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Vehicle Safety Design Methods to Comply with Emerging International Standards

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Vehicle Safety Design Methods to Comply with Emerging International Standards

by

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ABSTRACT

This research focuses on the development of a design methodology for vehicle safety design to comply with the different side impact crash regulations that are used around the world. The main differences of each side impact tests and potential influences on vehicle design were identified. Door intrusion velocity, door trim component stiffness and seat airbag were selected as three design variables. Sled test finite element models based on the Heidelberg buck sled test set-up were developed to investigate the sensitivity of three design factors to the occupant injury in both moving deformable barrier test and oblique pole test load conditions. Occupant injury response variations were assessed at different levels of the design factors. From the simulation results, for moving deformable barrier test, there is a balance between limiting the thorax injury and abdominal injury. For the Oblique pole test, the simulation results show that the padding system development may be more effective than the vehicle structure enhancement. Design guidelines that would enable vehicles to comply with different side impact tests were extracted based on the simulation results.

DEDICATION

To my loving niece Xing Gao

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LIST OF ACRONYMS

AIS	Abbreviated Injury Scale
ATD	Anthropomorphic Test Device
BAS	Brake Assist System
CATARC	China Automotive Technology and Research Center
CFC	Channel frequency class
CNCAP	China New Car Assessment Program
ECE	Economic Commission for Europe
EEVC WG13	European Enhanced Vehicle Safety Committee Working Group 13
ENCAP	European New Car Assessment Program
ESC	Electronic Stability Control
FEA	Finite element analysis
FMVSS	Federal Motor Vehicle Safety Standards
HIC	Head injury criterion
IIHS	Insurance Institute for Highway Safety
MDB	Moving Deformable Barrier
NASS	National Automotive Sampling System
NCAP	New Car Assessment Program
NHTSA	National Highway Traffic Safety Administration
SINCAP	Side Impact New Car Assessment Program
SUV	Sport Utility Vehicles
TTI	Thoracic Trauma Index
US-SID	The US side impact dummy

1. INTRODUCTION

Vehicle safety may have become an issue almost from the beginning of automobile development. Road traffic crashes cause 1.3 million deaths and up to 50 million injuries per year globally [1]. Major vehicle producing countries established the vehicle crashworthiness requirements in terms of crash test regulations to reduce the occupant fatalities in collisions. Third parties also released vehicle safety rating systems to encourage manufacturers to optimize vehicle safety levels and provided the test results to consumers.

The safety regulations and rating systems in various parts of the world have not achieved harmonisation while vehicle development and manufacturing processes are becoming global. A good example is the differing requirements of side impact protection. Between Europe, North America and China, there are twelve test items related to side impact.

The diversity in side impact tests causes significant challenges to vehicle manufacturers. The current situation has forced manufacturers to 'fine tune' their design to ensure compliance with the North American or European regulations. Depending on the market into which the vehicle is sold, this 'fine tuning' is unique for each car [2]. This will increase design investments and manufacturing costs. Vehicle companies are seeking a method to reduce the cost due to different safety standards. The ideal solution could be one vehicle version which is in overall compliance with different regulations and rating programs around the world.

The two main categories of side impact test configuration are moving deformable barrier (MDB) test and side pole test. The MDB test simulates the 'car-to-car' side collision and the side pole test simulates the ‘car-to-narrow object’ collision. The design concepts required to comply with the MDB test and the pole test are totally different. Understanding how the difference will potentially influence the vehicle design is essential for realizing overall compliance with existing regulations. This project started by a review of existing vehicle regulations and crash rating tests around the world, especially in Europe, North America and China. Side impact tests are compared in detail, to identify the main differences and potential impacts on vehicle design.

2. LITERATURE REVIEW

2.1 Introduction

Vehicle safety standards and regulations are written in terms of minimum safety performance requirements for vehicles or items of motor vehicle equipment. By law, the new models must pass safety tests before they are sold. Major vehicle producing countries and regions have defined their own safety standards. The two predominant vehicle safety regulations in the world were developed by the U.S. National Highway Traffic Safety Administration (NHTSA) and the Economic Commission for Europe (ECE) in the European Union. The largest vehicle market in the world is China [3], and so its crash scenario is also taken into consideration in this literature review. In recent years, China has established crash regulations. Last year the China New Car Assessment Program (CNCAP) released a new version of the test protocol in 2011, and it was implemented out on July 1st, 2012 [4]. The existing documents and literature related to China crash regulation scenarios are mostly written in Chinese. Fully understanding the differences between Chinese, European and North American vehicle safety standards is essential for realizing overall compliance with the Europe-North America-China regulations. Investigation of different side impact test procedures is also included in this chapter.

2.2 Diversity in crash tests

Crash tests are the method used to ensure that new vehicles meet safety standards in terms of occupant protection. The aim of these standards is to reduce the risk of serious or fatal injury to vehicle occupants in collisions by setting vehicle crashworthiness requirements. Anthropomorphic test devices (ATD) are put into the vehicle to assess the occupant injury response by accelerometer and force transducer measurements. Each test has different biomechanical requirements. The general test configurations adopted by most countries are frontal impact and side impact. This is because a significant proportion of passenger car accidents on the road are caused by frontal or side collisions. According to a fatality analysis data released by NHTSA in 2009, front and side crashes account for approximately 85% of all crashes [5].

