Politecnico di Torino

Integration of safety legislations on vehicle

Pedestrian Lower Leg Impact Simulation and Analysis

SONG XINRUI
S231345

Tutor: Alessandro Scattina

A Thesis of Master Degree

Submitted to

DEPARTMENT OF INGEGNERIA MECCANICA, AEROSPAZIALE, DELL'AUTOVEICOLO E DELLA PRODUZIONE

2018

Index

CHAPTER IIntroduction

For the beginning, this chapter includes a brief introduction of the safety regulation and safety evaluation tests, as well as the safety related history and milestones.

1. Vehicle Safety brief introduction

The automotive engineering has been developing for 200 years. The safety issues have been among the most critical engineering parts since modern vehicles were designed. Due to the ease to access to the product at present, massive amount of vehicle leads to an increase of accidents. More critical safety legislations are published to benchmark vehicles.

There are different third party benchmark safety ratings for various markets to satisfy the native customers, manufacturers and other organizations involved in the industry. Among them the most accepted are:

- Europe New Car Assessment Program (Euro-NCAP) for Europe
- The Insurance Institute for Highway Safety (IIHS) for The USA
- National Highway Traffic Safety Administration (NHTSA) for the USA

There are also other associations for specific market, such as C-NCAP for China, J-NCAP for Japan, A-NCAP for Australia and Latin-NCAP for Latina America.

Nowadays the manufacturers tends to build vehicle to integrated platform, in order to shorten product development cycle as well as to decrease costs. Car models become more international than before, which requires a model to be assessed in different markets. Therefore, the team needs to have complete awareness at the very beginning stage of the project about how to approach to safety legislations regarding the destination markets.

If there is already an existing model or calculation method, this approach could benefit a lot. It shall introduce an engineering point of view of how it is to design structure to improve performance.

1.1. Vehicle Safety History

Before the existence of conventional cars, some basic impact protection of vehicles has been included. Due to the faster traveling speed of the vehicles using machine power, traffic accidents start to happen.

During the first 40 years of 20st century, four-wheel hydraulic brakes, safety glass, crash barrier, back-up brakes and optimized interior are applied to improve the passive safety of the vehicle.

The following years until 1960s, structural safety grew very rapidly with padded dashboard, headlight with switch on steering wheel, safety cage, front safety chamber, disk brakes. In 1958, The United Nations established the World Forum for Harmonization of Vehicle Regulations, an international standards body advancing auto safety. The same year three-point seat belt was introduced by Volvo and became mandatory gradually. The following year the first optional head rest came as optional elements.

The 1960s the very first specific vehicle legislations were published. On September 9, 1966, the National Traffic and Motor Vehicle Safety Act became law in the U.S, the first mandatory federal safety standards for motor vehicles. Also in 1966, US-market passenger cars were forced to be equipped with padded instrument panels, front and rear outboard lap belts and while reverse lamps, and established the United States Department of Transportation (DOT) with automobile safety as one of its purposes. The next year the National Transportation Safety Board (NTSB) was created as an independent organization.

In 1968, the precursor agency to the US National Highway Traffic Safety Administration's first Federal Motor Vehicle Safety Standards took effect. The next year the addition of head restraints addressing the problem of whiplash in rear-end collisions.

In 1974 GM started to offer airbags as optional equipment on large size vehicles. Starts in 1979, NTHSA began to have crash tests on popular cars and publish the results, and became member of the NCAP program during 1990s.

In 1980s, car manufacturers began to realize the importance of airbags and seat belts working together to prevent severe injuries. So the standard equipment of airbags and seat belts became popular for large cars and even mid-class cars.

In 1995, the Insurance Institute for Highway Safety (IIHS) starts its program of offset crash tests. At the same year, Volvo used the very first side airbags. In 1997, Europe New Car Assessment Program (Euro NCAP) was founded.

Starting from 2003 the IIHS began side impact crashes and the next year NHTSA introduced the evaluation for roll over resistance. In 2009, the IIHS starts the test of roof crush considering a rolling action vehicle with the load of self-curb weight. In 2012, all cars under 10000 lbs (roughly 4536 kg) sold in USA are required to have Electric Stability Control (ESC).

Nowadays with the development of automated driving assistance systems, there has been a new generation of safety legislations, as well as the new version test protocols.

1.2. Current situations

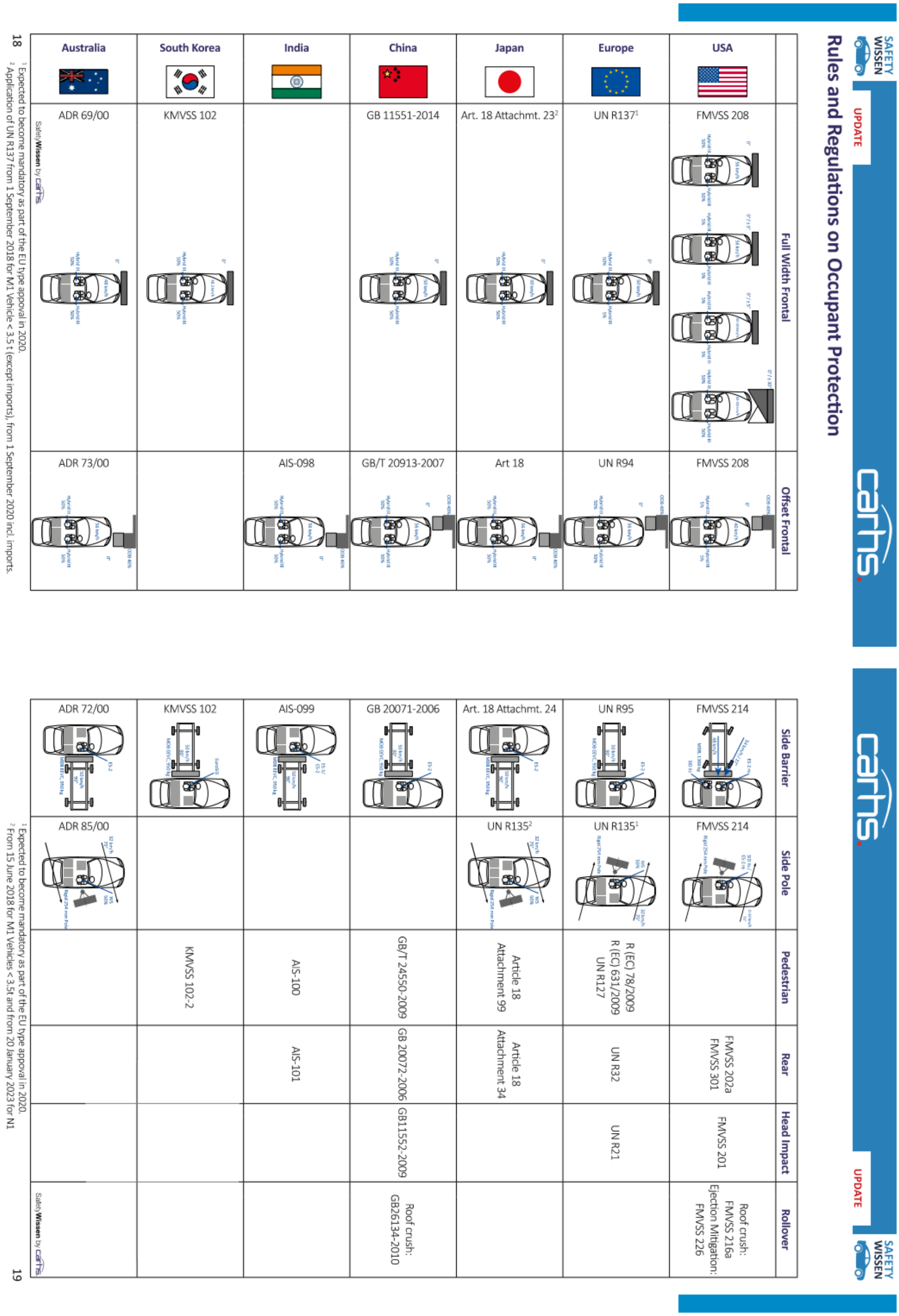


Figure 1.1 2018 CARHS rules and regulations on occupant protection

After decades of analyses and upgrades, the safety regulations on vehicle have been homologated to a set of tests which would simulate the most critical and common collisions. There are full width frontal impact, overlap frontal test, side barrier and side pole, pedestrian tests, rear impact, head impact and rollover test. According to different requirements in different markets, the test contents are not the same.

At present, each market has a current version of legislation and a pre-defined protocol for the future. The trend is to evaluate the vehicle safety to a more practical usage simulation as well as to simulate the real situation while the driving assistant systems working to test the ability of automated driving.

Two of the leading markets are the European market and the US market. The legislations they apply are UNECE vehicle regulations in Europe and FMVSS [Federal Motor vehicle Safety Standards] in the US. The main difference between them are due to road profiles and geographic reasons.

Safety test is a measurement converting the descriptive word safety into a measurable benchmark, which is important for both car manufacturers and customers as well as others involved in the industry to have a direct acknowledge of the safety features of the product. So the legislations should be specifically designed for the market

At present the most accepted test is the New Car Assessment Program (NCAP). In different markets there are different associations who manage this kind of tests and publish the regulations and protocols. The NCAP test is running by NHTSA in America, while there is another safety test from IIHS. NCAP test star rating is one of the most important considerations when customers make decisions.

While the IIHS is an association founded by auto insurance industry, who need to justify the level of insurance payment for various car models. A proper benchmarking system can contribute for a more precise evaluation to offer a convincing price to customers. Another specialty is that it contains test for minimal damage of slowest speed collision, which relates to insurance payment most commonly happening.

The test result is published on the website to give performance parameters of cars and help customers and manufacturers make decisions.

Currently both Euro-NCAP and IIHS have published protocols for the next period (2025).

For Euro-NCAP, the next generation would not focus only on passive and active safety, but separate the safety rating into:

Primary safety:

- Driver monitoring (2020)
- Automatic Emergency Steering (2020, 2022)
- Autonomous Emergency Braking (2020, 2022)

- V2x (2024)

Secondary safety:

- Whiplash/Rear-end Crash Protection (2020)
- Pedestrian and Cyclist Safety (2022)

Tertiary Safety:

- Rescue, Extrication and Safety (2020)
- Child Presence Detection (2022)

In the next decade, the vehicles would be more intelligent and telecommunicated. The primary safety is a kind of active safety that the vehicle check itself as well as the pilot to make sure the vehicle has no potential danger. The secondary safety is the passive safety, or structural safety. The structural safety that protect the occupants and the pedestrians in the traffic. The tertiary safety is the safety of post-accident and specified occasion safety. The basic is that the vehicle need also to protect the lives after the accident.

The requirement is always growing with attention on accident prevention and lifesaving. Both the rule makers and players on the field are working together to format the new regulations and evaluation system. The manufacturers need to investigate on new technologies on autonomous driving with the direction of the new legislations.

The road map of the Euro NCAP protocol is as follow:

AEB: Autonomous Emergency Braking

VRU: Vulnerable Road Users

V2X: Vehicle To Everything

AD: Autonomous Driving

The Euro NCAP has published the road map of next period how the safety ratings would performs on passenger cars. Latest technologies with contribution on autonomous driving as well as crash prevention can result in higher rating level, as figure1.2.

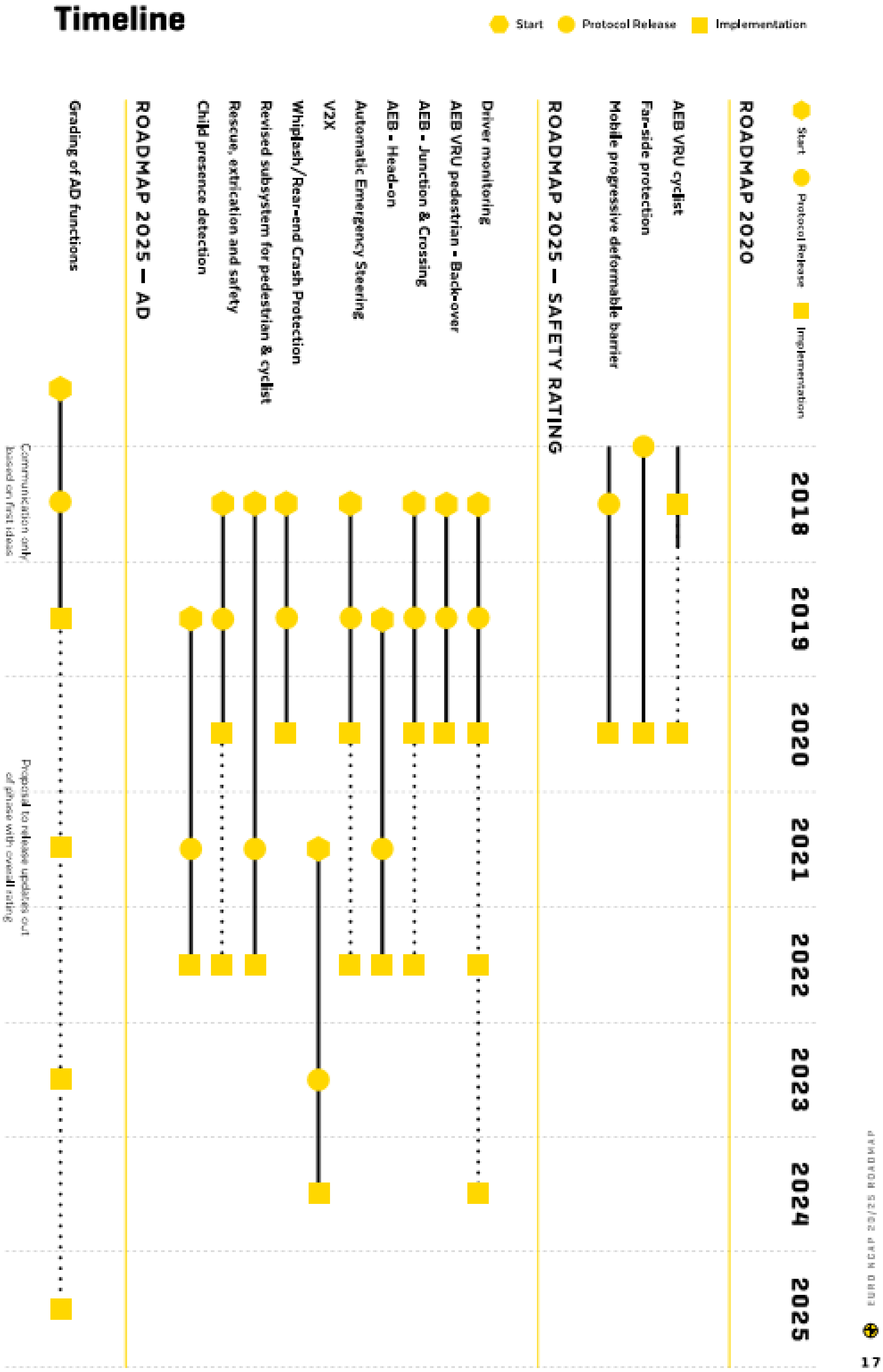


Figure 1.2 Road Map 2025 Euro NCAP

In conclusion, extra credits are offered to those cars equipped with more intelligent self-check & driver sensor system. The vehicle would be more active to prevent the accidents due to human errors by contemporary control ahead of the driver. Moreover, communication between vehicles would be a bonus for safety benchmarking. The secondary safety, which is passive safety, changes the model simulated with whiplash and pedestrian closer to the real collision.

Another thing is that the legislation takes into consider that the motorcycle and cyclist, which requires a more precise advanced driver-assistance system (ADAS) , who can distinguish the four wheelers and two wheelers and responds with the most proper instructions to the vehicle.

In the following years, the third level automation would enter the mainstream market. There are already part of the ‘’Level 3’’ class functions available and the others under study, and in which Euro NCAP may have an interest are:

- Parking
- City driving
- Inter-Urban driving
- Traffic Jam
- Highway driving

New technologies are under investigation to build a more intelligent and safer transportation. Together the manufacturer and the safety rating associations are cooperating to guarantee a future with better safety performance vehicles.

Regarding the fact that the minimum safety performance is defined under legislations in the local market. Then to differentiate how well it performs, safety rating protocols come up with the process of testing and presentation to the public. Together the legislations and test ratings are leading the safety performance of vehicle to keep improving.

CHAPTER II Safety Ratings Specifications

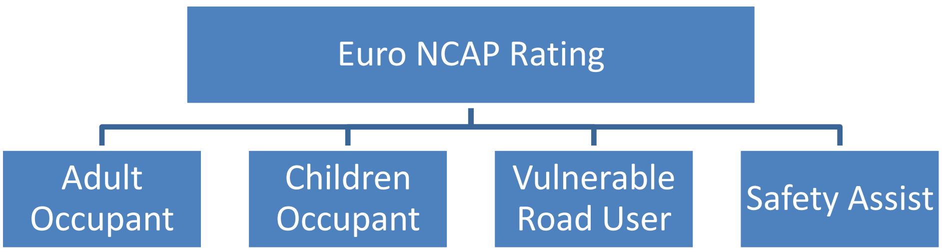
The safety rating associations publish the testing protocols and offer tests to evaluate the vehicle safety performance, and deliver worthiness information to the market. It is very important to study rating systems on vehicle safety. In this chapter the safety ratings would be introduced and compared with each other.

1. Euro NCAP

New Car Assessment Program is a safety rating system to evaluate the vehicle safety performance. Each market has its own NCAP for the products. The test protocols have differences in content and detail.

The very first NCAPs was Euro NCAP, founded by the Transport Research Laboratory for the UK Department for Transport and backed by several European governments, as well as by the European Union. It is recognized one of the most respectful evaluations around the world.

The rating system contains four parts, which focus on each part of the participants in the traffic. Each part has its own weight factor, test process and evaluation methods.



1.1. Euro NCAP Weight Factors and limits

There are items under each of the four parts of the Euro NCAP rating. The sum of the score of each items would be the total score of that part.

Tabella 1.1 Euro NCAP scoring criteria

EURO NCAP SCORING CRITERIA	
ADULT OCCUPANT	***38***
FRONTAL OFFSET DEFORMABLE BARRIER	8
FRONTAL FULL WIDTH	8
WHIPLASH REAR IMPACT	2
LATERAL IMPACT	16
AEB CITY	4
CHILD OCCUPANTS	***49***
FRONTAL IMPACT	16
LATERAL IMPACT	8
SAFETY FEATURES	13
CRS INSTALLATION CHECK	12
VULNERABLE ROAD USERS	***48***
PEDESTRIAN IMPACT PROTECTION (HEAD+PELVIS+LEGFORM)	36

VULNERABLE ROAD USERS (PEDESTRIAN+CYCLIST)	12
SAFETY ASSIST	***13***
SPEED ASSISTANCE	3
SEAT BELT REMINDER	3
LANE SUPPORT	4
AEB INTERURBAN	3

The entire safety performance is not simply adding together the four parts. There are two methods from Euro NCAP evaluation safety tests.

1.1.1. The weighted final score

This one is the weighted sum of each score from the four parts mentioned, which is used to define the best vehicle in the segment at the end of the year.

The performance of each one of the four parts of Euro NCAP rating is calculated from the

The weight factors may be updated from time to time as priorities or the contents of the boxes change, as shown in the table.

Tabella 1.2 Weight factor of Euro NCAP star rrating

Year	2016/2017	2018/2019	2020
Adult Occupant Protection	40%	40%	40%
Child Occupant Protection	20%	20%	20%
Pedestrian Protection	20%	20%	20%
Safety Assist	20%	20%	20%

According to current scoring criteria, the maximum score would be:

38*0.4+49*0.2+48*0.2+13*0.2=37.2

1.1.2. Star rating

For each of the four parts, individual scores in each box using weight factors. Theoretical limits apply which are now equal to the minimum weighted overall score per star rating.

The Balance Limits are applied to transfer rounded data into stars rating to represent better to the customer, which is easier to read. Calculate the percentage of credits the vehicle has got and the star rating is given by fulfilling all of the four boxes in percentage value. The next tables give us the criteria.

Tabella 1.3 Percentage of credits necessary for Star rating Euro NCAP

2016/2017	Adult Occupant	Child Occupant	Vulnerable Road Users	Safety Assist
5 stars	80%	75%	60%	50%
4 stars	70%	70%	50%	40%
3 stars	60%	30%	40%	25%
2 stars	50%	25%	30%	15%

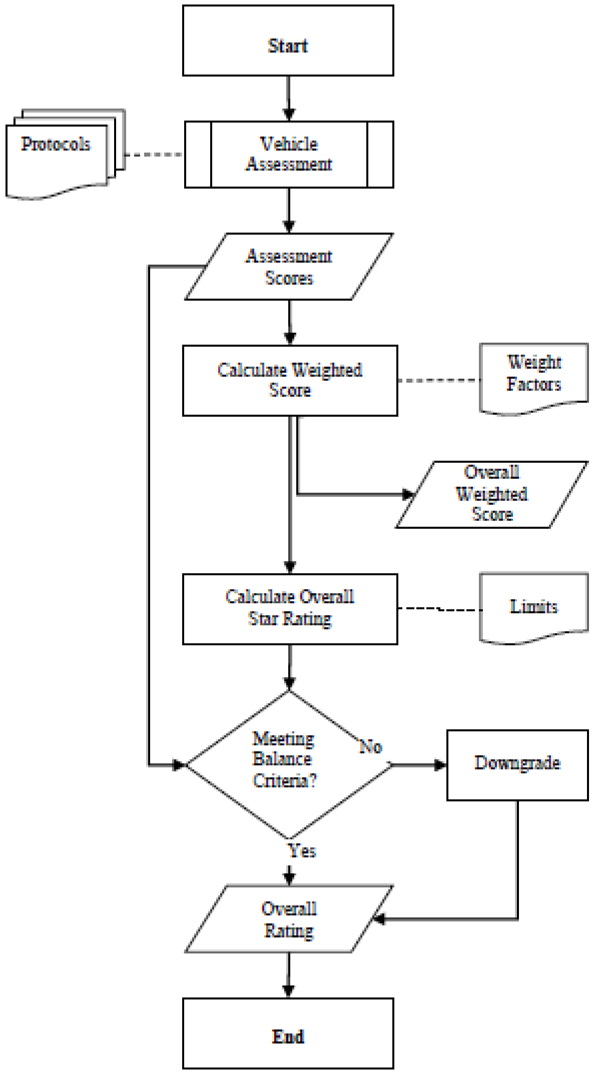
1 star	40%	15%	20%	10%

2018/2019	Adult Occupant	Child Occupant	Vulnerable Road Users	Safety Assist
5 stars	80%	80%	60%	70%
4 stars	70%	70%	50%	60%
3 stars	60%	60%	40%	50%
2 stars	50%	50%	30%	40%
1 star	40%	40%	20%	30%

With this chart the star rating would be given to the vehicle. It is obvious that the requirement of safety assist as well as vulnerable road users parts is more critical than before.

1.2. Evaluation flow

The evaluation flow would output a report on the official website. The report would contain star rating, figures on performance on each evaluated point, as well as charts with the equipment onboard.



The inputs of evaluation flow are Protocols, weight factors and limits. The out puts should be Overall weighted score and Overall Rating.

2. C-NCAP

China is one of the fastest growing market in the world. The annual production amount and the number of sales are the largest in the world and the car ownership has reached 0.3 billion vehicles.

Although the safety test associations are young in China, the testing protocols and technics are following quite near to Euro NCAP. Run by China Automotive Technology and Research Center Co. Ltd (CATARC), it is a very convincing safety reference in Chinese market.

2.1. Score value and star rating

The C-NCAP has a similar scoring and star rating system refer to the Euro NCAP. An overall score would be given to the vehicle. The star rating would be under

Tabella 1.4 Credit distribution in C-NCAP

Parts	Categories of the items	Items	Score value		Total score of each part
			Front row	Back row	
Occupant Protection	Test item	100% frontal collision	16	4	70
		40% offset collision	16	4	
		Lateral collision	16	4	
		Whiplash	5		
	Score adding item	Lateral curtain airbag	3		
		Safety belt reminding	2		
Pedestrian protection	Test items	Head form	12		15
		Leg form	3		
Active safety	Examination item	ESC	4		15
	Test item	AEB CCR	8		
		AEB VRU Ped	3		

ESC: Electric Stability Control; AEB: Autonomous Emergency Braking; CCR: Car to Car Rear; VRU: Vulnerable road user; PED: pedestrian

Note:

a) For vehicle with single row of seats, the back row score is not counted, and the full score for occupant protection is 57 points
b) 1 point is awarded if safety belt reminder at occupant side of front row meets requirements, and 1 point is awarded if safety belt reminder at all seats of 2nd row meet requirements.

c) The maximum available score for active safety part is 15 points, even if total score is exceeded during calculation due to different AEB configuration factors, it is still counted as 15 points.

Divide the actual score of each of three parts of occupant protection, pedestrian protection and active safety by the total score of relevant parts to result in the respective scoring rates for the entire three part, then multiply the respective scoring rates by weight factor of the three parts (occupant protection: 0.7; pedestrian protection: 0.15; active safety: 0.15), then sum up to get the comprehensive scoring rate. In accordance with the final comprehensive scoring rate, perform star rating of test vehicle as per the following star rating criteria.

Tabella 1.5 Star rating C-NCAP necessary percentage of credits

Star Level	Comprehensive score rate
5+ (★★★★★☆)	≥90%
5 (★★★★★)	≥82% and <90%
4 (★★★★)	≥72% and <82%
3 (★★★)	≥60% and <72%
2 (★★)	≥45% and <60%
1 (★)	<45%

Take into consideration of vehicle safety performance balance as well as the compliance with the above mentioned requirements on comprehensive score rate, a minimum limit for each sector is necessary in order to obtain final star rating. Requirements on the minimum score rate for each part of C-NCAP as table 1.6.

Table 1.6 Star rating C-NCAP necessary percentage of credits for each section

Star level	Minimum score rate for each section				
	Occupant protection	Pedestrian protection	Active safety		
			2018	2019	2020
5+ (★★★★★☆)	≥95%	≥75%	≥50%	≥55%	≥72%
5 (★★★★★)	≥85%	≥65%	≥26%	≥38%	≥55%
4 (★★★★)	≥75%	≥50%	≥26%	≥26%	≥26%
3 (★★★)	≥65%	≥40%	/	/	/
2 (★★)	≥55%	≥20%	/	/	/
1 (★)	<55%	<20%	/	/	/

From the chart, the rating in C-NCAP increases the weight of active safety in the following years. The protocol recommend the manufacturer to investigate on intelligent driving assistant systems to fulfill the requirements of high star rating.

3. IIHS rating

The Insurance Institute for Highway Safety and Highway Loss Data Institute operate the IIHS safety rating. It focus on highway safety as well as insurance related safety performance.

3.1. Rating systems

Categories:

1. **Crashworthiness**
    - Moderate overlap frontal rating
    - Driver-side small overlap rating
    - Side test rating
    - Roof strength

    Head restraints & seats

2. **Crash avoidance & mitigation**

    Front crash prevention

    Headlights

3. **Child seat anchors (latch) ease of use**

    Different evaluation items :

    - Chest
    - Head/neck
    - Leg/ Foot. Right
    - Leg/Foot. Left
    - Restraints/ dummy kinetics rating
    - Vehicle structure rating

The IIHS uses a set of easy symbol to rate the safety performance of the vehicle.

Rating: G Good/ A Acceptable/ M Marginal/ P Poor

The rating is given by parameters from sensors.

3.2. Rewarding excellence

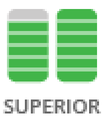
The vehicle with sufficient safety ratings would be given rewards as a proof. There are two kinds of rewards with specific performance limit:

1. Top safety pick +:

    G Good ratings in the driver-side small overlap front, moderate overlap front, side ,roof strength and head restraint tests.

    A G Acceptable or good rating in the passenger-side small overlap front test.

    or
    

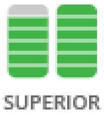
    rating for front crash prevention.

    G Good headlight rating

2. Top safety pick:

   G Good ratings in the driver-side small overlap front, moderate overlap front, side ,roof strength and head restraint tests.

   or 

   rating for front crash prevention.

   G Good headlight rating

The safety issues are not limited with protection on occupants, the safety of pedestrians and other participants should also be involved. According to IIHS latest report, the pedestrian deaths keep raising for the last decade, especially for the urban traffic and dark light:

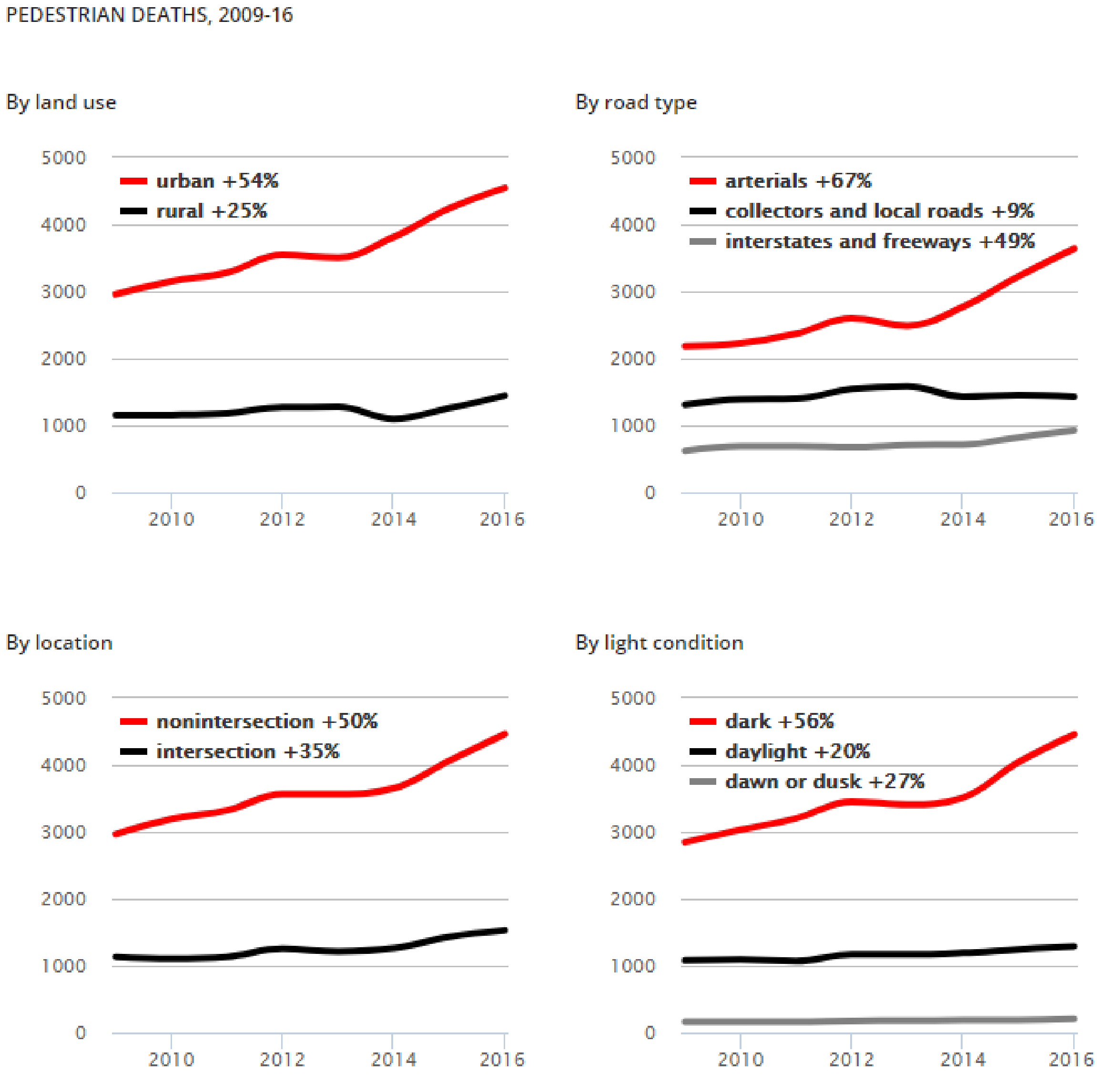


Figure 1.3 IIHS the United States Pedestrian accident death 2009-2016

Although the new technology has smart systems on pedestrian impact prevention, the amount of pedestrian accidents and deaths is still increasing. There are also accidents with autonomous driving vehicles with pedestrians. The passive safety for pedestrian impact protection is more and more important.

