with random pairing
2	Generalized LHS design with random pairing
3	Given an LHS design, permutes the values in each column of the LHS matrix so as to optimize the maximin distance criterion taking into account a set of existing (fixed) design points. This is done using simulated annealing. Fixed points influence the maximin distance criterion but are not allowed to be changed by Simulated Annealing moves.
4	Given an LHS design, moves the points within each LHS subinterval preserving the starting LHS structure, optimizing the maximin distance criterion and taking into consideration a set of fixed points.
5	Given an arbitrary design (and a set of fixed points), randomly moves the points so as to optimize the maximin distance criterion using simulated annealing

Table 5: Description of space-filling algorithms

The algorithm number 3 is used by default.

When used, the space-filling algorithm generates experiments in scatter plot in multiple dimension that is equal the number of variables. Below on Figure 48., it is illustrated a 3-D view of scatter plots of three variables and their ranges that are used in this thesis.

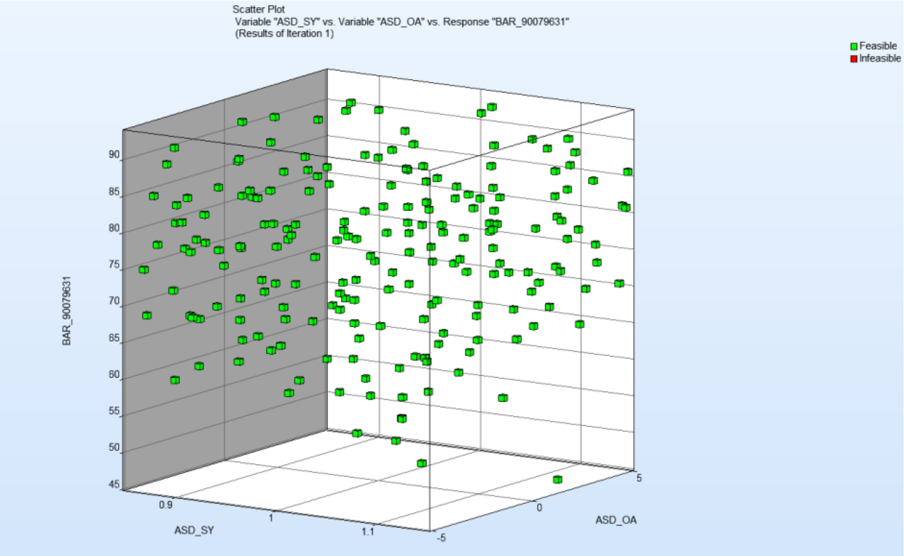


Figure 48: Space-filling scatter plot

There are other tools for statistical and probability analysis and also for accuracy and robustness analyses. On top, there is a possibility to perform optimization with n-iteration cycles and determining the optimal design or Pareto optimum (when more objective functions apply) and trade-off curves can be constructed.

Even though LS-OPT has been developed for LS-DYNA explicit solver as it has incorporated its native pre- and post-processing and also job management, it is capable of process any data. The only requirement is that it has to be in specific format. That makes LS-OPT very powerful tool for statistical analyses.

The overall workflow is displayed on Figure 49, where setup describes how many variables and parameters are to be considered in the problem size.

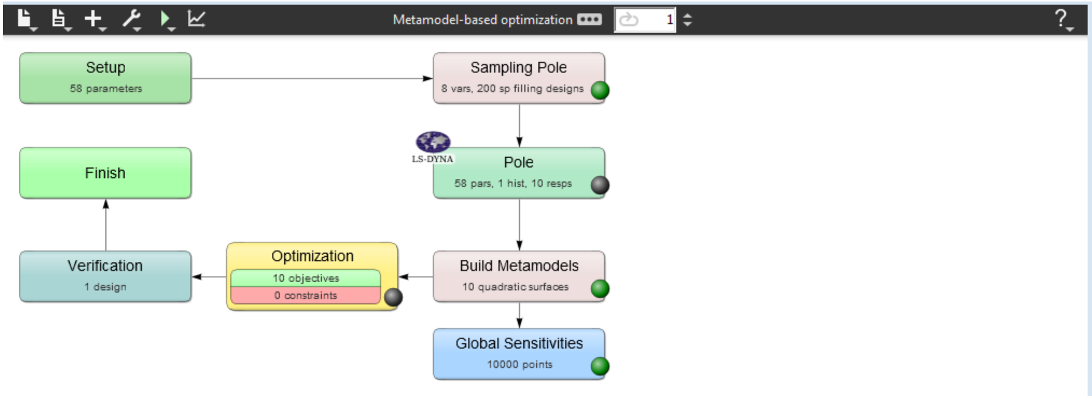
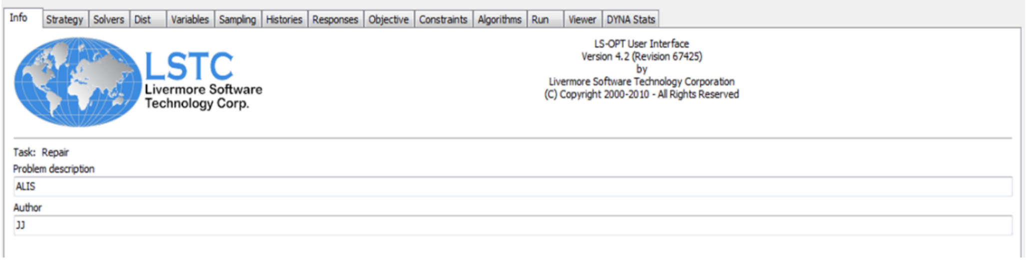


Figure 49: LS-OPT Process flow of ALIS [48]

For more information about DoE and statistical tools please see [48][49][50][51][52][53][54][55]

5.1.4.1.5 Setup of experiments [A02]

LS-OPT has got simple GUI as its input file is simple text file with all necessary information. The very first page of LS-OPT 4.2 is displayed on Figure 50 and holds basic information regarding project data a general overview.

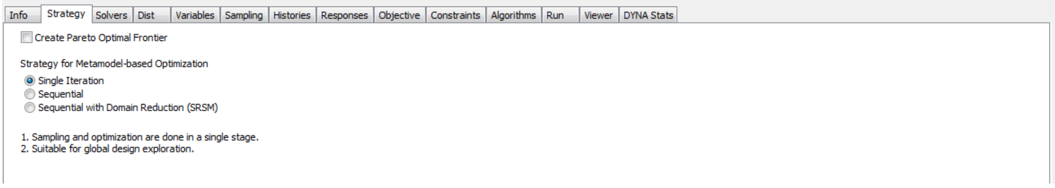


LS-OPT User Interface
Version 4.2 (Revision 67425)
by
Livermore Software Technology Corporation
(C) Copyright 2000-2010 - All Rights Reserved

Task: Repair
Problem description
ALIS
Author
JJ

Figure 50: LS-OPT Intro screen

Next tab is strategy and defines what is to be approach to the problem as shown on Figure 51.



☐ Create Pareto Optimal Frontier

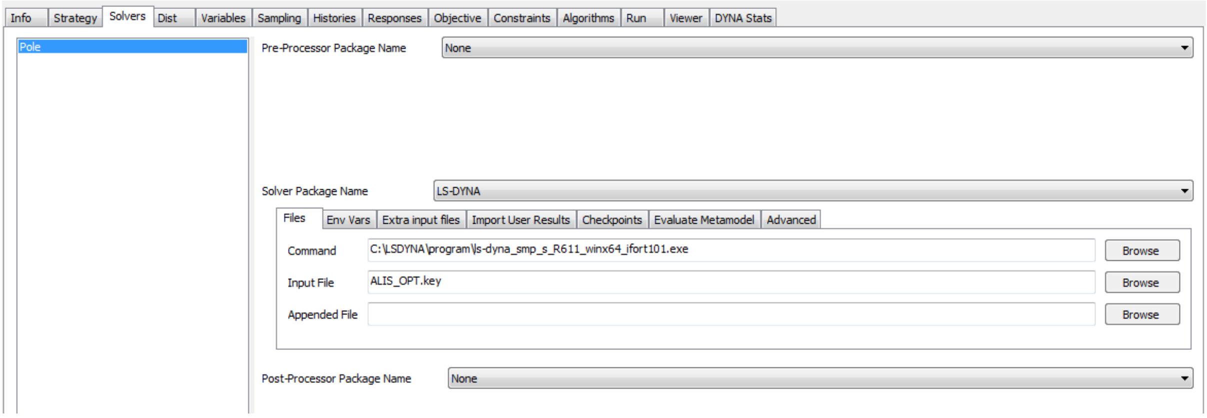
Strategy for Metamodel-based Optimization
● Single Iteration
○ Sequential
○ Sequential with Domain Reduction (SRSM)

1. Sampling and optimization are done in a single stage.
2. Suitable for global design exploration.

Figure 51: LS-OPT Strategy definition tab

Single iteration is the simplest approach and yet in this case also the most suitable one as the main focus is on “exploration” of the system behaviour and no sequential (iterative) optimization.

Solver tab manages pre- and post-processor and solver associated with simulations. In this case there is only one loadcase – pole as seen on Figure 52.



Pole

Pre-Processor Package Name: None

Solver Package Name: LS-DYNA

Command: C:\LSDYNA\program\ls-dyna_smp_s_R611_winx64_ifort101.exe

Input File: ALIS_OPT.key

Appended File:

Post-Processor Package Name: None

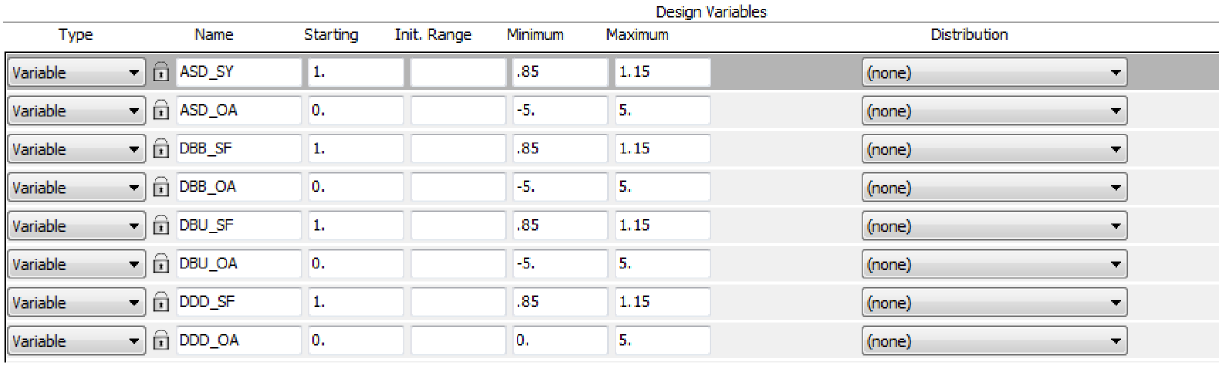
Figure 52: LS-OPT Solver tab

5.1.4.1.6 Variables

Initial pulses (Figure 41 and Figure 43) of ALIS setup, mentioned in Chapter 5.1.3.4, are our design variables and domain. There are four pulses that are considered and they can be broken-down to several input variables that may vary within limits that one can specify. The basic method of pulse tweaking is via scale factors and offset. Scale factors affect the values of both axes ordinate (y-values) and abscissa (x-values). Offset can shift the pulse again in both axes ordinate (y-values) and abscissa (x-values).

Variables can be named and can be limited, i.e. set their maximal and minimal values and also initial value. All this is later used during sampling procedure.

In variables tab there are listed all available variables, their ranges, initial values and distribution as displayed on Figure 53.



Design Variables

Type	Name	Starting	Init. Range	Minimum	Maximum	Distribution
Variable	ASD_SY	1.		.85	1.15	(none)
Variable	ASD_OA	0.		-5.	5.	(none)
Variable	DBB_SF	1.		.85	1.15	(none)
Variable	DBB_OA	0.		-5.	5.	(none)
Variable	DBU_SF	1.		.85	1.15	(none)
Variable	DBU_OA	0.		-5.	5.	(none)
Variable	DDD_SF	1.		.85	1.15	(none)
Variable	DDD_OA	0.		0.	5.	(none)

Figure 53: Variables settings

Following variable abbreviations are used and shown on Figure 54:

- ASD_SY – scale factor of sled
- ASD_OA – pulse offset of sled
- DBB_SF – scale factor of actuator at B-pillar bottom (see Figure 39)
- DBB_OA – pulse offset of actuator at B-pillar bottom (see Figure 39)
- DBU_SF – scale factor of actuator at B-pillar upper (see Figure 39)

- DBB_OA – pulse offset of actuator at B-pillar upper (see Figure 39)
- DDD_SF – scale factor of actuator at door structure (see Figure 39)
- DDD_OA – pulse offset of actuator at door structure (see Figure 39)

There are 8 variables in total that have been used for the DoE.

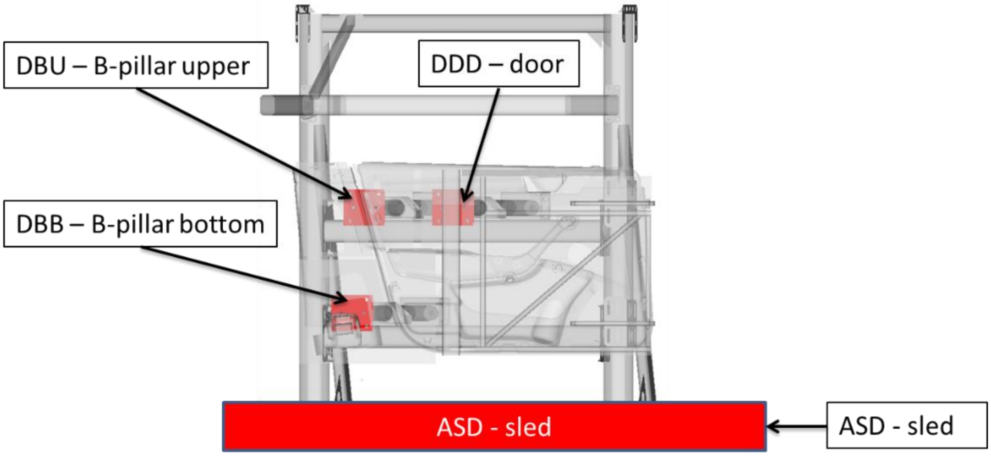
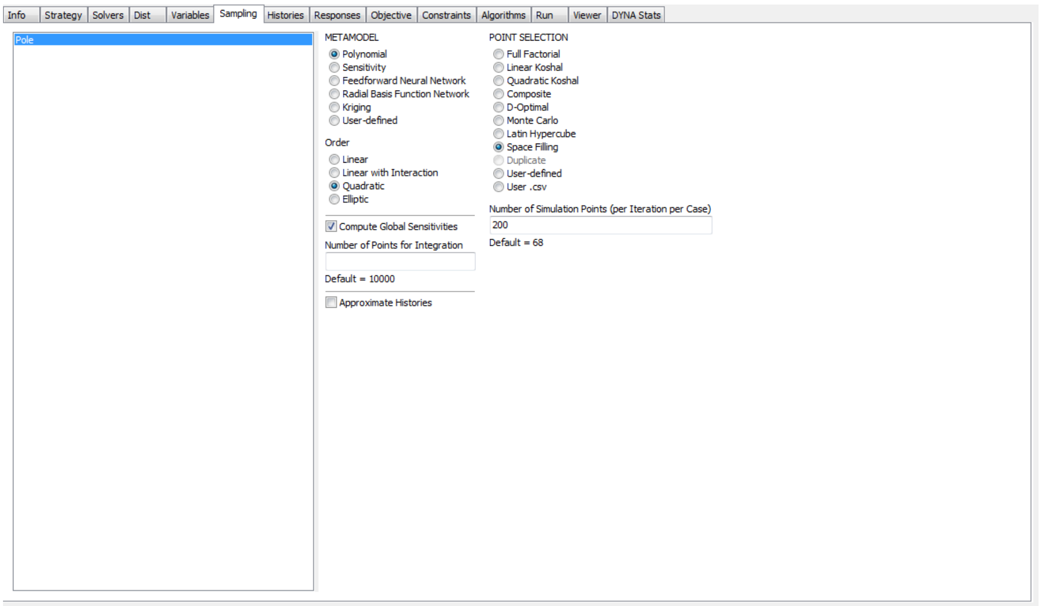


Figure 54: Variables and their location (Courtesy of Škoda Auto)

5.1.4.1.7 Sampling

It is important to point out that the include file that contains pulse definitions has to be slightly updated so LS-OPT is able to read the data correctly. User is then able to switch the variable to the constant, dependent variable or discrete variable if necessary. These are necessary information for the sampling task which is next tab as shown on Figure 55.