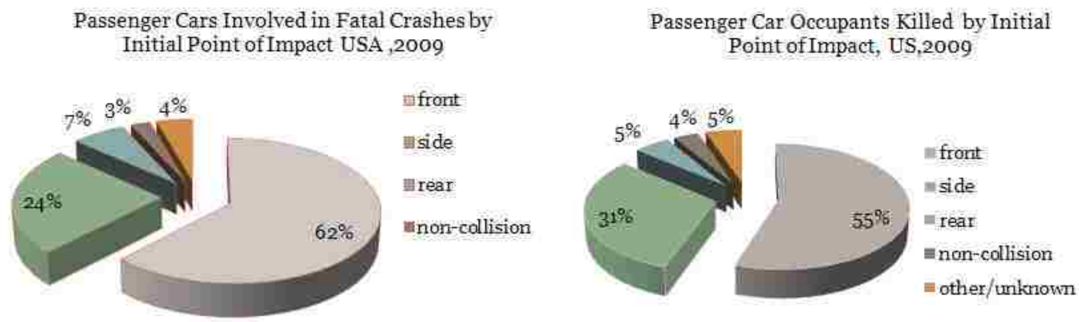
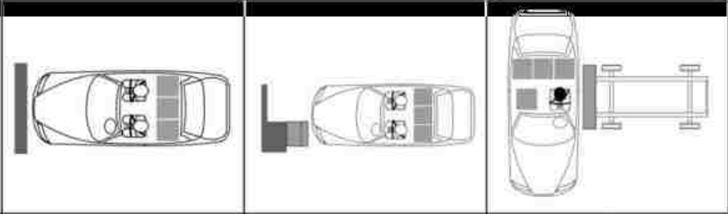


Figure 2-1: US passenger car fatality analysis report in 2009.

In addition to frontal and side impacts, other tests are also used to improve vehicle safety. Table 2-1 list the existing tests in different regions. The dummy H-III is a Hybrid III 50% male crash test dummy, H-III 5% is the Hybrid-III 5% female crash test dummy. The Euro side impact dummy EuroSID includes ES-1, ES-2 and ES-2re.



	Full frontal test	40% offset frontal test	Side impact test
USA	FMVSS 208 4 Tests at 32 to 56 km/h belted and unbeletd 2 H-III / 2 H-III 5 % female	FMVSS 208 40 km/h 40 % Offset 2 H-III 5 % female belted	FMVSS 214 (new) 54 km/h 27° crab angle 1368 kg ES-2re front SID-IIs rear 32 km/h 75° on Pole 254mm ES-2re or SID-IIs
Europa		ECE-R94; 96/79/EC 56 km/h 40 % Offset 2 H-III	ECE-R95; 96/27/EC 50 km/h 950 kg ES-2
Japan	TRIAS 47 50 km/h 2 H-III	TRIAS 47-4 56 km/h 40 % Offset 2 H-III	TRIAS 47-3-2000 50 km/h 950 kg ES-2
China	GB 11551-2003 50 km/h 2 H-III	GB 20913-2007 56 km/h 40 % Offset 2 H-III (optional test)	GB 20071-2006 50 km/h 950 kg EuroSID
India		AIS-098/F 56 km/h 40 % Offset 2 H-III (from 2012)	AIS-099/F 50 km/h 950 kg EuroSID (from 2012)
Korea	KMVSS 102 48,3 km/h 2 H-III		KMVSS 102 50 km/h 950 kg EuroSID
Australia	ADR 69/00 48 km/h 2 H-III	ADR 73/00 56 km/h 40 % Offset 2 H-III	ADR 72/00 50 km/h 950 kg EuroSID

Pedestrian
78/2009
631/2009
TRIAS 63
GB 24550-2009 (optional test)

Rollover
FMVSS 216 upgrade
FMVSS 208 (tilted ramp)

Head Impact
FMVSS 201u
ECE-R21

Ejection Mitigation
FMVSS 226

Rear Impact
FMVSS 301 (new)
FMVSS 202a (new)
ECE-R32

Table 2-1: Rules and regulations on occupant protection around the world. [6].

The new car assessment program (NCAP) is a voluntary vehicle safety 5-star rating program. It has a set of mature safety assessment methods, converting the determination of ‘pass’ and ‘fail’ for the regular test into a perceivable and quantified star rating assessment, which are published for consumers. This was done to encourage manufacturers to optimize the safety level of vehicles beyond the legal minimum standards and give consumers safety information to use when making their vehicle purchase decision. The influence of these test programs has been enormous. It motivates automakers to be competitive and to seek more effective countermeasures to improve vehicle safety performance. Achieving a 5-star rating in NCAP is the best advertisement for a vehicle and vice versa consumers will hesitate to purchase a vehicle with the poor NCAP scores. One notable example of this is the Rover 100, which after receiving a one-star Adult Occupant Rating in the tests in 1997, suffered from poor sales and was withdrawn from production soon afterward [7].

The rating program has been adopted by several organizations globally and further developed using each country's specific criteria. The activities of the various NCAP program and the way they operate in their respective countries and regions are listed in Table 2-2 .The multitude of tests and especially the differences in the assessment of crash tests have often led to uncertainties with consumers. While there are many similarities among the programs, the car selection process, the actual tests, the test criteria and the way that ratings are achieved may vary significantly. This makes it difficult to directly compare results [8].