4. Pedestrian Safety

4.1 Introduction

As the population of the world keeps growing, the right of safe walking on the road is challenged by the amount of vehicles running on the road and the lack of sufficient facilities to guarantee safe traffic. The weakness of human body causes the priority of pedestrians rather than vehicles. However, pedestrian faculty studies show a disproportionate involvement of pedestrians, cyclists and motorized two-wheelers in road traffic injuries. For instance, the first Global status report on road safety revealed that nearly half (46%) of those killed in road traffic crashes are pedestrians, cyclists or users of motorized two wheelers.

More recently, road safety annual report 2017 said: More than half of the road fatalities among seniors above 65 falls into the vulnerable road users category, i.e. concern older pedestrians, cyclists and motorcyclists.

According to NHTSA, 5,376 pedestrians killed in the USA in 2015, UP from 4,884 in 2014, Pedestrian fatalities is 71% at non-intersections versus intersections for pedestrian location (19%). 26% highest percentage of pedestrian fatalities occur between 6 p.m. and 8:59 p.m.

Due to these results, pedestrian protection needs to be taken into consider at the very beginning of the automotive engineering. Both active and passive methods should be equipped as standard in the predictable future.

4.2 Severity of injury on pedestrians

Most pedestrian–vehicle crashes involve frontal impacts. The most likely injuries are with legs and heads.

Normally a pedestrian-vehicle crash happens at side section of pedestrians. The procedures can simplify as:

1. The first contact occurs between the bumper and either the leg or the knee-joint area, followed by thigh-to-bonnet edge contact.
2. The lower extremity of the body is accelerated forwards, and the upper body is rotated and accelerated relative to the car.
3. Consequently, the pelvis and thorax are struck by the bonnet edge and top, respectively.
4. The head will hit the bonnet or windscreen at a velocity that is at, or close to, that of the striking car.
5. The victim then falls to the ground.

The most serious injuries are usually caused by the direct impacts with the striking car rather than when the pedestrian is thrown to the road. The severity of injuries occurring to the head, brain, thorax, pelvis and extremities is influenced by:

1) Car impact speed;
2) Type of vehicle (segmentation of vehicle) ;
3) Stiffness and shape of the vehicle (equipment and structural design) ;
4) Front structural parameters (such as the bumper height, bonnet height and length, windscreen frame);
5) Age and height of the pedestrian;
6) Standing position of the pedestrian relative to the vehicle front

5. Risk factors on Pedestrian traffic safety

5.1. Cause of speeding and driver fault

According to physic laws, for pedestrian- vehicle crash the human body absorbs more energy in the crash with higher vehicle speed, which means higher displacement of organs and bones, higher acceleration of the body and more likely fatality. Therefore, the critical point is to decrease as much as possible the relative speed of pedestrian-vehicle at contact.

The speed limits on the road effectively controls this kind of injury. The automotive industry also has investment on active prevention system, like Driver Fatigue Monitor System, Autonomous Emergency Brake system, Active Pedestrian Protection system, to decrease the response time of braking and the severity of pedestrian injury.

Impairment by alcohol is an important factor influencing both the risk of a road traffic crash as well as the severity and outcome of injuries that result from it. Human response time can grow up to 3 times as usual. The delay of braking result in higher impact speed with no doubt.

5.2. Design features on board

The outer shape of the vehicle has changed during more than 100 years. Many of the features are vanished not due to design trend but rather safety issues. Pedestrian protection is one of the key point.

The shiny chrome fancy bumpers of 60s are a represent feature of American muscle cars, as well as some of the off roaders; they may protect the vehicle itself in tough usage, and give it a strong firm exterior outcome. Nevertheless, the huge bumper and fender would give huge effect into body while impact with pedestrians, cause fatally displacement. Today, most of the cars use deformable material bumper and add foam fillings between the outer face and the inner solid chassis structure such as the cross bumper beam.

Another example is the pop-up headlights. They occurred due to regulation of the US and styling requirements on front lamp height. They may give soul to a car face similar to human eyes with eyelids, but the outgoing edges can as well deliver a huge displacement into pedestrian body during crash. The pop-up headlights are almost disappeared after the late 90s because of strict legislations and the current usage of more integrated aerodynamic solutions. The same can happen while there is a hood scoop standing higher than the hood surface.

5.3. Traffic facilities

Reasonable traffic rules and signal systems can effectively reduce interference of pedestrians and vehicles. A good traffic system should consider the human will for convenience to avoid them make fault mistakes to do short cut or brake traffic rules.

It is very important to make specific divisions on the road for every participants of traffic. Facilities like underground passage and skywalks should be present if necessary. The specific rule for judging interference between pedestrian and vehicle can also contribute. The safety education for both civilians and drivers should be mandatory.

The vehicle safety is engineered under regulations and legislations. Moreover, the safety performance would be evaluated by tests. The tests are defined under specific regulations and based on the feature of the local market.

In order to decrease the severity on accidents happened between vehicles and pedestrians, it is important to test the pedestrian protection performance of the vehicle.

5.4. Safety evaluation related to pedestrian

The safety issues related with the pedestrians have been taken into consider since 1990s. New regulations and new test protocols are supporting it to decrease the injury severity and fatality.

5.4.1. Euro NCAP

The Euro NCAP is always the leading association who creates the latest and safest protocols to test the performance of pedestrian protection.

The section name is called Vulnerable Road User (VRU) protection.

Vulnerable Road User protection includes:

- Head Impact
- Upper leg impact
- Lower leg impact
- AEB Pedestrian
- AEB Cyclist

The goal is to protect those who are not under cover from the strong structure of vehicles. The other road users apart from occupants inside vehicle, are called venerable road users, with whom the vehicle might collide.

This evaluation test system take into consider of the passive safety when the vehicle hit the head, pelvis, upper and lower leg, as well as the active safety system autonomous emergency braking (AEB) system which can recognize pedestrians and cyclists who have potential impact onto the vehicle.

5.4.2. C-NCAP

In Chinese market, the C-NCAP program is following the Europe equivalent, and it create protocols to evaluate the pedestrian protection performance.

Current on going 2015 version protocol has no content related to pedestrian passive safety as well as the AEB evaluation. Starting from July 2018, the new 2018 version protocol would include the above content.

- Head form impact
- Legform impact including lower leg (Flex PLI) and upper leg form

The AEB test is inside the part of active safety section. The test protocol is related with *Euro NCAP Pedestrian Test Protocol.*

Based on the process of the project and that the most likely happened pedestrian impact injury is the leg injury, I choose to examine deeply into the pedestrian leg form impact study. More precisely, the testing procedures in the leg form impact on passenger vehicles.

CHAPTER III Real Test Procedure on leg form impact

The legfom test is an important reference in the CAE design process. The engineers should be aware of the key points on structure to improve the test performance. There are regulations to define the procedures.

The first is the legislation, which in this case is R127r2, UNECE. The legislation is the one that the manufacturer consider before the sale of the car. It is somehow mandatory to design the structure under the legislation guidance.

Meanwhile the test protocols of the third party safety test, is more specific and more demanding with respect to the legislations. Normally this type of protocols offer higher and lower performance limits, to give an evaluation to differentiate the safety performance when the models all fulfill the legislation limit. Sometimes it is not mandatory to meet the best performance line, which means the full mark of that test, but it does affect the public impression on safety performance of the vehicle.

1. Legform Test (ECE R127r2)

1.1. Definitions:

The inputs parameters in legform test UNECE are defined under R127 r2, to standardize the measurement procedure.

1) "*Lower bumper height*" is the parameter that defines the vertical distance between the ground reference plane and the lower bumper reference line, with the vehicle positioned in its normal ride attitude.
2) "*Lower bumper reference line*" is the lowest significant points, which are related to pedestrian impact. The straight edge 700mm long with a forward inclination of 25°, held parallel to the vertical-longitudinal plane (XZ plane), contact the vertical longitudinal plane of the vehicle. The resultant points traverse, and form a geometric trace of the contact points. (see figure 3.1)

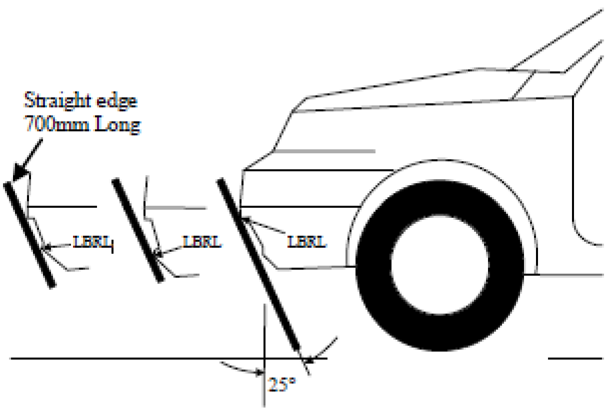


Figure 3.1 Lower bumper reference line

3) "*Side reference line*" is the geometric trace of highest points of contact between the side of the vehicle and an edge. The straight edge 700mm long, transverse down, held parallel to the transverse vertical plane (YZ plane) with an inclination inwards of 45°, contact the side of the vehicle. The resultant points traverse and maintains in contact with the side of the front vehicle, and form a geometric trace of the contact points. (see figure 3.2)

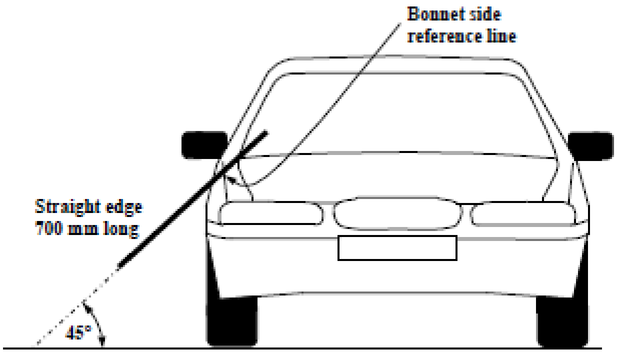


Figure 3.2 contact with the side of front structure

4) "*Tibia*" of the lower legform impactor. The Tibia has the definition that it includes all components or parts of components (including flesh, skin covering, instrumentation and brackets, pulleys, etc. attached to the impactor for the purpose of launching it) below the level of the center of the knee. Attention that the tibia as defined includes allowances for the mass, for example of the foot.
5) "*Upper bumper reference line*" is the upper limit to significant points, which are related to pedestrian impact. The straight edge 700mm long with a rearward inclination of 20°, held parallel to the vertical-longitudinal plane (XZ plane), contact the bumper of the vehicle. The resultant points traverse in the front of the front of the vehicle while maintain contact with ground and with the bumper, and form a geometric trace of the contact points. (see figure 3.3).
Where necessary the straight edge shall be shortened to avoid any contact with structures above the bumper.

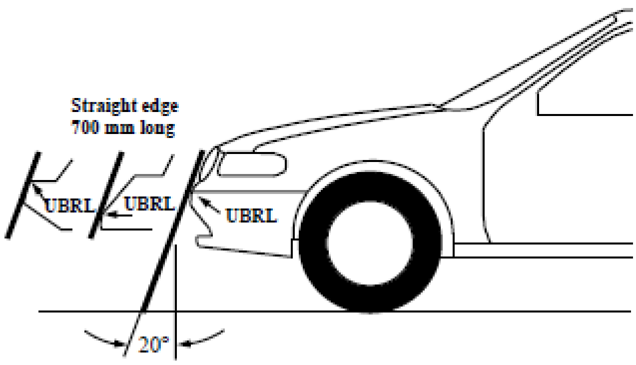


Figure 3.3 UBRL contact in the front

6) "*Wrap Around Distance (WAD)*": Use a flexible tape placed from the ground reference plane vertically below the bumper and the other end keep contact with the front car

surface. The tape is in a vertical longitudinal plane of the vehicle (XZ plane) across the front structure and is always tight to maintain an accurate measurement.

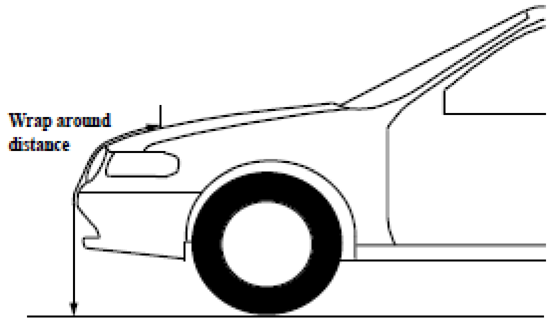


Figure 3.4 WAD distance

1.2. Specifications:

Legform test to bumper:

When tested in lower legform to bumper, the maximum dynamic knee bending angle shall not exceed 19° the maximum dynamic knee shearing displacement shall not exceed 6.0 mm, and the acceleration measured at the upper end of the tibia shall not exceed 170 g. In addition, the manufacturer may nominate bumper test widths up to a maximum of 264 mm in total where the acceleration measured at the upper end of the tibia shall not exceed 250 g.

1.3. Test Procedures

Under definition in UNECE R127r2, the test procedures for Lower legform to bumper:

1.3.1. Pretest

The foam flesh on the impactor should be one of up to four consecutive heet of type CF-45 material or equivalent form the same manufacturer. One of the sheets would be used in dynamic certification test and individual weight tolerance should be within ±2%.
At least four hours of controlled storage in specified area is mandatory before test. The humidity should be stabilized at 35 ± 15 % with temperature at 20 ± 4 °C.
Eah test should be completed within two hours after the impactor exit the storage area to assure the aligned performance with the standby impactor.

1.3.2. During test

The selected target points shall be in the bumper test area.

At least three lower leg for to bumper tests are mandatory, distributed on the bumper surface where injuries most likely happen..The minimum between impact points should be 132mm apart and 66 mm distance to the defined corners of the bumper. Flexible tapes are used to define these distances along the outer surface.

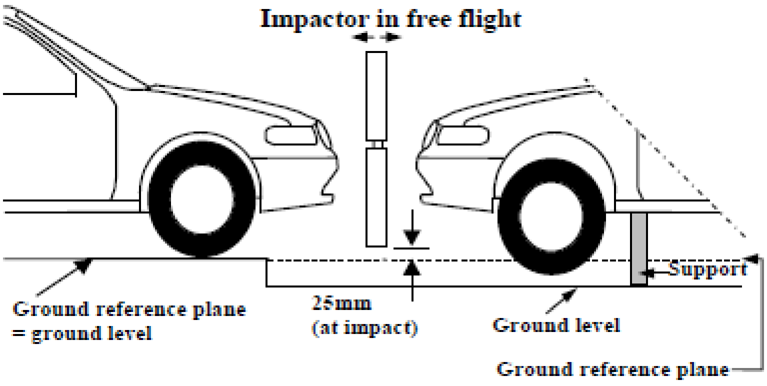


Figure 3.5 Lower legform to bumper tests for complete vehicle in normal ride attitude (left) and for cut-body mounted on supports (right)

The impact velocity vector should stay in the horizontal plane and parallel to the longitudinal vertical (XZ) plane of the vehicle, with a tolerance of ±2° at the impact moment. The axis of the impactor shall be perpendicular to the horizontal plane with a tolerance of ±2° in the lateral and longitudinal plane (XY). See figure 3.6.

The impactor stand 25 mm from its bottom to the ground reference plane at the time of the first contact (see figure 3.5), with tolerance ±10 mm. The effect of gravity must be included. At the time of contact, the knee joint should be in proper working impact position, with tolerance of ±5°, see figure 3.6. The center line of the impactor shall be a ± 10 mm tolerance to the selected impact location.

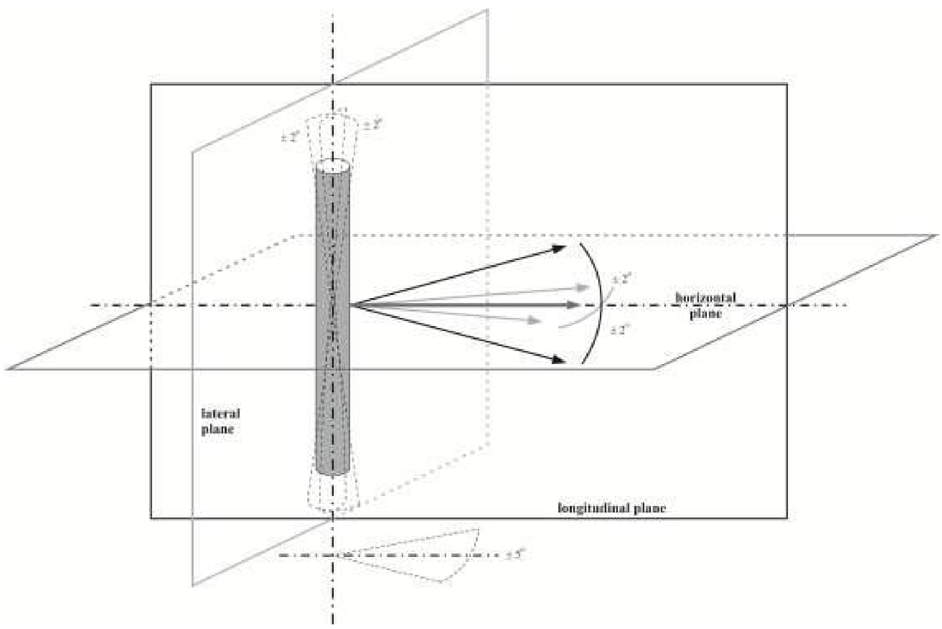


Figure 3.6 The tolerances of +angles for the lower legform impactor at the time of the first impact

The impactor should be released at a distance that guarantee the “free flight” at the moment of contact to the bumper. The contact of rebound the impactor with propulsion system should also be avoided. During contact between the impactor and the vehicle, there should not be any contact with items other than the vehicle.

Propulsion system should be air, spring or hydraulic gun or other means that can achieve same movement.

The impact velocity shall be 11.1 ± 0.2 m/s taking into consider the effect of gravity.

2. Euro-NCAP

Typical injuries resulting from leg to bumper impacts include fractures to the leg, knee and ligaments. These leg injuries are rarely fatal however are often associated with permanent medical impairment.

To estimate the potential risk of leg injuries in the event of a vehicle striking an adult, a series of impact tests is carried out at 40 km/h using an adult leg form impactor. Impact sites are then assessed and the protection offered is rated as good, adequate, marginal, weak or poor. The procedure promotes energy absorbing structures and a more forgiving geometry that mitigates injuries to the leg.

The test specification was introduced in 1997. Then due to evolution of the impactor and road regulations, it was updated in 2014

Before the test, the vehicle should be prepared under homologation procedures, to insure the homogeneous condition of vehicle before test, and avoid the impact of non-related inputs.

2.1. Vehicle preparation:

The vehicle should be prepared under the regulation to guarantee there is no ambient effect on the result. All the vehicles should go through the same preparation process before the test.

2.1.1. Unladen Kerb Weight

The unladen kerb weight is a specific definition of vehicle weight under regulated conditions. The vehicle is on the bench with standard equipment.

The fuel tank is emptied and refilled to maximum volume. The spare wheel as well as other tools included in the vehicle are on their position and all the tires are inflated to recommended pressure.

Remove the plate and mounting devices if removable.

Measure the front and rear axle weight and the total weight of the vehicle. Then the total weight is the unladen kerb weight of the vehicle. This parameter would be input of the test details.

2.1.2. Additional Weights

The additional weight is the part that simulate the occupants, with weight distributed at specific positions on board.

Both the front seat longitudinal adjustment are in mid positions, if there is no notch at the very mid position, use the rearward next notch instead.

Put 75kg mass on driver seat and 75 mass on the front passenger seat.

Make sure the vehicle is straight ahead with both steering wheel and connected front wheels.

IF in any case the suspension is adjustable, set them to the exact position when the vehicle tavels at 40km/h.

2.1.3. Suspension settling

Roll the vehicle forward and then rearward each by 1 meters at least to stabilize the vehicle. This cycle should be 3 times. (This process may not appropriate for cars with adjustable suspensions). On the wheel arch in the same transverse plane as the wheel centers, measure and record the ride height of the vehicle for all four wheels.

2.1.4. Normal Ride Attitude

After the previous procedures the vehicle now is in its Normal Ride Attitude

- The vehicle is full function in running order position on the ground
- Tires inflated with the normal pressure
- Front wheel straight ahead position
- Each necessary liquid operating correctly in standard amount.
- Correct mass to simulate the mass of driver and front seat passenger on both of the front seats
- Suspension settings are modified to be exactly where it should be while doing 40km/h travel velocity in normal running conditions specified by the manufacturer. (especially for those vehicles equipped with dynamic or adjustable suspensions for automatic leveling)

The manufacturer should specify the Normal Ride Attitude, reference to the vertical (Z axis) position of marks, holes, surfaces and identification signs on the vehicle body, above ground. The chosen marks should be able to check the vehicle front and rear ride heights and the vehicle attitude easily. The reference marks are within 25mm of the design position in vertical position (Z axis), therefore the design position shall be considered to be the normal ride height

The manufacturer shall specify the Normal Ride Attitude with reference to the vertical (Z) position of any marks, holes, surfaces and identification signs on the vehicle body, above the ground. These marks shall be selected such as to be able to easily check the vehicle front and rear ride heights and vehicle attitude. If the reference marks are found to be within ±25mm of the design position in the vertical (Z) axis, then the design position shall be considered to be the normal ride height. If this condition is met, either the vehicle shall be adjusted to the design position, or all further measurements shall be adjusted, and test performed, to simulate the vehicle being at the design position. Where this is not the case, the normal ride height as determined within section 1.3, Chapter III, will be used.

All ride heights measured are the Normal Ride Attitude ride heights.

2.2. Test impactor specifications

2.2.1. The legform impactor

The impactor is specified in UNECE/TRANS/WP-29/GRSP/2013/26, Annex 4. It is the flex PLI impactor with the sensors. The mechanism represent the knee ligaments and tibia.

A. The flexible lower leg has two form segments (representing femur and tibia). The assembled impactor shall have a total mass of 13.2kg ± 0.4kg. The dimensions of the fully assembled impactor shall be as defined in the Figure 3.7.
B. The mass of the femur and the tibia without the flesh and skin, including the connection parts to the knee joint, shall be 2.46 kg ± 0.21kg. The assembled mass of the femur, the knee joint and the tibia without the flesh and skin shall be 9.38kg ± 0.3kg. The center of gravity of the femur and tibia without the flesh and skin, including the connection parts to the knee joint, and the gravity of the knee joint should be defined as in the figure 3.7
   The moment of inertia of the femur and the tibia without the flesh and skin, including the connection parts inserted to the knee joint, about the X-axis through the respective center of gravity shall be 0.0325kgm^2 ± 0.0016 kgm^2 and 0.0467 kgm^2± 0.0023 kgm^2 respectively. The moment of inertia of the knee joint about the X-axis through the respective center of gravity shall be 0.0180 kgm^2 ± 0.0009 kgm^2.

2.3. Lower leg form instrumentation

Four transducers shall be installed in the tibia to measure bending moments at the locations within the tibia. Three transducers shall be installed in the femur to measure bending moments applied to the femur. The sensing locations of each of the transducers are as defined in Figure 3.7. The measurement axis of each transducer shall be the X-axis of the impactor.

Three transducers shall be installed in the knee joint to measure elongations of the Medial Collateral Ligament (MCL), Anterior Cruciate Ligament (ACL), and the Posterior Cruciate Ligament (PCL). The measurement locations of each transducer are shown in Figure 3.7. The measurement locations shall be within ± 4mm along the X-axis from the knee joint center.

Channel Frequency Class (CFC) is the instrumentation response value, which is defined in *ISO 6487:2002*, shall be 180 for all transducers.

The Channel Amplitude Class (CAC) is the response values, which is defined in *ISO 6487:2002*, shall be 30 mm for the knee ligament elongations and 400 Nm for the tibia and femur bending moments. This does not require that the impactor itself be able to physically elongate or bend until these values.

The determination of all flexible lower legform impactor peak tibia bending moments and ligament elongations shall be limited to the assessment interval (AI) as defined in paragraph 2.2. of this Regulation

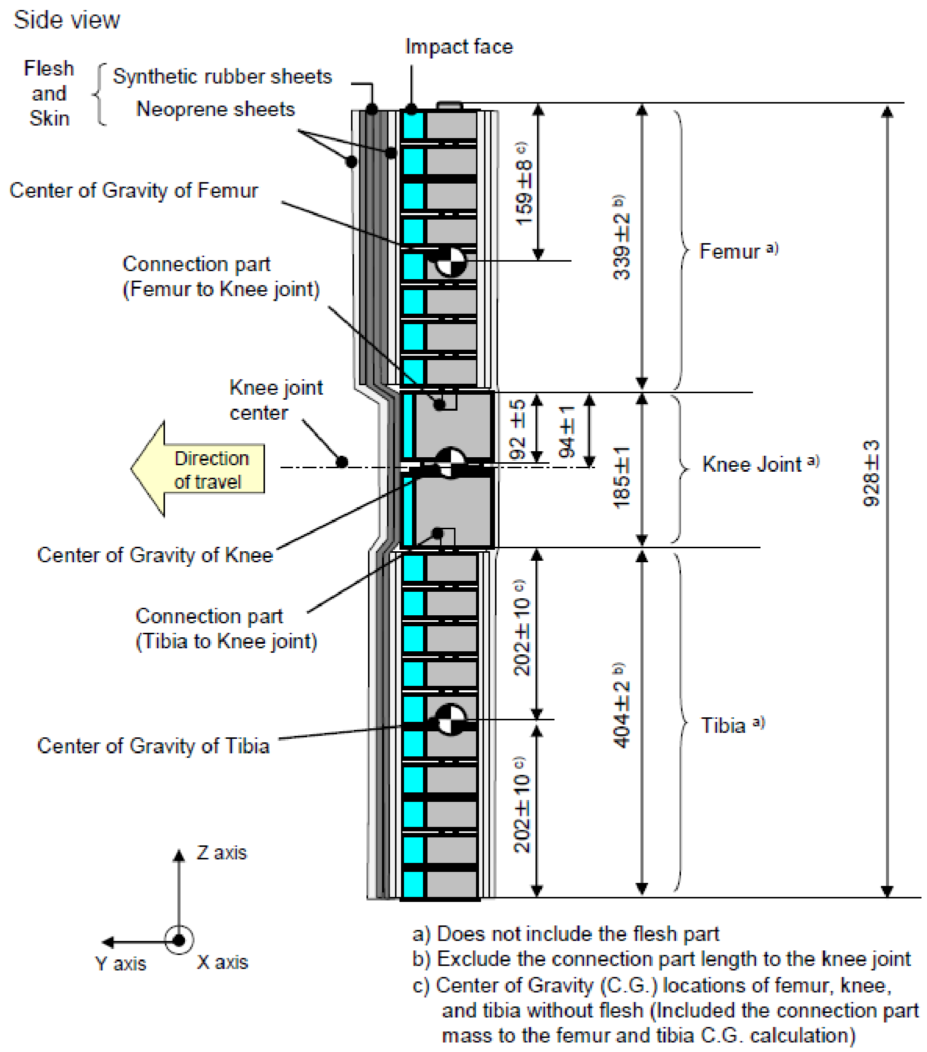


Figura 3.7 Flexible lower legform impactor. Dimensions and centre of gravitiy locations of femur, knee joint and tibia (Side view)

The measurement is performed on the knee joints and tibia bone position.

For knee joint, there are three displacement sensors within the knee joints to simulate the elongation of the ligaments PCL, ACL and MCL. The PCL and ACL ligaments are crossed with a max distance of 30mm on the knee joint center plane and the 25.8mm height position the distance is

25mm as biologic is and the MCL is placed at the back of the knee with 36mm distance to the center. See figure 3.9.

The four measuring points of Tibia linearly apply on the tibia bone equivalent with corresponding distance from the knee joint center, 134mm, 214mm, 294mm, and 374mm. The tolerance should be within 1 mm. See figure 3.9.