METAMODEL
● Polynomial
○ Sensitivity
○ Feedforward Neural Network
○ Radial Basis Function Network
○ Kriging
○ User-defined

Order
○ Linear
○ Linear with Interaction
● Quadratic
○ Elliptic

☑ Compute Global Sensitivities
Number of Points for Integration
Default = 10000
☐ Approximate Histories

POINT SELECTION
○ Full Factorial
○ Linear Koshal
○ Quadratic Koshal
○ Composite
○ D-Optimal
○ Monte Carlo
○ Latin Hypercube
● Space Filling
○ Duplicate
○ User-defined
○ User .csv

Number of Simulation Points (per Iteration per Case)
200
Default = 68

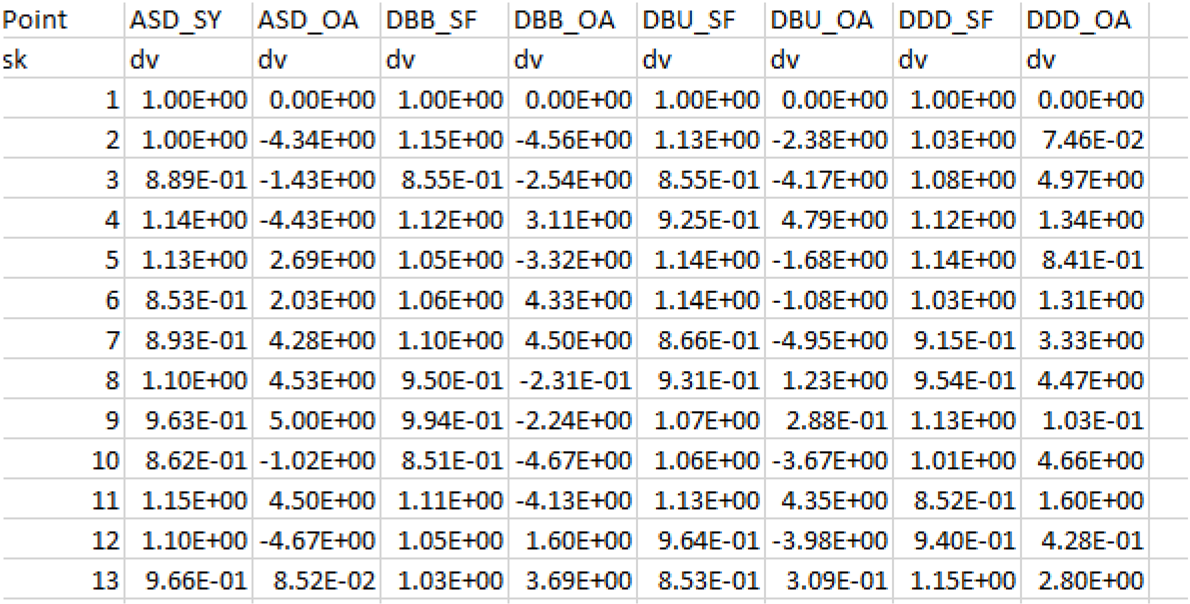
Figure 55: LS-OPT Sampling tab

This tab covers the most important decision regarding the definition of the response surface and metamodel, their order and also design points selection as mention in Chapter 5.1.4.1.4.

Polynomial metamodel has been chosen as it enables to use ANOVA (The ANalysis Of VAriance) later for results evaluation and further steps. For more details about ANOVA see [45.]. It also allows one to use up to quadratic order of the surface.

Due to highly complex and nonlinear nature of the side crash system behaviour, the quadratic order has been chosen. It requires much more experiments to perform, but it repays it with more accurate investigations and relationships among the variables.

As we lack of experience, nor we have any estimated system behaviour, the space-filling point selection has been chosen as mentioned in 5.1.4.1.4. The minimum number experiments for generation of such metamodel is 68. In case, some of the simulations would results in unsuitable design (numerical error, limit state behaviour, etc) and the number of appropriate/valid simulations would drop below 68, the design surface will not be modelled due to insufficient amount of data. Never the less, it is valid that the more, the better and in this case it is valid twice as much. Due to size of ALIS reduced model, we can afford to run more experiments compared to the full vehicle crash within the same time constraints. Therefore, it has been chosen to run 200 experiments in order to get much smoother and accurate response surface. The first thirteen rows of matrix of experiments is displayed on Figure 56.

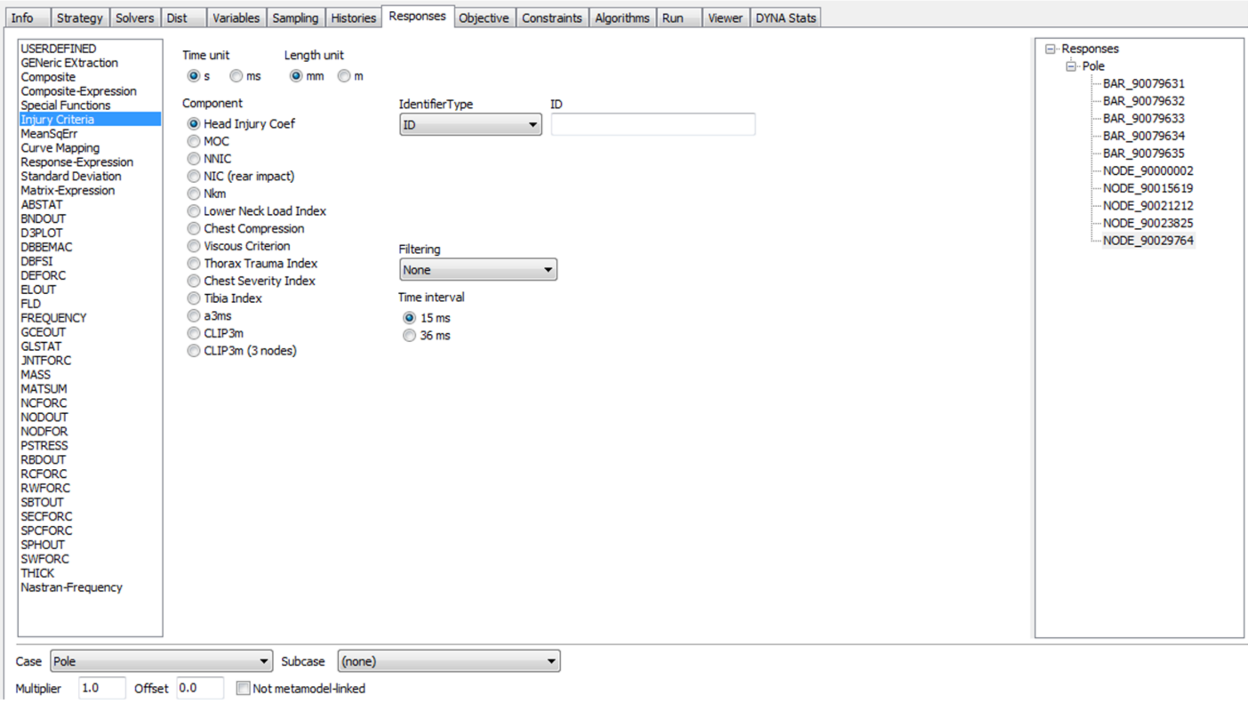


Point	ASD_SY	ASD_OA	DBB_SF	DBB_OA	DBU_SF	DBU_OA	DDD_SF	DDD_OA
sk	dv	dv	dv	dv	dv	dv	dv	dv
1	1.00E+00	0.00E+00	1.00E+00	0.00E+00	1.00E+00	0.00E+00	1.00E+00	0.00E+00
2	1.00E+00	-4.34E+00	1.15E+00	-4.56E+00	1.13E+00	-2.38E+00	1.03E+00	7.46E-02
3	8.89E-01	-1.43E+00	8.55E-01	-2.54E+00	8.55E-01	-4.17E+00	1.08E+00	4.97E+00
4	1.14E+00	-4.43E+00	1.12E+00	3.11E+00	9.25E-01	4.79E+00	1.12E+00	1.34E+00
5	1.13E+00	2.69E+00	1.05E+00	-3.32E+00	1.14E+00	-1.68E+00	1.14E+00	8.41E-01
6	8.53E-01	2.03E+00	1.06E+00	4.33E+00	1.14E+00	-1.08E+00	1.03E+00	1.31E+00
7	8.93E-01	4.28E+00	1.10E+00	4.50E+00	8.66E-01	-4.95E+00	9.15E-01	3.33E+00
8	1.10E+00	4.53E+00	9.50E-01	-2.31E-01	9.31E-01	1.23E+00	9.54E-01	4.47E+00
9	9.63E-01	5.00E+00	9.94E-01	-2.24E+00	1.07E+00	2.88E-01	1.13E+00	1.03E-01
10	8.62E-01	-1.02E+00	8.51E-01	-4.67E+00	1.06E+00	-3.67E+00	1.01E+00	4.66E+00
11	1.15E+00	4.50E+00	1.11E+00	-4.13E+00	1.13E+00	4.35E+00	8.52E-01	1.60E+00
12	1.10E+00	-4.67E+00	1.05E+00	1.60E+00	9.64E-01	-3.98E+00	9.40E-01	4.28E-01
13	9.66E-01	8.52E-02	1.03E+00	3.69E+00	8.53E-01	3.09E-01	1.15E+00	2.80E+00

Figure 56: Partial matrix of experiments (first 13 rows)

5.1.4.1.8 Responses

For response surface determination it is necessary to get responses (on Figure 56) respective to our objectives. Responses are resultants of any measurements such as force, displacement, acceleration, angle, etc. Response list is given by the scope of the sensitivity study. In our case it is listed on the right column on Figure 57.



Time unit ● s ○ ms
Length unit ● mm ○ m

Component
● Head Injury Coef
○ MOC
○ NNIC
○ NIC (rear impact)
○ Nkm
○ Lower Neck Load Index
○ Chest Compression
○ Viscous Criterion
○ Thorax Trauma Index
○ Chest Severity Index
○ Tibia Index
○ a3ms
○ CLIP3m
○ CLIP3m (3 nodes)

IdentifierType: ID
ID:

Filtering: None
Time interval
● 15 ms
○ 36 ms

Responses
- Pole
  - BAR_90079631
  - BAR_90079632
  - BAR_90079633
  - BAR_90079634
  - BAR_90079635
  - NODE_90000002
  - NODE_90015619
  - NODE_90021212
  - NODE_90023825
  - NODE_90029764

Case: Pole
Subcase: (none)
Multiplier: 1.0
Offset: 0.0
☐ Not metamodel-linked

Figure 57: LS-OPT Response tab

In all crash simulations, the most important are biomechanical loads that describes the behaviour of a human body during the crash event. The requirements differ very much from case to case so it is always unique set of criteria that are ideally to be matched. In our pole strike, it is ribs compression. Nowadays, most of the dummies and solvers are able to calculate and/or evaluate these criteria directly via sensors/points of interests. In our case several node and bars have been selected. Nodes are used for tuning of controlled trim deformation and its velocity. Simply the velocity and deformation of the trim ensures the same initial conditions as per full crash. Bar then are used for force (shoulder) and displacement (rib compression) evaluation. This metric is the most important for most of the safety crash engineers.

Responses are used for response surface modelling and results evaluation. In our case there are several responses taken into account. They have been chosen according to the requirements of the customer and also EuroNCAP. Responses that have been used are shown in Table 6.

ID	Type	Name	Component	Units
90079631	BAR	First thorax rib	Compression	mm
90079632		Second thorax rib	Compression	mm
90079633		Third thorax rib	Compression	mm
90079634		First abdomen rib	Compression	mm
90079635		Second abdomen rib	Compression	mm
90000002	NODE	Head acc	Acceleration, velocity	mm ms^{-2} / mm ms^{-1}
90015619		T1 Lower neck acc	Acceleration, velocity	mm ms^{-2} / mm ms^{-1}
90021212		T4 first thorax acc	Acceleration, velocity	mm ms^{-2} / mm ms^{-1}
90023825		T12 second abdomen acc	Acceleration, velocity	mm ms^{-2} / mm ms^{-1}
90029764		Pelvis acc	Acceleration, velocity	mm ms^{-2} / mm ms^{-1}

Table 6: List of responses

It also shows what components and their units are used. Location of the ribs (bars) and accelerometers (nodes) are displayed on Figures 58 and Figure 59.

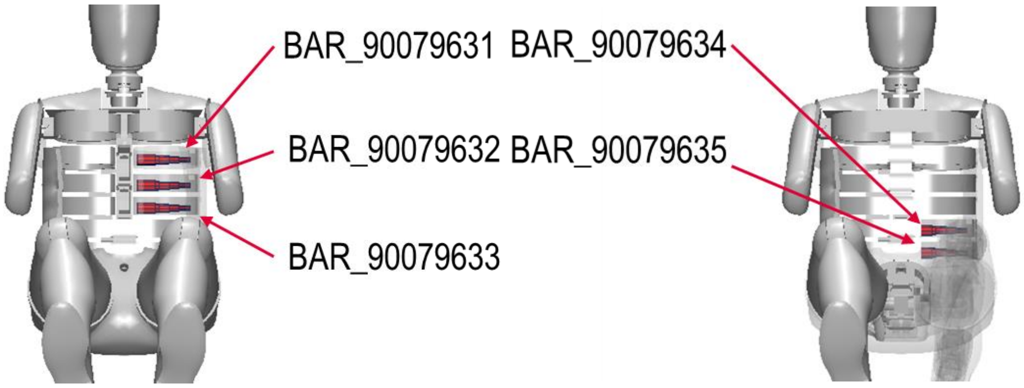


Figure 58: Positions of springs (bars) in WorldSID 50%

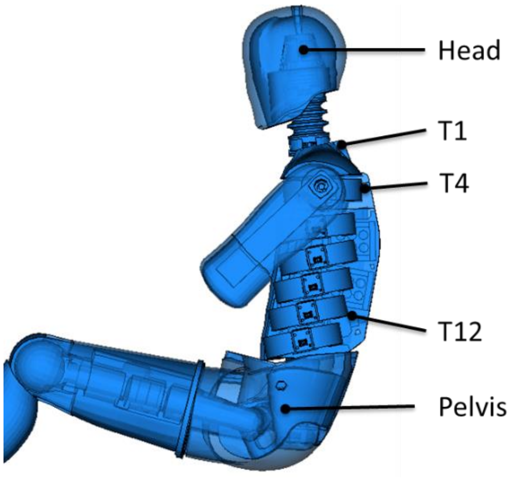
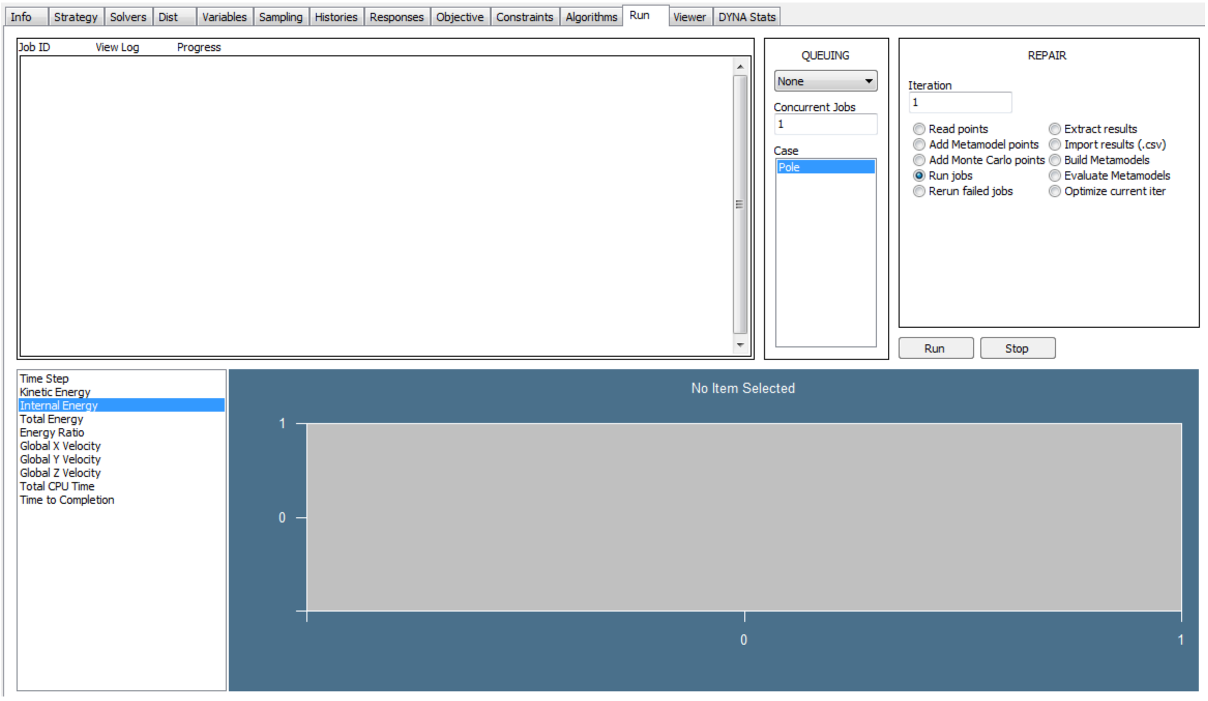