<table>
<tr><th>Euro NCAP</th><th>US NCAP</th><th>USA IIHS</th><th>China NCAP</th></tr>
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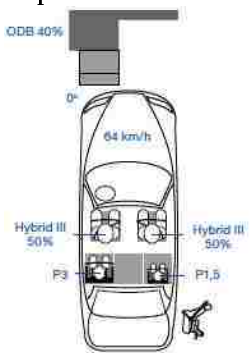
<td>40% offset frontal impact

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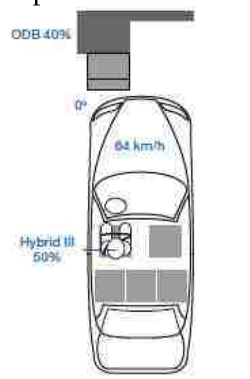
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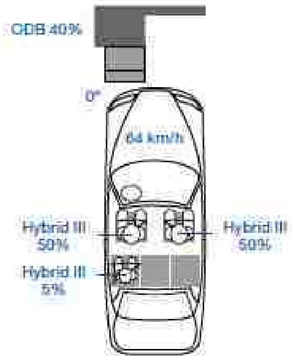
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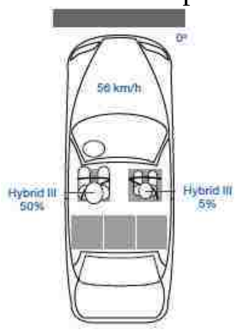
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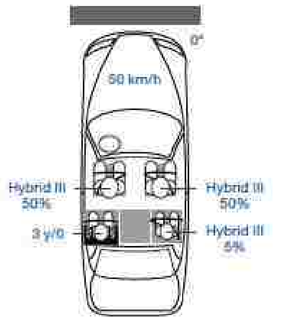
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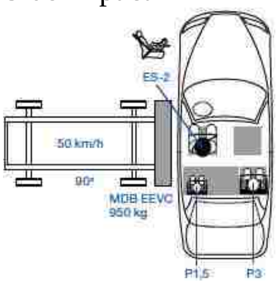
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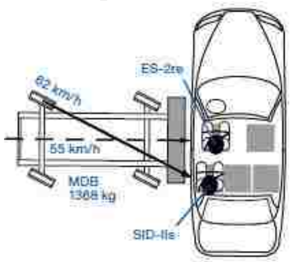
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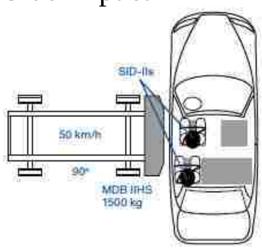
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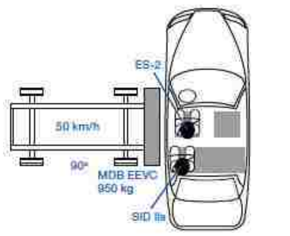
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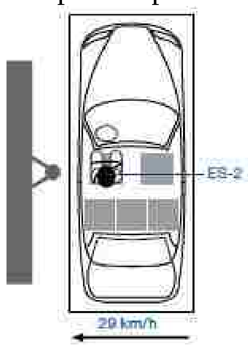
<td>Side pole impact

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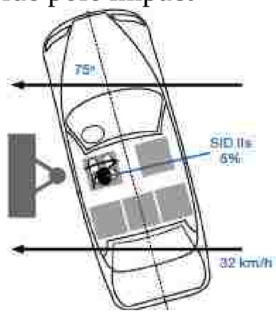
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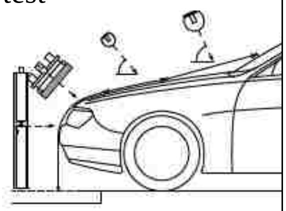
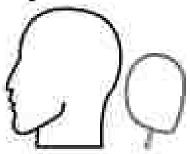
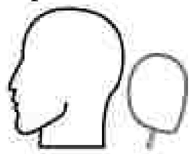
pedestrian protection test 			
Whiplash test 		Whiplash test 	Whiplash test 
	Static stability factor and fishhook maneuver	Roof crush impact 	
Child protection/ Assistance systems		ESC	Additional points for SBR, ESC, ISORX, Curtain-airbags

Table 2-2: NCAP tests in Europe, U.S. and China.

2.2.1 Crash regulations and ratings in North America

The first Federal Motor Vehicle Safety Standards (FMVSS) issued by NHTSA is FMVSS 209 (Seat Belt Assemblies) in 1967. A number of FMVSS became effective for vehicles manufactured after this year. The standards and regulations published include crash avoidance, crashworthiness, post-crash standards and other regulations so that 'the public is protected against unreasonable risk of crashes occurring as a result of the design, construction or performance of motor vehicles and is also protected against unreasonable risk of death or injury in the event crashes do occur.' [9].

The testing of a full-width engagement impact of a vehicle into a fixed rigid barrier was used to assess vehicle frontal impact protection in U.S. This test was codified in FMVSS 208. It aims to simulate the vehicle hitting a solid object or another vehicle exactly head on at a speed of 56 km/h. The Hybrid-III 50^{th} and 5^{th} dummies are tested under both belted and unbelted condition.

FMVSS 214 specifies performance requirements for protection of occupants in side impact crashes. The wheels of the barrier were crabbed at an angle of 27 degrees from the longitudinal direction of the barrier. The stationary vehicle is impacted by MDB at 54 km/h. This test was intended to simulate an intersection crash involving two moving vehicles. Dummy injuries to the thorax and pelvic area were assessed along with vehicle structural damage.