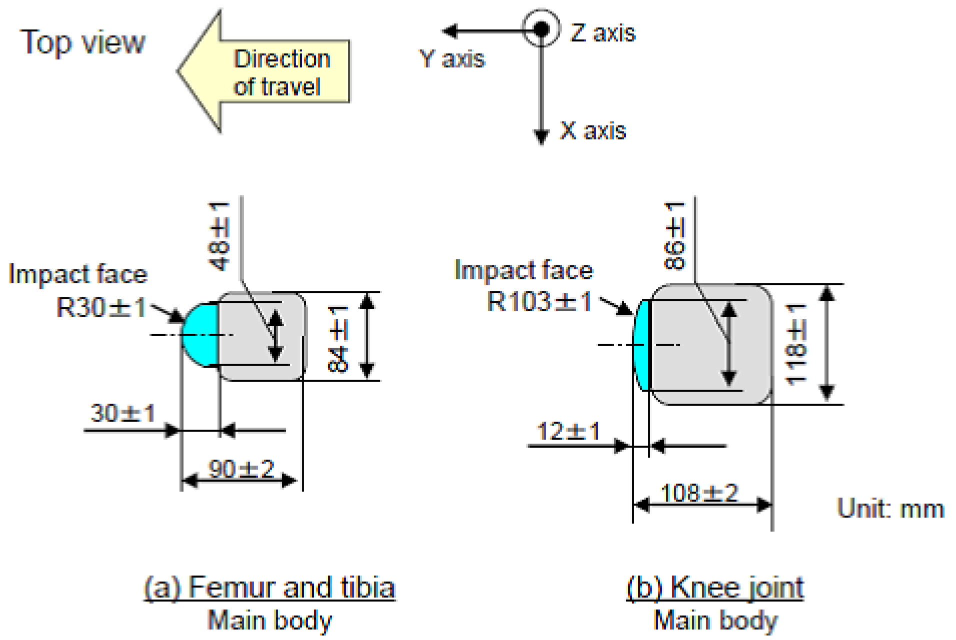


Figura 3.8 Flexible lower legform impactor schematic plan views of femur, tibia, and knee dimensions (top view)

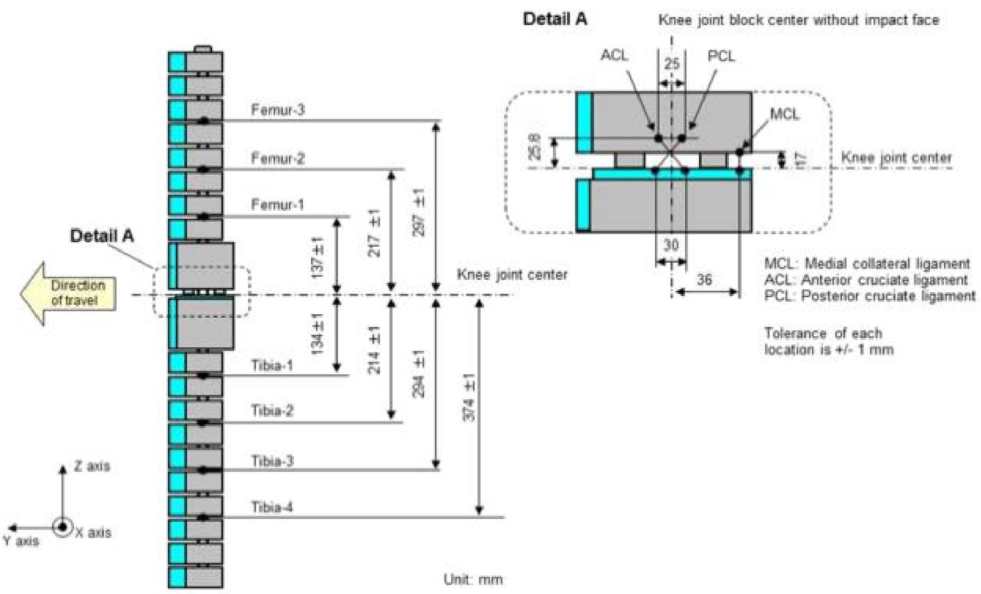


Figura 3.9 Flexible lower legform impactor instrument locations

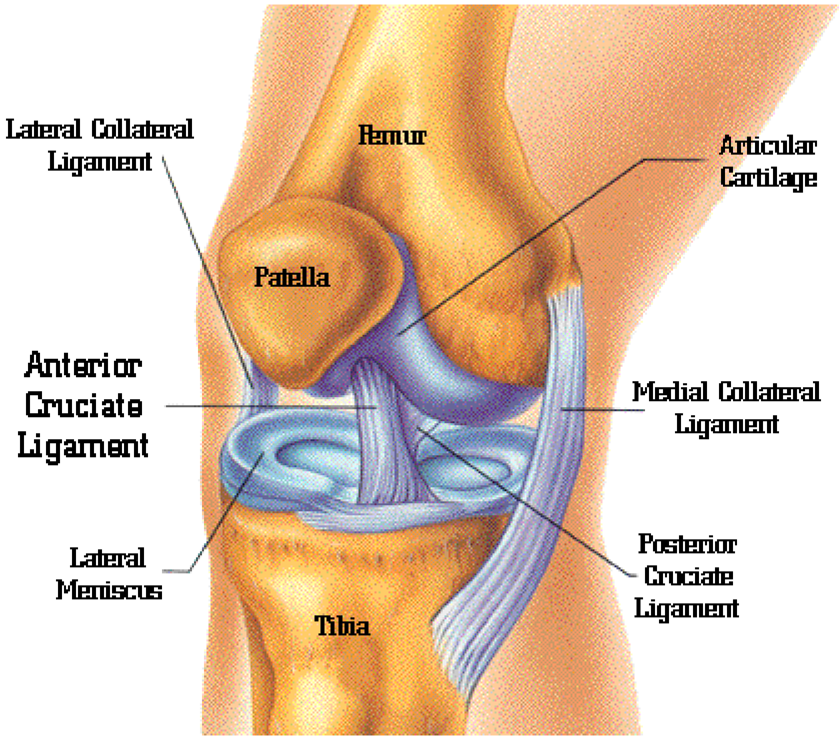


Figure 3.10 Human knee biological structure

This graph is the real case of a human knee, which we can see that the flex-PLI is sufficient to represent the basic structure. The Predecessor did not separate the different two ligament PCL and ACL. It was also without MCL.

Table 3.1 Instrumentation parameters

Location	Measurement	CFC(Hz)	CAC	No of Channels
Tibia Bending	Tibia-1 Tibia-2 Tibia-3 Tibia-4	180	400Nm	4
Knee Elongation	Medial collateral ligament Anterior cruciate ligament Posterior cruciate ligament	180	300mm	3
Tibia*	Acceleration	180	500g	1

*Optional

2.4. Euro NCAP Test Protocol Update: Flex-PLI

Starting from February 2014, the Pedestrian Protection Safety Assessment by Euro NCAP was executed by using the Flexible Pedestrian Legform Impactor (Flex-PLI).

Due to its high biofidelic characteristics along with its excellent leg injury assessment ability, the Flex-PLI is now preferred to the EEVC WG 17 pedestrian legform impactor.

UN Global Technical Regulation No. 9 (Pedestrian safety) (agenda item 3), (a), The Flex PLI was introduced by Germany representative expert, on behalf of the chair of the IWG

2.5. Certification

Certification is a necessary procedure to ensure the leg form impactor is in order before the test under certain rules. It contributes to homogeneous test process and convincing results.

The certification procedures are detailed in *UNECE/TRANS/WP.29/GRSP/2013/26 Annex 6, chapter 1.4.*

Under the following occasions, the leg form should be re-certified:

1) Before each vehicle assessment test.
2) After a maximum of 10 impacts.
3) At least every 12 months regardless of the number of impacts, even with no impact undergone.
4) If the legform exceeds any of its CACs then it shall be re-certified.
5) The legform shall be re-certified according to the procedures prescribed in *UNEVE/TRANS/WP.29/GRSP/2013/26 Annex 6, Chapter 1.2* at least once a year.

2.6. Test Procedure – Pre Test

The vehicle should be fully test prepared as described in section 1.1 to 1.4, Chapter III.

The legform system, the vehicle, the propulsion system and the data acquisition equipment have soaked in an atmosphere of temperature in the range of 16°C to 24°C for at least 4 hours before testing.

Align the vehicle straight so that the propulsion system can aim at the impact position and fire the legform in a direction that is parallel to the vehicle centre line.

Roll the vehicle forwards to give the desired free flight distance.

At the exact moment of first contact, the bottom of the legform shall be 75 mm above Ground Reference Level ±10mm. The measurement must be taken from the bottom of the legform without any protective covers.

The vehicle height is lifted with the block under wheel and the vehicle should be measured by the gravity correction method used to ensure the above tolerance; and the tolerance for direction of impact are both satisfied. Alternatively, ensure that the vehicle is positioned above a trench in the floor. See figure 3.11.

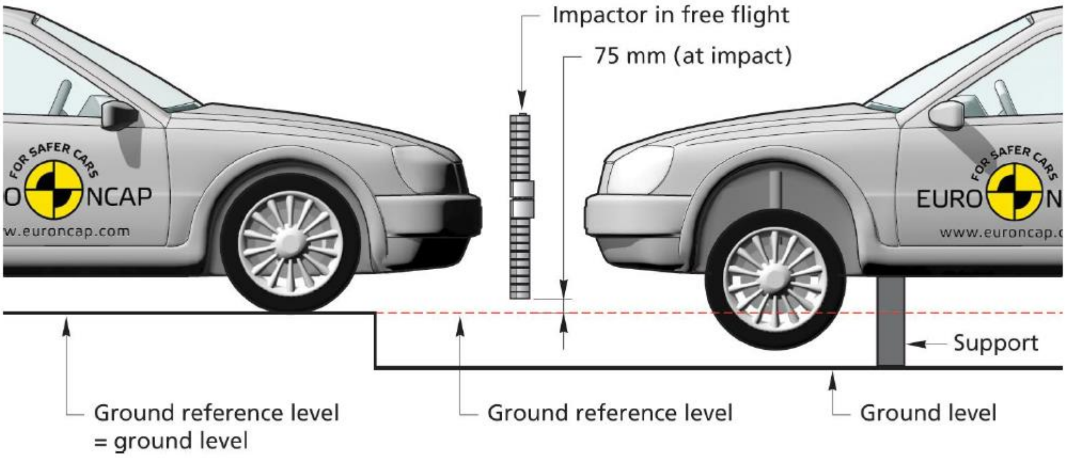


Figure 3.11 leg form impactor and vehicle reference position

If required, ensure the vehicle is at the same ride heights as those recorded during marking up of the vehicle, friction in the vehicle's suspension system may be a source of variance.

The contact height during the impact should be assured, which requires a correction factor at the firing of the legform. The free flight of legform due to gravity can result in height reduction and can be calculated to add the corresponding amount at the firing point, in section 2.6, Chapter III. This correction can be used only for free fight under 400 mm. For those with a free flight higher than 400mm, the leg form would use ballistic firing, which would be included in the following section 2.7, Chapter III.

2.7. Compensation for Gravity (horizontal firing)

Measure the distance of free flight d, which is the between the release point and the corresponding fisrt contact point.

According to Newton Laws, the height drop due to gravity during this period is:

$$h = \frac{gd^2}{2v^2}$$

Assuming a nominal value for acceleration of gravity is decimal to 9.81 ms^{-2}

Firing release velocity of the legform from the propulsion system is 40km/h (at the release point =11.1 ms^{-2} .

Then the fall due to Gravity is

$$h = 0.03981d^2$$

Raise the propulsion system by this calculated amount h. The angle ϴ changes, therefore it must remain within the tolerance. The direction of impact at the point of first contact shall be in the horizontal plane and parallel to the longitudinal vertical plane of the vehicle. The axis of the legform shall be vertical at the time of first contact. The tolerance to these directions is ±2°, which means ϴ should be less than 2°.

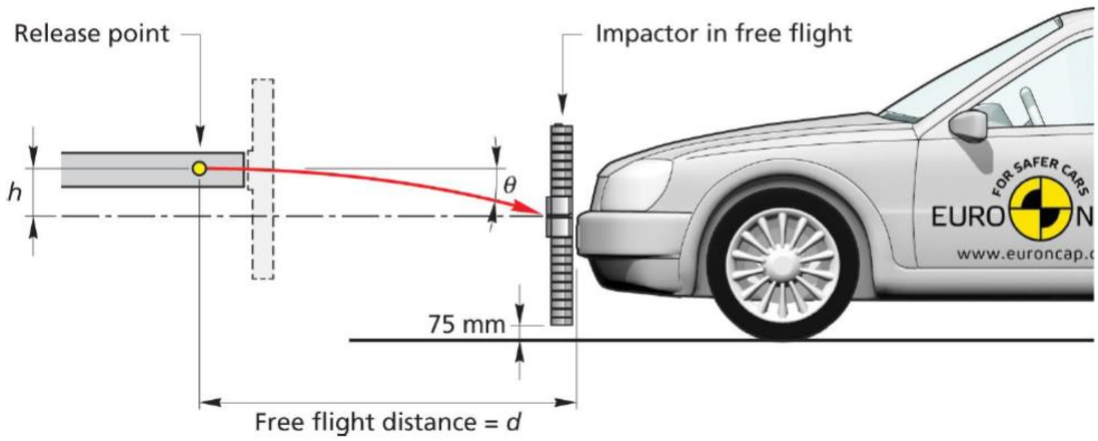


Figure 3.12 Droop comprehension

2.8. Ballistic Compensation

The ballistic comprehension is an appropriate method to correct the gravity fall.

The parameters included in the calculation is:

At the release point:

u= initial velocity

ϕ= firing angle

At the point of first contact:

v= impactor velocity at first contact (11.1m/s)

θ= direction of impact (0°)

d= free flight distance

h= height increase

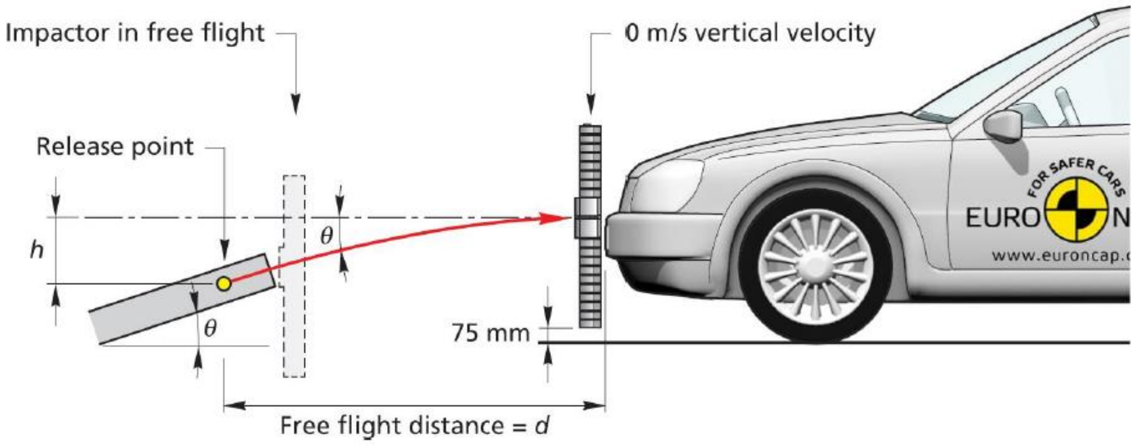


Figure 3.13 Ballistic comprehension of the leg form

There are two cases in calculation:

First case:

Parameter ϕ is fixed, and θ= 0°, v=11.1m/s. Aligned vehicle and impact point with the ballistic propulsion system. Therefore, u, d and h are the subjects.
According to Newton law and geometric math, the equations are:

$$u = \frac{v}{\cos \varphi}$$

$$d = \frac{v^2}{g} \tan \varphi$$

$$h = \frac{v^2}{2g} tan^2 \varphi$$

The vehicle should be positioned with proper distance to the release point, as well as the height above.

The second case:

Parameter d is fixed, and θ= 0°, v=11.1m/s. Aligned vehicle and impact point with the ballistic propulsion system. Therefore, u, h and ϕ are the subjects.
According to Newton law and geometric math, the equations are:

$$u = v\left(1 + \frac{g^2 d^2}{v^4}\right)^{\frac{1}{2}}$$

$$h = \frac{g d^2}{2v^2}$$

$$\varphi = \tan^{-1}\left(\frac{gd}{v^2}\right)$$

The vehicle should be positioned with proper distance to the release point, as well as the height above.
The angle ϕ shall be set so that the impactor is at the tip of the ballistic at the point of first contact.

Finish the two cases in relation to ballistic propulsion system, the following requirements are recommended:

The propulsion system should have a speed control to guarantee a speed at 11.1m/s with an accuracy of measurement at least ±0.2m/s. The Gravity effect should also be considered before the first contact.

The direction of impact at the point first contact shall be in the horizontal plane and parallel to the longitudinal vertical plane of the vehicle. The axis of the legform shall be vertical at the time of the first contact. The impactor must remain intended orientation about its vertical axis at the first contact point, which would assure the proper function of the knee joint. The tolerance is within ±2°.

The bending moments shall be ±210Nm within the 30ms immediately prior to the impact.

At the time of the first contact, the centerline of the legform impactor shall be within ±10mm of the selected impact point.

In order to meet the requirement of Euro NCAP, the above tolerances are recommended.

The impactor should not contact the ground or any object aside from the parts of the vehicle during contact.

2.9. Test Procedure – Post Test

After the test, it should do at least two still photographs of the resultant dent. One is for the side view and the other is in the front. The photograph should be representative to identify the vehicle and test location. Photograph plan aligned with each test would be recommended.

Take at least two still photographs of the resultant dent, one from the side and one from the front. Each photograph shall have some means of identifying the vehicle and test location. The preferred method shall be to use unique run number for each test.

Additional photographs are possible for further information.

Refer to section 2.4, Chapter III, the measurement of CAC should not exceed the limit before the next test. Re-certify procedure should be included if so.

Replace any damaged parts related to the impact to guarantee the next test, and repeat the same procedure for the next impact location.

3. Results Analysis

The test output would be analyzed with certain limit related to regulations.

3.1. Legform Euro NCAP

Each of the grid points can be awarded up to one point resulting in a maximum total of points equal to the number of grid points. A linear sliding scale is applied between the relevant limits of each parameter. The one point per grid point is divided into two independent assessment areas of equal weight:

1. Tibia injury assessment based on the worst performing of tibia moments Tibia 1, Tibia 2, Tibia 3, Tibia 4 (0.500 point).

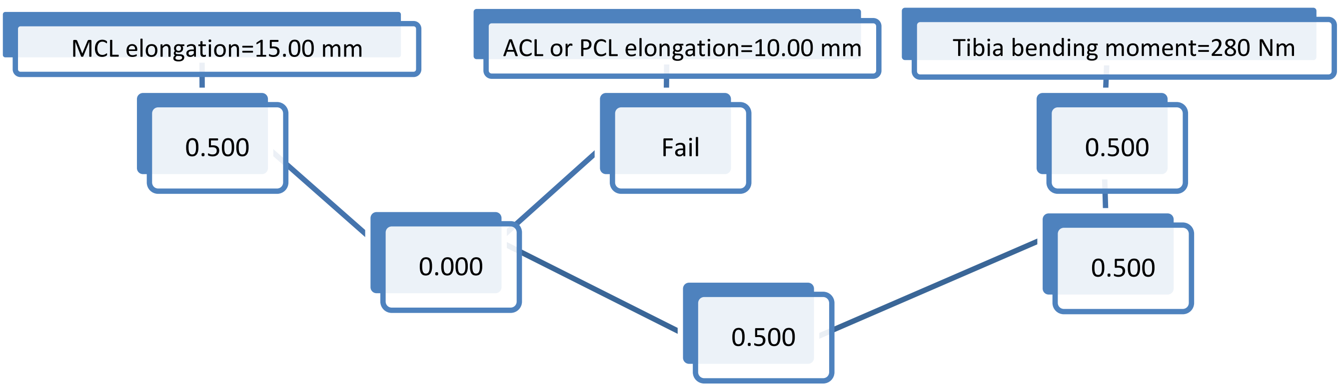
2. Knee injury assessment based upon MCL elongation, as long as ACL/PCL elongation is smaller than the threshold (0.500 point).

The total score for the legform area will be calculated out of six by scale down the sum of grid points scores by the relevant number of grid points.

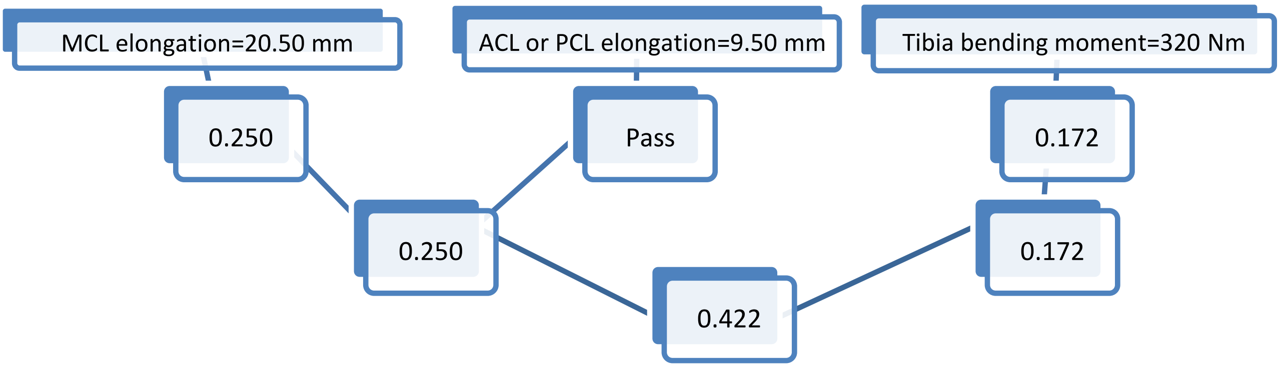
Table 3.2 Legform performance limits Euro NCAP

	Lower performance limit	*Higher performance limit*
Tibia Bending Moment	340 Nm	282 Nm
MCL Elongation	22 mm	19 mm
ACL/PCL Elongation	10 mm	10 mm

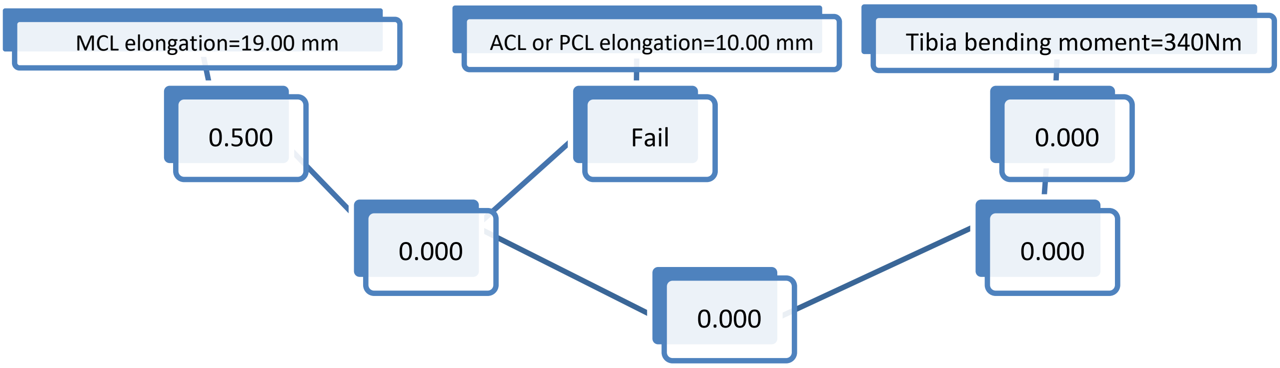
Example:
A vehicle that has 11 grid points and the tests are performed to points L+1, L+3 & L+5 with the following results:
Test result L+1



Test result L+3



Test result L+5



Grid points that have no test will be awarded the worst result from one of the neighbor points. Given that L0, L+2 & L+4 have not been tested, L0 will be awarded the score from L+1, L+2 will be awarded the score from L+3 and L+4 will be awarded the score from L+5. Symmetry will also be applied to the other side of the vehicle.

Table 3.3 An example of test result calculation

L+5	L+4	L+3	L+2	L+1	L0	L-1	L-2	L-3	L-4	L-5
0.0	0.0	0.422	0.422	0.500	0.500	0.500	0.422	0.422	0.0	0.0

The score for each individual grid point is then summed, this produces a score in terms of the maximum achievable percentage of 3.188/11 = 28.981%.
The final upper legform score is 28.981% x 6 = **1.739 points**

3.2. Legform & upper legform pattern

The protection provided by each grid location is illustrated by a colored point on an outline of the front of the car. The color used is based on the points awarded for that test site (rounded to three decimal places), as follows:

Green grid point score = 1.000
Yellow 0.750 <= grid point score < 1.000
Orange 0.500 <= grid point score < 0.750
Brown 0.250 <= grid point score < 0.500
Red 0.000 <= grid point score < 0.250

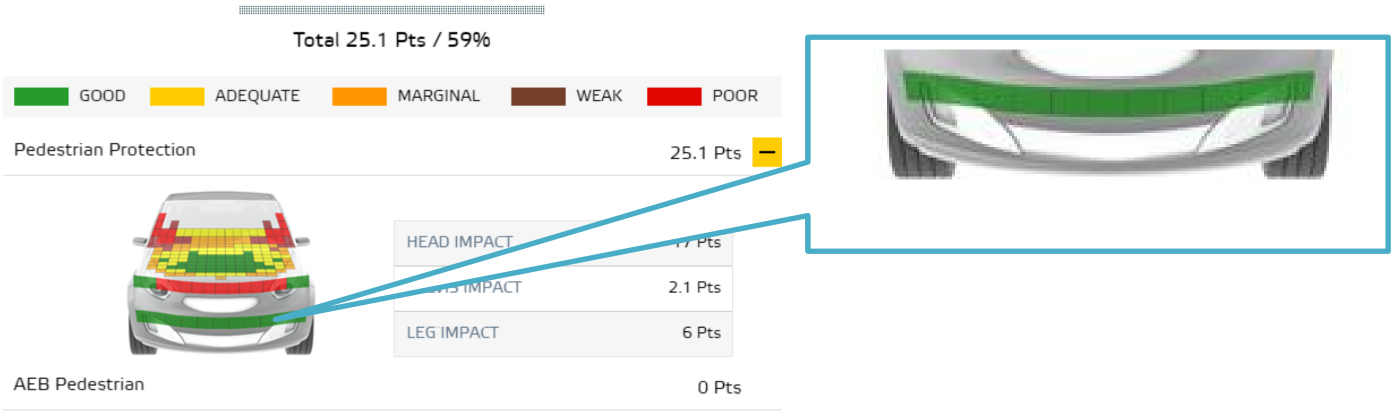


Figura 3.14 An example of pedestrian protection performance

4. Conclusion

The safety legislations together with safety legislations give the test procedures of legform impact. The test inputs are controlled by pre-test preparations and specified test process to guarantee the alignment of all the impact tests, which make it possible to evaluate the leg impact performance into performance parameters.

An example of engineering process for leg form impact would be virtual simulation on leg form impact, with CAE models. The result can be a reference during the engineering phase, to give support on further modifications to improve the performance

Diving deeply through vehicle safety, pedestrian safety and finally into leg form impact test, the following part would be a real case application of the integration of the legislation and the test regulation of the leg form impact test.

CHAPTER IV Case Simulation and Analysis

1. Introduction of basis

This chapter include the introduction of software usage and test plan.

1.1. Pre-Process software ANSA

ANSA is a convenient software from BETA company to do the pre-process treatment on the 3D model and mesh process. It supports vast formats of engineering software, and can be easily loaded to other simulation software later.

In this case, I choose LS-Dyna to follow the simulation and analysis of pedestrian legform impact.

The model should be formatted with CAE software, with suitable mesh accuracy, as well as material information, property settings, contact details and connection settings, boundary conditions of all parts and proper set includes, due to the software preset test procedure.

The model I use is F segment vehicle, front-end partial vehicle model, properly meshed with property and material from real car. The total elements are at 150k level.

The impact points are set according to ECE r127 regulation, which is also the one as reference to Euro-NCAP impact tests.

In the CAE plan, not all of the impact points are included inside the simulation calculation. The three points we take into consider are:

Y0, Y400 and Y700.

Which represent the middle of the body, the intermedia position, and the side of the body.

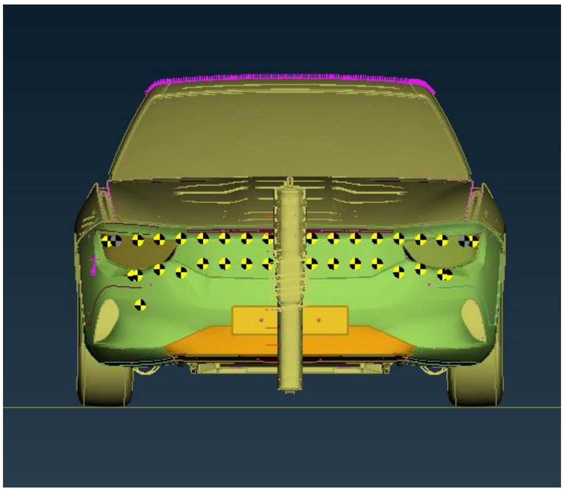


Figure 4.1 Impact points on the bumper Y0 position

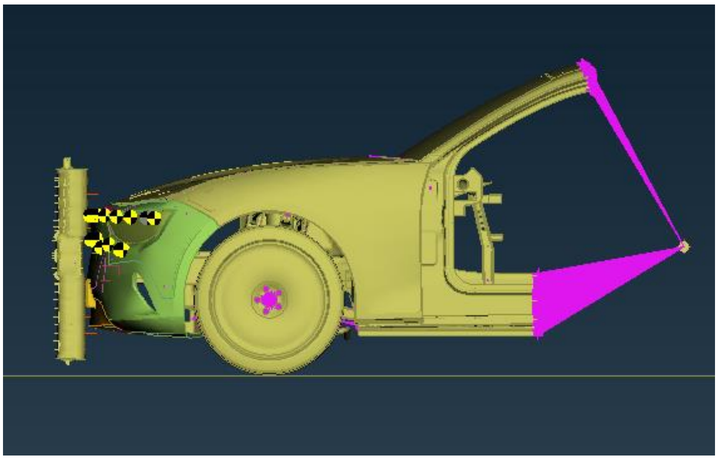


Figure 4.2 Impact points on the bumper, side view

The software ANSA can modify the CAD model with constraints, which would not change other components while doing specific parameter modification. This can avoid change of the styling point of view and also control the parameters involved.

1.2. Calculation

LS-Dyna is a commonly used software to do the dynamic simulation calculation.

The software is launched on Linux server. Each file should be transformed correctly to Linux readable.

With different master file, ls-dyna can run the impact with the same CAE model. It is only necessary to preset the correct test inputs, such as leg form position, displacement, velocity, and the components involved.

1.3. Post process

META is the after process software pared with ANSA. It can automatically output pptx format report based on the calculation result from LS-Dyna. (ANSA-META can be used for a dozen of calculators, in this case LS-Dyna).

The sensors in the Flex PLI model would give the curve of each parameter during the impact. The entire period is 500ms. The curve can be written on the graph by META software and the leg form impact on the model can be recorded, too.

1.4. Performance target

For leg form impact there are two kinds of performance measurement. The ECE legal target for legislation and the Euro NCAP protocol for safety test.

The ECE legal target is written in legislation R127. Due to uncertainty of CAE calculation a 20% margin is necessary, as a safety margin for calculation.

The Euro NCAP performance limit has a lower performance limit, which is slightly more acquiring than the ECE limit. There is also a higher performance limit, which means the case that has higher performance than this limit can reach a maximum credit. In this case a 20% margin is also in consider with respect to lower limit as well as the higher performance limit (consider that the higher performance limit has already some kind of margin reserved)

The global performance target is the synthesis of the above two performance limits. With this global limit, the vehicle can achieve both legislation performance and a good test result in Euro NCAP evaluation and other third party tests with reference to it.

Table 4.1 Global performance limit chart

	ACL (mm)	PCL (mm)	MCL (mm)	Tibia 1 (Nm)	Tibia 2 (Nm)	Tibia 3 (Nm)	Tibia 4 (Nm)	Tibia MAX (Nm)
ECE limit	13	13	22	340				
ECE limit (20%margin)	10.4	10.4	17.6	272				
Euro-NCAP Lower performance	10	10	22	340				
Euro-NCAP Higher performance	10	10	19	282				
Euro NCAP with 20% margin	8	8	19	282				
Global limit	8	8	17.6	272				

2. Test 3d view

The Legform impactor is preset as regulated in ECE R127r2, With an initial velocity of 40km/h, height 75mm, the Flex PLI impactor would hit the model.