Figure 59: Positions of accelerometers (nodes) in WorldSID 50%

We are using both types of responses bars and nodes as matching criteria for system tuning. EuroNCAP takes into account rib compression. Nodal accelerations and velocities are used for pulse tuning purposes that ensure correct behaviour.

5.1.4.1.9 Job (Run) management

The last pre-processing tab is related to the Job management and can be seen on Figure 60.



QUEUING
None
Concurrent Jobs: 1
Case: Pole

REPAIR
Iteration: 1
○ Read points
○ Add Metamodel points
○ Add Monte Carlo points
● Run jobs
○ Rerun failed jobs
○ Extract results
○ Import results (.csv)
○ Build Metamodels
○ Evaluate Metamodels
○ Optimize current iter

Figure 60: LS-OPT Run tab

This tab closes the pre-processing stage. Now the setup of experiments is ready and needs to be created, simulated and evaluated. Since 200 experiments have been selected, the LS-OPT is to create 200 input decks with all possible combinations of variables according to the space-filling algorithm 5 (see Chapter 5.1.4.1.4), which is default settings.

Number of variables in fact defines dimension of the design space. Since there are 8 variables, the resultant design space will be 8D. Since there is no simple way of illustrating the 8D interactions, we have to go down to 3D visualisation. When always 3 variables are selected and can be switched for any other variable. Scatter plot of the pole strike variable combination is shown on Figure 48.

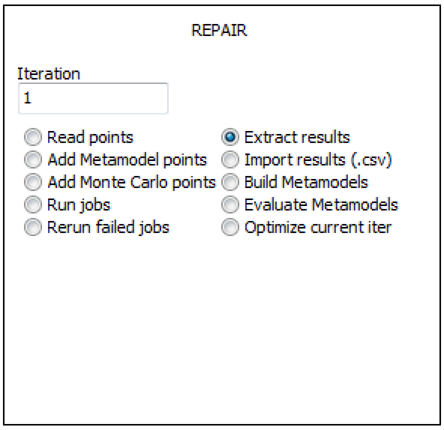
All 200 experiments (simulations) have to be run.

5.1.4.1.10 Post-processing

Firstly, all simulations have to be checked. The aim is to ensure correct behaviour and no ill results (responses). This check is very important, because if it would not have been done, it would have significant effect on the accuracy of the response surface. In case, some of the simulations are not valid due to any reason, they have to be eliminated from the matrix of experiments. That will reduce the amount of valid experiments, however it also ensures desired accuracy. That is also a reason why to make much more than minimal number of experiments as mentioned in Chapter 5.1.4.1.7.

5.1.4.1.11 Results extraction

Luckily all results can be extracted from all experiments on single click via Extract results button as displayed on Figure 61. The software generates matrix of all available results (responses) assigned to respective experiments.



REPAIR

Iteration
1

○ Read points
○ Add Metamodel points
○ Add Monte Carlo points
○ Run jobs
○ Rerun failed jobs
● Extract results
○ Import results (.csv)
○ Build Metamodels
○ Evaluate Metamodels
○ Optimize current iter

Figure 61: Extract results button on Job tab

5.1.4.1.12 Experiments extension and import

Since ALIS tuning is on the full crash simulation, it is necessary to study initial results and decide what values are of interest. The biomechanical results of rib compressions of the full crash are shown on Figure 62.

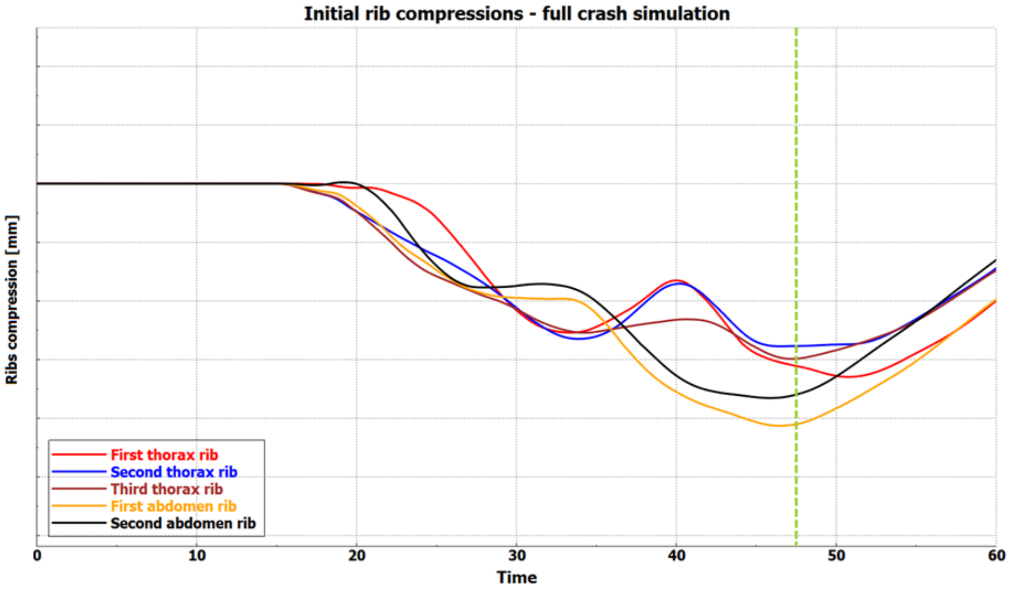


Figure 62: Target values at time 48ms

Based on the graph, it is clear, that maximal values for most of the ribs is around 48ms. This is the time, when all responses are to be extracted from all experiments.

The matrix of experiments, cleared from unsuitable simulations, and with all variable combinations that have been used is then updated – extended with all responses. That means the matrix of experiments now contains also values of responses in respective experiments

When the matrix of experiments meets all necessary requirements in terms of length, width and data content is has to be loaded into LS-OPT again and used for results import as shown on Figure 63.

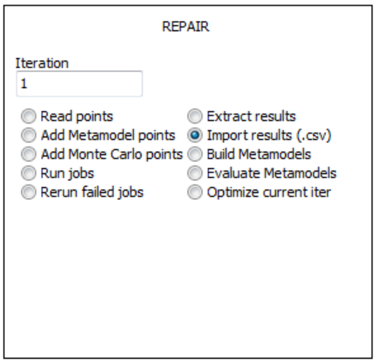


Figure 63: Import results button on Job tab

5.1.4.1.13 Metamodel setup and validation

Since a polynomial and quadratic response surface has been chosen during sampling stage, the higher order of the response surface will be generated from all available values of variables and responses. The response surface is constructed via command Build metamodels as shown on Figure 64 left. In order to validate the metamodel, responses are derived back from the response surface and compared to the initial ones. In ideal case they are the same. This method eliminates potentially corrupted data. This is triggered by command Evaluate Metamodels as indicated on Figure 64 right.

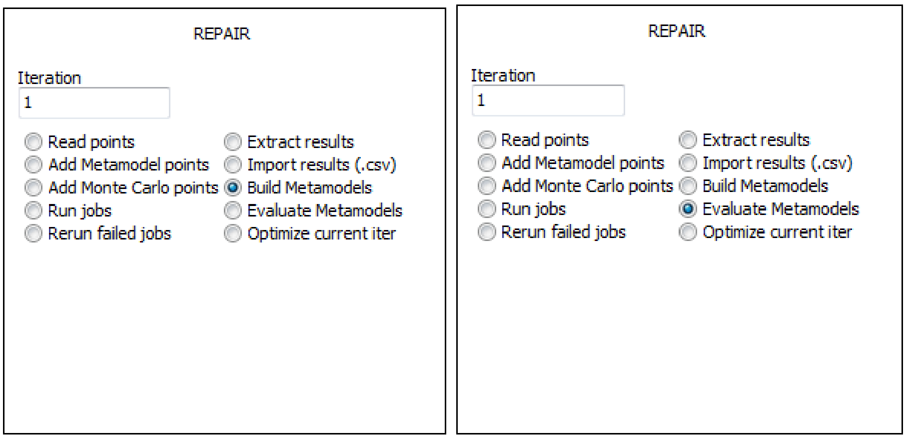


Figure 64: Button of metamodel creation (left) and metamodel evaluation button (right)

5.1.4.1.14 Results visualization

LS-OPT has got also graphical user interface for results visualization as shown on Figure 65. The main menu is split into five categories:

- Simulations
- Metamodel
- Optimization
- Pareto Optimal Solutions
- Stochastic Analysis

Only highlighted icons can be chosen. Other do not have sufficient data. As our primary target is to carry out sensitivity study and no optimization, these data are not available.

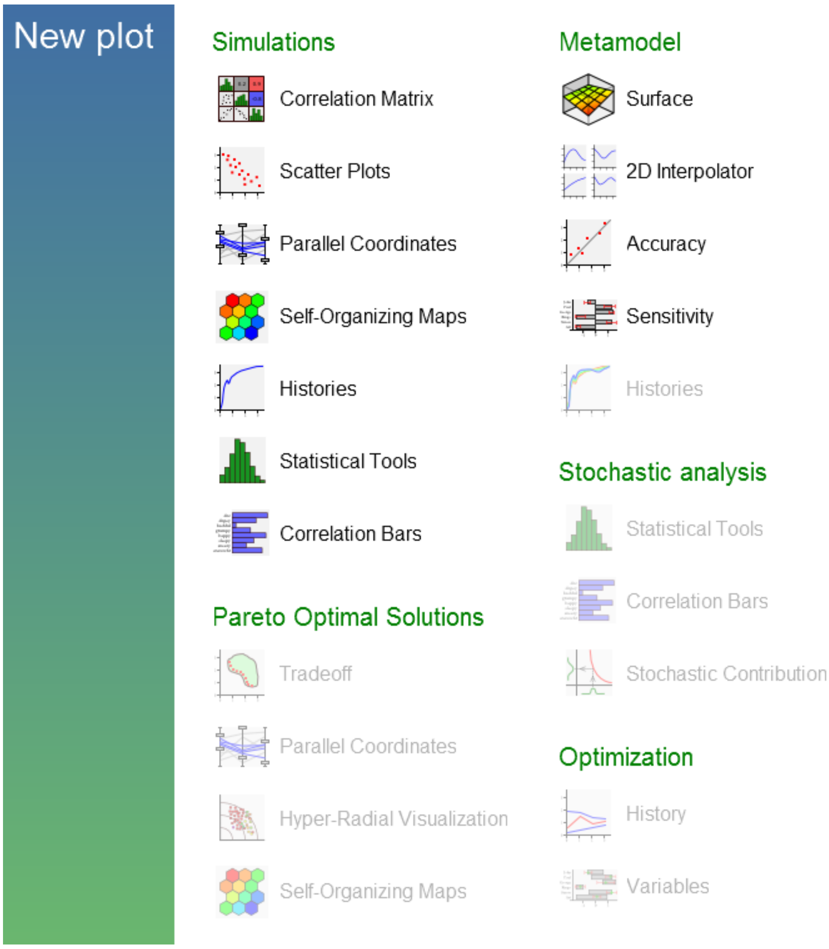
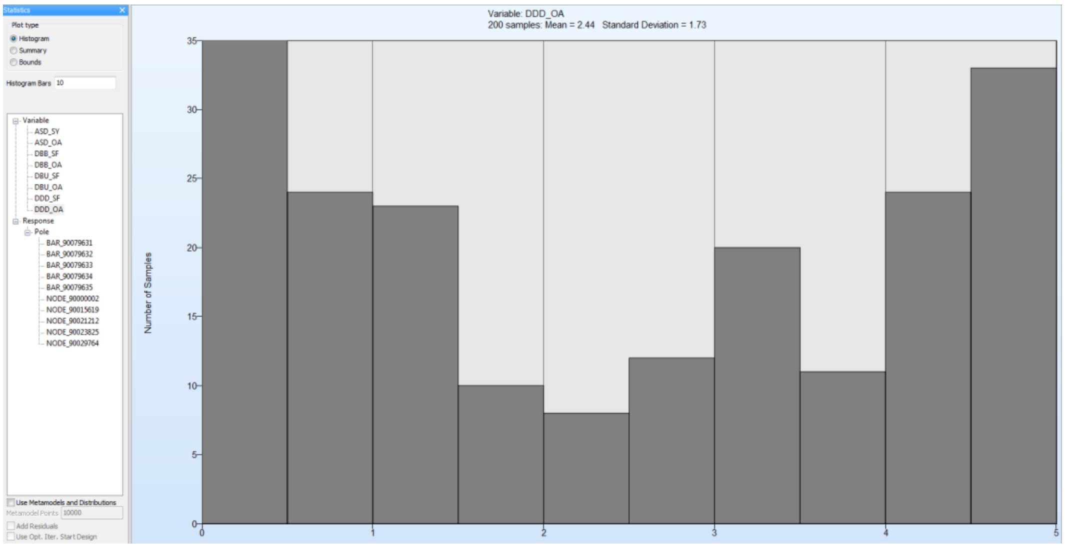


Figure 65: Main page of LS-OPT viewer

5.1.4.1.15 Visualization of simulation results

There are several options available for simulation results. We will not go through all of them but will select only the ones of interest

Statistics allows to visually check the distribution of the variables and response within the given range. On Figure 66, the distribution of variable DDD_OA through experiments can be seen. It is reasonable to have slightly higher amount of experiments around boundaries as no one knows what is just behind the limit and in what slope. The more boundary values, the higher accuracy around the limit values of ranges.