In 1979, the NHTSA created a five-star rating program to examine popular vehicle safety aspects by crash-testing. This is the first New Car Assessment Program in the world. Later on, the agency improved the program by adding rating programs to make it easier for consumers to understand the test results. The test results can be easily accessed from the official website [10].

The latest version of U.S. New Car Assessment Program for the 2010 model year was adopted by NHTSA in 2008. It is a new milestone for the improvement of occupant protection. It includes frontal and side crashworthiness and rollover resistance. Occupant injury criteria are measured and converted to the probability of life threatening injury based on formulas. The vehicle rating is according to the probability of life threatening injury. Crash avoidance technologies are also taken into consideration. U.S. NCAP recommends electronic stability control, lane departure warning, and forward collision warning systems. Separately, U.S. NCAP provides child restraint usability ratings to help consumers make informed purchasing decisions. Compared to the compliance tests FMVSS 208 and FMVSS 214, the higher severity NCAP crash tests result in increasing intrusion and higher acceleration in the occupant compartment. The MDB in NCAP side impact is towed at an 8 km/h higher speed compared to FMVSS 214. Raising the speed enables users to more easily distinguish any crashworthiness differences [11].

In June 2003, an independent, non-profit organization, the Insurance Institute for Highway Safety (IIHS) in the U.S. focused predominately on the issue of heavy Sport Utility Vehicles (SUV) involved in North American road accidents. The IIHS test consisted of high-speed front and side crash tests, a rollover test and sled tests for whiplash prevention during rear-end crash. The vehicle rating includes good, acceptable, marginal or poor in a four level scale. Except for the occupant injury criteria, there is a separate assessment system for structural performance rating. In effect the structural rating contributes to one third of the overall rating. This is one of the main differences between IIHS and U.S. NCAP. In the NCAP test, generally chest and tibia scores do not earn maximum points therefore poor structural performance may have very little influence on the overall vehicle rating. There have been several cases where a vehicle achieved relatively good injury measurements even though structural performance was very poor [12].

2.2.2 Crash regulations and ratings in Europe

The European Union started the vehicle regulatory framework even earlier than the U.S. According to the 1958 Agreement, the World Forum for Harmonization of

Vehicle Regulations created a set of ECE regulations for type approval of vehicles and components more than 50 years ago.

The ECE-R94 test procedure in Table 2-1 developed by the European Union was designed primarily to duplicate the crash patterns seen in real world crashes. The test consists of crashing a car at 56 km/h into an energy absorbing aluminum honeycomb face which is mounted to a fixed barrier, with 40% of the front vehicle width engaging the honeycomb. Two Hybrid-III dummies are placed in the front seats to assess the injury response. The ECE-R95 test aims to offer protection to occupants by requiring manufacturers to meet certain crash performance criteria. The moving barrier impacts the stationary vehicle perpendicularly at 50 km/h.

Pedestrian protection is also included in European regulations. The test aimed to simulate the impact of the front of a vehicle with a pedestrian at 40 km/h. Typically during the collision between a vehicle and a pedestrian, the bumper impacts the leg of the pedestrian near the knee, the pedestrian rotates and the upper leg is impacted by the bonnet hood leading edge, then the pedestrian’s head impacts windshield or bonnet. It is very difficult to assess pedestrian protection using a full dummy. A series of component tests are carried out to replicate possible impacts involving child and adult pedestrians.

Euro NCAP was established in 1997. It is a non-profit international association, independent of the automotive industry. Through the Euro NCAP, cars have been tested in 40% offset frontal and side impacts. Whiplash and pedestrian protection performance has also been assessed [13]. The test procedures are based on ECE regulations. The frontal impact testing speed is raised from 56 km/h which is used in by ECE-R94 to 64 km/h in Euro NCAP. The overall rating with a maximum of 5 stars is comprised of scores in four important areas: adult protection for driver and passenger, child protection, pedestrian protection and safety assist technologies. The child protection assessment is performed by putting restrained child dummies in the rear seat of the car in both frontal and side impact tests. The overall score is calculated by weighing the four scores with respect to each other, while making sure that no one area is underachieving. Seat belt reminders, speed limiters, and electronic stability control also boost a vehicle's rating.

The 40% offset frontal test in European crash scenarios has a different test procedure as compared to the full frontal impact test used by NHTSA. The National Automotive Sampling System (NASS) has found that 42% of all frontal automotive crashes are full-frontal and 56 % of all real world crashes are offset-frontal [14]. These two tests lead to different design concepts. The 40% offset test primarily assesses the vehicle structure, as the energy of the impact is not distributed across the vehicle's front end. In this test, the crash forces are concentrated on the driver's side of the vehicle. This test mainly evaluates the ability of the vehicle structure to resist intrusion [15]. The full-frontal tests primarily assess occupant restraint systems. In this test the impact is spread evenly across the front of the vehicle. In addition, the full frontal test provides a means to assess head injury whereas the offset-frontal test provides a good means to assess injury to lower extremities [16].