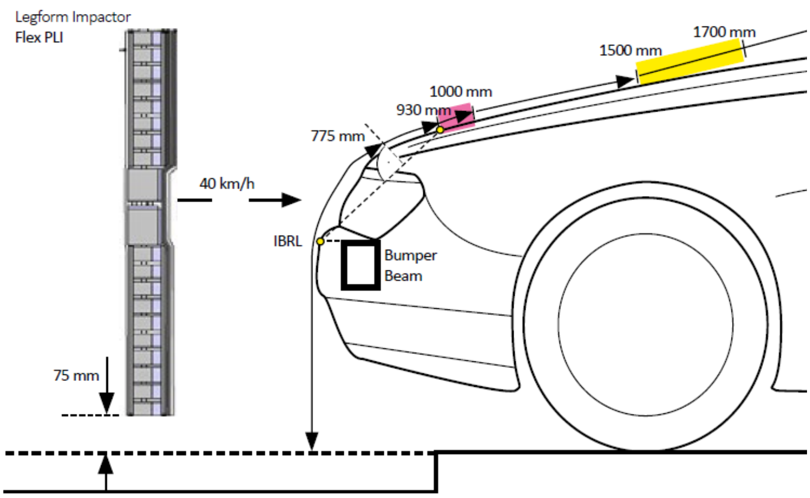


Figure 4.3 Test example of leg form impact

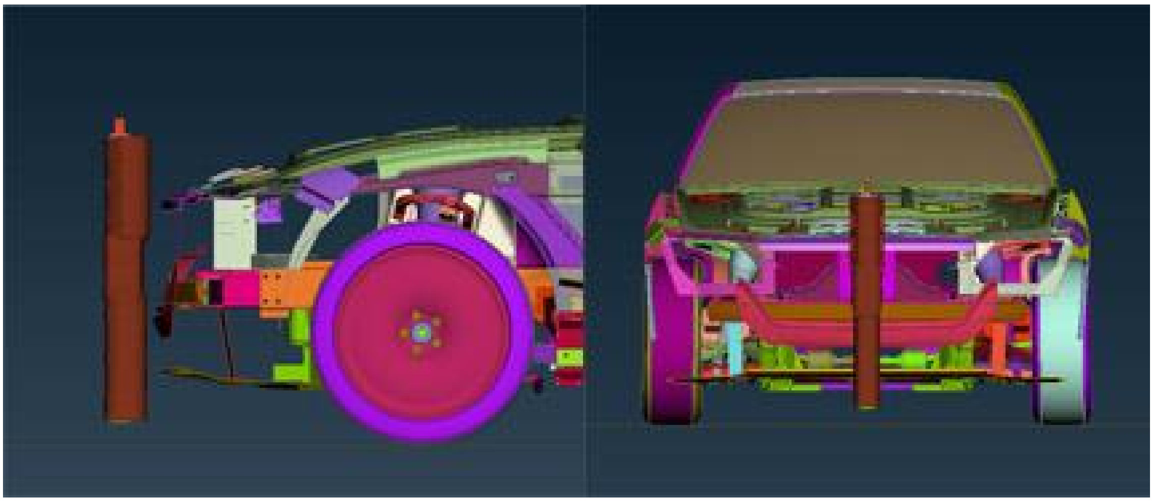


Figure 4.4 relative position of the impactor and the white body

The impact would be simulated on three positions, Y0, Y400 and Y700. The three-point strategy is used by the CAE team to simulate the performance of center section, intermediate position and the side edge performance, while limit the entire amount of running simulations.

Figure 4.5 Impact position of leg forms Y0, Y400 and Y700

2.1. MCL/ACL/PCL elongation, Tibia moments

The following figure 4.6, 4.7, 4.8 show the baseline test with 80g/L density and original very thin bumper foam on Y0, Y400 and Y700 position.

The original structure use the medium density foam and a very thin bumper foam as a start point.

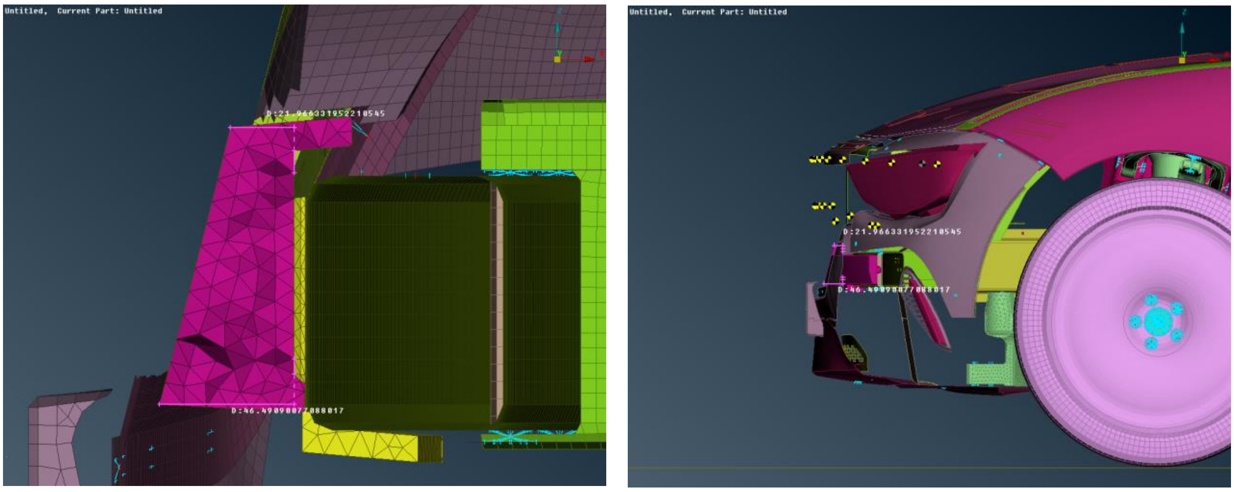


Figure 4.6 Y0 position original thickness

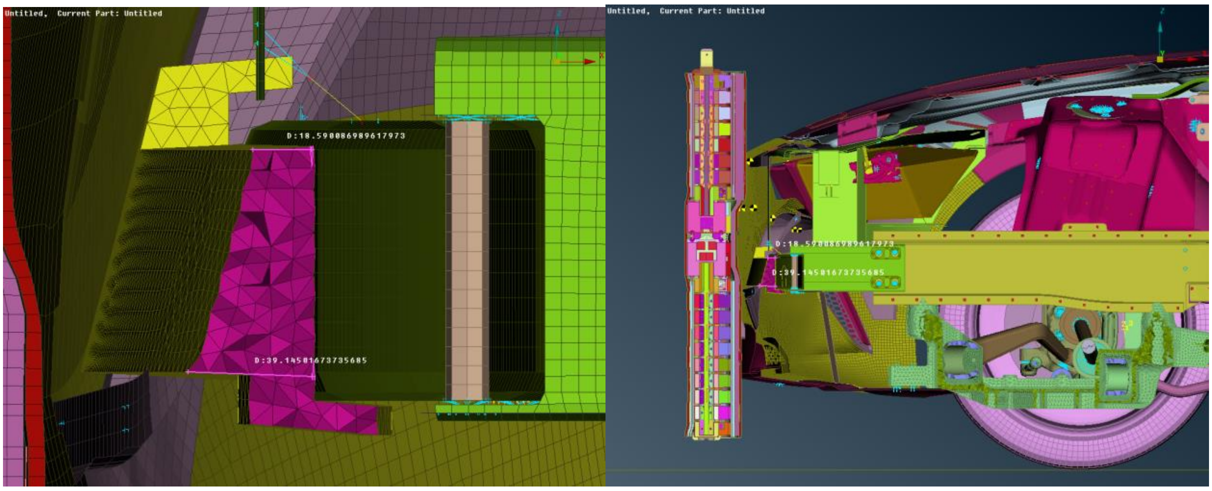


Figure 4.7 Y400 position original thickness

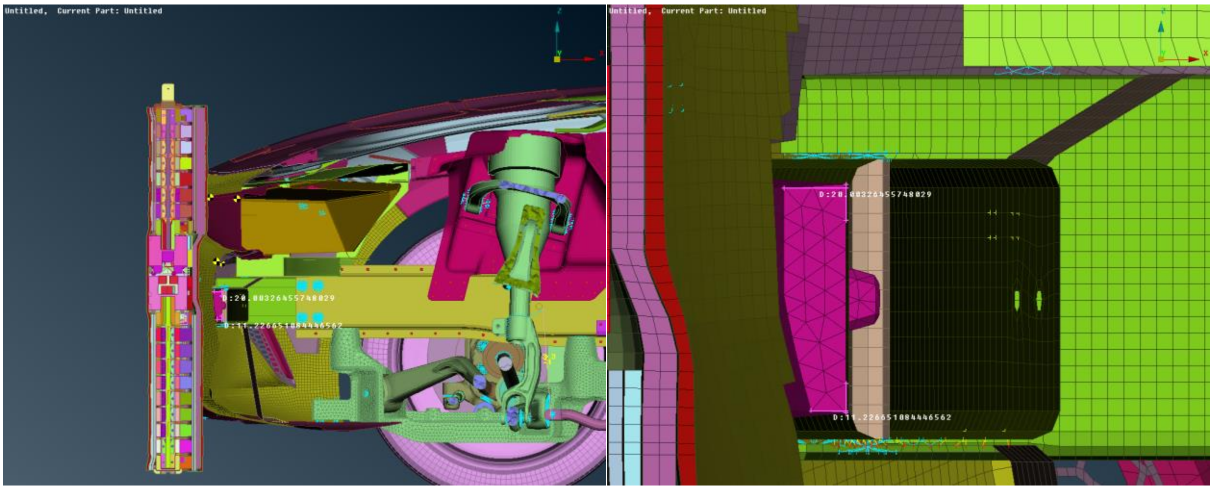


Figure 4.8 Y700 position original thickness

The Y700 position is outside the edge of the foam bumper. The thickness of Y0, Y400 and Y700 position is as following chart. (Due to non-uniform shape of the bumper, the thickness is measured at the thinnest and the thickest point on the section plane)

Table 4.2 Bumper foam original thickness

	Y0	Y400	Y700
Max section thickness	46.50	39.15	20.00
Min section thickness	21.97	18.60	11.23

In addition, the default bumper performance is shown in the following graphs. The four graphs show the section view of the front car, the ACL and PCL elongation, the MCL elongation and the tibia bending moments of the four measuring positions.

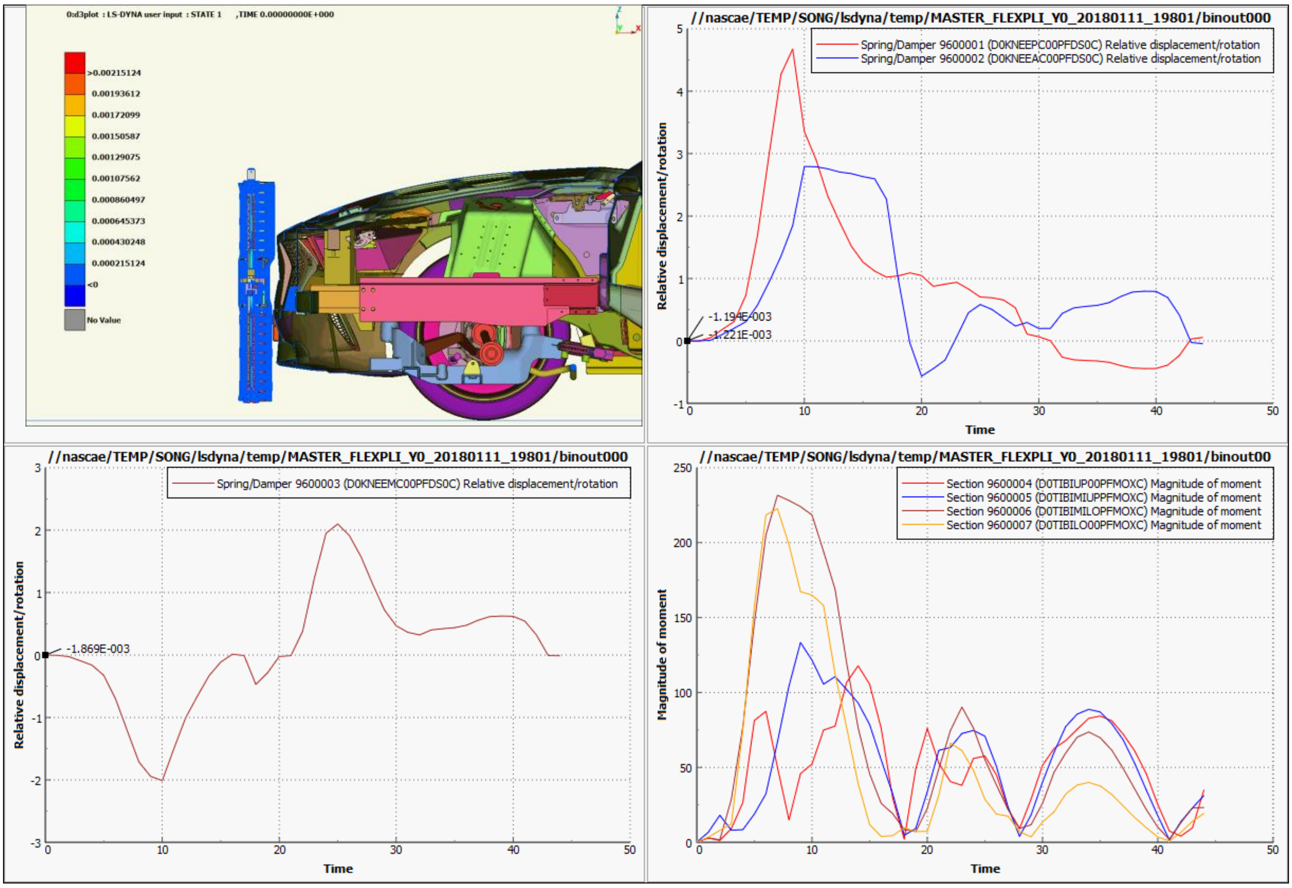


Figure 4.9 Default performance on leg form impact

The performance with global performance target is in chart. The yellow and red boxes mean that the Y700 performance need optimization and the other two points may have also improvement.

Table 4.3 Default performance on leg form impact

	PCL [mm]	ACL [mm]	MCL [mm]	Tibia 1 [Nm]	Tibia2 [Nm]	Tibia3 [Nm]	Tibia4 [Nm]	Tibia max [Nm]
Global target	8	8	17.6	272				
Y=0	4.187	2.893	2.054	105.1	132.8	231.9	224.7	231.9
Y=400	3.688	3.317	6.678	148.1	142.4	212.4	196.4	212.4
Y=700	9.25	10.28	24.2	308.7	246.1	185.6	119.9	308.7

- Green: within the higher performance target
- Yellow: within the lower performance target but not higher performance target
- Red: Exceed the lower performance limit

Although the Y0 Y400 performances are within the homologation limit, the Y700 is not as optimistic, so further investigation should be on the way. It is also plausible to improve the y0 and y400 position performance.

3. Evaluation methods of performance

Since there are ECE limit as well as Euro NCAP limit, it is necessary to integrate both the two boundaries together to create an integrated evaluation method.

According to the weight distribution of the Euro NCAP test in 4.1, chapter III, the max credit of each impact position is 1. Of which 0.5 is when the largest value of bending moment of tibia is within limit; the other 0.5 belongs to MCL lower than the maximum performance limit while the ACL and PCL cannot reach the higher performance limit.

I would introduce the percentage performance, which means the average percentage of each parameter performance with respect to the global higher performance limit in both ECE and Euro NCAP, with 20% margin.

Under these circumstances, I give 0.125 to ACL and PCL, 0.25 to MCL, and 0.125 to each one of the four tibia points as the weight factor. Then the credit for each impact point is the weight average of their percentage performance.

$A=0.125*PCL\%+0.125*ACL\%+0.25*MCL\%+0.125*\sum_4 Tibia\%$

The sum of performance factor is $\sum A$ (Y=0,400,700), represents the performance of the specific foam setting.

Table 2.4 Global limit chart with weight factor

		PCL [mm]	ACL [mm]	MCL [mm]	Tibia 1 [Nm]	Tibia 2 [Nm]	Tibia 3 [Nm]	Tibia 4 [Nm]
ece	limit	13	13	22	340	340	340	340
ece	limit20%margin	10.4	10.4	17.6	272	272	272	272
Euro ncap	limit	10	10	22	340	340	340	340
Euro ncap	limit min	10	10	19	282	282	282	282
Euro ncap	20% MARGIN	8	8	19	282	282	282	282
Global		8	8	17.6	272	272	272	272
Weight factor		0.125	0.125	0.25	0.125	0.125	0.125	0.125

The weight factor was defined under the consideration of evaluation of Euro-NCAP credits. Max credit is one for each impact position.

4. Geometric approach

The dimension of buffering elements in the front vehicle contributes to the leg form impact performance. Tipically the dimensions are shown as the following image.

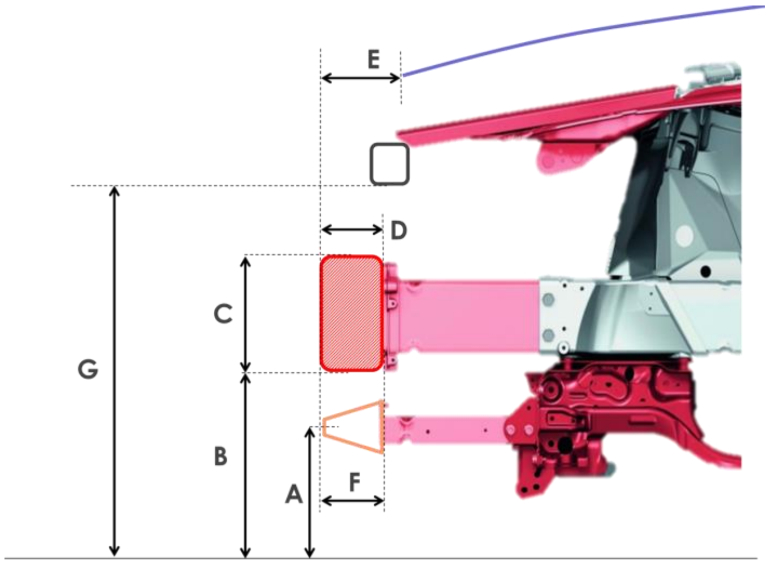


Figure 4.10 Theoratical section model of the car front

Quote	Definition	Status [mm]
A	Height of lower crossmember (leg catcher)	241.6
B	Z position of pedestrian foam lower face	429.2
C	Height of pedestrian foam	98.9
D	Pedestrian foam thickness	24.5-58.8
E	X distance between leg catcher and bonnet or headlamps	50.0
F	X distance between leg catcher and bumper beam	53.2
G	Z position of upper crossmember	751.1

Table 4.5 Data on dimensions front car

This part is focusing on D & F, because of experience engineering. Moreover, It is reasonable when the knee joint is stretched when the attach points on the bumper are not aligned, which would create huge ligament elongation.

4.1. Test plan

Three groups with D=F+50, D=F, D=F-50, which would give the concept that which kind of relation between D and F can contribute the best performance.

Table 4.5 Tests on geometry

Test groups	Group 1	Group2	Group 3
D, F relation	D=F+50mm	D, F similar amount	D=F-50mm
Foam	80g/L	80g/L	80g/L

4.2. Result

The test result would be collected and used as input. Certain limit present as the integration of legislation and regulation. The analysis would base on the data input, and use mathematic methods to improve the performance.

4.2.1. Y0 position

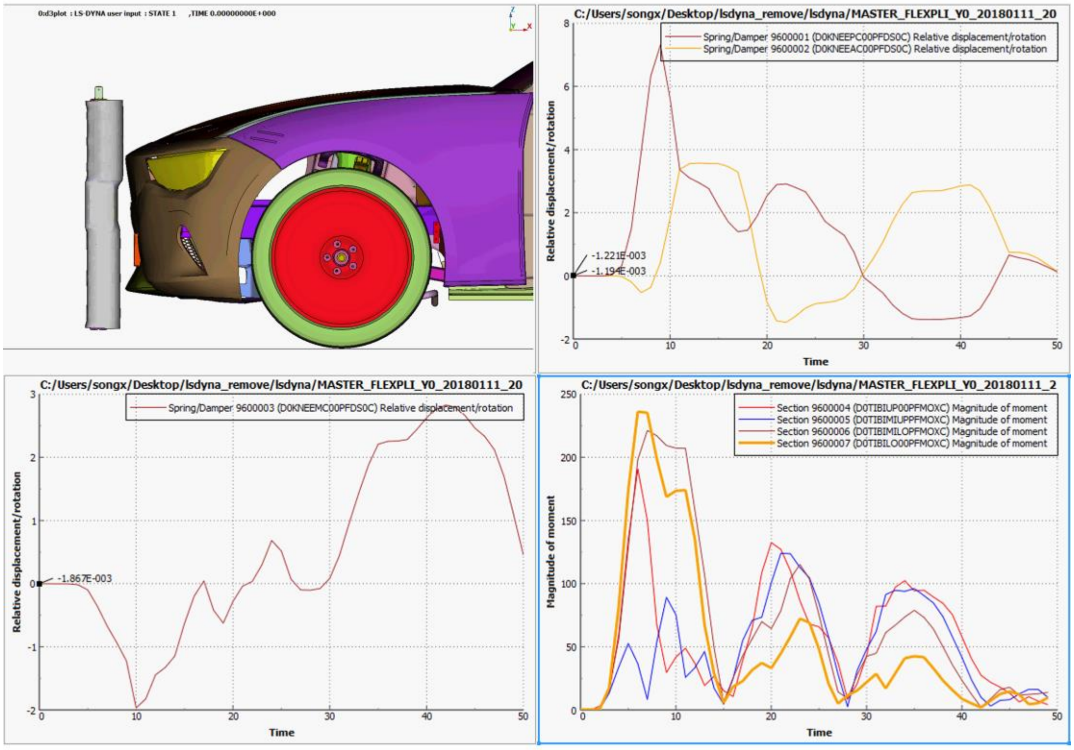


Figure 4.11 Group 1 Y0 position

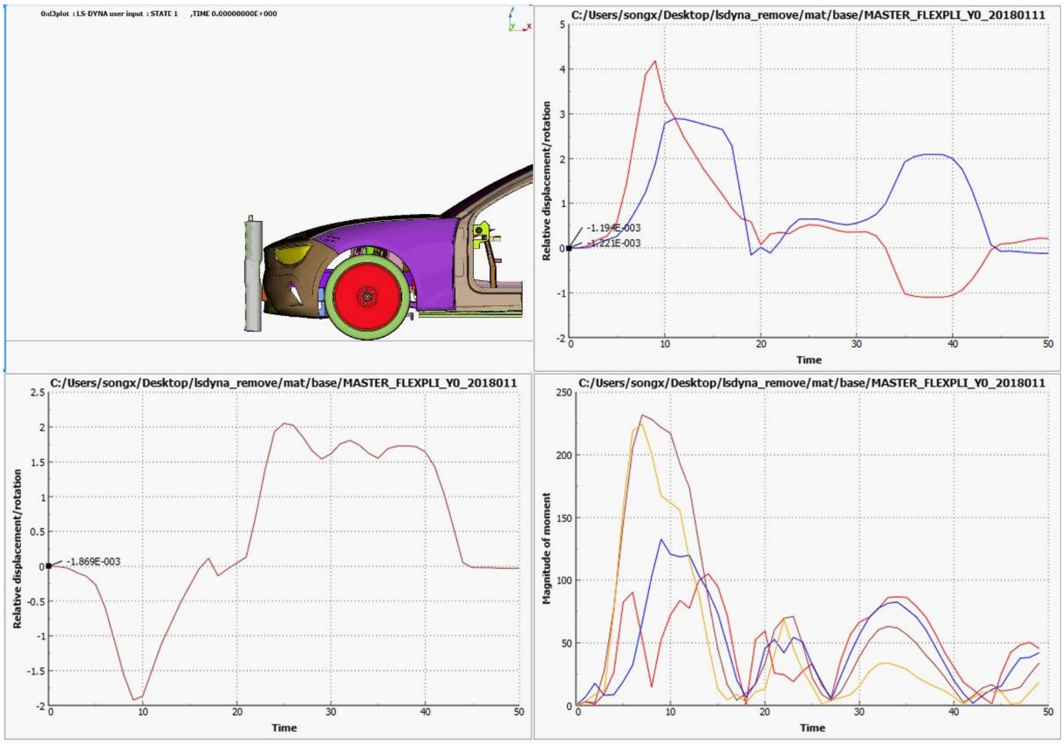


Figure 4.12 Group 2 Y0 position

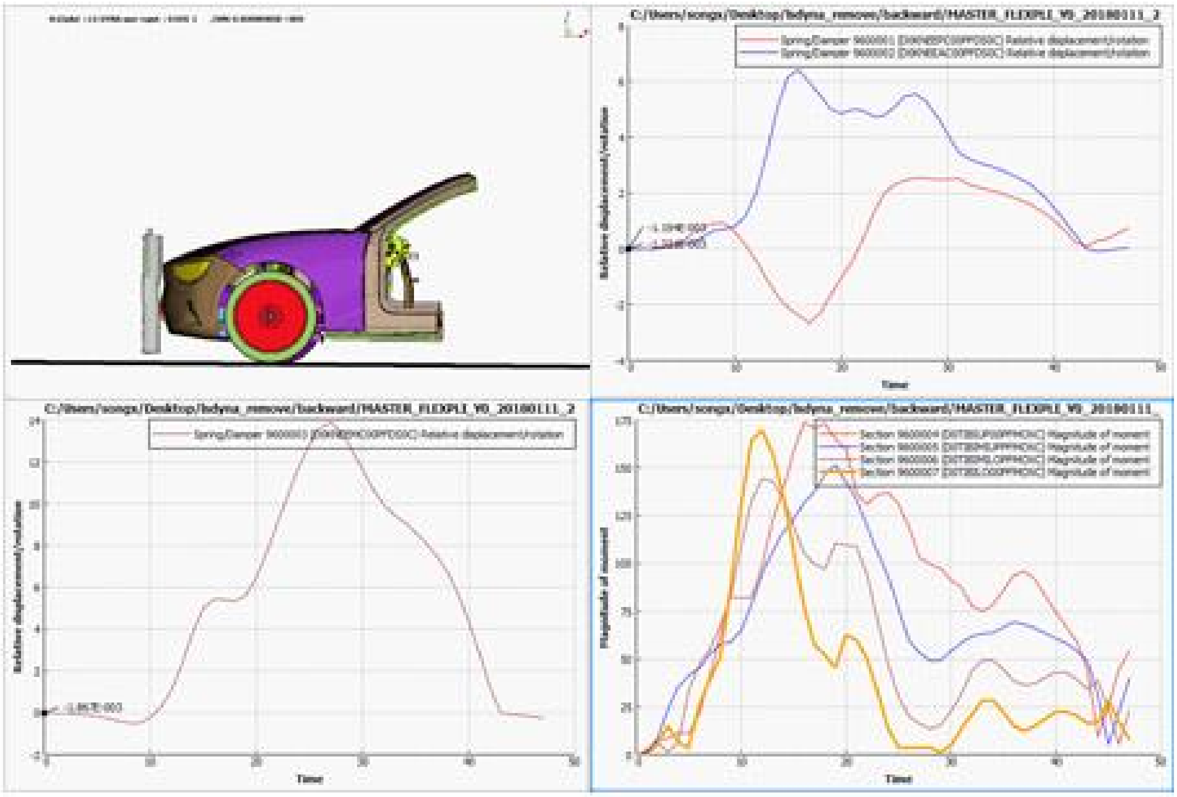


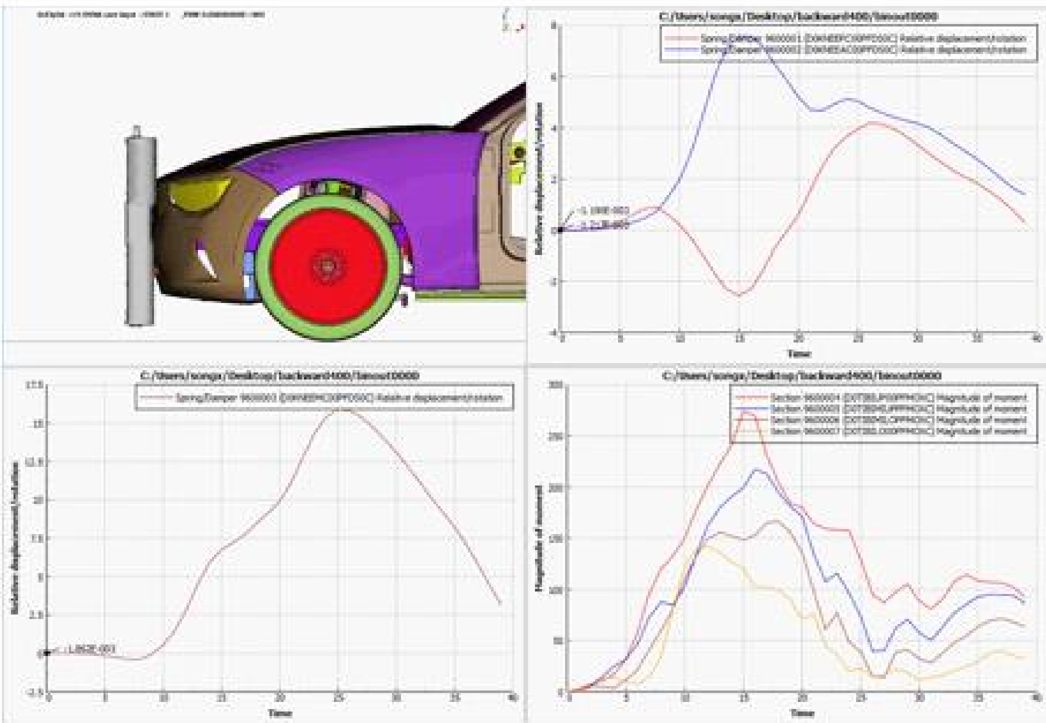
Figure 4.13 Group 3 Y0 position

Tabella 3 Geometry approach performance on lower leg, Y0 position

Y0 test	Foam	PCL [mm]	ACL [mm]	MCL [mm]	Tibia 1 [Nm]	Tibia 2 [Nm]	Tibia 3 [Nm]	Tibia 4 [Nm]
Group 1	80g/L+0mm	7,31	3,57	2,845	190,7	124	221,3	236,2
Group 2	80g/L+0mm	4,676	2,795	2,1	117,8	133,4	231,6	222,7
Group 3	80g/L+0mm	2.700	6.413	13.88	173.7	151.3	144.4	168.8

The Group 1 and Group2 have more parameters in critical situations than Group 2. Group 1 has higher Tibia1 bending moment and higher PCL Elongation, while group 2 has a lot higher MCL elongation and higher Tibia1 and Tibia2 bending moment.