Plot type
● Histogram
○ Summary
○ Bounds

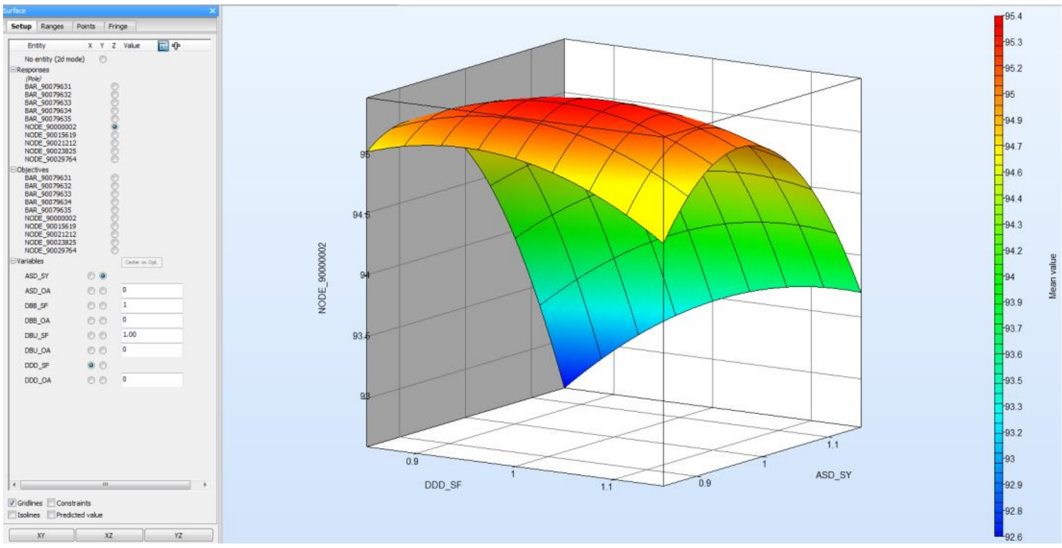
Histogram Bars 10

☐ Use Metamodels and Distributions
Metamodel Points 10000
☐ Add Residuals
☐ Use Opt. Iter. Start Design

Variable: DDD_OA
200 samples: Mean = 2.44 Standard Deviation = 1.73

Figure 66: Statistical tool for distribution of values

So far these features have been extracted from simulations data. Metamodel is built and created via mathematical apparatus from available data. Even though it may be of high order, it does not have to perfectly match all experiments. The main goal is to describe all relationships among input variables and responses. Example and visual relationship among variables and response is illustrated on Figure 67.



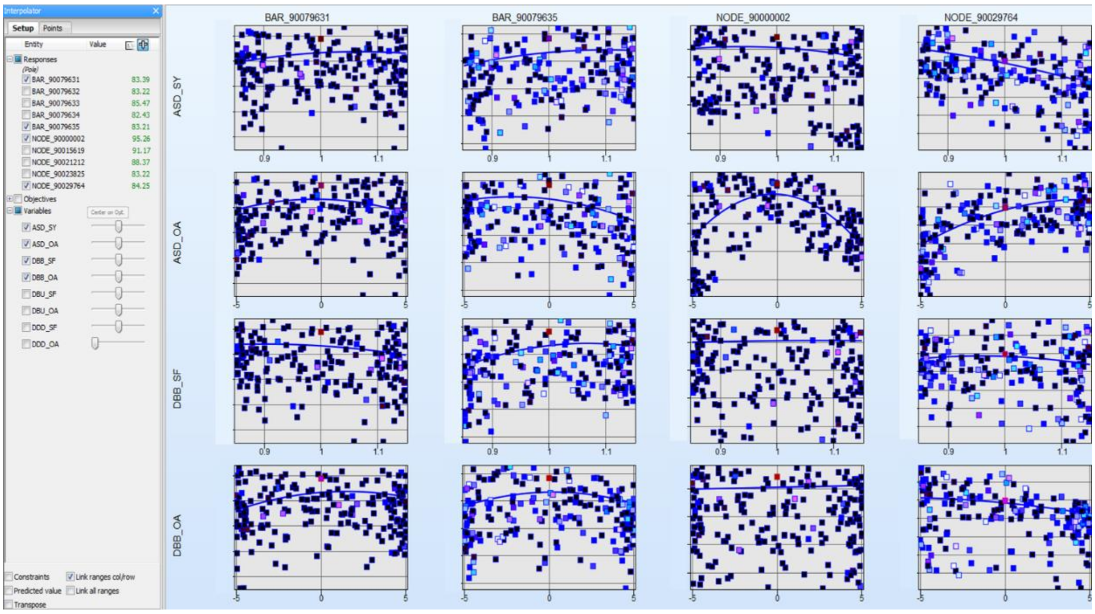
Responses (Pole): ● NODE_90000002
Variables:
ASD_SY: Y ●
ASD_OA: 0
DBB_SF: 1
DBB_OA: 0
DBU_SF: 1.00
DBU_OA: 0
DDD_SF: X ●
DDD_OA: 0

☑ Gridlines ☐ Constraints
☐ Isolines ☐ Predicted value

Figure 67: RSM between variables and response

One may also notice that it is not a plane surface but shaped. This is due to higher order (quadratic) option chosen during sample stage. It is very useful when one has to trade off one variable for another in order to get the best combination for his own design.

Example of 2D interpolator, that is pretty much simple conversion of the surface data into graphs, is shown on Figure 68.



Interpolator

Setup | Points

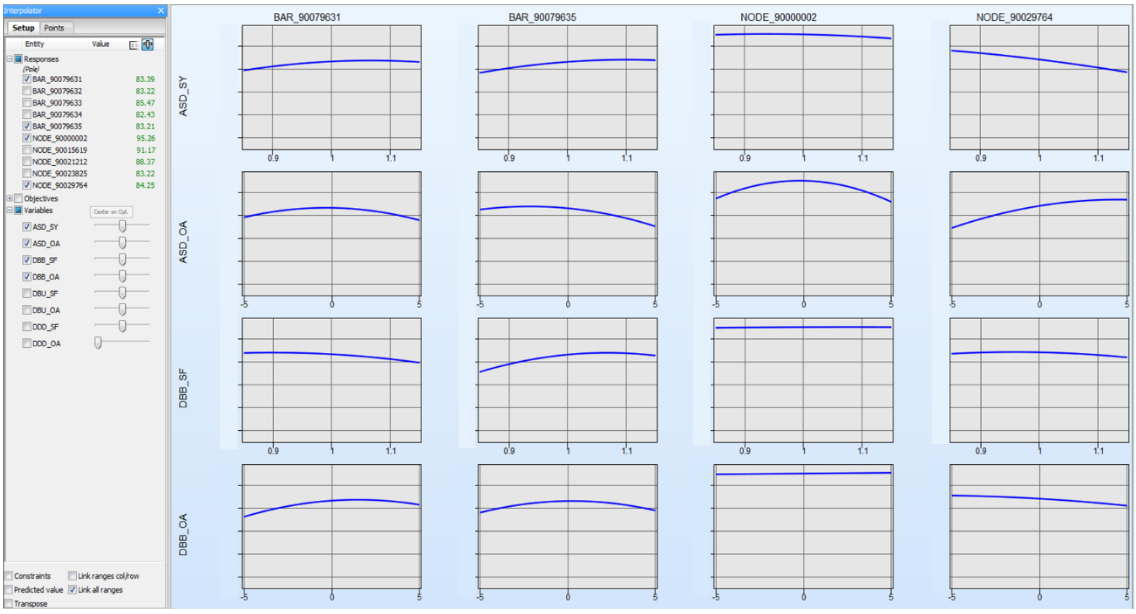
Entity	Value
⊟ Responses	
(Pole)	
☑ BAR_90079631	83.39
☐ BAR_90079632	83.22
☐ BAR_90079633	85.47
☐ BAR_90079634	82.43
☑ BAR_90079635	83.21
☑ NODE_90000002	95.26
☐ NODE_90015619	91.17
☐ NODE_90021212	88.37
☐ NODE_90023825	83.22
☑ NODE_90029764	84.25
⊞ ☐ Objectives	
⊟ Variables	Center on Opt.
☑ ASD_SY	
☑ ASD_OA	
☑ DBB_SF	
☑ DBB_OA	
☐ DBU_SF	
☐ DBU_OA	
☐ DDD_SF	
☐ DDD_OA	

☐ Constraints ☑ Link ranges col/row
☐ Predicted value ☐ Link all ranges
☐ Transpose

Figure 68: Trend visualisation in 2D interpolator (selected responses and variables)

There are also shown all experiments (points) and cut section through RSM. The same figure without experiments (points) and with link ranges is displayed below on Figure 69. Link ranges put all axes into uniform range so one can easily identify right trends. The sliders next to the variables on the left column also enables one to changes values of variables and instantaneously see effect on responses.

This tool is extremely useful when one is trying to understand system behaviour as it simply shows how is the response changes with variable changing and yet it is in instant.



Interpolator

Setup | Points

Entity	Value
Responses (Pole)	
☑ BAR_90079631	83.39
☐ BAR_90079632	83.22
☐ BAR_90079633	85.47
☐ BAR_90079634	82.43
☑ BAR_90079635	83.21
☑ NODE_90000002	95.26
☐ NODE_90015619	91.17
☐ NODE_90021212	88.37
☐ NODE_90023825	83.22
☑ NODE_90029764	84.25

☐ Objectives

Variables

- ☑ ASD_SY
- ☑ ASD_OA
- ☑ DBB_SF
- ☑ DBB_OA
- ☐ DBU_SF
- ☐ DBU_OA
- ☐ DDD_SF
- ☐ DDD_OA

☐ Constraints ☐ Link ranges col/row
☐ Predicted value ☑ Link all ranges
☐ Transpose

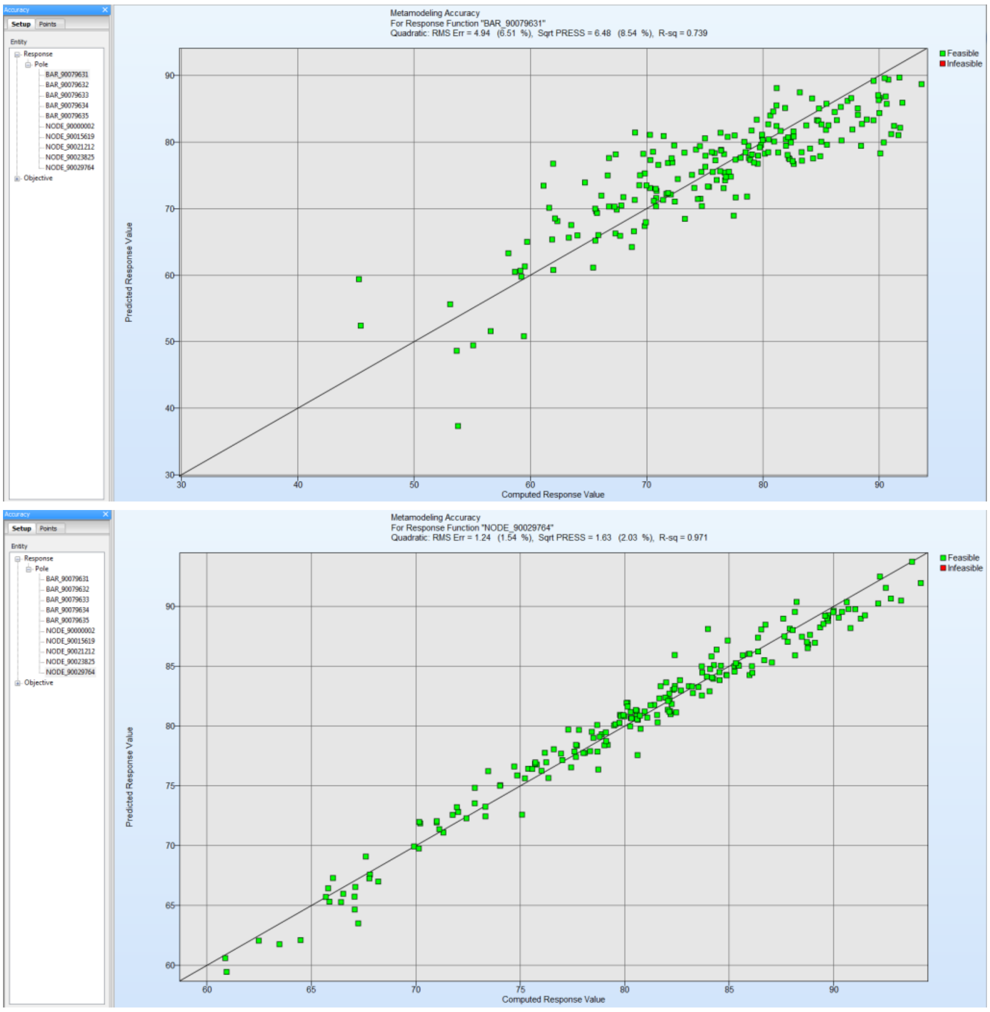
Figure 69: Trend visualisation in 2D interpolator (selected responses and variables)

It is very important to note, that expect for the experiments, the predicted results are based on mathematical approximation and have to be validated. The main response surface benefit is that is fills out non-computed combinations of variables and therefore still can predict a response value.

Until now we have looked at results and mathematical description of response surface. One of the most important topics has not been discussed yet. Accuracy of the response surface. How can one say the response surface and results that are derived from there are accurate?

5.1.4.1.16 Accuracy plot

The metamodel accuracy is shown on Figure 70. It is for selected response and it is shown as computed vs. predicted plots. Accuracy of each response is measure as an error in header together with experiment points along the line. Ideally the predicted and computed values are the same and hence would be along the axis of the 1st quadrant. For illustration two accuracy plots are displayed. One with the worst (top) and one with best accuracy (bottom).

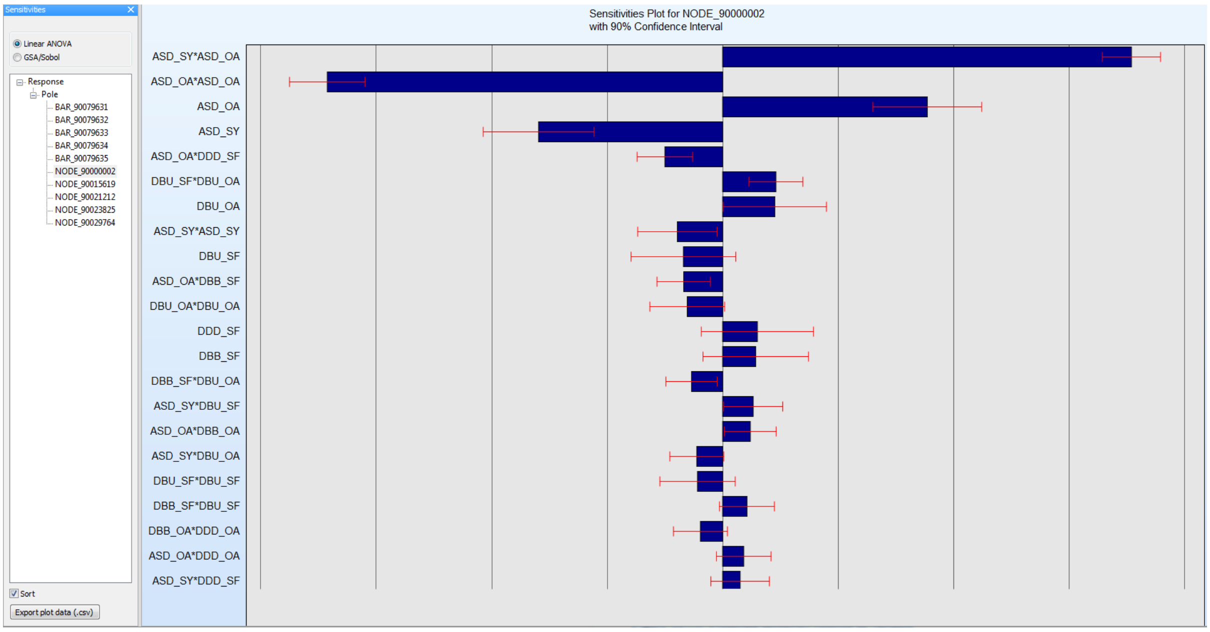


Metamodeling Accuracy
For Response Function "BAR_90079631"
Quadratic: RMS Err = 4.94 (6.51 %), Sqrt PRESS = 6.48 (8.54 %), R-sq = 0.739

Metamodeling Accuracy
For Response Function "NODE_90029764"
Quadratic: RMS Err = 1.24 (1.54 %), Sqrt PRESS = 1.63 (2.03 %), R-sq = 0.971

Figure 70: Accuracy plots with scatter plots of all valid experiments - the worst accuracy error 6.54% (top) and the best accuracy error 1.54% (bottom)

There is another very useful feature in LS-OPT. It is ANOVA of the approximation to the experimental design. The ANOVA method is very often used for identification of insignificant variables and it is more sophisticated version of DoE or Sensitivity study. An example is illustrated on Figure 71.