Another major difference between European crash regulations and U.S standards is the means by which manufacturers are required by authorities to prove that their vehicles meet these standards. The U.S. system is one of 'self-certification' where it is assumed that manufacturers' vehicles meet these standards unless crash testing by NHTSA on a representative production vehicle proves otherwise. Monetary penalties can be prescribed and recall action mandated if non-compliance is discovered. The Europeans, on the other hand, administer a ‘type approval’ system where a vehicle model is certified by the authorities prior to it being allowed on the market. This involves prototype testing, witnessed by the approval authority. Both systems are aimed at ensuring that production vehicles meet the requirements. As a result, many manufacturers design to a higher level than the legislative requirement to ensure a level of confidence to comply with the test [17].

2.2.3 Crash regulations and ratings in China

China is a key player in the global automotive market. As the number of automobiles increased rapidly in China after 2000, road safety has become a top priority in China in recent years. According to data released by Development Research Center of the State Council, close to 80,000 people die each year on Chinese roads. The death toll per vehicle is 9.5 time and 12.2 times larger than that of Germany and Japan, respectively [18].

Chinese authorities started to launch national awareness activities and seek global cooperation on vehicle safety standards and regulations. China signed the ECE Working Party 29 agreement ‘Harmonization of Vehicle Regulation’ in Geneva. After this action, the first safety standard of ‘The protection of the occupants in the event of a frontal collision for passenger cars’ (GB 11551-2003) was established in 2003. In 2007, ‘The protection of the occupants in the event of an off-set frontal collision for passenger cars’ (GB/T 20913-2007) was released as a recommended standard. Also ‘The protection of motor vehicle for pedestrians in the event of a collision’ (GB/T 24550-2009) is at the stage of being recommended to car makers [18]. These four standards were referred to the corresponding ECE regulations, the slight difference are highlighted in Table 2-3.

Chinese Standard	Refer to EU standard	Comparison
GB 11551-2003 Frontal 100% impact	ECE R94 (00 version,1995)	GB 11551-2003 is frontal perpendicular impact, ECE-R94 is frontal impact with an angle The seat adjustment is based on Japanese front impact regulation TRIAS-47
GB/T 20913-2007 Frontal 40% impact	ECE R94 (01 version,2003)	The seat adjustment is based on Japanese frontal impact regulation TRIAS 47-4
GB 20071-2006 Side impact	ECE R95	The test dummy can be either Euro-SID-1 or Euro-SID-2 The seat adjustment is based on Japanese side impact regulation TRIAS 47-3-2000.
GB/T 24550-2009 Pedestrian protection	GTR 9	

Table 2-3: Comparison of Chinese crash standards and European standards.

Currently, the Chinese vehicle crash test regulations are mainly reflected in the occupant protection of frontal and side collision. Compared to European and North American countries, these safety regulations are less developed. The main transport mode on the roads of China is a mix of vehicles: bicycles, motorcycles and pedestrians along with trucks and cars. The protection for bicycles or motorcycle crashes still needs improvement. Child protection is an important issue, legislation will also be implemented in this area.

In 2006, the China New Car Assessment Program (CNCAP) was established by the China Automotive Technology and Research Center (CATARC). The CNCAP was developed on the basis of research and reference of other countries' experiences on NCAP and was executed on August 1, 2006. The test results of CNCAP are evaluated by six star grades: the lowest grade is 1 star and the highest is 5+ stars. Since then, CNCAP has tested more than 100 models. The vast majority of those tested cars were locally built by either domestic or Sino-foreign joint venture companies. In 2010, CNCAP also started to test imported vehicles.

CNCAP has been a controversial program since the beginning. It was pointed out to be an insufficient, less strict test procedure compared to other NCAP tests of the world. Its name misleads many to believe it is similar to, or on a par with, U.S. NCAP, Euro NCAP, Australia NCAP. In fact the CNCAP omits pedestrian protection, rear impact, and side pole impact tests and the impact velocity is lower than other NCAPs. 100% front impact is conducted at 50km/h (56km/h in US NCAP), 40% front impact at 56km/h (64km/h in Euro NCAP, Japan NCAP, Australia NCAP, Korea NCAP, Latin-NCAP). In September 2011, CATARC released a new CNCAP Management regulation for 2012, making it more difficult for participating models to achieve high scores. The test configuration and rating criteria are compared in Table 2-4 and Table 2-5 between the previous version and new version.

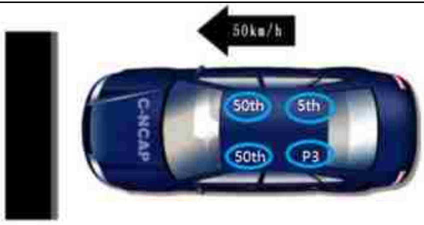
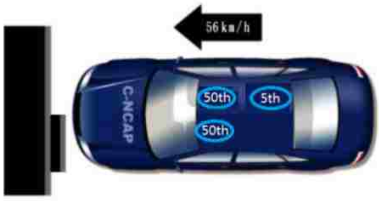
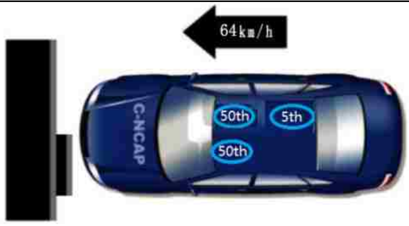
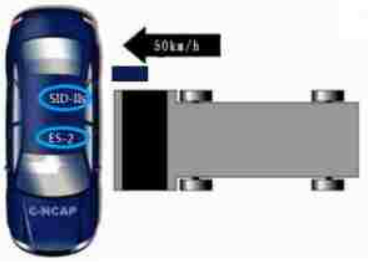
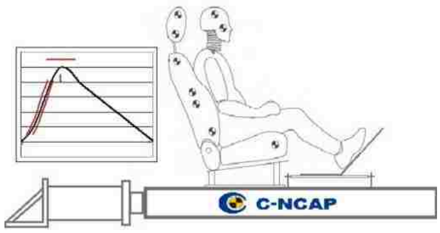
		CNCAP 2009 version	CNCAP 2012 version
Front impact	100%	 50Km/h vehicle speed	 50Km/h vehicle speed
	40%	 56Km/h vehicle speed	 64Km/h vehicle speed
Side impact		 50Km/h MDB speed	 50Km/h MDB speed
Whiplash test			

Table 2-4: Test configuration of CNCAP 2009 and 2012 versions [19] [4].