4.2.2. Y400 position



n

Figure 4.14 Group 1 Y400 position

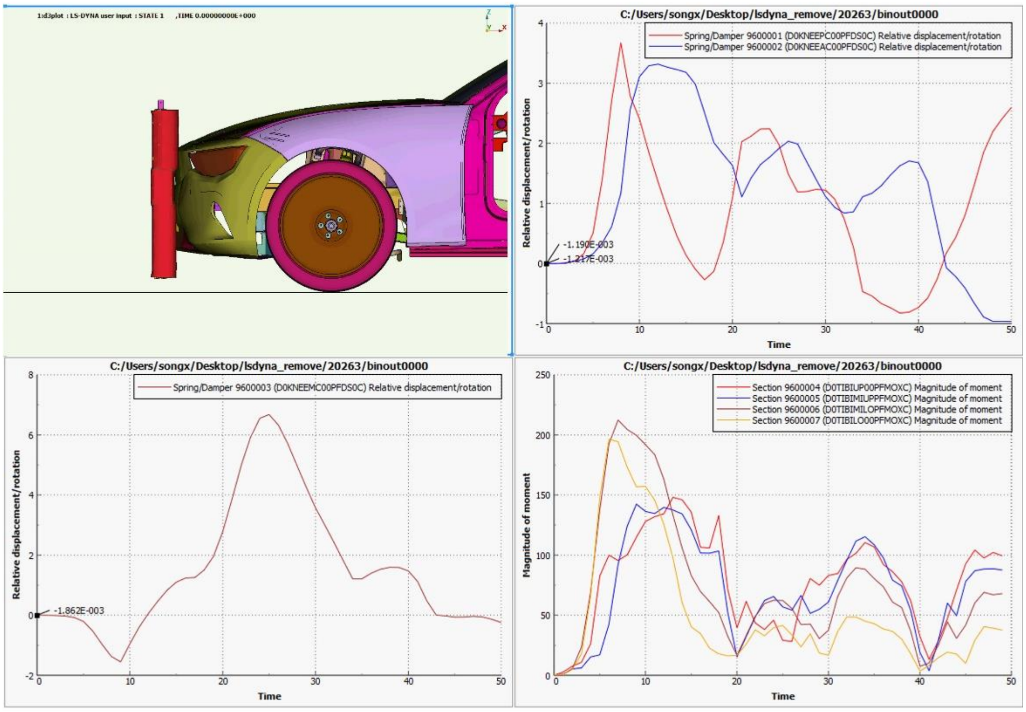


Figure 4.15 Group2 Y400

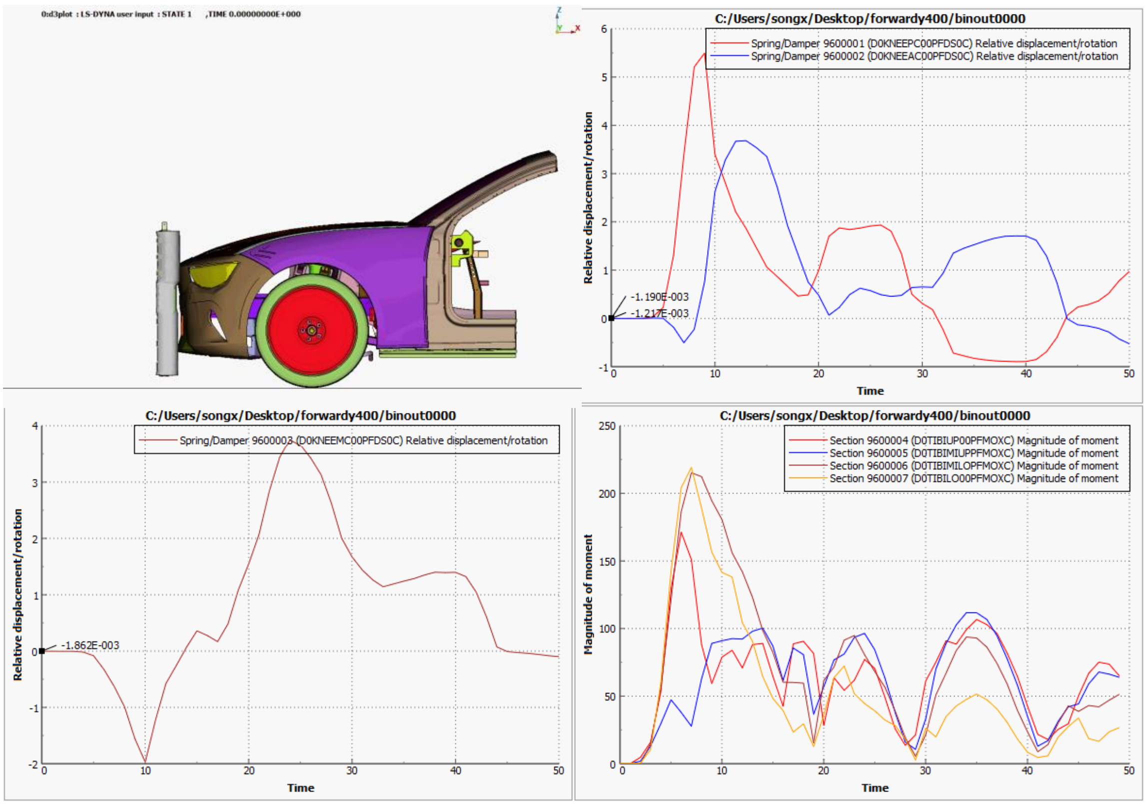


Figure 4.16 Group3 Y400

Y400 test	Foam	PCL [mm]	ACL [mm]	MCL [mm]	Tibia 1 [Nm]	Tibia 2 [Nm]	Tibia 3 [Nm]	Tibia 4 [Nm]
Group 1	80g/L+0mm	4.196	7.624	15.90	274.0	217.5	166.6	141.9
Group 2	80g/L+0mm	3.688	3.317	6.678	148.1	142.4	212.4	196.4
Group 3	80g/L+0mm	5.496	3.682	3.766	171.3	111.8	215.3	215.2

Table 4.6 Geometry approach performance on lower leg, Y400 position

The group 1 has much more MCL elongation and the tibia1 moment. The group 2 has larger Tibia3 moment and the Group 3 has larger Tibia3 as well as tibia4 moment.

4.2.3. Y700 position

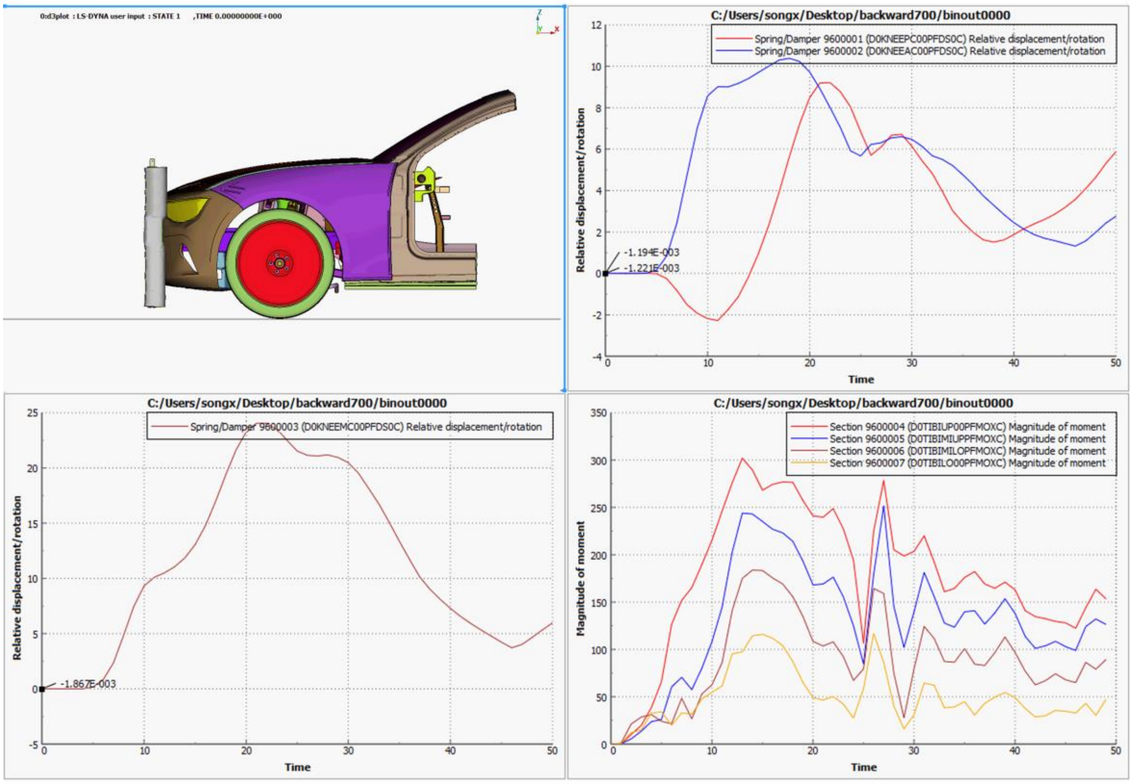


Figure 4.17 Group 1 Y700 position

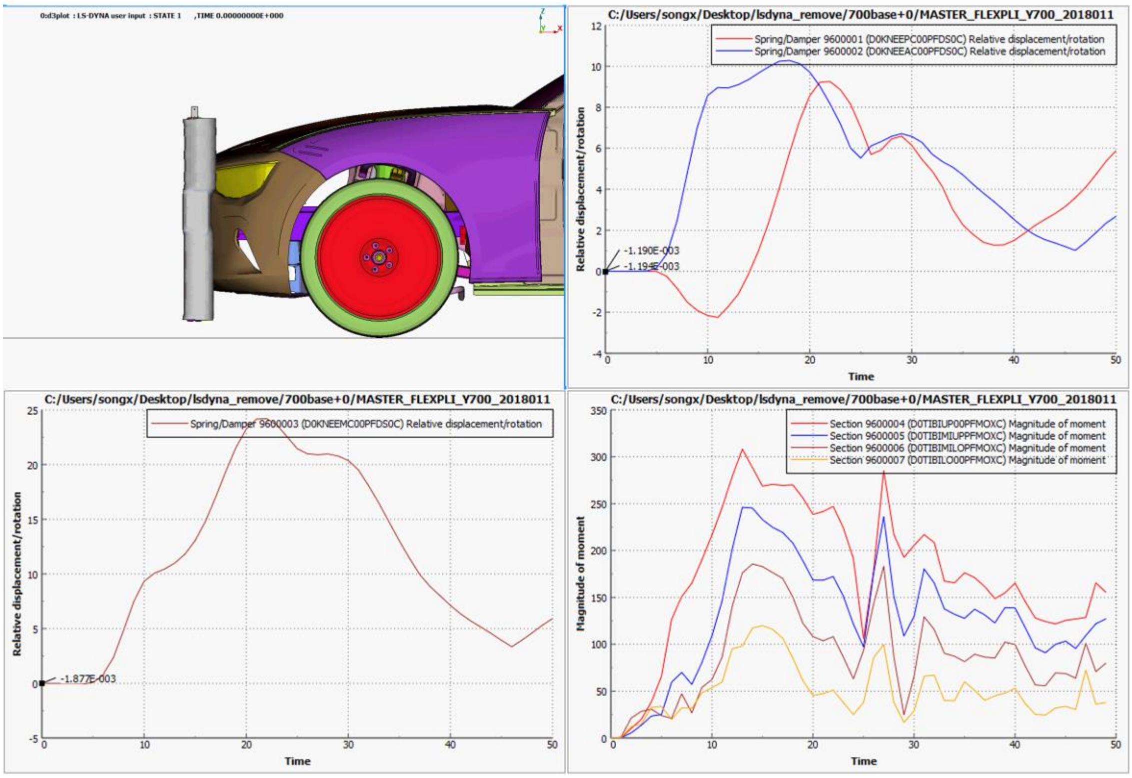


Figure 4.18 Group 2 Y700 position

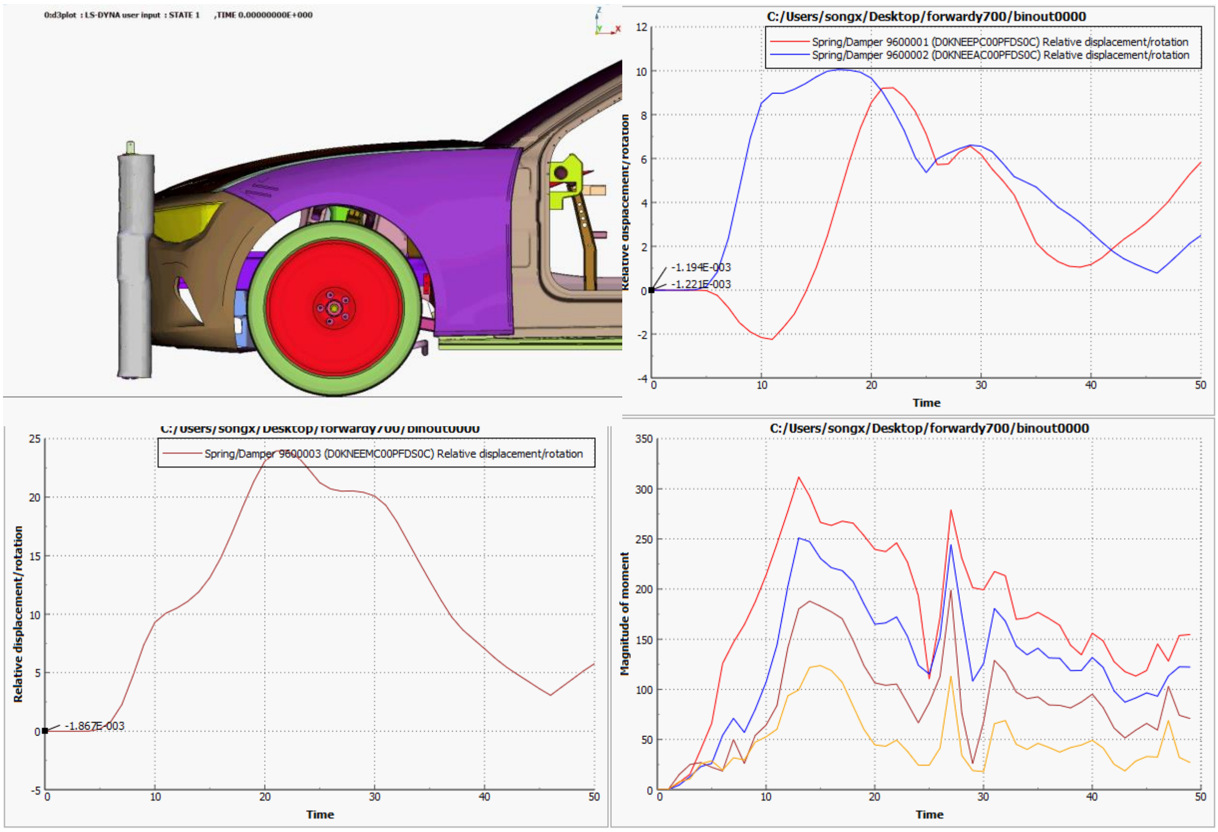


Figure 4.19 Group 3 Y700 position

Y700 test	Foam	PCL [mm]	ACL [mm]	MCL [mm]	Tibia 1 [Nm]	Tibia 2 [Nm]	Tibia 3 [Nm]	Tibia 4 [Nm]
Group 1	80g/L+0mm	9.213	10.39	24.14	302.1	251.7	183.7	116.8
Group 2	80g/L+0mm	9.25	10.28	24.2	308.7	246.1	185.6	119.9
Group 3	80g/L+0mm	9.277	10.06	24.08	311.6	250.9	198.9	123.7

Table 4.7 Test result for D and F relation

The group 1, 2, 3 have similar result both on ligament elongation and tibia moments on Y700.

4.2.4. Analysis

Use the percentage performance method by add-up to have an entire envelope of performance for each group.

Table 4.8 Percentage performance for D and F relation

Group	Position	Percentage performance	Overall performance parameter
Group1	Y0	56.53%	2.385266
	Y400	77.82%	
	Y700	104.18%	
Group2	Y0	47.08%	2.04073
	Y400	52.57%	
	Y700	104.43%	
Group3	Y0	63.28%	2.208623
	Y400	52.48%	
	Y700	105.09%	

The percentage performance calculated by test result divided by the global higher performance limit of each impact position, sums up to form a overall performance parameter. In this test the Group 2 is the best performance group, which means the leg stopper and the bumper front surface should be aligned.

5. Foam parameters related tests

5.1. Definition of tests

The tests are defined by parameters as input, and all the test results would be output.

5.1.1. Foam thickness

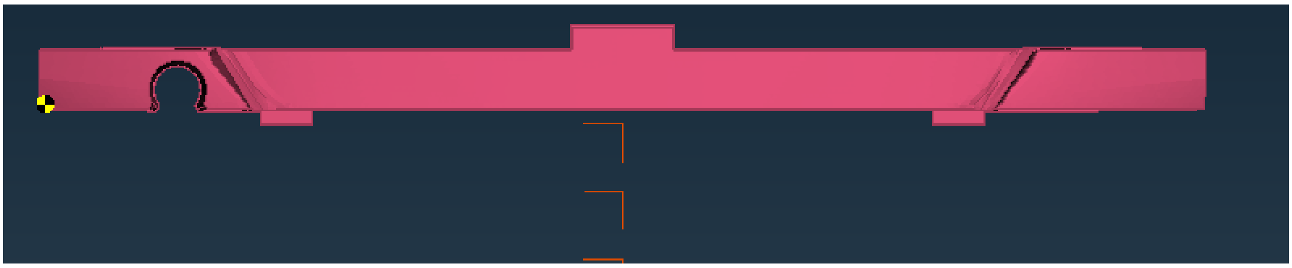


Figure 4.20 Bumper foam front view

The segment F flagship is S class, which is used as a benchmark vehicle. The benchmark model has the most thick bumper foam in the segment. It was around 140mm.

The default bumper-foam thickness is from 11.23mm to 46.49mm as shown in table 4.9. Therefore, the maximum increase should be around 125mm.

By a division of 25mm we have 6 cases:

Table 4.9 Foam thickness figures with respect to increase on impact positions

Cases	Baseline [mm]	Case 1 [mm]	Case 2 [mm]	Case 3 [mm]	Case 4 [mm]	Case 5 [mm]
Thickness increase	0	+25	+50	+75	+100	+125
Y0 Min thickness in section	21.97	46.96	71.95	96.95	121.95	146.94
Y0 Max thickness in section	46.49	71.46	96.44	121.44	146.44	171.44
Y400 Min thickness in section	18.59	43.78	67.38	92.27	117.18	142.11
Y400 Max thickness in section	39.15	64.07	89.04	114.02	139.00	163.99
Y700 Min thickness in section	11.23	36.00	60.96	85.94	110.93	135.92
Y700 Max thickness in section	20.00	44.69	69.59	94.55	119.52	144.59

The thickness of foam increase requires a related absorber beam shorten due to not effects on other components, especially the ones related with styling, for example, the bumper surface.

5.2. Foam density

The material is EPP, Expanded polypropylene.

Engineering use of bumper foam on passenger cars is around 40g/L to 120g/L. The baseline design was 80g/L.

Therefore, for material there are three cases.

Table 4.10 Density setting cases

Cases	Case1	baseline	Case2
Density	40g/L	80g/L	120g/L

The materials are from same series, which has similar curve of performance to avoid other unexpected influence on the test.

5.3. Test plan

The tests will run by a six by three matrix according to the six thickness settings and the three density settings. The output parameters would be the Posterior Cruciate Ligament (PCL) elongation, Anterior Cruciate Ligament (ACL) elongation, the Medial Collateral Ligament (MCL) elongation, as well as the four measuring points on Tibia bending moment.

The impact points are Y0, Y400 and Y700 positions, the impactor Flex PLI would be released under the regulation ECE 127, referring to Chapter III, to hit on the bumper at 40 km/h.

Collect the results and analysis the data using mathematic models to search for improvement.

5.4. Result

The chart are each position impact with each setting of foam. The parameters are

PCL, ACL, MCL elongation in [mm] and 4 positions of Tibia bending moment in [Nm].

Result Chart:

5.4.1. *Y0 performance*

Table 4.11 Y0 Performance in real figure

Foam	PCL [mm]	ACL [mm]	MCL [mm]	Tibia 1 [Nm]	Tibia 2 [Nm]	Tibia 3 [Nm]	Tibia 4 [Nm]	Tibia Max [Nm]	Average percentage performance
40g/L+0mm	4.296	2.605	2.151	92.08	128.06	233.6	225.8	233.6	45.1%
40g/L+25mm	4.324	2.629	2.274	92.01	129.3	233.3	226.5	233.3	45.4%
40g/L+50mm	4.37	2.841	2.584	92.26	129.6	233.4	226.3	233.4	46.3%
40g/L+75mm	4.387	2.956	2.642	92.44	130.5	233.8	226.2	233.4	46.6%
40g/L+100mm	4.392	2.766	2.604	91.92	130.9	233.3	226	233.4	46.2%
40g/L+125mm	4.402	2.645	2.642	91.76	132.1	233.1	225.8	233.4	46.1%
80g/L+0mm	4.187	2.893	2.054	105.1	132.8	231.9	224.7	231.9	45.9%
80g/L+25mm	4.216	2.868	2.025	96.4	134.3	231.8	225.5	231.8	45.6%
80g/L+50mm	4.224	2.812	1.923	92.9	134.5	230.9	225	230.9	45.1%
80g/L+75mm	4.218	2.833	2.052	97.61	136	231.4	224.8	231.4	45.6%
80g/L+100mm	4.226	2.844	2.192	101.2	137.7	230.9	224.9	230.9	46.1%
80g/L+125mm	4.247	2.871	2.334	106.4	139	230.5	224.4	230.5	46.6%
120g/L+0mm	4.088	3.92	3.55	142.3	138.4	229.8	224.1	229.8	51.3%
120g/L+25mm	4.112	3.332	3.188	127.9	140.3	229.3	224.2	229.3	49.3%
120g/L+50mm	4.12	3.075	2.859	122.8	140.9	229.9	224	229.9	48.3%
120g/L+75mm	4.054	3.128	3.14	127.5	142.3	229	223.6	229	48.9%
120g/L+100mm	4.086	3.173	3.193	128.9	144.8	228.7	223.7	228.7	49.2%
120g/L+125mm	4.108	3.239	3.1	133.3	145.4	228.5	223.6	228.5	49.5%

Table 4.12. Y0 Performance in percentage

Foam	PCL	ACL	MCL	Tibia 1	Tibia 2	Tibia 3	Tibia 4
40g/L+0mm	54%	33%	12%	34%	47%	86%	83%
40g/L+25mm	54%	33%	13%	34%	48%	86%	83%
40g/L+50mm	55%	36%	15%	34%	48%	86%	83%
40g/L+75mm	55%	37%	15%	34%	48%	86%	83%
40g/L+100mm	55%	35%	15%	34%	48%	86%	83%
40g/L+125mm	55%	35%	15%	34%	48%	86%	83%
80g/L+0mm	52%	36%	12%	39%	49%	85%	83%
80g/L+25mm	53%	36%	12%	35%	49%	85%	83%
80g/L+50mm	53%	35%	11%	34%	49%	85%	83%
80g/L+75mm	53%	35%	12%	36%	50%	85%	83%

80g/L+100mm	53%	35%	12%	36%	50%	85%	83%
80g/L+125mm	53%	35%	12%	36%	50%	85%	83%
120g/L+0mm	51%	49%	20%	52%	51%	84%	82%
120g/L+25mm	51%	42%	18%	47%	52%	84%	82%
120g/L+50mm	52%	38%	16%	45%	52%	85%	82%
120g/L+75mm	51%	39%	18%	47%	52%	84%	82%
120g/L+100mm	51%	40%	18%	47%	53%	84%	82%
120g/L+125mm	51%	40%	18%	47%	53%	84%	82%

5.4.2. Y400 performance

Table 4.13 Y400 performance in real figure

Foam	PCL [mm]	ACL [mm]	MCL [mm]	Tibia 1 [Nm]	Tibia 2 [Nm]	Tibia 3 [Nm]	Tibia 4 [Nm]	Tibia Max	Percentage Performance
40g/L+0mm	3.969	2.632	3.933	120.5	127.9	216.4	198.5	216.4	46.4%
40g/L+25mm	4.053	2.668	2.623	116.5	126.9	216.6	199.3	216.6	44.5%
40g/L+50mm	4.122	2.616	2.278	116.7	124.3	216.3	199.1	216.3	43.9%
40g/L+75mm	4.231	2.715	2.371	117.8	124.9	216.6	199.5	216.6	44.5%
40g/L+100mm	4.236	2.827	2.549	118.3	125.7	216.9	199.4	216.9	45.0%
40g/L+125mm	4.403	2.673	2.404	119	124.8	217.8	200.5	217.8	44.9%
80g/L+0mm	3.688	3.317	6.678	148.1	142.4	212.4	196.4	212.4	52.6%
80g/L+25mm	3.733	2.993	6.067	134.8	136.6	214.2	196.5	214.2	50.5%
80g/L+50mm	3.825	2.875	5.643	126.7	135.6	215.1	196.6	215.1	49.5%
80g/L+75mm	3.882	2.803	5.275	123.3	136.1	215.4	197	215.4	48.8%
80g/L+100mm	3.921	2.781	5.032	122.3	134.9	216.2	197.8	216.2	48.5%
80g/L+125mm	3.943	2.751	4.773	121.3	134.4	216	197.6	216	48.0%
120g/L+0mm	3.457	4.587	8.284	178.1	170.3	209.1	195.4	209.1	58.9%
120g/L+25mm	3.542	3.707	6.529	150.8	143.7	211.7	195.8	211.7	52.9%
120g/L+50mm	3.661	3.448	6.077	146	142.3	212.4	196.2	212.4	51.8%
120g/L+75mm	3.729	3.358	6.682	144.2	143.4	212.8	196.5	212.8	52.6%
120g/L+100mm	3.764	3.253	6.317	142.1	142.4	213.5	196.5	213.5	51.9%
120g/L+125mm	3.788	3.164	5.875	141.3	141.8	213.6	198.5	213.6	51.2%

Table 4.14 Y400 performance in percentage

Foam	PCL	ACL	MCL	Tibia 1	Tibia 2	Tibia 3	Tibia 4
40g/L+0mm	50%	33%	22%	44%	47%	80%	73%
40g/L+25mm	51%	33%	15%	43%	47%	80%	73%
40g/L+50mm	52%	33%	13%	43%	46%	80%	73%
40g/L+75mm	53%	34%	13%	43%	46%	80%	73%
40g/L+100mm	53%	35%	14%	43%	46%	80%	73%
40g/L+125mm	55%	33%	14%	44%	46%	80%	74%
80g/L+0mm	46%	41%	38%	54%	52%	78%	72%
80g/L+25mm	47%	37%	34%	50%	50%	79%	72%
80g/L+50mm	48%	36%	32%	47%	50%	79%	72%
80g/L+75mm	49%	35%	30%	45%	50%	79%	72%
80g/L+100mm	49%	35%	29%	45%	50%	79%	73%
80g/L+125mm	49%	34%	27%	45%	49%	79%	73%

120g/L+0mm	43%	57%	47%	65%	63%	77%	72%
120g/L+25mm	44%	46%	37%	55%	53%	78%	72%
120g/L+50mm	46%	43%	35%	54%	52%	78%	72%
120g/L+75mm	47%	42%	38%	53%	53%	78%	72%
120g/L+100mm	47%	41%	36%	52%	52%	78%	72%
120g/L+125mm	47%	40%	33%	52%	52%	79%	73%

5.4.3. Y700 performance

Table 4.15 Y700 performance in real figure

Foam	PCL [mm]	ACL [mm]	MCL [mm]	Tibia 1 [Nm]	Tibia 2 [Nm]	Tibia 3 [Nm]	Tibia 4 [Nm]	max tibia	Percentage performance
40g/L+0mm	8.668	9.142	22.95	277.7	240.9	175.2	114.9	277.7	98%
40g/L+25mm	7.792	8.094	19.44	270.3	242.3	191.5	146.4	270.3	92%
40g/L+50mm	7.119	6.391	16.7	273.3	221.1	182.6	86.8	273.3	80%
40g/L+75mm	6.764	6.192	16.14	249.2	238.5	152.2	86.17	249.2	70%
40g/L+100mm	6.732	6.161	16.05	261.5	195.4	162.9	100.3	261.5	69%
40g/L+125mm	6.646	6.189	16.17	248.8	236.6	162.8	83.4	248.8	70%
80g/L+0mm	9.25	10.28	24.2	308.7	246.1	185.6	119.9	308.7	104%
80g/L+25mm	8.583	10.11	22.41	357.5	297	200.2	123.8	357.5	106%
80g/L+50mm	8.7578	9.962	22.06	308.7	324.1	216.2	97.21	324.1	104%
80g/L+75mm	8.31	10.38	21.87	337.3	312.3	209.3	106.6	337.3	95%
80g/L+100mm	8.334	10.67	22.13	344.8	306.2	202.1	127.9	344.8	96%
80g/L+125mm	8.35	10.96	22.5	355.7	268.7	203.7	148.8	355.7	97%
120g/L+0mm	10.21	10.6	25.43	340.1	280.4	219.8	135.3	340.1	113%
120g/L+25mm	8.592	10.75	24.06	317.6	272.4	217.6	117.0	317.6	107%
120g/L+50mm	9.586	10.91	24.45	302.4	277.2	233.6	122.6	302.4	110%
120g/L+75mm	8.31	10.38	21.87	337.3	312.3	209.3	106.6	337.3	95%
120g/L+100mm	8.334	10.67	22.13	344.8	306.2	202.1	127.9	344.8	96%
120g/L+125mm	8.334	10.67	22.13	344.8	306.2	202.1	127.9	344.8	96%

Table 4.16 Y700 performance in percentage

Foam	PCL	ACL	MCL	Tibia 1	Tibia 2	Tibia 3	Tibia 4
40g/L+0mm	108%	114%	130%	102%	89%	64%	42%
40g/L+25mm	97%	101%	110%	99%	89%	70%	54%
40g/L+50mm	89%	80%	95%	100%	81%	67%	32%
40g/L+75mm	85%	77%	92%	92%	88%	56%	32%
40g/L+100mm	84%	77%	91%	96%	72%	60%	37%
40g/L+125mm	83%	77%	92%	91%	87%	60%	31%
80g/L+0mm	116%	129%	138%	113%	90%	68%	44%
80g/L+25mm	107%	126%	127%	131%	109%	74%	46%
80g/L+50mm	109%	125%	125%	113%	119%	79%	36%
80g/L+75mm	104%	130%	124%	124%	115%	77%	39%
80g/L+100mm	104%	133%	126%	127%	113%	74%	47%
80g/L+125mm	104%	137%	128%	131%	99%	75%	55%
120g/L+0mm	128%	133%	144%	125%	103%	81%	50%

120g/L+25mm	107%	134%	137%	117%	100%	80%	43%
120g/L+50mm	120%	136%	139%	111%	102%	86%	45%
120g/L+75mm	104%	130%	124%	124%	115%	77%	39%
120g/L+100mm	104%	133%	126%	127%	113%	74%	47%
120g/L+125mm	104%	133%	126%	127%	113%	74%	47%

5.5. Analysis

In order to evaluate the performance of the pedestrian leg form impact performance, it is necessary to summarize a method to provide better choices based on the data from laboratory results.

5.5.1. Euro NCAP

The method approach is that the neighbor point use the test result we have.

So that Y0=Y100=Y200, Y400=Y300=Y500, Y700=Y600

Each impact point have 1 credit and the total point is the percentage of credit we have multiply the maximum credit of 6.

Therefore, there are 15 impact points (each Y position count in two except for the Y0), with 15 credits, then calculate the impact credits with calculation regulation in Euro-NCAP, and calculate the percentage of the credits in total. Then multiply the percentage with the max credits in Euro-NCAP, which is 6, to get how much it has got in leg-form impact performance.