● Linear ANOVA
○ GSA/Sobol
☑ Sort

Figure 71: Linear ANOVA visualisation of significance

According to the picture the user can in latter stages reduce the number of variables and hence reduce the problem size or get into much more detail via higher number of experiments for less variables.

LS-OPT source file is printed in the Appendix A.

For more information and details see LS-OPT manual [46]

5.1.4.2 *Results of the virtual experiments [A04]*

So far we have been preparing ourselves for the main task. To choose suitable variables from all available sources to achieve the intended responses. Now, when the response surface has been created and validated, the selection of variable that would fit the intended values follows.

The main reason of the virtual experiments is to perform sensitivity analyses that would later give a good knowledge of the system behaviour. This is particularly useful during the physical testing, when quick response to the current behaviour and recommendation of the next steps is highly expected and there is no time for further simulations. The whole procedure as described in previous Chapter 5.1.4.1.16 has proven the response surface accuracy and hence result trustworthiness. In order to get ideal pulse configurations for respective biomechanical responses, it is necessary to set the target. EuroNCAP assessment is based on scoring system of the maximal biomechanical loads.

For illustration there is a comparison of initial ALIS run, with all variables equal to 1, and full crash model shown on Figure 72.

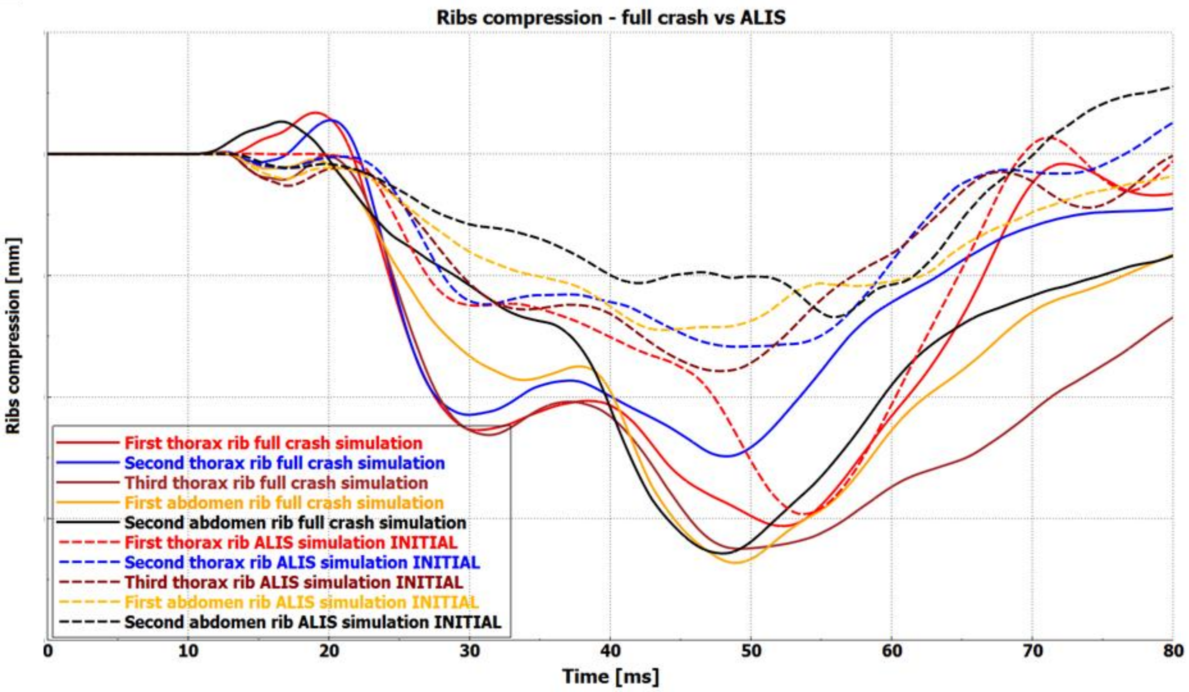
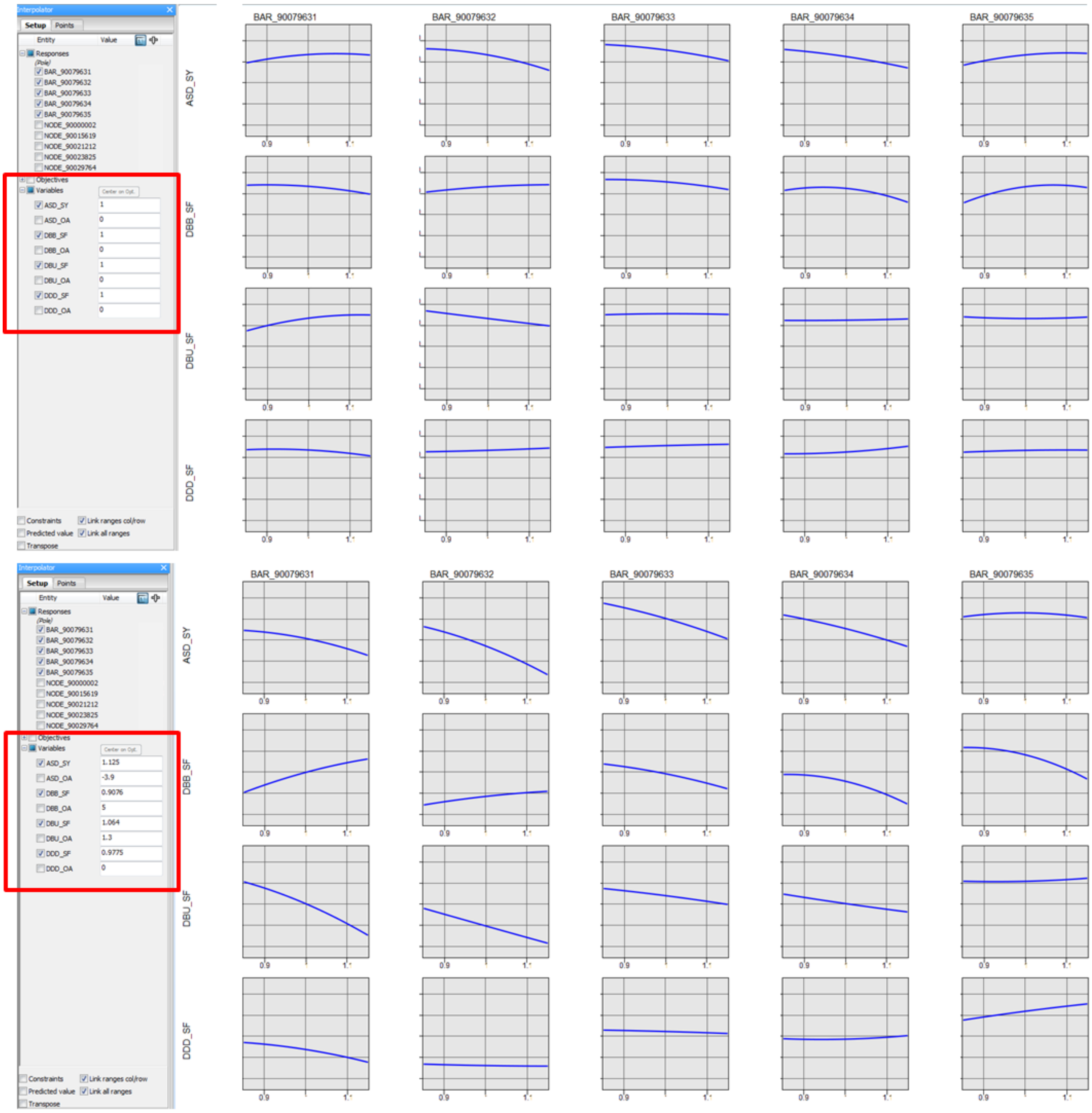


Figure 72: Comparison of initial ALIS vs full crash results (ribs)

The match is not ideal one at the moment and our goal is to get better match. Hence there has to be an update done of some or all available pulses (scale factor or offset). The suitable variable combinations can be found by user to achieve his requirements. LS-OPT can easily predict response values based when one changes the input variables as indicated on Figure 73.



☑ BAR_90079631
☑ BAR_90079632
☑ BAR_90079633
☑ BAR_90079634
☑ BAR_90079635
☐ NODE_90000002
☐ NODE_90015619
☐ NODE_90021212
☐ NODE_90023825
☐ NODE_90029764

☑ ASD_SY 1
☐ ASD_OA 0
☑ DBB_SF 1
☐ DBB_OA 0
☑ DBU_SF 1
☐ DBU_OA 0
☑ DDD_SF 1
☐ DDD_OA 0

☐ Constraints ☑ Link ranges col/row
☐ Predicted value ☑ Link all ranges
☐ Transpose

☑ BAR_90079631
☑ BAR_90079632
☑ BAR_90079633
☑ BAR_90079634
☑ BAR_90079635
☐ NODE_90000002
☐ NODE_90015619
☐ NODE_90021212
☐ NODE_90023825
☐ NODE_90029764

☑ ASD_SY 1.125
☐ ASD_OA -3.9
☑ DBB_SF 0.9076
☐ DBB_OA 5
☑ DBU_SF 1.064
☐ DBU_OA 1.3
☑ DDD_SF 0.9775
☐ DDD_OA 0

☐ Constraints ☑ Link ranges col/row
☐ Predicted value ☑ Link all ranges
☐ Transpose

Figure 73: The response trends based on initial variable combination (top) and response trends based on update variable combination (bottom)

This is exactly the way how to better understand mutual interaction between input variables and responses.

In our case, when the five ribs are of interest, we get desired response with following variables written in Table 7.

Label	Name	Value	Initial values
ASD_SY	scale factor of sled	1.02	No
ASD_OA	pulse offset of sled	0	Yes
DBB_SF	scale factor of actuator at B-pillar bottom	1.11	No
DBB_OA	pulse offset of actuator at B-pillar bottom	0	Yes
DBU_SF	scale factor of actuator at B-pillar upper	1.03	No
DBU_OA	pulse offset of actuator at B-pillar upper	0	Yes
DDD_SF	scale factor of actuator at door structure	0.98	No
DDD_OA	pulse offset of actuator at door structure	1	No

Table 7: Final variable values

As these values are predicted, another testing run has to be to verify the suitability. Updated three pulses for ALIS and one for sled are shown on Figure 74 and Figure 75.

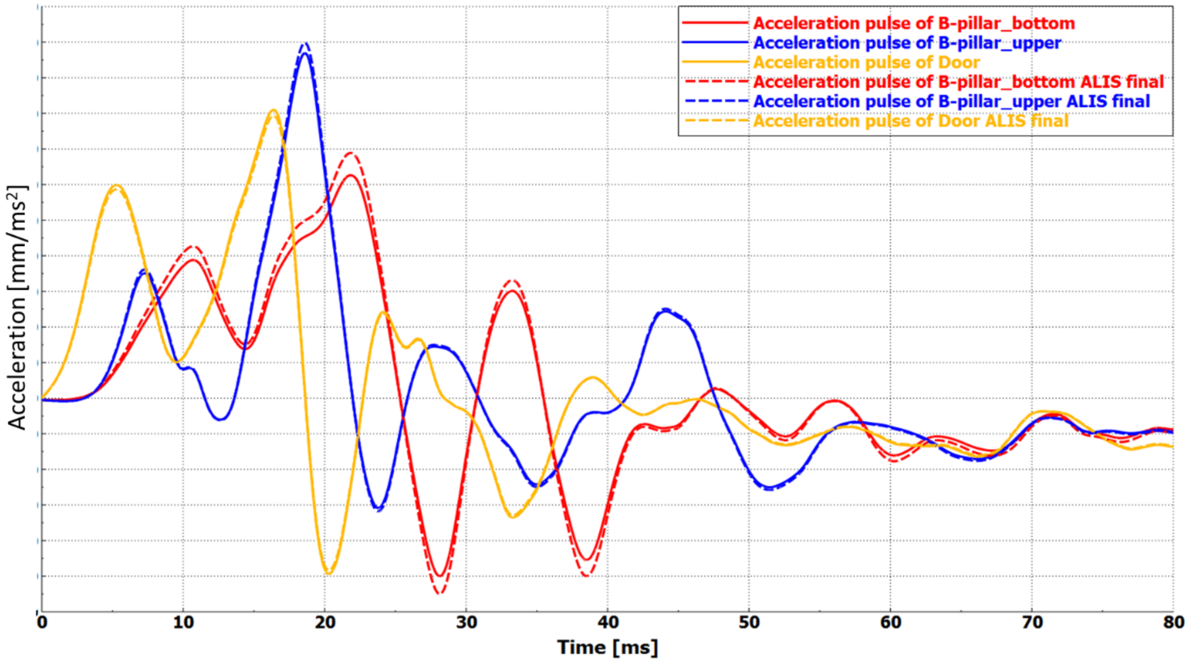


Figure 74: Comparison of initial and final ALIS pulses

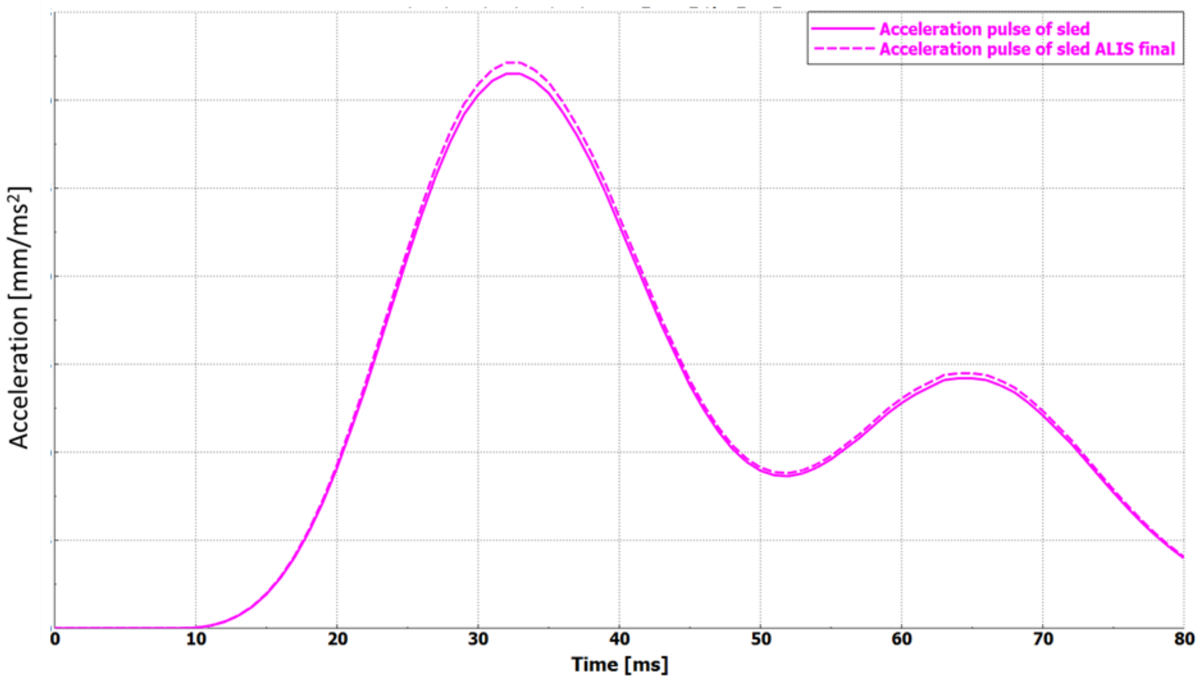


Figure 75: Comparison of initial and final sled pulse

Updated ALIS results of dummy biomechanical criteria compared to full crash data are displayed on Figure 76.