Test		CNCAP 2009 version			CNCAP 2012 version		
Test		Dummy	Maximum score		Dummy	Maximum score	
Front impact	100%	Hybrid-3 50%	Head	5	Hybrid-3 50%	Head	5
			Neck	2		Neck	2
			Chest	5		Chest	5
			Femur	2		Femur	2
			Tibia	2		Tibia	2
		Hybrid-3 5%	Not evaluated		Hybrid-3 5%	Head	0.8
						Neck	0.8
						Chest	1
		Total	16		Total	18	
	40%	Hybrid-3 50%	Head,neck	4	Hybrid-3 50%	Head,neck	4
			Chest	4		Chest	4
			Femur, knee	4		Femur, knee	4
			Tibia	4		Tibia	4
		Hybrid-3 5%	Not evaluated		Hybrid-3 5%	Head	1
						Neck	1
		Total	16		Total	18	
Side impact		ES-2	Head	4	ES-2	Head	4
			Chest	4		Chest	4
			Abdomen	4		Abdomen	4
			Pelvis	4		Pelvis	4
		SID-IIs	Not evaluated		SID-IIs	Head	1
						Pelvis	1
		Total	16		Total	18	
Whiplash test					0-4		
Additional bonus		Seat belt reminder		1.5	Seat belt reminder		1.5
		Side airbag and air curtain airbag		1	Side airbag and air curtain airbag		1
		ISOFIX anchorages		0.5	ISOFIX anchorages		0.5
					ESC		1
Total score		51			62		
Final star		★★★★★☆	5+	≥ 50	★★★★★☆	5+	≥ 60
		★★★★★	5	≥45 and<50	★★★★★	5	≥52 and<60
		★★★★	4	≥40 and<45	★★★★	4	≥44 and<52
		★★★	3	≥30 and<40	★★★	3	≥36 and<44
		★★	2	≥15 and<30	★★	2	≥28 and<36
		★	1	<15	★	1	<28

	With regard to a five star vehicle, no particular area of the dummy is awarded zero points in the 100% frontal impact, 40% frontal impact, side impact tests. Otherwise, it will be downgraded as a four-star vehicle. For the 100% and 40% frontal impact, particular areas include head, neck and chest. For side impact, particular areas include head, chest, abdomen and pelvis. In respect of a four-star vehicle, the score generated from each of the three tests shall be not lower than 10 points. Otherwise, it will be downgraded as a three-star vehicle.

Table 2-5: Rating scale of CNCAP 2009 and 2012 versions. [19] [4].

From Table 2-4 and Table 2-5, it is obvious that large revisions have been made to the rating standards:

- Add rear passenger injury measurement to assessment

The assessment added the injury measurement of rear passenger for head, neck, chest and pelvis in frontal and side impacts. In the previous test protocol, the rear dummies are only used to check the functionality of the rear seat belt. Taking the Chinese special circumstance of the higher usage rate of rear seats, CATARC added the quantitative evaluation of the injury of the rear dummies into the assessment. The rear passenger protection requires the function of seat belts to be improved.

- Upgrade the testing speed

The offset frontal barrier test upgrades the vehicle impact velocity from 56 km/h to 64 km/h. This additional 8 km/h results in about 30% crash energy increase, which gives the domestic-brand vehicles manufacturers a challenge. The new offset frontal test is more harmonized with Euro NCAP. An estimate by Yuguang Liu, the vice chairman of the Security Technology Branch in Society of Automotive Engineering of China, if the evaluation had been done with previous models without change, an average of 3 points per vehicle would be dropped compared to the original scores because of this 8 km/h. The 8 km/h will impact the body structure of the Chinese domestic vehicle [20].

- Additional new test term

With the new CNCAP, CATARC will add one new test procedure: whiplash test. This test assesses the performance of front seats and head restraints in relation to the risk of whiplash associated neck injuries in low severity rear collision events. This test procedure promotes best practices in seat design, in particular good head restraint geometry.

- Credits for active safety system

Vehicles equipped with Electronic Stability Control (ESC) which can meet the standard of GTR No. 8 (Electronic stability control systems) or FMVSS 126 (Electronic stability control systems) or ECE R13-H Annex 9 (Uniform provisions concerning the approval of passenger cars with regard to braking) will get 1 additional point. This is the first time CNCAP brings active safety into the assessment.

- Upgrade the star rating system

Total scores increase from 51 to 62, the star system is also modified accordingly. A 5-star rating will be harder to obtain than under the previous version of CNCAP.