The following table is the calculated result:

Table 4.17 Euro NCAP leg form impact performance evaluated by simulation

Foam	X(Y0)	X(Y100)	X(Y200)	X(Y300)	X(Y400)	X(Y500)	X(Y600)	X(Y700)	Total
40g/L+0mm	1	1	1	1	1	1	0,458088	0,458088	5,132941
40g/L+25mm	1	1	1	1	1	1	0,803409	0,803409	5,685455
40g/L+50mm	1	1	1	1	1	1	0.98	0.98	5.96
40g/L+75mm	1	1	1	1	1	1	1	1	6
40g/L+100mm	1	1	1	1	1	1	1	1	6
40g/L+125mm	1	1	1	1	1	1	1	1	6
80g/L+0mm	1	1	1	1	1	1	0,230147	0,230147	4,768235
80g/L+25mm	1	1	1	1	1	1	0	0	4,4
80g/L+50mm	1	1	1	1	1	1	0,116912	0,116912	4,587059
80g/L+75mm	1	1	1	1	1	1	0.04	0.04	4.432
80g/L+100mm	1	1	1	1	1	1	0	0	4.4
80g/L+125mm	1	1	1	1	1	1	0	0	4.4
120g/L+0mm	1	1	1	1	1	1	0	0	4,4
120g/L+25mm	1	1	1	1	1	1	0,164706	0,164706	4,663529
120g/L+50mm	1	1	1	1	1	1	0,276471	0,276471	4,842353
120g/L+75mm	1	1	1	1	1	1	0.04	0.04	4.432

120g/L+100mm	1	1	1	1	1	1	0	0	4.4
120g/L+125mm	1	1	1	1	1	1	0.313	0.313	4.65

As shown in the chart the performance in 40g/L with thickness of +75mm, +100mm, +125mm can achieve max score. However since the result is simulation, further study may cause better improvement with respect to the percentage performance method.

5.6. Prediction and optimization

With discrete data, a matlab mathematic model may find best performance points that are not these tested ones. Analysis the input parameters as well as the output, to find relationship in between, and predict the others ones which may have improvement.

5.6.1. Matlab mathematic model

With data simulated, as well as Matlab, it is possible to create mathematic model to better present the result and predict possible points with better performance.

The formats in use are *regress* and *scatter,* which can calculate a surface according to the result we have. In addition, based on the stats value it is possible to see if the model is convincing enough.

With nine point in 3D space, the Matlab can deliver a surface with best approach to the data and using mesh method it is easy to predict a point with best performance.

Code Matlab:

```
x1=[0,25,50,75,100,125,0,25,50,75,100,125,0,25,50,75,100,125]';
x2=[40,40,40,40,40,40,80,80,80,80,80,80,120,120,120,120,120,120]';
Y=xlsread('filename','sheet','column')
%%Reading data

y=Y';
X=[ones(length(y),1),x1.^2,x2.^2,x1,x2,x1.*x2];
[b,bint,r,rint,stats] = regress(Y,X);
%%Binary regression with two variables

format long

figure(1)
scatter3(x1,x2,y,'filled')


x1fit = min(x1):0.1:max(x1);
x2fit = min(x2):0.1:max(x2);
[X1FIT,X2FIT] = meshgrid(x1fit,x2fit);
YFIT = b(1) + b(2)*X1FIT.^2 + b(3)*X2FIT.^2 +
b(4)*X1FIT+b(5)*X2FIT+b(6)*X1FIT.*X2FIT;
mesh(X1FIT,X2FIT,YFIT)
%%Using Regression formula to reform the function
```

```
hold on

X1FT=0:50;
X2FT=40:120;
[X1FT,X2FT]=meshgrid(X1FT,X2FT);
view(10,10)
title('Y0 performance in Pencentage value');
xlabel('Thickness [mm]')
ylabel('Density [g/L]')
zlabel('Performance')
%%Plot the surface on the figure 1

yff1=min(min(YFIT));
[xx1, xx2] = find(YFIT==yff1);
XX1=xx1*0.1+0;
XX2=xx2*0.1+40;
%%find the minimum value of y and the corresponding XX1, XX2

[b,bint,r,rint,stats] = regress(Y,X);
```

This model is a multiple linear regression model, which means it is a binary function form.

- The parameter *b* is the coefficient estimates for multiple linear regression, returned as a numeric vector. The *b* is a p-by-1 vector, where p is the number of predictors in x. type double.
- The parameter *bint* is the lower and upper confidence bounds for coefficient estimates. It returned as a numeric matrix. The *bint* is a p-by-2 matrix, where p is the number of predictors in x. The first and second columns are the lower and upper confidence bounds for each of the coefficient estimates. Type double.
- The parameter *r* is the Residual. It returned as a numeric vector, *r* is a p-by-1 vector, where p is the number of the predictors in x. type double.
- The parameter *rint* is the intervals to diagnose outliers. It returned as numeric matrix. The *rint* is a p-by-2 matrix, where p is the number of predators x.
- The *stats* is the parameter for model statistics. It is a 1x4 parameter.
  - The first is R^2, which is the coefficient of determination
  - The second is F-statistic, which is the F-distribution under null hypothesis
  - The third is p-value, which is probability value or asymptotic significance
  - The fourth is an estimate of the error variance.

  The key is that the first parameter should be close to 1, and the second parameter p-value should be less than the default significance level of 0.05. Then there is a significant linear regression relationship exist between the response Y and the predictor variables of X.

The Independent variables are the thickness of the foam x1 and the density of the foam x2, the dependent variable Y is the performance parameter we are searching for, which should be a binary function of the two variables.

The Y can be percentage performance, and PCL, ACL and MCL elongations, as well as tibia points bending moments. It depends on the inputs.

The Yff parameter is the function to find the pole of the surface, which means the best performance point on the specific parameter surface.

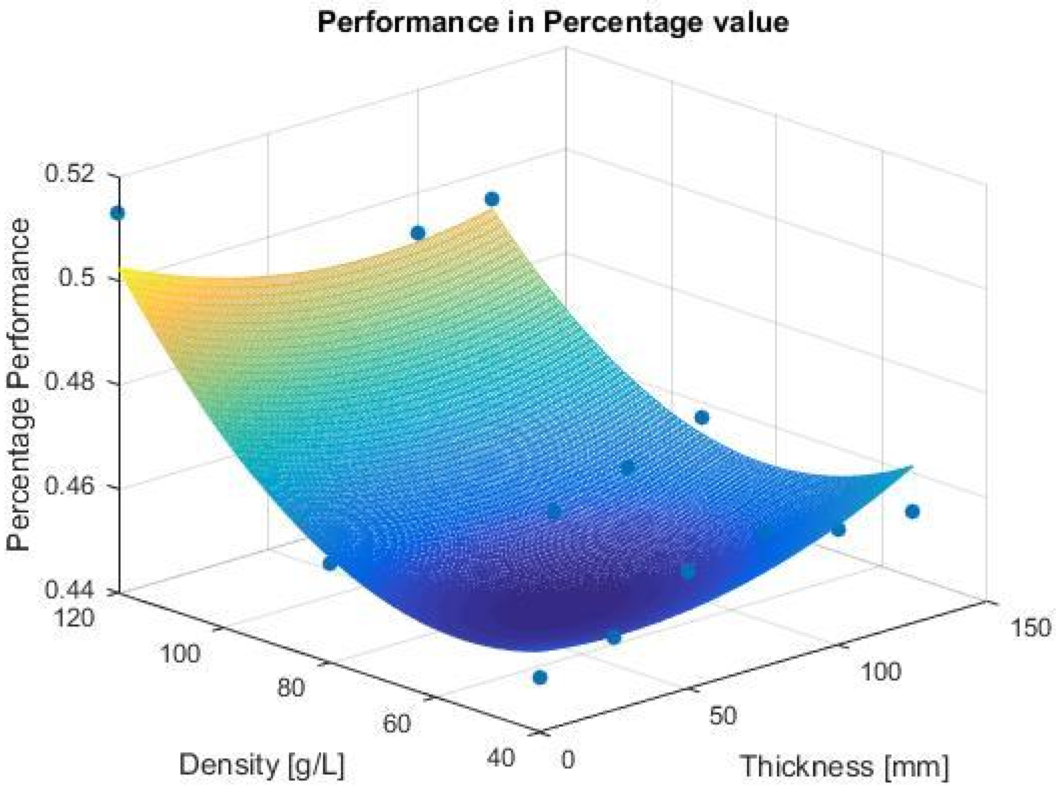


Figure 4.21 Y0 performance in Percentage value

As an inspiration of the regression surface, we can see there is a new pole in Y0 position, which can possibly deliver a better performance.

The ones without increase of thickness group has the highest percentage value due to the critical compression of the foam and an equivalence of impact directly to the crossbeam. Not enough distance to decelerate the leg form. Thick foam means better energy absorption.

After a modification on the model, table 4.18 shows that, Y0 performance is best on 58g/L&+17mm, where the predicted percentage performance is 44.9%. The calculated performance parameter is 44.7%. The difference is +0.45%, which makes the model convincing.

Table 4.18 Predict point with best Y0 performance

Foam	PCL	ACL	MCL	Tibia1	Tibia2	Tibia3	Tibia4	Tibia max	Percentage performance	Performance parameter
57.8+17y0	4.277	2.684	1.815	90.86	130.5	232.6	225.2	232.6	44.7%	
57.8+17y400	3.842	2.794	5.227	129.9	136	214.5	197	214.5	48.9%	1.94
57.8+17y700	8.262	9.364	21.69	310.2	312.6	203.8	96.02	312.6	100.8%	

Although the Y0 position performance is the best among all, the other two positions are not so good. The most critical one is Y700 position. It comes with very high value of bending moment, and MCL elongation, which have already exceed the homologation limit.

Therefore, it is necessary to analysis each of the parameters in Y400 and Y700 position to find the best solution. The graphs would contribute to find the tendency and the pole points so as to find the compromise of foam properties.

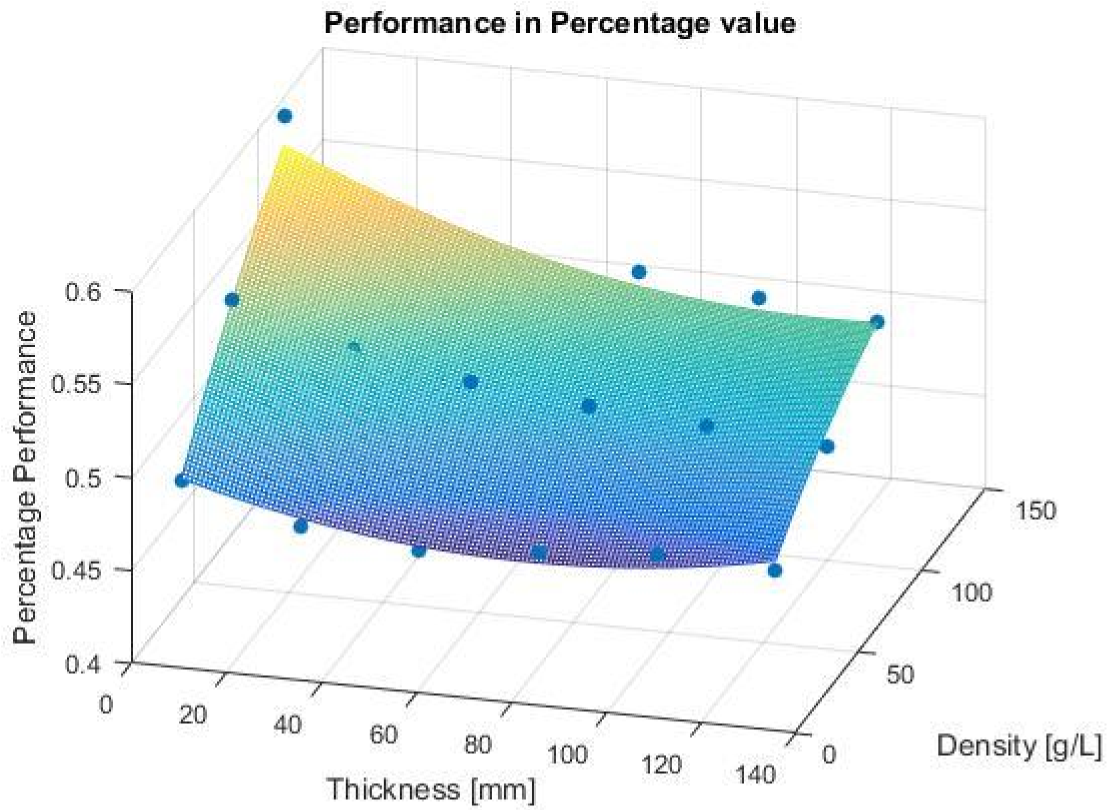


Figure 4.22 Y400 performance in Percentage value

.

For Y400 position, normal trend is that a soft material can help with the performance and a foam with larger thickness. The performance is not as good as it is while the thickness increase.

The surface has a rise after a certain curve. The best performance occurs at 40g/L density and +72 mm thickness.

In Y400 area, the density of the foam is the dominance. Small density foam gives a significant decrease in parameter.

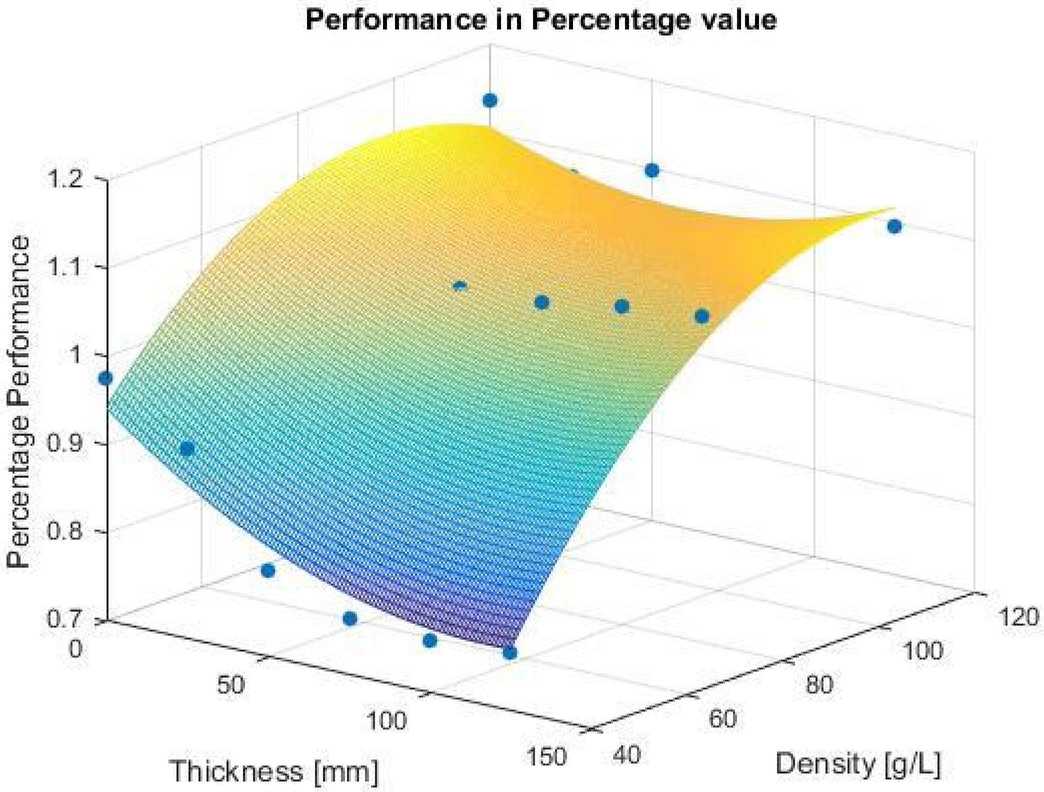


Figure 4.23 Y700 performance in Percentage value

For Y700 position, it is a little bit tricky.

There a part of surface area above 1, which means the average percentage performance is above one. It is not acceptable.

Again thick foam contribute to better performance. The original 80g/L foam has the worst performance while 120g/L was fairly better. The best solution is still a small density form of 40g/L and thicker foam.

Similar phenomenon occurs that thicker foam and softer material contributes to performance. However, the performance parameter is quite close to 1, which means although the global performance may be optimistic while some of the parameters are close to limit or even exceed the homologation limit.

The suggested pole is 40g/L and +125mm thickness.

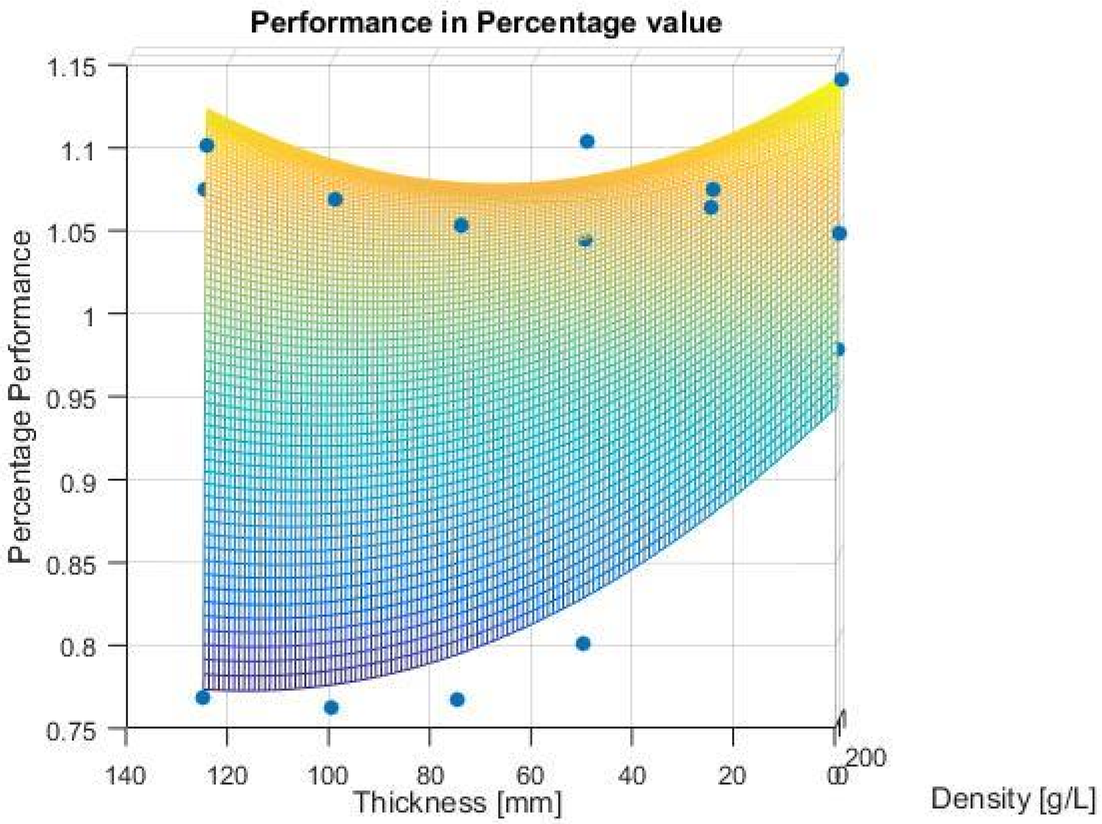


Figure 4.24 Side view of Y700 performance figure

Although the best points of each impact position is approached by model. The global performance should be evaluated by integration of the three graphs.

By adding the percentage performance of Y0 Y400 and Y700 together, we have the figure as bellow:

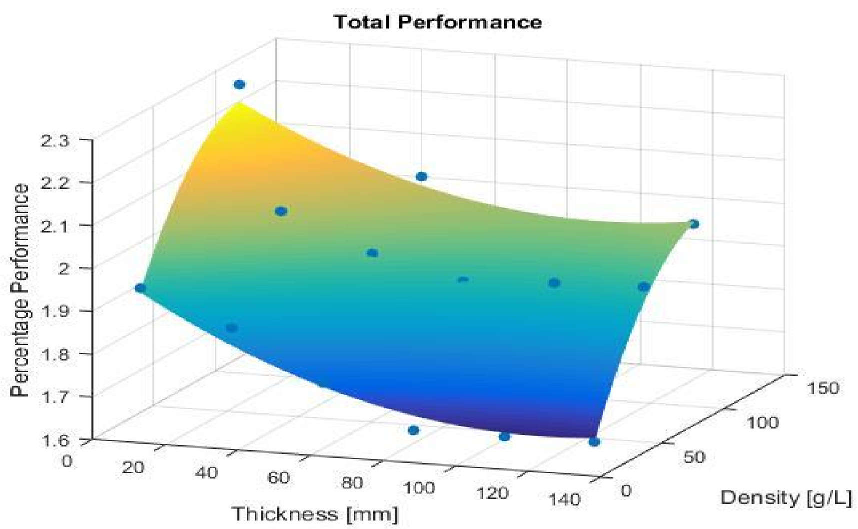


Figure 4.25 Add percentage performance

(Max score is 100%*3=3)

According to the surface we built, the best performance point we figured out is

40g/L density foam with +110mm thickness.

In order to make sure all of the parameters are within the homologation limit, it is necessary to go into each of them in the graph, be careful about all the parameters are within the higher performance limit.

The most critical part is Y400 and Y700 position, the following section we shall analysis into parameters.

5.6.2. Parameter analysis in Y400 and Y700 positions

In order to better present the result, all the graphs would include the integrated global limit to see how much the surface is within the performance limit.

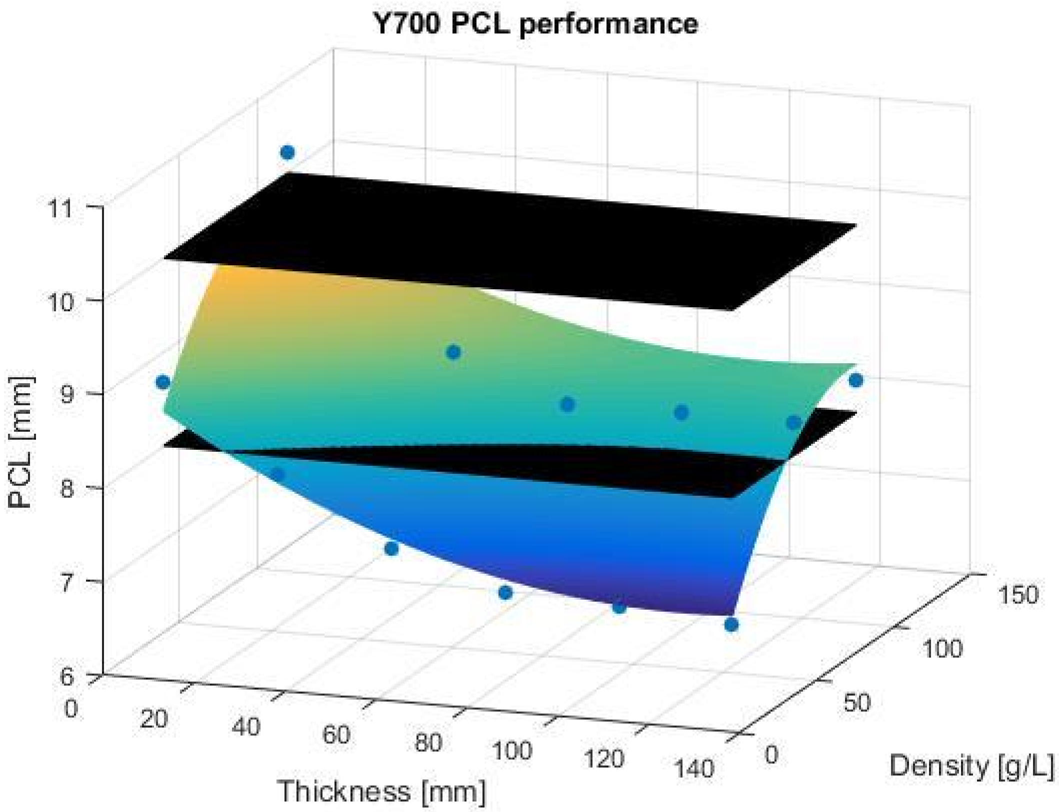


Figure 4.26 Y700 PCL performance with section PCL=10mm and PCL=8mm

It is obviously that the PCL performance of Y700 is all within the minimum homologation limit. But for 20% margin only part of the area is under 8mm elongation plane.

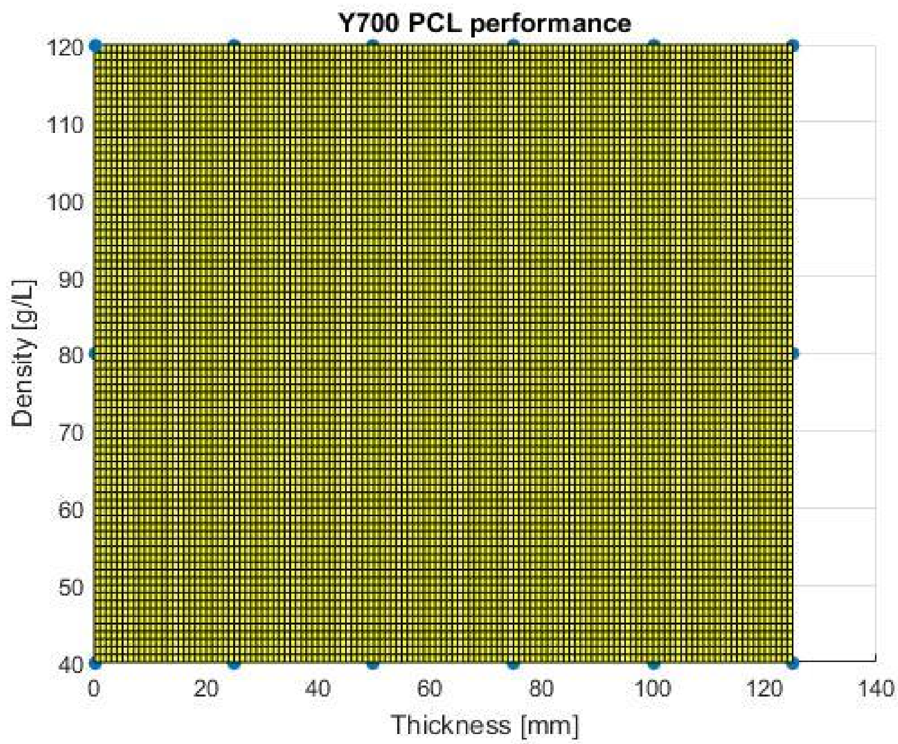


Figure 4.27 Y700 PCL performance with PCL=10mm section

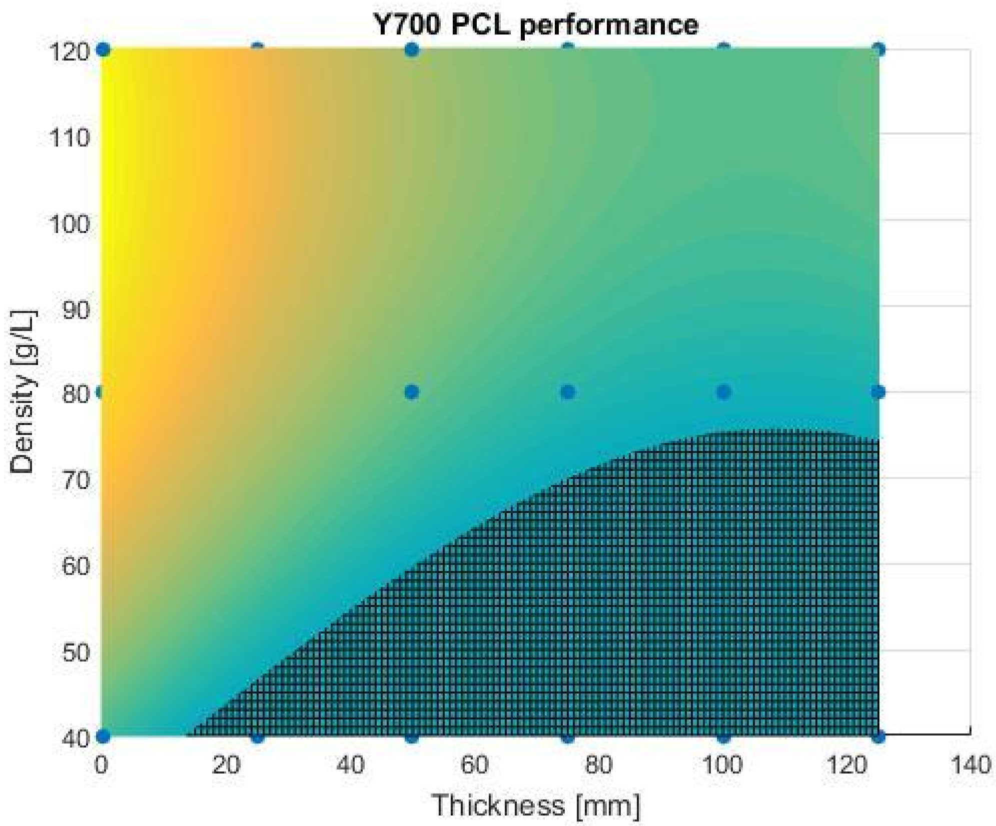


Figure 4.28 Y700 PCL performance with PCL=8mm section

Figure 4.28 is the top view of the figure4.26 for PCL Y700 position.

The meshed area is the part of surface under 20% margin limit, which is 8mm elongation.

Fortunately, the best performance point is within the available area.

As the figure shows, the graph has no part above 10mm PCL homologation limit.

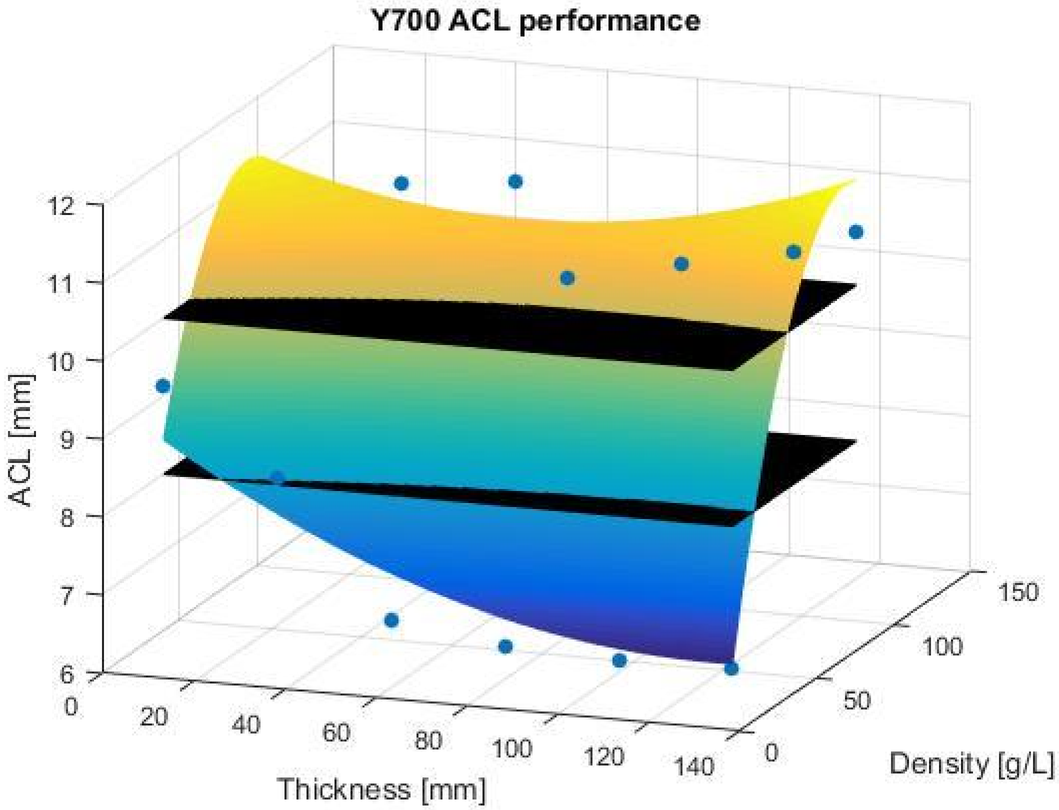


Figure 4.29 Y700 ACL performance with ACL=10mm and ACL=8mm plane

Figure 4.29 is the ACL performance with respect to thickness and density. The section plane 10mm and 8mm elongation cut the ACL surface. The following are the top view of them.