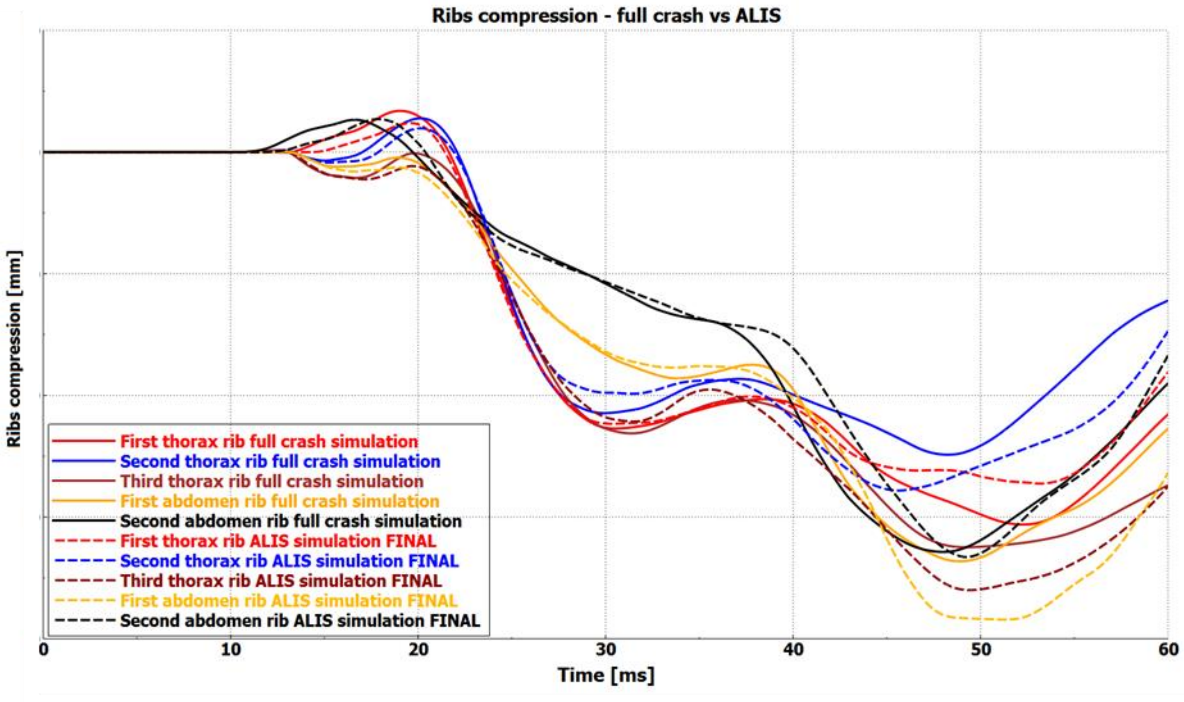


Figure 76: Comparison of rib compressions for initial and final sled pulses

The comparison shows rather good match of both simulation approaches. Reduced model is and always will be only approximation and can only get close to the full crash simulation model. Four pulses with reasonable match to the full crash model have been found and hence the first objective is complete. Secondary objective was to get a good knowledge of the system behaviour and it has also been done. It will become very useful in upcoming testing. This chapter has been done mostly by the author. Submitting and results evaluation have been done by CAE engineers under author's leadership.

5.1.5 Stage 5: Successful physical crash test with ALIS

Physical experiment presents the ultimate stage of every project. In the end the virtual simulation part is only a preparation work for the "moment of truth". Now all the outputs of simulation part become input of the physical experiment. Outputs are following:

- Impact structure (design + technical documentation)
- Specification of actuator positions with respect to the main frame
- Sled pulse
- Actuator pulses

5.1.5.1 Setup of experiment

For complete test setup the test house requires parts from OEM that are mentioned in Chapter Model size reduction (Stage 2). On top of that manufactured impact structure has to be also delivered. The first step is to assemble all the parts of the impact structure on the ALIS palette. After that the setup is based on test matrix or customer requirements. Complete restraint system is to be added as well as important trim parts and seat, followed by dummy seating positioning. Necessary part of the process is also setting up and testing of the measurement devices and cameras. The whole procedure of the very first setup takes around 8-12 hours. The complete test setup is shown on Figure 77.

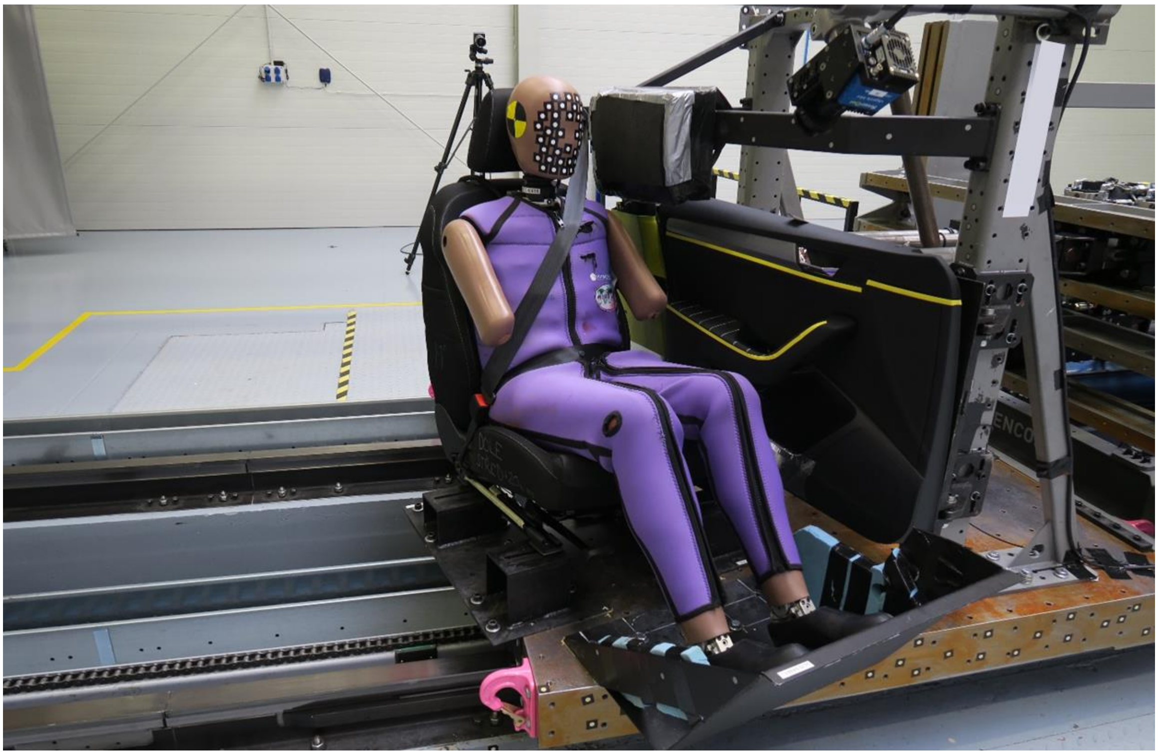


Figure 77: Complete ALIS test setup with all equipment (Courtesy of TÜV SÜD Czech and Škoda Auto)

Every testing loop starts with pulse learning process and it takes up to 5 shots to teach the system correct actuator and sled pulses. It is a time-consuming process, when control algorithm has to update its input parameters to get the right pulse. There are many parameters that affect the speed of learning such as stiffness of the construction, reaction forces from the mechanism, contacts with dummy and seat and other.

5.1.5.2 Results of the physical experiment

When to complete setup is ready, standing on sled tracks, fully instrumented and checked by test executive, the ALIS pneumatic tanks as well as the catapult get pressurized and ready for shot. Several learning shots have to be made in order to teach the system desired pulses. All the important happens within 0.1s. After the shot, technicians receive the raw data from all sensors and camera feeds. These data have to be post-processed as well. Complete relevant biomechanical results are shown on Figure 78.

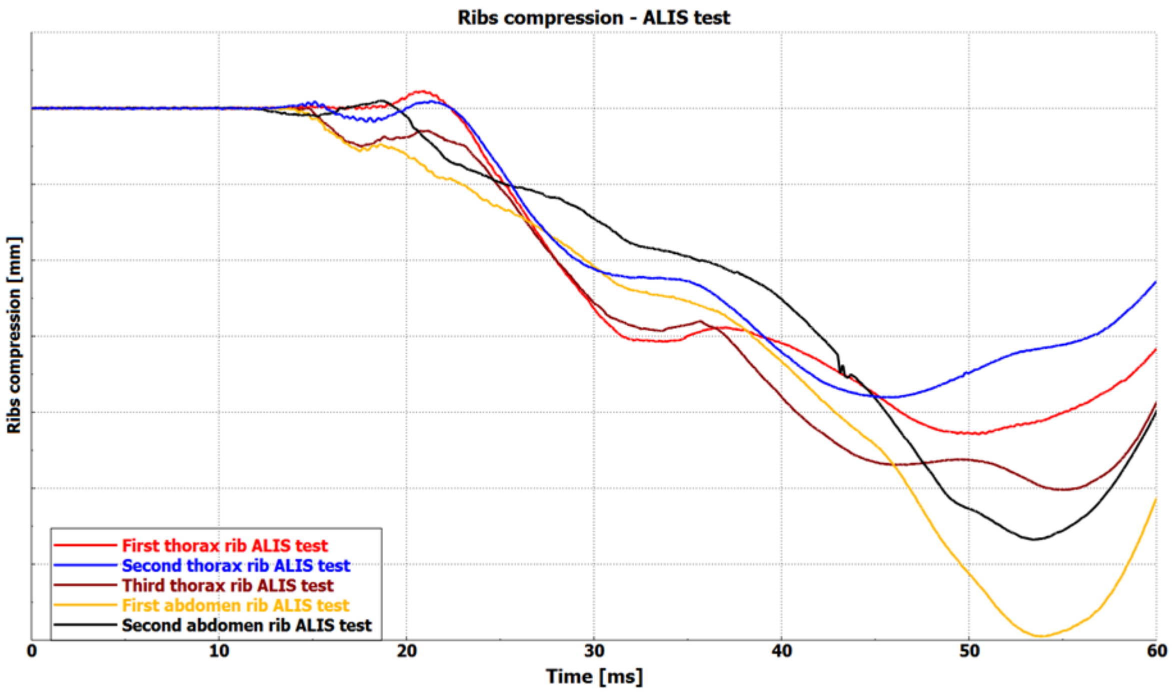


Figure 78: Biomechanical criteria tested on ALIS

There is no contribution by the author to this stage.

5.1.6 Stage 6: Comparison

There is a last missing piece into the mosaic, and it is the overall comparison and evaluation. Since we have mixed several inputs and outputs, it should be mentioned once again what has been used and how it gets into the frame of complete process.

There are following types of results in chronological order:

- Full virtual crash
- ALIS virtual test
- ALIS physical test
- Full physical crash

The complete results comparison is shown of Figure 79a – 79e, where all five ribs are compared among both virtual and physical tests. As most of the safety engineers are aware, side crash simulation has lower accuracy than frontal simulations. The final results can be only as good as good are inputs. This means, that there is a certain error in simulations compared to the physical test and everyone knows about that.

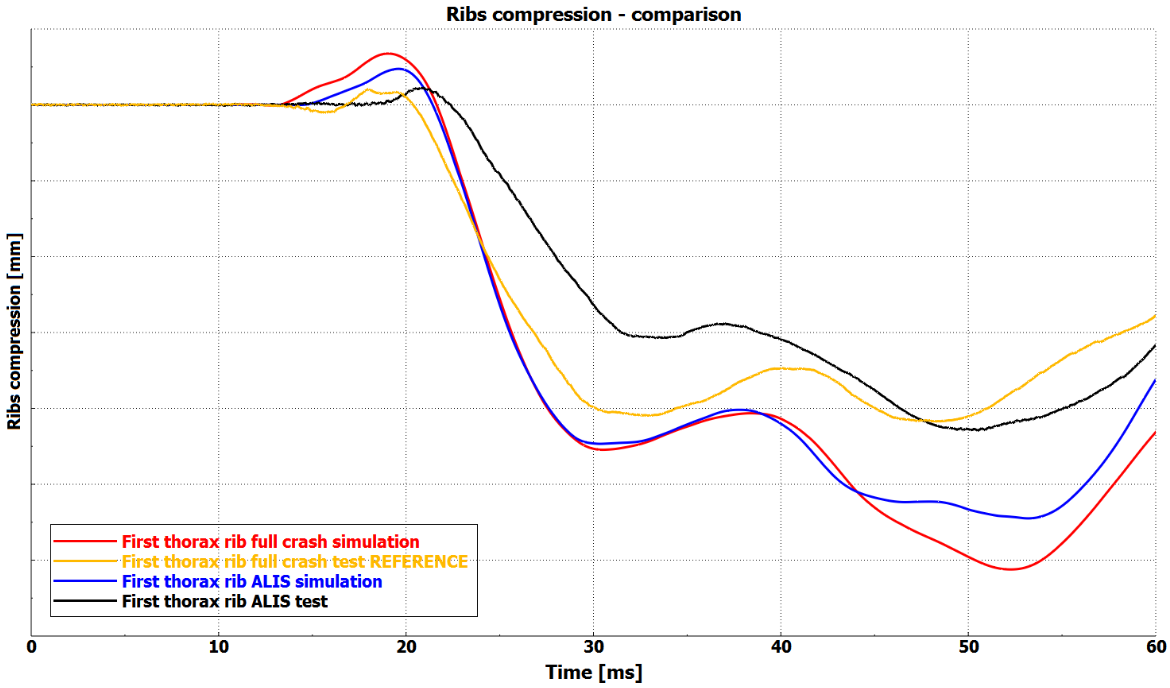


Figure 79a: Comparison of rib compression – first thorax

For brief comparison, Table 8 presents deviation of all types of tests that are cross-table referenced.