- Clarified rules when selecting the model of the test vehicle

In the previous testing management rules, the principle of choosing the test vehicle is ‘The manufacturer will be informed of the candidate vehicle types and will be asked to provide information on the configuration type with the largest sales volume, upon receipt of the manufacturer’s feedback information, the C-NCAP Management Center will finalize the vehicle types to be assessed. If the manufacturer’s feedback is not available, the determination will be made on the basis of the standard configuration of the basic model of that candidate' [19].In the 2012 version, one sentence was added to the previous one 'In the case where the vehicle to be assessed has several configurations and these configurations do not differ obviously in sales volume, the model with the simplest configuration will be selected for assessment' [4].

The new provision went into effect in July, 2012. With the more rigorous NCAP requirements, officials from the C-NCAP Management Center are confident that the new assessment rules will help raise the overall safety of automobiles on the road in the future. With the 5-star rating being more difficult to obtain than before, Chinese consumers and manufacturers are sure to increase their awareness of vehicle safety.

For the crash rating program future development in China, Dr. Fuquan Zhao believes that the active safety standards and regulations will be the main research direction for Chinese national regulations. Standards for child safety devices and electronic stability control systems will be established in the near future. The CNCAP will add more test terms. The multi-angle impact test and pedestrian protection test will be incorporated into the new assessment system. CATARC director Hang Zhao also predicts that shifting from passive safety to active safety will be a developing trend in the future. Scores in terms of active safety configuration will be further increased, such as Brake Assist System (BAS), vehicle speed limiting device, tire pressure monitoring system, adaptive front lighting system, and advanced vehicle collision avoidance system. Consequently, car manufacturers and suppliers are faced with completely new challenges for developing occupant restraint systems.

2.3 Side impact crashes

Side collisions are particularly dangerous since the space between an occupant and the side of the vehicle is limited. Unlike a frontal collision, there are no bumpers or engines to help absorb the energy of the impact. Hence, the occupant has very little protection when a vehicle is struck on its side. Global accident statistics show that side impacts account for approximately 30% of all impacts and 35% of the total fatalities [21].

According to the NHTSA fatality analysis 2009 reporting data, passenger car side impacts accounted for about 24% of the passenger vehicle fatal crashes, but led to 31% occupant fatalities. In China, because of the implementation of traffic laws and the peculiarities of the road situation, fatalities in side impacts are even higher than other regions. According to data collected by Traffic Management Bureau of China in 2000, front impacts and side impacts are 20.83% and 34.41% of all impacts, occupants injured by side crashes are 7.59% higher than frontal crash [22]. Governments and third parties like NCAP play a direct role in dictating safety requirements to protect occupants during side collision.

3. SIDE IMPACT TESTS

Side impact is the crash safety regulation with the lowest degree of international harmonization [23]. In each of the major markets of the world, side impact testing requirements are set by the regulatory agencies and the tests are generally different [24]. Differences include the type of dummy used, the injury criteria, the impact speed, the impactor height, the impactor mass, the impactor stiffness, and the impact point on the struck car.

3.1 Side impact test diversity

The first side impact standard was developed in the 1980s at NHTSA. A quasi-static side intrusion test was developed, which became the FMVSS 214. This test can only measure the structure stiffness under a quasi-static load condition. In 1996 FMVSS 214 was extended to include the dynamic crabbed barrier test, in which the moving deformable barrier impacts the vehicle at 54 km/h with a crabbed angle. In 1997 NHTSA included a test known as Side Impact New Car Assessment Program (SINCAP). The test is conducted at a speed that is 5 mph (8 km/h) higher than FMVSS 214, and there are also different measurements for the occupant injury response. The non-profit organization IIHS predominately focused on the North American issue of heavy SUVs involved in side impact. In June 2003 it released a side impact test procedure to measure the occupant protection ability and vehicle structure integrity. The dummy used by IIHS is a small dummy to represent female occupants.

A new FMVSS 214 enacted late in 2007 by NHTSA mandates that all automakers in the US market must phase in the more stringent requirements in their vehicles within four years. As shown in Figure 3-1, the new FMVSS 214 implements more stringent requirements by adding two oblique pole tests.

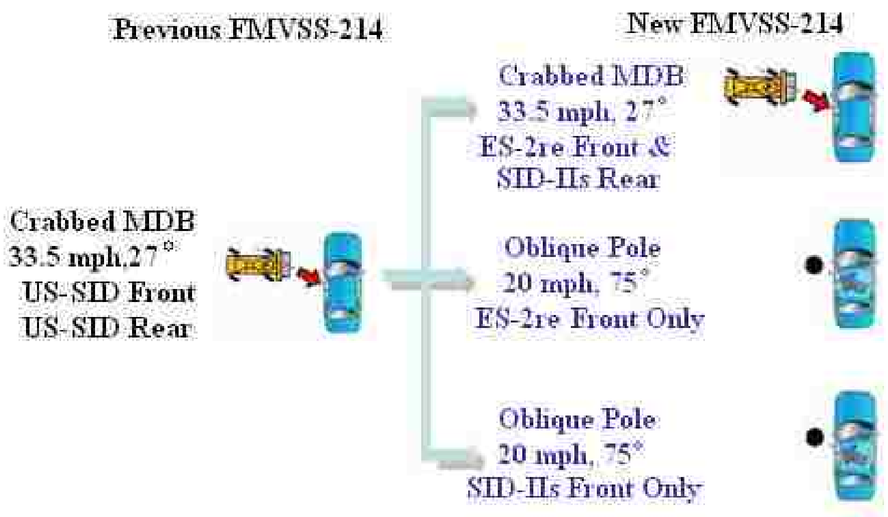


Figure 3-1: Updated FMVSS214 side impact test procedure [25].