The graph shows that the best performance is around the part with larger thickness and small density.

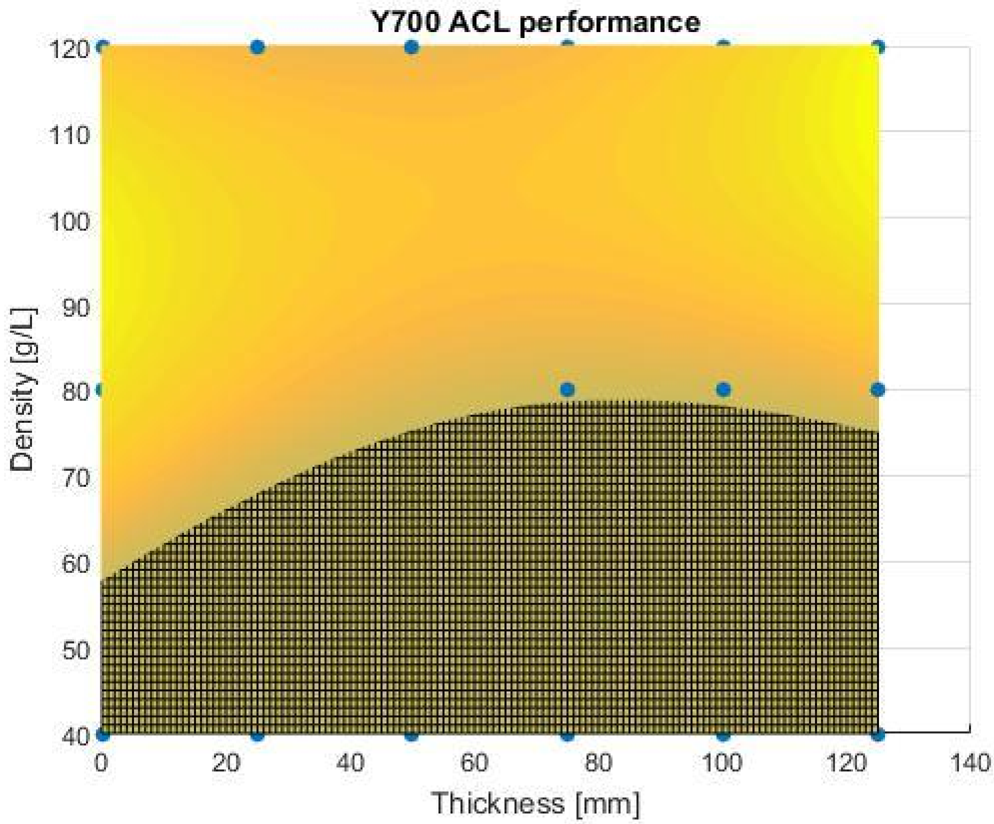


Figure 4.30 Top view of Y700 ACL performance and 10 mm ACL elongation

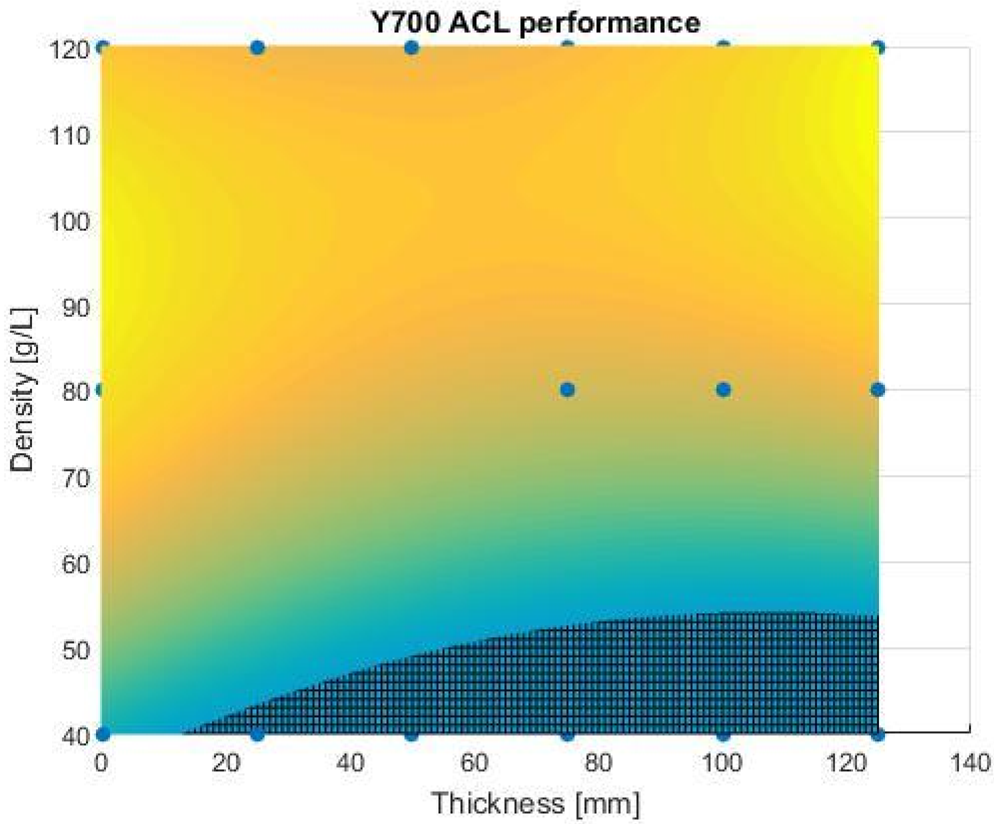


Figure 4.31 Top view of Y700 ACL performance and 8 mm ACL elongation

After changing the camera view, the 2d graph means that the meshed area of the graph is within the 10mm and 8mm elongation plane. Small density and larger thickness can achieve better performance in ACL performance.

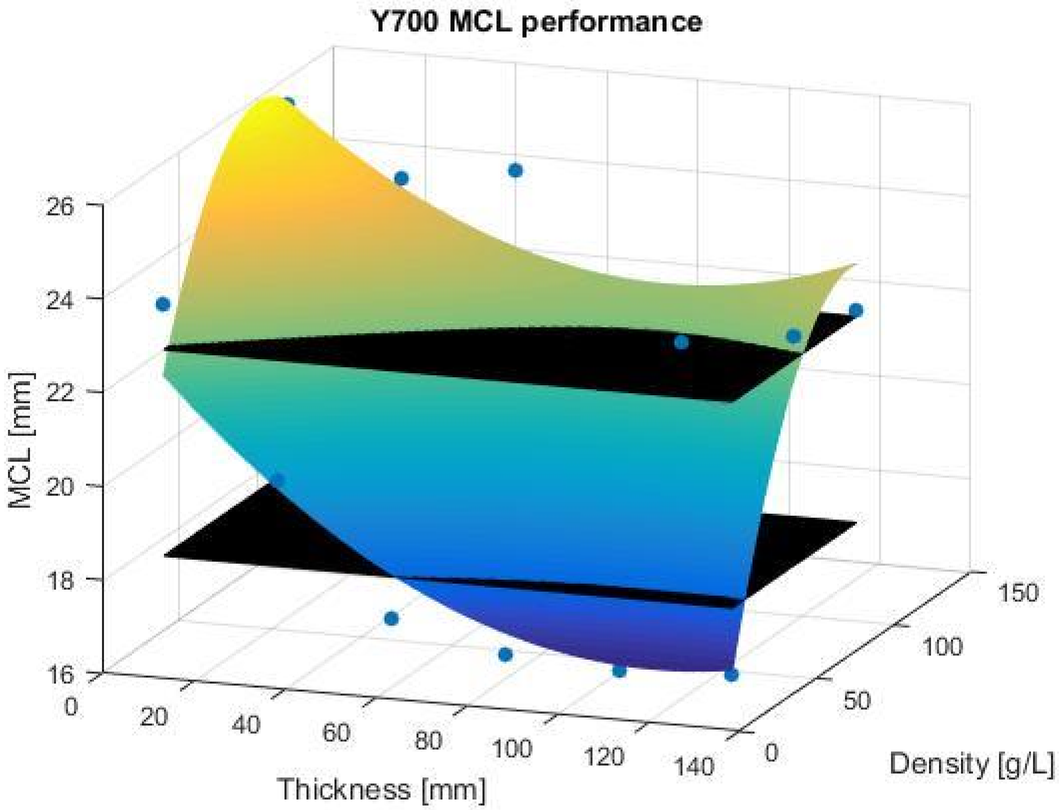


Figure 4.32 Y700 MCL performance with MCL=22mm and MCL=17.6mm plane

Figure 4.32 shows a tendency of larger thickness and smaller density can contribute to improvement in MCL performance.

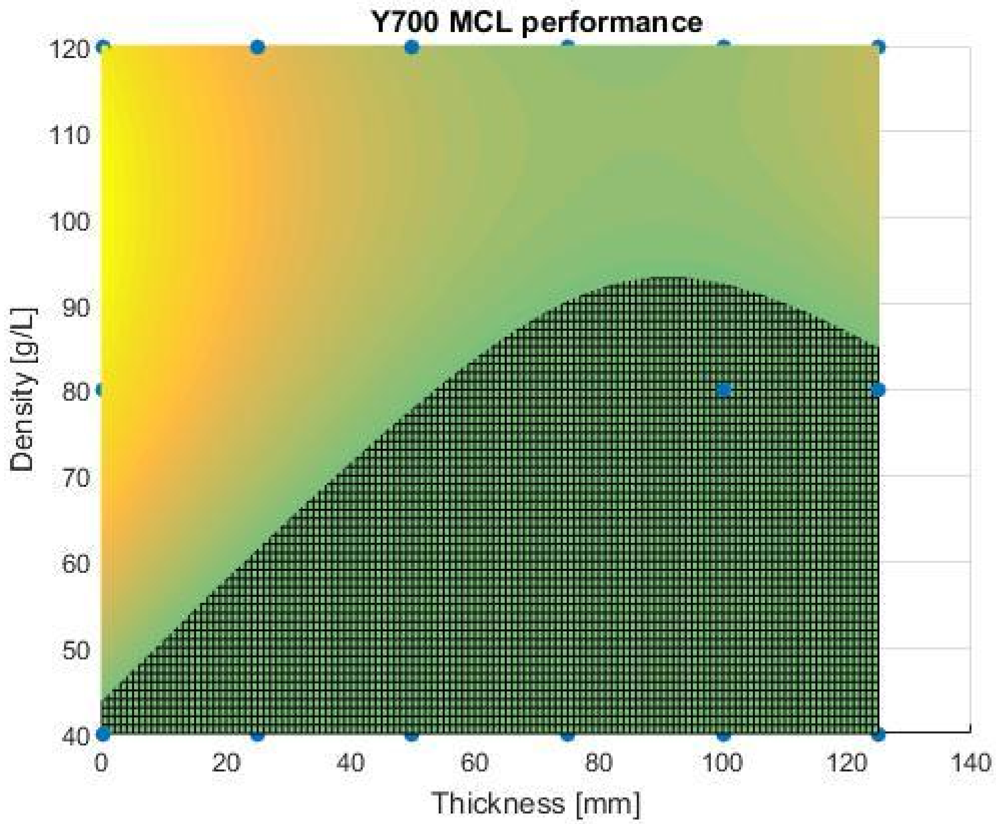
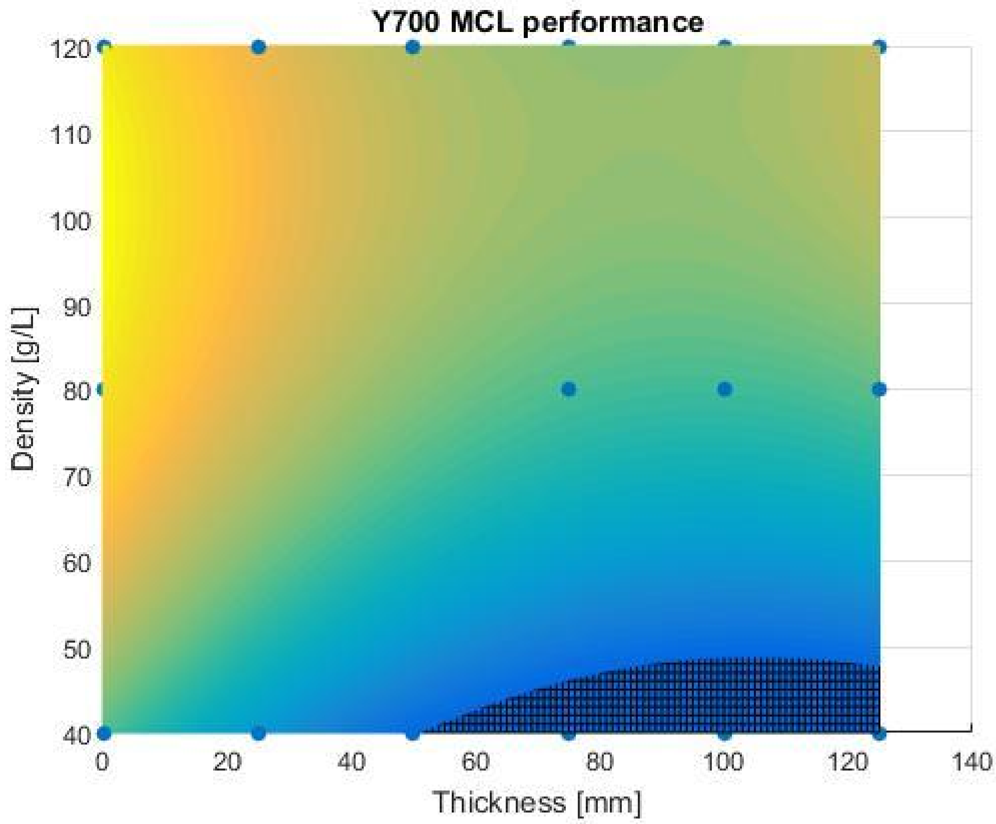


Figure 4.33 Top view with respect to MCL=22mm, Y700

Figure 4.33 is the section view of MCL=22mm on Y700 MCL performance. The meshed zone is the area where performance is within the lowest limit MCL=22mm. Exceed this area is not recommended, which would result in no credit on this position.



\

Figure 4.34 Top view with respect to MCL=17.6mm, Y700

Figure 4.34 shows that the small area near +110mm&40g/L, can achieve the maximum score of the MCL performance. While the others are above the 17.6 mm elongation.

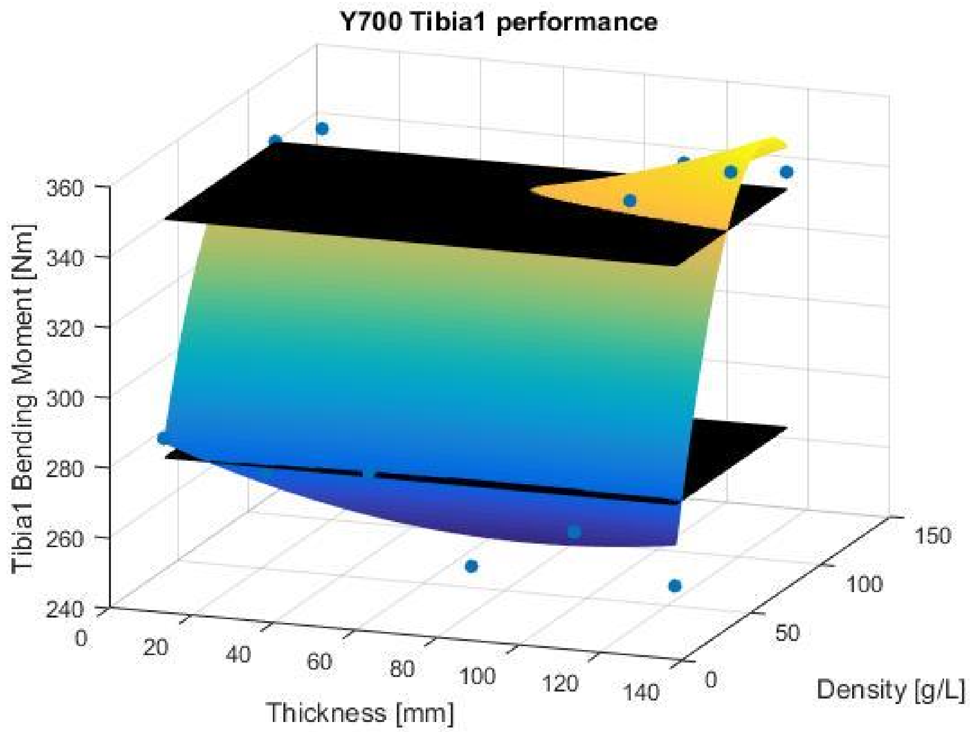


Figure 4.35 Tibia1 bending moment performance

The two section planes represent tibia bending moment equals to 272Nm and 340Nm, which represent the lowest and highest performance of bending moment Tibia1.

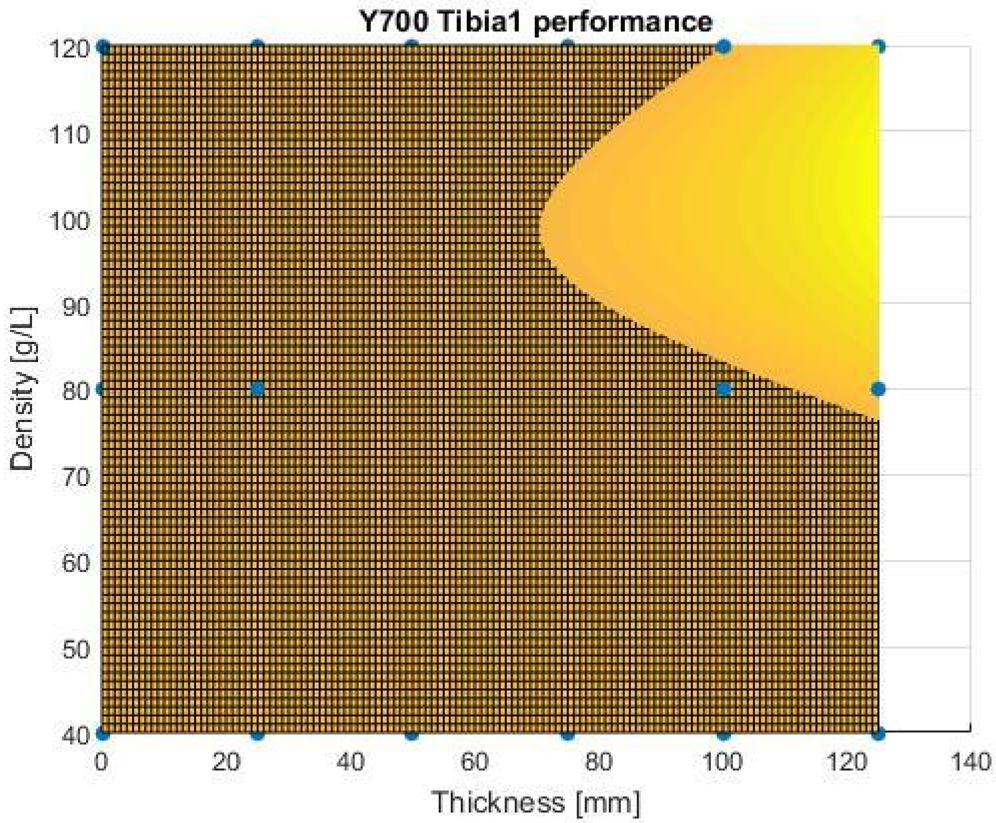


Figure 4.36 Y700 Tibia1 top view with respect to Tibia1=340Nm

The yellow area is where the performance of bending moment Tibia1 exceeds the lowest performance limit 340Nm. It is obvious that even though the majority of surface is within the lowest limit, it is still very critical because nearly the entire surface does not yet arrived inside the 272Nm limit, which means a maximum score of performance.

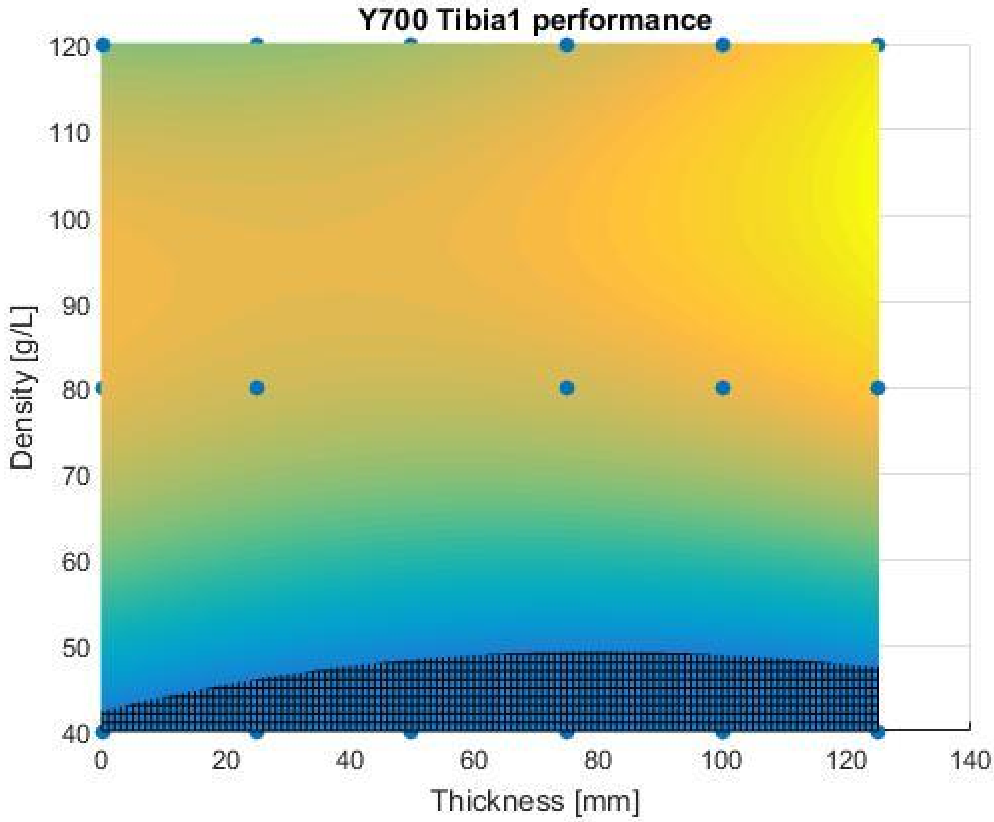


Figure 4.37 Y700 tibia1 top view with respect to Tibia1=282 Nm

Figure 4.37 is 282Nm plane and the surface. The meshed part is within the amount. Which means in this region the performance is within the Euro NCAP maximum score.

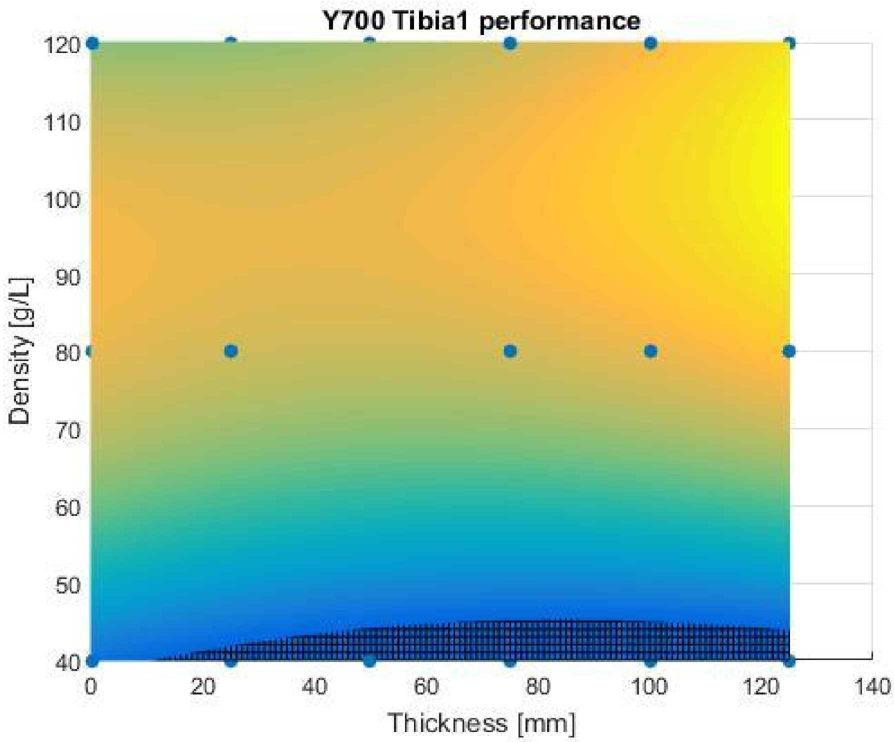


Figure 4.38 Y700 tibia1 top view with respect to Tibia1=272 Nm

Figure 4.38 shows that only a tiny can reach under 272Nm bending moment Tibia1, which means maximum score in test.

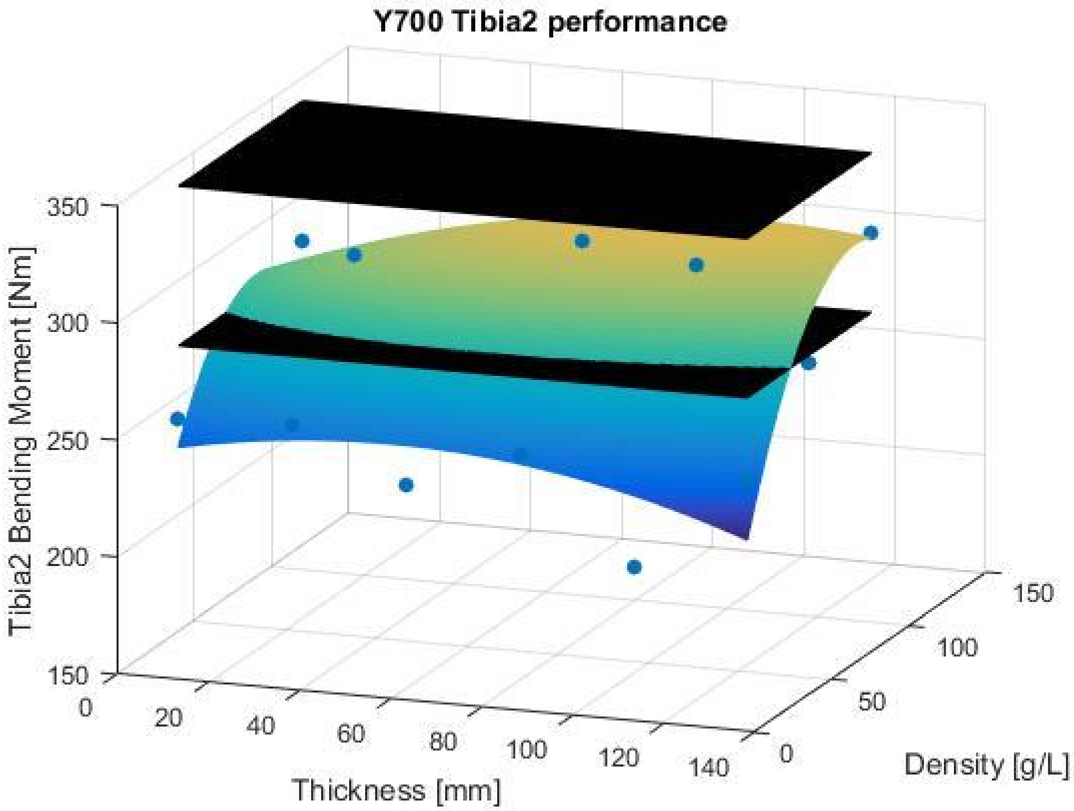


Figure 4.39 Tibia2 bending moment performance

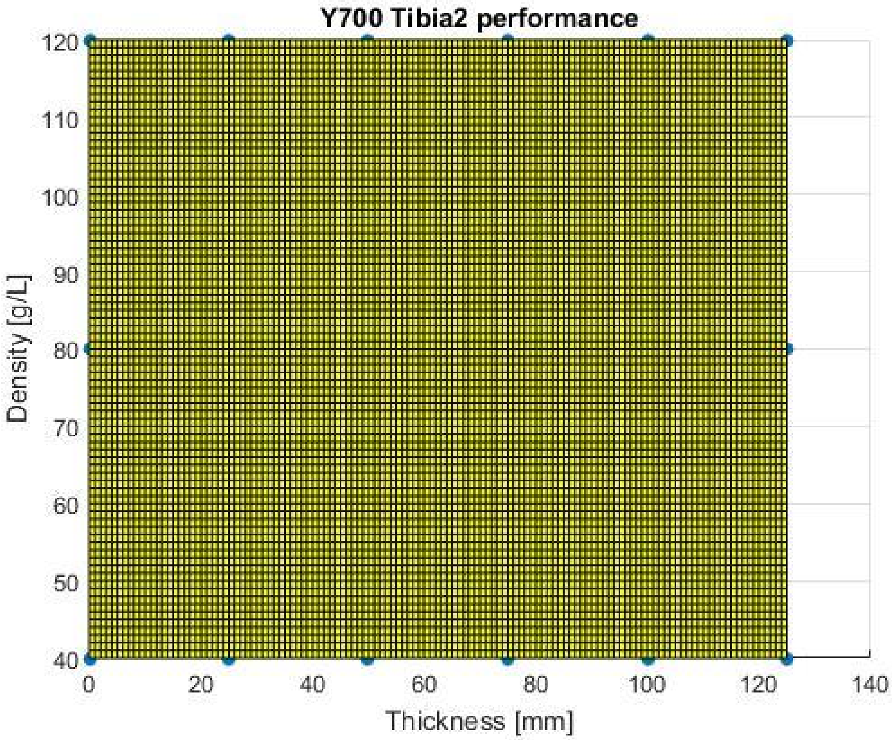


Figure 4.40 Tibia2 bending moment with respect to 340Nm plane

Figure 4.40 show that for tibia2 bending moment the performance, all of the points are below 340Nm, which is the maximum homologation limit.