First thorax rib	Deviation at 48ms in [%]			
	Full crash simulation	ALIS simulation	ALIS test	Full crash test
Full crash simulation		8.0	34.9	35.6
ALIS simulation	7.4		24.9	25.5
ALIS test	25.9	19.9		0.5
Full crash test	26.2	20.3	0.5	

Table 8: Comparison of the first thorax rib results

There are three ranges of acceptance:

- Green - Deviation within 10% is considered as a very good match
- Yellow – deviation between 10%-20% is considered as a decent match
- Red – deviation above 20% is considered as not good correlation with the physical test

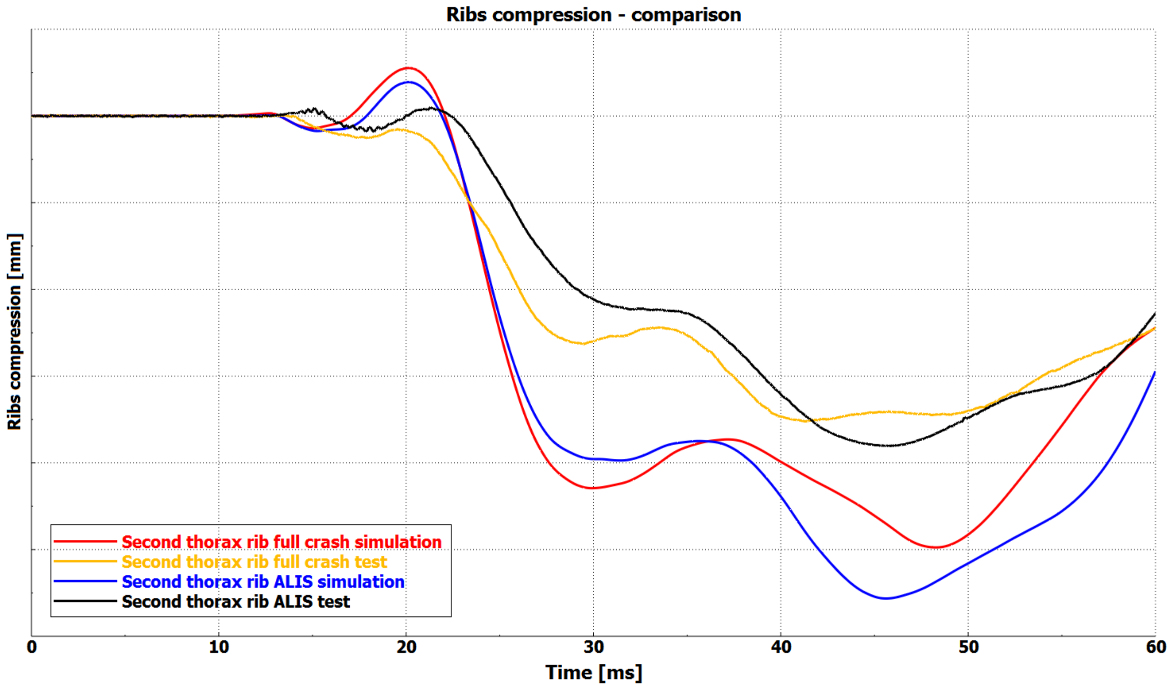


Figure 79b: Comparison of rib compression – second thorax

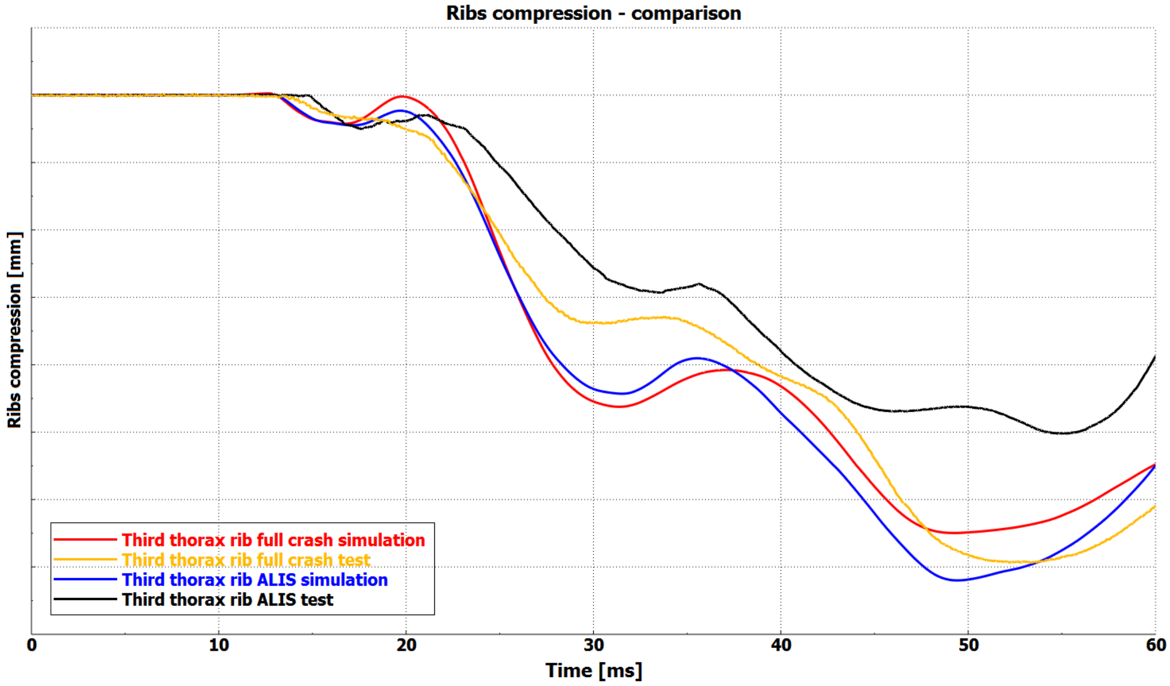


Figure 79c: Comparison of rib compression – third thorax

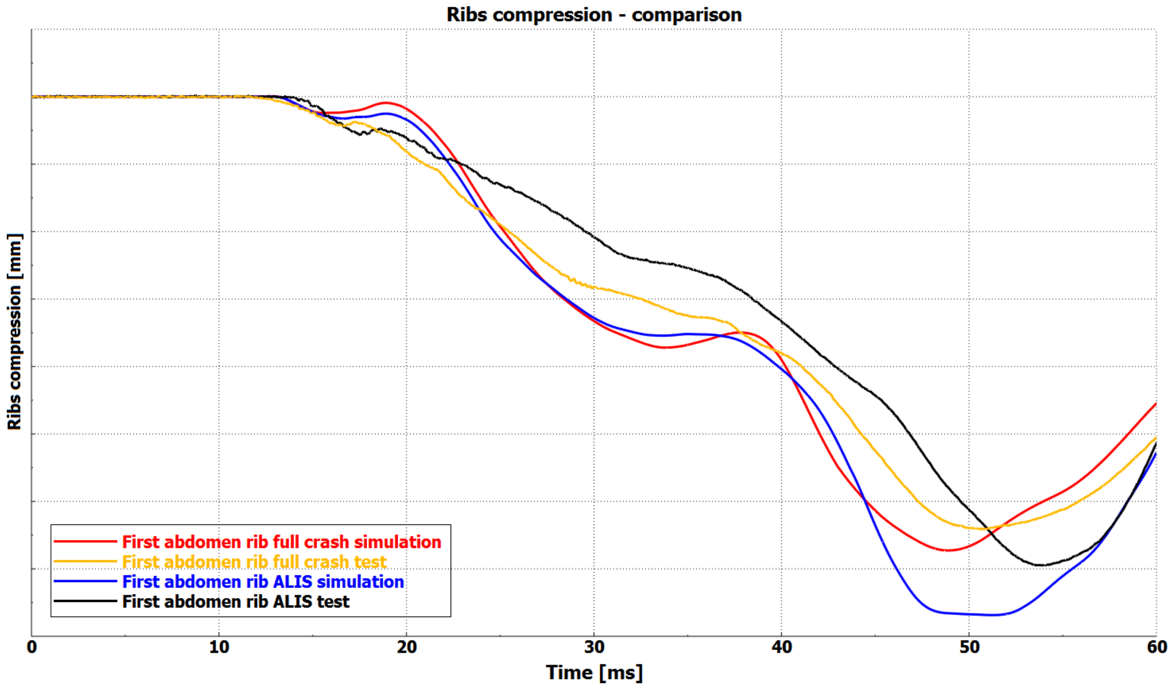


Figure 79d: Comparison of rib compression – first abdomen

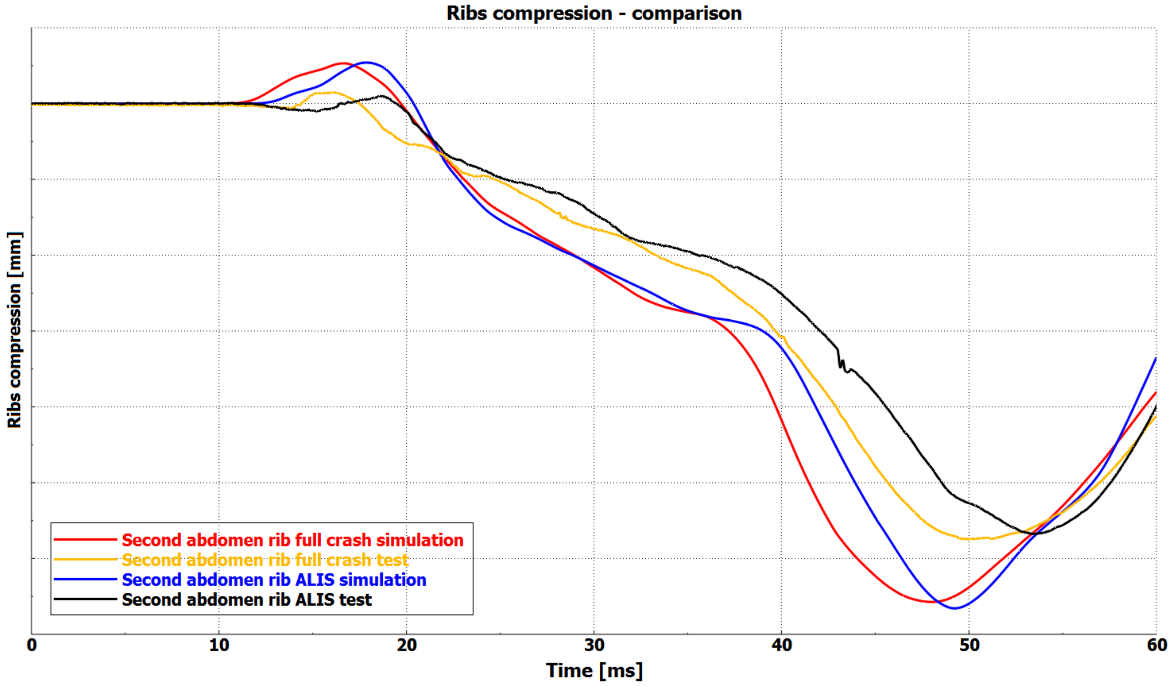


Figure 79e: Comparison of rib compression – second abdomen

Comparisons however also show, difference between physical and virtual testing. On the other hand, the difference of full side crash simulation vs. physical test is fairly similar to the difference of ALIS simulation vs. ALIS physical test which is the main objective. This fact is also displayed in Table 9.

Name	Deviation of	Deviation at max value	Deviation of	Deviation at max value
First thorax rib	ALIS simulation vs full simulation	11.2%	ALIS test vs full crash test	3.2%
Second thorax rib	ALIS simulation vs full simulation	10.6%	ALIS test vs full crash test	7.4%
Third thorax rib	ALIS simulation vs full simulation	8.5%	ALIS test vs full crash test	37.4%
First abdomen rib	ALIS simulation vs full simulation	12.4%	ALIS test vs full crash test	7.5%
Second abdomen rib	ALIS simulation vs full simulation	1.4%	ALIS test vs full crash test	1.1%

Table 9: Quantified deviation between the test results

There are three ranges of acceptance:

- Green - Deviation within 10% is considered as a very good match
- Yellow – deviation between 10%-20% is considered as a decent match
- Red – deviation above 20% is considered as not good correlation with the physical test

It is also clear that not all of the absolute values have been reasonably achieved, except for the third thorax rib, but as ALIS is only a sled reduced representation of the full vehicle crash, there is no such ambition. It is obvious that ALIS has got only several actuators that try to generate the same conditions, whereas in full crash there are unlimited "actuators" and therefore it is impossible to replace crashes fully by sled testing only. Sled testing is only an add-on to the full crash testing. This is also why no legislation, nor consumer tests allow purely sled testing. Simply it cannot substitute the full vehicle crash tests.

5.2 2nd Iteration loop

The second iteration loop is exactly the same one except for one very important detail. All data input data coming into the simulations are this time extracted from full physical crash of prototype.

The second iteration loop follows, where simple modification of the impact structure is made to ensure the highest achievable accuracy of the test compared to the complete vehicle crash. In other words, simulations as well as impact structure design in being finally-tuned based on results from prototype crash. The project finishes after development tests, where all ALIS parameters are fixed and customers changes only restraint system settings and evaluates ideal combination of parts and their initial setup (e.g. seatbelt trigger time, airbag vent size, timing)

6 Results for science and praxis

6.1 Results for science

The main accomplishment is combination of newly developed methodology with DoE application into the automotive industry. It opens broad options for other applications.

6.2 Results for praxis

Main advantages for the practice can be seen in less time demanding and so less expensive development and swifter testing. Also, less prototype parts for the testing are required. Should the approach be used in broader scale, it may get cars and other vehicle affordable to more people.

7 Conclusions and future work

7.1 Conclusions

In this work the ALIS has been introduced as well as current car development cycle. It has been showed how ALIS can speed up the development while decrease costs. Several nowadays solutions for sled have been presented. The literature survey has clearly implied that there is a similar approach for physical testing, however with very little computational effort. ALIS potential has been presented and new methodology suggested. Fundamentals of Design of Experiment have been selected and presented. DoE approach has been then applied during the computational part in order to determine ALIS physical setup and also to prepare sensitivity study for later testing. Finally, the results from all testing phases have been extracted and compared.

This work is to give an answer to the question, whether computational testing can support the physical testing with sufficient accuracy and predictability. It has been proven that DoE approach is able to assess the necessary data from experiments and turn them into physical test inputs.

To sum all up, the evaluation of all partial objectives is below:

- Stage 1: Take over initial complete side crash simulation of virtual car – All information and solutions are available in the Chapter 5.1.1. This stage is completed.
- Stage 2: Evaluation of objectives and model size reduction – This stage is completed, and all information and details are in Chapter 5.1.2.
- Stage 3: Creation of ALIS virtual model and setup – Chapter 5.1.3 is dedicated to this stage. Several sub-tasks were defined and also this stage is completed.
- Stage 4: Initial determination of physical setup input parameters of ALIS via Design of Experiment (DoE) – Chapter 5.1.4 is the backbone of the thesis and gives comprehensive information about the overall solution. This stage is completed.
- Stage 5: Successful physical test – This stage is described in chapter 5.1.5 and its status is completed.
- Stage 6: Comparison of sled test and full vehicle crash – Final results are presented in chapter 5.1.6, where all four models are compared, and conclusions are presented. This is also completed.

This work is also summarized and published in MECCA [A03] and International Journal of Crashworthiness [A04]. Furthermore, it will be presented on global engineering conference FISITA 2021 [A05] held in Prague.

7.2 Discussion

During the writing the thesis I have realized how many enhancements and additional topics this work generates. It has been purely focused on implementation of DoE into presented methodology. It should be noted that our assumptions are based on only one experiment and one analysis. It would be very useful to get more experiments and get better statistics.

As crash engineers may be also interested in biomechanical distribution over time and not just maximal values, it can be of interest to apply so-called curve matching function/algorithm, that would further improve the pulse settings and hence whole accuracy of the ALIS.

Additionally, implementation of curtain airbag, which is integral part of the testing seems necessary to offer even more accurate overall results.

It also leads to further work regarding angle of impact for side pole loadcase. It may turn out that currently used 15° is not the ideal for sled system and the optimum can be between 0-15°. This work also opened new questions, regarding localised floor wrinkling and hence lateral tilting of the seat and dummy.

The Design of Experiment is currently being used mainly in aerospace industry. From my point of view, it is very powerful tool for automotive sector as well due to many combinations of restrain system that is fine-tuned to its perfection.

This work should inspire any engineer to adopt DoE in their own work to push the limits of simulations and physical testing and find the good weighing out between them as they have to always go together in parallel to get best results.

The thesis proved that suggested approach is feasible. It is possible to use model reduction approach together with mathematical apparatus to solve side crash test on sled device. There are a lot of areas of the reduced model representation to be improved, such as design of mechanism, including rigid bodies and more accurate boundary conditions and so on to achieve better representation of the full crash model.

References

[1] History of the automobile, Updated 6/11/2016, online: https://en.wikipedia.org/wiki/History_of_the_automobile

[2] The history of car safety testing – how cars came to be rigorously tested, 07/2012, only: http://www.johnhughes.com.au/blog/the-history-of-car-safety-testing-how-cars-came-to-be-rigorously-tested/

[3] The Evolution of car safety - history, Updated: 31/01/2015, online: http://www.autoexpress.co.uk/car-news/90221/the-evolution-of-car-safety-a-history

[4] CARHS magazine: Safety Companion 2016, 2016, pages 4-39

[5] Šotola M., 2016. DYCOT presentation, TÜV SÜD Czech, pages 3-7

[6] MDB; DYNAmore; figure online: https://www.dynamore.de/en/products/models/side-barrier

[7] AE-MDB; Cellbond; figure online: http://www.cellbond.com/products/barriers/

[8] Crash Course: How current impact tests make cars safer; Car and Driver magazine, January 2013; figure online: http://www.caranddriver.com/features/crash-course-how-current-impact-tests-make-cars-safer-feature

[9] Panait M., 2016. Safety news: Ford Escape rated acceptable in small overlap front crash test, Auto Evolution, figure online: http://www.autoevolution.com/news/2017-ford-escape-rated-acceptable-in-small-overlap-front-crash-test-110162.html;

[10] Euro NCAP 2015: Škoda Superb figure online:https://www.auto.cz/euro-ncap-2015-skoda-superb-pet-hvezd-pro-velikana-z-kvasin-87904

[11] Chung J, Cavanaugh JM, Mason M, King AI. Development of a sled-to-sled subsystem side impact test methodology. (No. 970569). *SAE Technical Papers*. 1997.

[12] Stein DJ. Apparatus and method for side impact testing. (No. 970572). *SAE Technical Papers*. 1997

[13] Aekbote K, Sundararajan S, Chou CC, Lim GG, Prater JA. A new component test methodology concept for side impact simulation. (No. 1999-01-0427). *SAE Technical Papers*. 1999

[14] Miller PM, Nowak T, MacKlem W. A compact sled system for linear impact, pole impact, and side impact testing. (No.2002-01-0695). *SAE Technical Papers*. 2002.

[15] Owen G. Demand Driven Side Impact Restraint System Development Method. In: *9th International LS-DYNA Users Conference*. Detroit, USA: DYNAmore GmbH; 2006

[16] Aekbote K, Sobick J, Zhao L, Abramczyk JE, Maltarich M, Stiyer M, Bailey T. A dynamic sled-to-sled test methodology for simulating dummy responses in side impact. (No. 2007-01-0710). *SAE Technical Papers*. 2007

[17] Chou C.et al. „A review of side impact component test methodologies", International Journal of Vehicle Safety, Vol 2, Nos.1/2,2007, pp.141–184

[18] Lee H, Park H, Na H, Kim J, Jeon O, Jang I, Younghan Y. Simplified side impact test methodologies for door interior trim armrest in automotive vehicle. (No. 2007-01-3722). *SAE Technical Papers*. 2007

[19] Dix J, Stein D. A validated oblique pole side impact sled test methodology. (No. 2009-01-1433). *SAE Technical Papers*. 2009

[20] Lessley D. et al. „Whole-Body Response to Pure Lateral Impact", Stapp Car Crash Journal 54, Paper No.2010-22-0014, 2010, pp. 289-336

[21] Kinoshita A, Shigeno N, Fukushima T, Steffan H. Development of a side impact sled test method using multiple actuators. (No. 11-0072). In: *22th ESV (Enhanced Safety of Vehicles)*. Washington DC, USA: NHTSA; 2011

[22] Liu Z. et al. „Study on One Kind of Test Method of Simplified Side Impact Using Sled Test", Advanced Materials Research Vols. 301-303, 2011, pp 1249-1253

[23] Kinoshita A, Shigeno N, Fukushima T, Steffan H. Development of pole side impact sled test method using multiple actuators for EuroNCAP. (No. 2012-01-0095). *SAE Technical Papers*. 2012

[24] Janca, S., Shanks, K., Brelin-Fornari, J., Tangirala, R. et al., „Side Impact Testing of the Near-Side, Rear Seat Occupant Using a Deceleration Sled", SAE Technical Paper 2014-01-0547, 2014, doi:10.4271/2014-01-0547

[25] Seattle Safety, figure online: https://hitech.com.sg/images/SLED/Acc_3.png

[26] Instron US, figure online: https://www.instron.co.hu/-/media/images/instron/catalog/products/testing-systems/crash-simulation-components/crashsim.jpg

[27] Continental automotive, figure online: https://www.continental-automotive.com/getattachment/Passenger-Cars/Services/Testing-Portfolio/DYSIN-%E2%80%93-Dynamischer-Seitenaufprall-und-Intrusion/DYSIN_01-(1).jpg.aspx?width=350&height=178

[28] DSD ASIS, figure online: http://www.tecpond.at/wp-content/uploads/2013/11/ASIS_web.jpg

[29] Car services, figure online: https://www.carwow.co.uk/blog/2015-volkswagen-passat-dimensions-interior-and-exterior-sizes

[30] Hyundai forum, figure online: http://www.team-bhp.com/forum/indian-car-scene/31563-hyundai-launch-b-segment-car-i20-soon-8.html

[31] EuroNCAP, Side Pole, 2015, figure online: http://www.euroncap.com/en/vehicle-safety/the-ratings-explained/adult-occupant-protection/side-pole/

[32] Lobdell TE, Kroell CK, Schneider DC, et al. 1973. Impact response of the human thorax. In King WF, Mertz HJ (eds), Human Impact Response Measurement and Simulation, pp 201–245. New York, Plenum Press

[33] Viano, D. C., King, A. I. " Biomechanics of Chest and Abdomen Impact.", The Biomedical Engineering Handbook: Second Edition. Ed. Joseph D. Bronzino Boca Raton: CRC Press LLC, 2000

[34] Foster JK, Kortge JO, Wolanin MJ. 1977. Hybrid III—A biomechanically-based crash test dummy. In Proceedings of the Stapp Car Crash Conference, pp 975–1014, SAE Paper no. 770938. Warrendale, Pa, Society of Automotive Engineers

[35] Rouhana SW, Viano D, Jedrzejczak E, et al. 1989. Assessing submarining and abdominal injury risk in the Hybrid III family of dummies. In Proceedings of the 33rd Stapp Car Crash Conference, pp 257–279, SAE Paper no. 892440. Warrendale, Pa, Society of Automotive Engineers.

[36] Mertz HJ. 1993. Anthropomorphic test devices. In Nahum AM, Melvin JW (eds), Accidental Injury: Biomechanis and Prevention, pp 66–84. New York, Springer-Verlag.

[37] Eppinger R. et al. „Development of Improved Injury Criteria for the Assessment of Advanced Automotive Restraint Systems – II", NHTSA, November 1999

[38] Hayes W. et al. „Forensic Injury Biomechanics", Annu. Rev. Biomed. Eng. 2007. 9:55–86; http://10.0.4.122/annurev.bioeng.9.060906.151946

[39] McLean A. et Anderson W. „Biomechanics of closed head injury", Chapman & Hall London, ISBN 0 412 58540 5

[40] Huelke D. et Melvin J. „Anatomy, injury frequency, biomechanics and human tolerances NCSS project literature review", NHTSA, May 1979, Report Number UM-HSRI - 79-33

[41] LaPlaca M. et al. „CNS injury biomechanics and experimental models", Weber & Maas (Eds.), Progress in Brain Research, Vol. 161, ISSN 0079-6123, DOI: 0.1016/S0079-6123(06)61002-9

[42] Hume P. et al. „Biomechanics: injury mechanisms and risk factors“, Gymnastics, First Edition, 2013 International Olympic Committee, 2013 John Wiley & Sons, Ltd.

[43] Porta D. „Biomechanics of Impact Injury“, Forensic Science and Medicine, Forensic Medicine of the Lower Extremity: Human Identification and Trauma Analysis of the Thigh, Leg, and Foot; The Humana Press Inc.,

[44] Durakovic, B. “Design of Experiments Application, Concepts, Examples: State of the Art”; Periodicals of Engineering and Natural Sciences Vol 5, No 3, December 2017, p.422-433; ISSN 2303-4521; http://pen.ius.edu.ba

[45] HUMANETICS, Side impact dummy, http://www.humaneticsatd.com/crash-test-dummies/side-impact/worldsid-50m

[46] Stander, N. et al. LS-OPT 4.2 Manual; https://www.lsoptsupport.com/documents/manuals

[47] Wilson, B., Cappelleri, D.J., Frecker, M.I. and Simpson, T.W. Efficient Pareto frontier exploration using surrogate approximations. Optimization and Engineering, 2 (1), pp.31-50, 2001

[48] Karian A., Dudewicz E. „Handbook of Fitting statistical distributions with R“, ISBN: 13:978-1-58488-712-6

[49] Guo H., Mettas A. „Design of Experiments and Data analysis“, 2010 Annual RELIABILITY and MAINTAINABILITY Symposium; https://www.weibull.com/pubs/2010_RAMS_doe_and_data_analysis.pdf

[50] Myers R. et al. „Response Surface Methodology: Process and product optimization using designed experiments 4th edition“, Wiley, 2016; ISBN 978-1-118-91601-8

[51] Rutherford A. et al. „Use of response surface metamodels for identification of stiffness and damping coefficients in a simple dynamic system“, Shock and Vibration 12 (2005) 317–331, ISSN 1070-9622/05

[52] Dean A., Voss D. „Design and Analysis of Experiments”, Springer Verlag, 1999, ISBN 0-387-98561-1

[53] Cundy, A., et al. „Use of Response Surface Metamodels for Damage Identification of a Simple Nonlinear System”, Key Engineering Materials. 245-246., 2003, 10.2172/812182, https://permalink.lanl.gov/object/tr?what=info:lanl-repo/lareport/LA-UR-03-1182

[54] Cundy, A. „Use of Response Surface Metamodels in Damage Identification of Dynamic Structures”, master thesis, 2003, Virginia Polytechnic Institute and State University, https://vtechworks.lib.vt.edu/handle/10919/30842

[55] Jiju, A. „Design of Experiments for Engineers and Scientists", Elsevoer's Science and Technology, 2003, ISBN 0 7506 4709 4

Author Publications

[A01] Jelínek J, Růžička M, Kalinský M.: Advanced methods in crash safety testing. EAN 2018 56th conference on experimental stress analysis, Conference Proceedings. Praha: Czech Mechanics Society, 2018. p. 150-156. ISBN 978-80-270-4062-9. (Effort split 70%, 10%, 20%).

[A02] Jelínek J, Růžička M.: Advanced methods in crash safety testing. 21st Workshop of Applied Mechanics - Proceedings. Praha: Czech Technical University in Prague, Faculty of Mechanical Engineering, 2016. pp. 17-20. ISBN 978-80-01-06085-8. (Effort split 90%, 10%).

[A03] Jelínek J, Růžička M, Kafková A.: New advanced methods in side crash testing, MECCA Journal of Middle European Construction and Design of Cars, 2020. DOI: 10.14311/mecdc.2020.02.01. (Effort split 75%, 10%, 15%).

[A04] Jelínek J, Růžička M, Kafková A.: New methods in the side sled crash testing, International Journal of Crashworthiness, 2021. DOI:10.1080/13588265.2021.1904651. (Effort split 70%, 10%, 20%).

[A05] Jelínek J, Růžička M.: Side crash testing on sled. Proceeding of FISITA World Congress 2021; FISITA 2021 World Congress. DOI: https://doi.org/10.46720/F2020-PIF-028 Accepted for publication (Effort split 70%, 30%)

Author publications that are not related to the thesis

[A06] Záruba P, Jelínek J, Kalinský M.: Dynamic testing of buses and their components, MECCA Journal of Middle European Construction and Design of Cars, 2017, DOI: 10.1515/mecdc-2017-0002. (Effort split 40%, 30%, 30%)

[A07] Jelínek J, Hnilica J.: Pasivni bezpecnost v homologacni praxe 20161211. TÜV SÜD Czech internal presentation; Prague, Czech Republic, 2016, pages 3-33. (Effort split 60%, 40%)

Appendix A

View of LS-OPT input file

```
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$

Command file "ALIS.com"

$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$

$ Generated using LS-OPT Version 4.2

$

"ALIS Pole strike"

$

Author "JJ"

solvers 1

responses 10

histories 1

$

$ DESIGN VARIABLES

$

variables 8

 Variable 'ASD_SY' 1.

  Lower bound variable 'ASD_SY' .85

  Upper bound variable 'ASD_SY' 1.15

 Variable 'ASD_OA' 0.

  Lower bound variable 'ASD_OA' -5.

  Upper bound variable 'ASD_OA' 5.

 Variable 'DBB_SF' 1.

  Lower bound variable 'DBB_SF' .85

  Upper bound variable 'DBB_SF' 1.15

 Variable 'DBB_OA' 0.

  Lower bound variable 'DBB_OA' -5.

  Upper bound variable 'DBB_OA' 5.
```

```
 Variable 'DBU_SF' 1.
  Lower bound variable 'DBU_SF' .85
  Upper bound variable 'DBU_SF' 1.15
 Variable 'DBU_OA' 0.
  Lower bound variable 'DBU_OA' -5.
  Upper bound variable 'DBU_OA' 5.
 Variable 'DDD_SF' 1.
  Lower bound variable 'DDD_SF' .85
  Upper bound variable 'DDD_SF' 1.15
 Variable 'DDD_OA' 0.
  Lower bound variable 'DDD_OA' 0.
  Upper bound variable 'DDD_OA' 5.
$
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$      SOLVER "Pole"
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$
$ DEFINITION OF SOLVER "Pole"
$
  solver input file "ALIS_OPT.opt"
  solver check output on
$ ------ Pre-processor --------
$   NO PREPROCESSOR SPECIFIED
$ ------ Post-processor --------
$   NO POSTPROCESSOR SPECIFIED
$ ------ Metamodeling ---------
  solver order quadratic
  solver experiment design space_filling
   solver number experiments 200
```

```
$ ------ Job information ------
  solver concurrent jobs 1
$
$ RESPONSES FOR SOLVER "Pole"
$
 response 'BAR_20079631' 1 0 "BinoutResponse -res_type Nodout  -cmp x_displacement -id 90079631 -select TIME "
 response 'BAR_20079632' 1 0 "BinoutResponse -res_type Nodout  -cmp x_displacement -id 90079632 -select TIME "
 response 'BAR_20079633' 1 0 "BinoutResponse -res_type Nodout  -cmp x_displacement -id 90079633 -select TIME "
 response 'BAR_20079634' 1 0 "BinoutResponse -res_type Nodout  -cmp x_displacement -id 90079634 -select TIME "
 response 'BAR_20079635' 1 0 "BinoutResponse -res_type Nodout  -cmp x_displacement -id 90079635 -select TIME "
 response 'NODE_10000002' 1 0 "BinoutResponse -res_type Nodout  -cmp y_velocity -id 90000002 -select TIME "
 response 'NODE_10015619' 1 0 "BinoutResponse -res_type Nodout  -cmp y_velocity -id 90015619 -select TIME "
 response 'NODE_10021212' 1 0 "BinoutResponse -res_type Nodout  -cmp y_velocity -id 9002121 -select TIME "
 response 'NODE_10023825' 1 0 "BinoutResponse -res_type Nodout  -cmp y_velocity -id 90023825 -select TIME "
 response 'NODE_10029764' 1 0 "BinoutResponse -res_type Nodout  -cmp y_velocity -id 90029764 -select TIME "
$
$ HISTORIES FOR SOLVER "Pole"
$
$
$ OBJECTIVE FUNCTIONS
$
 objectives 10
 objective 'BAR_20079631' 1
```

```
 objective 'BAR_20079632' 1
 objective 'BAR_20079633' 1
 objective 'BAR_20079634' 1
 objective 'BAR_20079635' 1
 objective 'NODE_10000002' 1
 objective 'NODE_10015619' 1
 objective 'NODE_10021212' 1
 objective 'NODE_10023825' 1
 objective 'NODE_10029764' 1
$
$ THERE ARE NO CONSTRAINTS!!!
$
 constraints 0
$
$ PARAMETERS FOR METAMODEL OPTIMIZATION
$
 Metamodel Optimization Strategy DOMAINREDUCTION
$
  iterate param design 0.01
  iterate param objective 0.01
  iterate param stoppingtype and
  iterate param response 0.01
$
$ OPTIMIZATION ALGORITHM
$
 Optimization Algorithm hybrid simulated annealing
  Use GSA
$
$ JOB INFO
```

$

check file 1

STOP