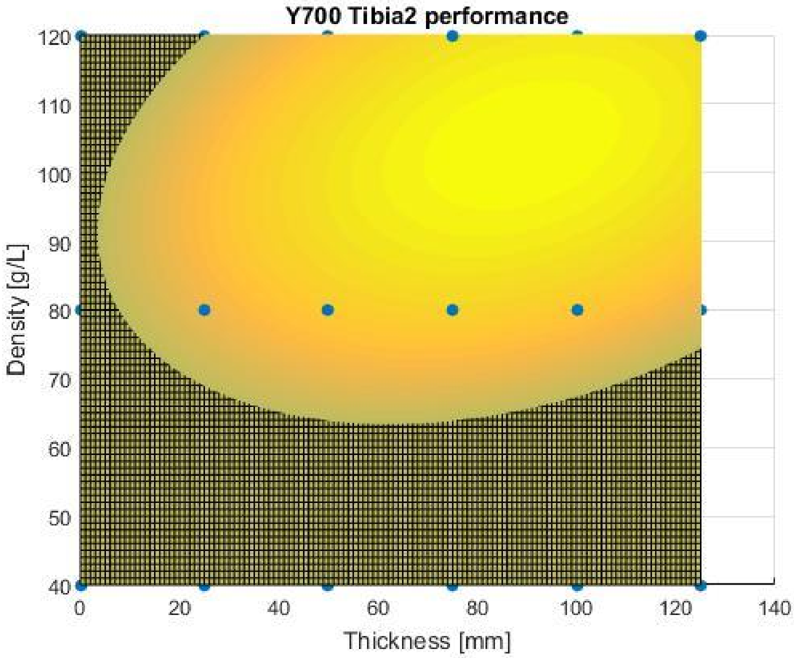


Figure 4.41 Tibia2 bending moment with respect to 282Nm plane

For Euro NCAP evaluation, 282 Nm is the point when the vehicle get maximum credit. As shown in the figure the point we are looking for is within the area. The meshed area means the performance of this area is better than the higher performance limit.

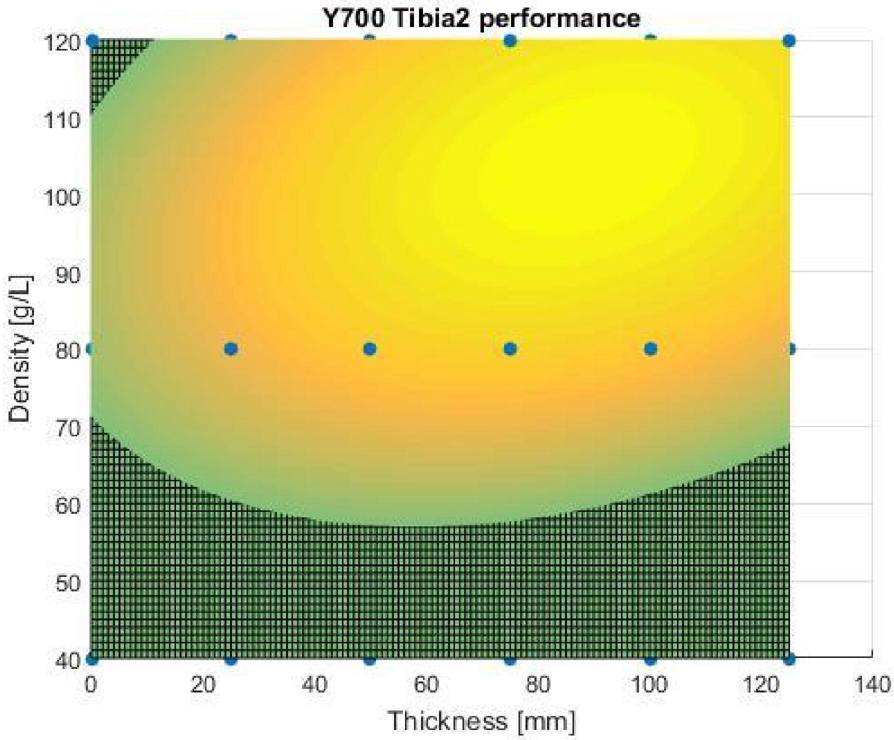


Figure 4.42 Tibia2 bending moment with respect to 272Nm plane

Figure 4.42 shows that for ECE r127 with 20% margin, the bending moment of Tibia2 is shown in the figure. The point is also inside the positive area.

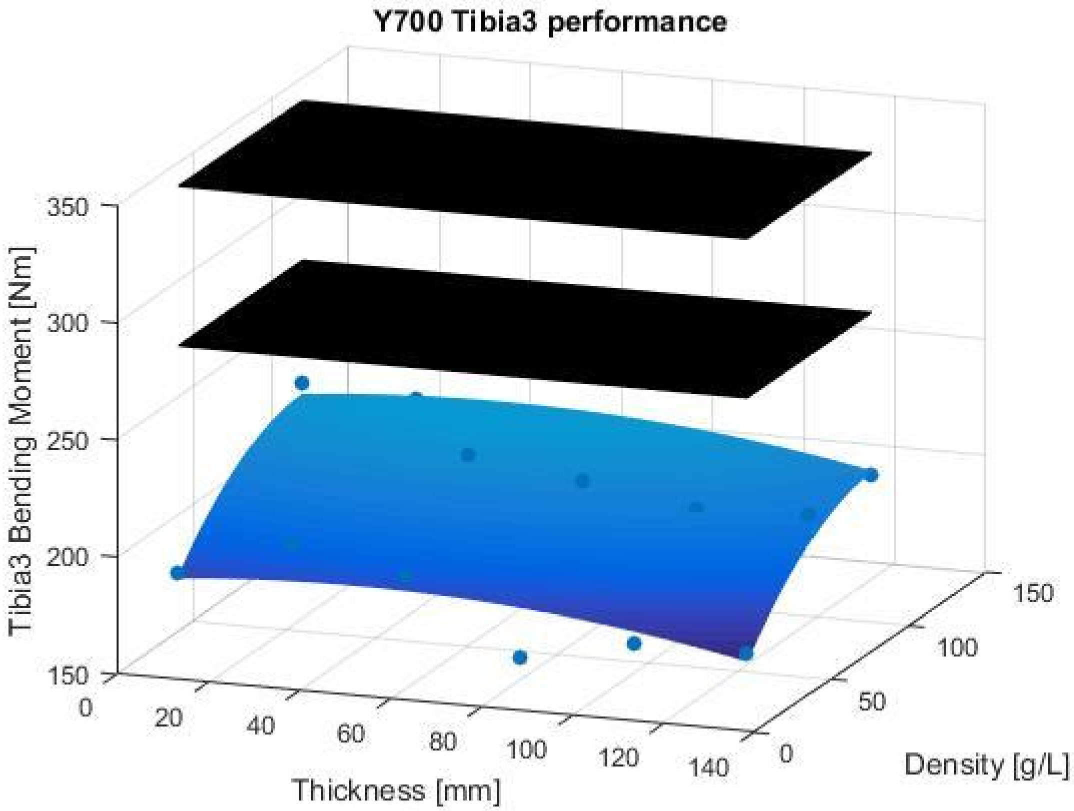


Figure 4.43 Tibia3 bending moment with respect to 340Nm and 272Nm plane

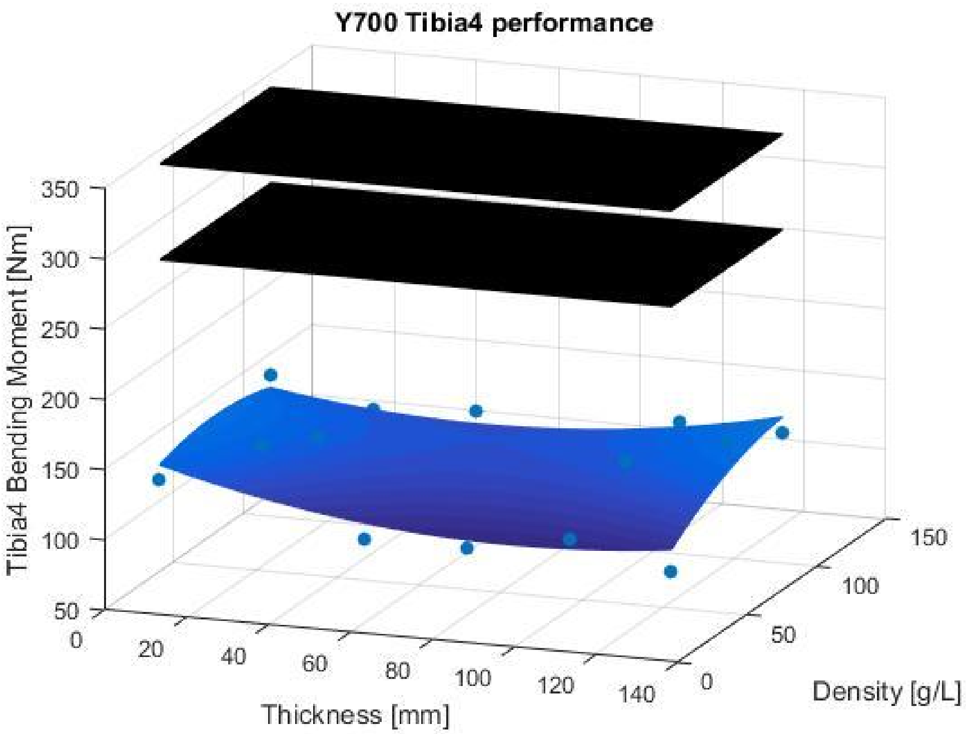


Figure 4.44 Tibia4 bending moment with respect to 340Nm and 272Nm plane

According to Figure 4.43 and Figure 4.44, obviously Tibia3 and Tibia4 bending moment performance is all within 272 Nm. No further consideration is needed for these two parameters.

After the analysis, we can see that all of the 40g/L density and +110mm thickness parameters including PCL, ACL, MCL elongation and Tibia bending moments are within the homologation limits, this setting can be the best choice till now. But the thickness is not necessarily increased together for all the impact positions.

It is easy to notice that the best performance of each impact point is not with the same tendency. And it is possible to find the foam with best performance.

5.6.3. Bumper with multiple setting foam (both density and thickness)

In order to find the best performance result, in each impact position the foam should be the one 0we calculated with the surface minimum. In this case, the density and thickness of the foam should be different in Y0, Y400 and Y700 position.

With multiple setting of thickness increase and density, the bumper contains two part of foam.

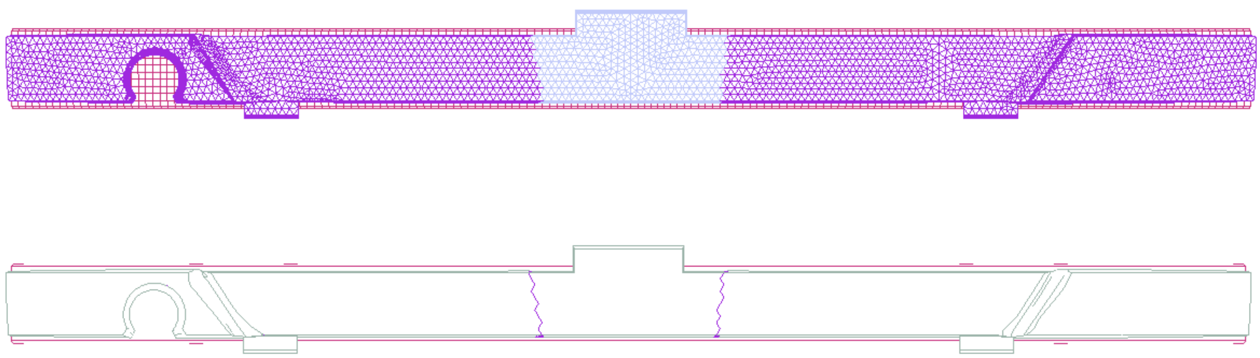


Figure 4.45 Multiple density & thickness foam

For optimization to the prediction from mathematic model, the center changed to 58g/L foam and +17mm thickness, while the other two part are at the 40g/L density and +125mm thickness, Table 4.19.

Table 4.19 Foam settings with multiple density & thickness

Position	Y0	Y400	Y700
Density	58g/L	40g/L	40g/L
Thickness	+17mm	+72mm	+118mm

The original data collected has the best performance point in each impact point as Table 4.20.

Table 4.20 Calculation result with multiple density & thickness foam

Foam	PCL [mm]	ACL [mm]	MCL [mm]	Tibia 1 [Nm]	Tibia 2 [Nm]	Tibia 3 [Nm]	Tibia 4 [Nm]	max tibia	Percentage performance
Y0, 40g/L +0mm	4.296	2.605	2.151	92.08	128.06	233.6	225.8	233.6	45.07%
Y400, 40g/L +50mm	4.122	2.616	2.278	116.7	124.3	216.3	199.1	216.3	43.93%
Y700, 40g/L +100mm	6.646	6.189	16.17	248.8	236.6	162.8	83.4	248.8	76.04%

As Table 4.21, after the pick-up of best performance points on Y0, Y400 and Y700 surface, and modify the model in ANSA. The best performance of variant density and variant thickness increase is:

Table 4.21 Test result with multiple setting foam

Foam	PCL [mm]	ACL [mm]	MCL [mm]	Tibia 1 [Nm]	Tibia 2 [Nm]	Tibia 3 [Nm]	Tibia 4 [Nm]	max tibia	Percentage performance	Refer
Y0	4.268	2.699	2.194	91.16	131	232.9	225.4	232.9	45.27%	+0.46%
Y400	4.135	2.544	2.354	117.5	124.9	216.8	199.7	216.8	44.06%	+0.30%
Y700	6.229	5.636	15.03	237.6	191.5	141.1	70.38	237.6	69.33%	-8.82%

The refer is respect to the best performer of the discrete points we tested at the very beginning.

The Y700 position performance has a good improvement.

However, it shows that the foams need to be glued together and the transversal beam has changed its shape to have a non-uniform tube shape. The cost would increase dramatically and not so easy for assemble and disassemble. In addition, it creates difficulties for maintenance in the future.

5.6.4. Differentiate the thickness while remain the same material density

A more practical and engineering way is to keep the foam with single material and differentiate the thickness settings to improve the performance while maintain the low cost and ease to manufacture.

Using mat lab code to pick up the point with best performance parameter along the density axle, and compare the data of these parameters. Then choose the best-fit density.

Mat lab code:

```
[min_y,index]=min(YFIT,[],2);
xlswrite('pick_thickness',min_y,'sheet1','C1');
```

YFIT is the predicted value on the surface of each point, use mat lab function min to pick the best performance point (min_y) in each position with the same density, we can have a group of performance parameters. The index is the corresponding thickness increase of each point.

Table 4.22 Short view of the data collected by matlab

Density(g/L)	y0	y400	y700	SUM
40	0.45473499	0.432354	0.688453	1.575542
41	0.45429381	0.433387	0.696731	1.584412
42	0.45387397	0.434415	0.704897	1.593186
……	……	……	……	……

By making sum of the three performance parameters together, we can have the corresponding global performance of each density point. Then pick the best point as the uniform density.

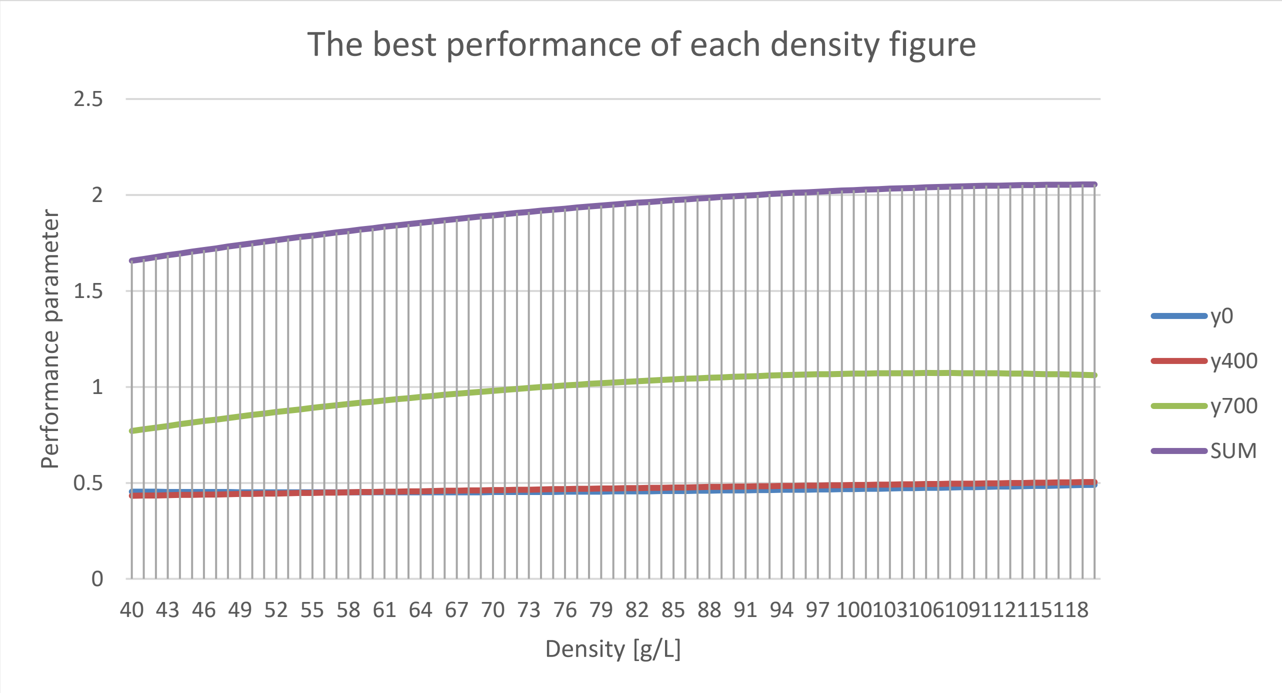


Figure 2.46 Performance Curve with density

The SUM line keeps growing. In this case, the best one is the 40g/L.

Then return to the ''index'' group which was written in Matlab, and find the corresponding thickness increases are +28mm for Y0, +72mm for Y400 and +110mm for Y700.

Table 4.23. 40g/L performance parameters predicted and corresponding thickness increase in index

Density(g/L)	y0	y400	y700	SUM
Prediction value	0.454417	0.439275	0.770388	1.664081
Thickness increase Due to index	+28mm	+72mm	+110mm	

Then use ANSA to modify the model and use ls-dyna to run the simulation, as Figure 4.47.

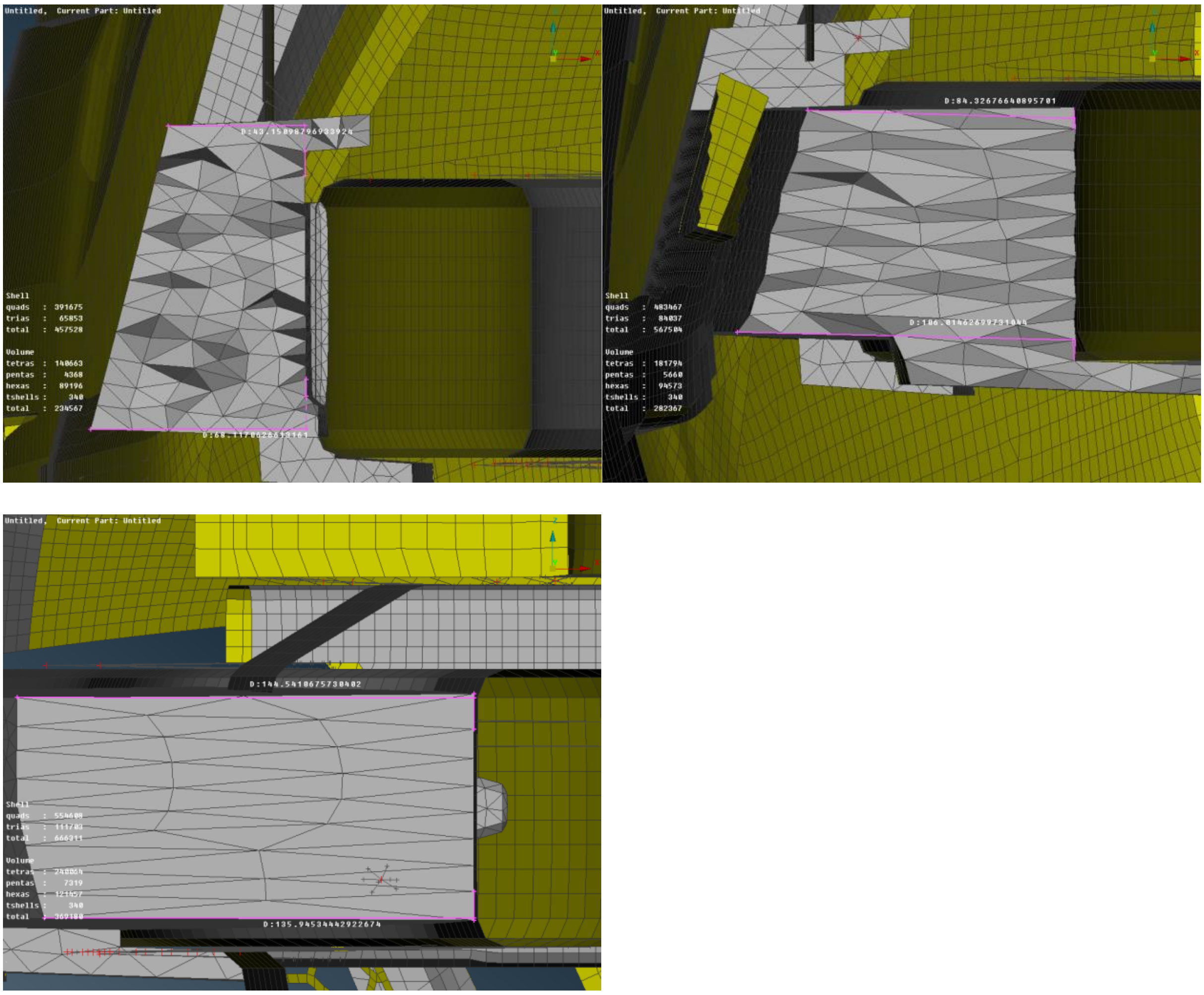


Figure 4.47 Y0, Y400 and Y700 position section

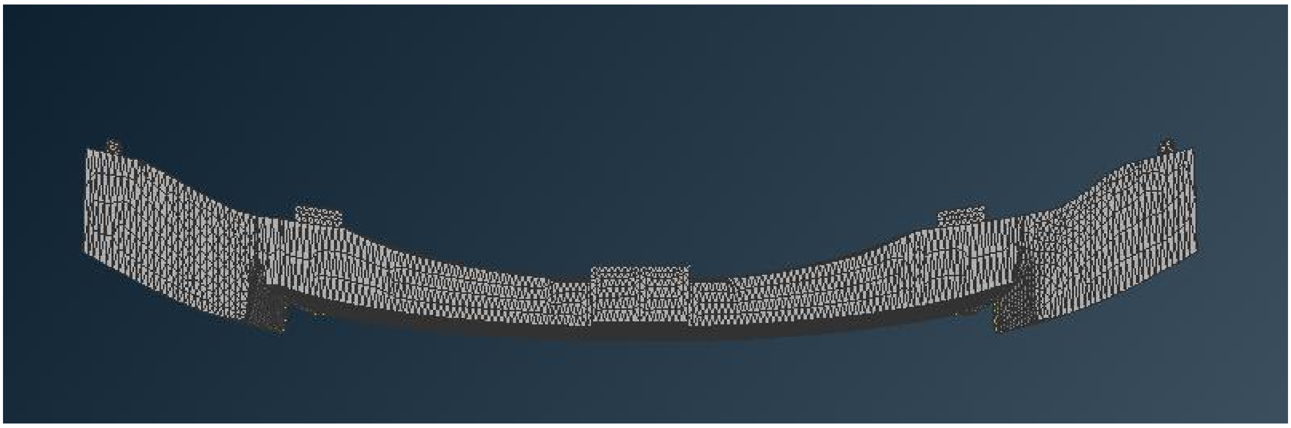


Figure 4.48 New bumper with impact position Y0 Y400 and Y700 the best thickness

As figure 4.48, the bumper has varies thickness increase with the homogeneous density 40g/L.

Table 4.24 Foam thickness model measurement

Position	Y0	Y400	Y700
Min thickness [mm]	49.97 (+28.00)	89.29 (+70.7)	119.85 (+108.62)
Max thickness [mm]	74.52 (+28.03)	110.99 (+71.84)	128.50 (+108.50)

After calculation, the performance parameter is Table 4.25:

Table 4.25 Density 40g/L with variate thickness increase performance

Foam	PCL [mm]	ACL [mm]	MCL [mm]	Tibia 1 [Nm]	Tibia 2 [Nm]	Tibia 3 [Nm]	Tibia 4 [Nm]	max tibia [Nm]	Performance parameter	Refer
40multiY0	4.331	2.684	2.379	91.61	128.3	233	225.9	233	45.5%	+1.04%
40multiY400	4.232	2.824	2.448	117.8	124.6	216.5	199.5	216.5	44.8%	+1.89%
40multiY700	6.999	6.277	15.99	247.2	188.1	160	83.42	247.2	74.6%	-1.83%

The refer is with respect to the best performance existed points of each impact position.

5.6.5. Conclusion

Although it might not be so optimistic compared to the best points. Since the test is based on the fact that it is recommended to use one single material density, another compare should exist with the global performance parameter.

Table 4.26 Comparison chart of performance

Foam	Best performer of the tested points	Multiple density of foam with multiple thickness increase	40g/L with variant thickness increase
Performance parameter	1.673	1.587	1.658
Compare	100%	-5.15%	-1.39%

The tolerance of the prediction model is :

(1.664081-1.658) /1.658= 0.003668≈0.37%

The result is again quite optimistic, that the prediction meets the test result.

Although the improvement is not as much as variant density & thickness increase ones, the engineering possible solution can still increase the performance for 1.55%, as Table 4.26.

CHAPTER V Conclusion

1. Vehicle safety topic

The vehicle safety issues are one of the most important problem in automotive industry. The passive and active safety systems onboard contribute to protection of both occupants as well as vulnerable road users.

Different markets have diverse requirement on vehicle safety issues. Each individual market has its own legislations and the test regulations to evaluate the vehicle safety performance.

Manufacturers today would like to build vehicles from same platform to save cost and time. Different models from same platform need to be designed to fulfill all the safety related legislations on the aiming markets while gaining good ratings in safety tests. An integration method of both legislations and regulations should be taken into account.

The legform test will be a good example for passive safety design applying this method. By integrated all involved legislation limit as well as test performance limits, we can achieve an integrated performance limit that once our model fulfill this global limit, it can pass all the above safety limits together.

2. Leg form test and analysis

The leg form test have three references to evaluate the performance, C-NCAP test protocol, Euro NCAP test protocol and the UNECE legislation. The integration method is to create the global limit of all the related evaluation systems, and design the vehicle to fulfill the unified limit to fulfill all the limits.

For engineering process, the evaluation procedures can start at multiple settings of foam property and simulate the impact using calculation software. Then a mathematic model can be built exploiting the data gathered. Engineers can found potential points with better solutions and then run the calculation again. It should be a much faster way to do the simulation rather to evaluate each of the points inside the range.

The parameters involved in the pedestrian legform impact are not only properties of foam. For other parameters, it is also available to use mathematic method to approach the optimized performance. Of course, if necessary, the regression can be not only binary quadric regression but also more complex models.

Although in CAE model it is plausible to use multiple settings on the foam, it is still not sufficient in engineering real case. Double or triple properties used in foam can result in double or triple the supplier for foam material, with extra cost of glue, assemble procedures and extra humanpower. Not to mention the extra maintenance and storage necessary.

In engineering case, bumper foam material should be uniform. With this constraint, the engineering process is to find the best fit as solution. Although it might not compare with the theoretical best one, it still improved the performance and it is the best compromise under constraints.

In our case, considering the constraints that in engineering case it is not possible to use multiple material in a single piece of bumper foam, the performance was increased by choosing a proper foam with a specific density, and change the shape of the original design with varies thickness increase, we achieved a 1.55% of performance increase.

3. Further application

For engineering process, especially these simulation runs with multiple parameters, it is not so easy to build test plans and analyses the results. It is not possible to see what the result would change without enough output data.

However, with mathematic methods, test plan amount can be decreased and it is more accurate to analysis the data and take into consideration of compromise. The compromise is that in real case, there would be constraints in parameter range. And it is not so easy to repeat the tests as much as we need. A sufficient mathematic model can use minimum input data to create a performance surface, to predict a potential point with better performance.

However, there should be concerns. The modification on the elements would possibly cause modification of involved parts of the car, and resulting in difference in output. Maintaining the other parameters unchanged is seriously needed.

References

[1]. Euro NCAP Protocols, 2018

General-Euro NCAP Assessment Protocol - *Overall Rating, v7.0.1*, from March 2016

General-Euro NCAP Assessment Protocol - *Application of Star Rating, v1.5*, from January 2018

Vulnerable Road User (VRU) Protection – *Euro NCAP Assessment Protocol – PP v9.0.2*, from January 2018

Vulnerable Road User (VRU) Protection – *Euro NCAP Pedestrian Test Protocol – v8.4*, from January 2018

Vulnerable Road User (VRU) Protection – *Euro NCAP AEB VRU Test Protocol – v2.0.2*, from January 2018

From *https://www.euroncap.com/en/for-engineers/protocols/*

[2]. Euro NCAP, technical papers, 2018
Euro NCAP roadmap 2015
From https://www.euroncap.com/en/for-engineers/technical-papers/

[3]. IIHS HLDI, 2018

Rewarding excellence, 2018

From http://www.iihs.org/iihs/ratings

[4]. IIHS HLDI, Status Report, May 8, 2018

ON FOOT, AT RISK, Study highlights rising pedestrian deaths, points toward solutions

From http://www.iihs.org/iihs/sr/statusreport/article/53/3/1

[5]. IIHS Test protocols and technical information, Technical protocols, current, 2018
HOW IIHS CLASSIFIES VEHICLE BY SIZE, WEIGHT, TYPE AND PRICE, technical appendix, September 2010, Highway loss Data Institute
From http://www.iihs.org/iihs/ratings/technical-information/technical-protocols

[6]. NHTSA, 2018

Pedestrian safety

From https://www.nhtsa.gov/road-safety/pedestrian-safety#2231

[7]. Thomas Kinsky, Dr. Flavio Firesen, Bnejamin Buenger,

[8]. *THE FLEXIBLE PEDESTRIAN LEGFORM IMPACTOR AND ITS IMPACT ON VEHICLE DESIGN*, Paper Nr. 11-0328
[9]. Humanetics, Flex PLI GTR, User Manuel
[10]. CARHS, *safety companion 2017, safety companion 2018*
[11]. UNECE-ECE, Vehicle Regulations, agreements and regulations, UN regulations (1958 agreement), REGS 121-140
Regulation 127 00 series, *Pedestrian Safety, Corr.1, Amend.1*
Regulation 127-01 series*, Rev.1*
Regulation 127-02 series*, Rev.1-Amend.1, Rev.2*
From https://www.unece.org/?id=39147
[12]. UNECE minutes, Transport-vehicle regulations/home vehicle regulation/working party on passive safety (GRSP)/ Pedestrian Safety (PS)

PS Previous Sessions

From https://wiki.unece.org/display/trans/PS+Previous+Sessions
[13]. Ulrich Seiffert and Lothar Wech, SAE international, 2003

Automotive Safety Handbook, second edition

[14]. European Comission, 2016

Vehicle Safety 2016

[15]. World Health Organization, 2013
Pedestrian Safety: a road safety manual for decision-makers and practitioners.