In Europe the European Enhanced Vehicle Safety Committee Working Group 13 (EEVC WG13) implemented a regulation ECE-R95 in 1998. Euro NCAP also applied a side impact test which uses the same test procedure as ECE-R95, but with more stringent targets, especially rib intrusion and abdominal forces.

In China, the GB 20071-2006 ‘The protection of the occupants in the event of a lateral collision’ was enacted in 2004 and implemented in 2006. The GB 20071 is based on ECE-R95. The only two differences are that the test dummy can be either a Euro-Side impact dummy-1 (ES1) or a Euro-Side impact dummy -2 (ES2). Also the seat adjustment is based on Japanese side impact regulation TRIAS 47-3-2000 [26].

So there are actually twelve different side impact test procedures in Europe, U.S. and China. They can be divided them into four categories according to the test configuration as shown in Table 3-1 and the differences compared between them from Table 3-2 to Table 3-5.

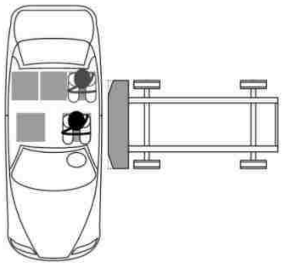
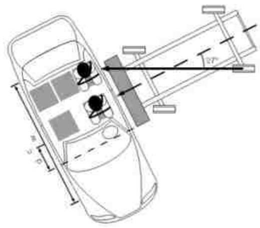
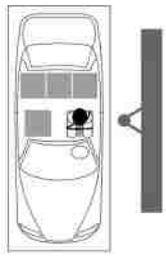
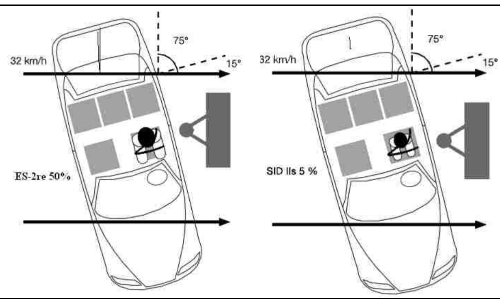
MDB test	ECE-R95 GB20071-2006 ENCAP CNCAP IIHS	
	US FMVSS Std.214 current US FMVSS Std.214 new (after 1-9-2012) SINCAP	
Pole test	Euro NCAP FMVSS 201	
	FMVSS 214 new (Oblique Pole Test) U.S. NCAP	

Table 3-1: Different side impact test configurations.

Requirement	ECE-R95, GB20071-2006, ENCAP, CNCAP	IIHS
Test configuration	50 km/h	50 km/h
Impact angle	Side 90°	Side 90°
Dummy	ECE-R95: 1 ES-2 frontal seat on impact side; GB20071-2006: 1 ES-1 or ES-2 frontal seat on impact side CNAP: 1 ES-2 frontal seat on impact side, 1 SID-II2 rear seat on impact side ENCAP: 1 ES-2 frontal seat on impact side, P1.5 on rear seat on impact side and P3 on the other side	2 SID-IIs on impact side
Impact point	Centered on the front seat H-point	Impact reference distance is between 610mm and 810mm
Moving deformable barrier (MDB)	950Kg 300mm above ground 800mm height 1500mm width	1500 kg 379 mm above ground 759 mm height 1676 mm width
Injury Criteria	Head :HIC_{36} ≤1000 Torax: Rib deflection≤42 [mm], Viscous criterion≤ 1.0[m/s] Abdomen: Abdominal peak force ≤ 2.5[KN] Pelvis: Pubic symphysis peak force ≤ 6 [kN]	Different weight in assessment driver and passenger values for HIC_{15} , Neck-Tension/ Compression, head kinematics, Shoulder, Chest deflection, Viscous criterion, Pelvis and Femur, Car body evaluation, B- pillar

Table 3-2: Moving deformable barrier perpendicular side impact.

H-point is the theoretical location of an occupant's hip.

HIC is the abbreviation of head injury criterion. HIC_{36} is the standardized maximum integral value of the head acceleration with the time interval up to 36 ms. The maximum time interval to calculate HIC_{15} is 15 ms.

Requirement	US FMVSS Std.214 current	US FMVSS Std.214 new (after 1-9-2012)	SINCAP
Test configuration	54km/h	54km/h	62 km/h
Impact angle	27°crab angle	27°crab angle	27°crab angle
Dummy	1 US-SID front 1 US-SID rear	1 ES-2re front 1 SID-IIs rear	1 ES-2re front 1 SID-IIs rear
Impact point	940mm forward of the center of the vehicle's wheelbase if W≤2896mm (508mm if W≥ 2896mm)	940mm forward of the center of the vehicle's wheelbase if W≤2896mm (508mm if W≥ 2896mm)	940mm forward of the center of the vehicle's wheelbase if W≤2896mm (508mm if W≥ 2896mm)
MDB	1368Kg Bottom edge 279mm above ground Bumper edge 300mm above ground 1676mm width	1368 kg Bottom edge 279mm above ground Bumper edge 300mm above ground 1676mm width	1368 kg Bottom edge 279mm above ground Bumper edge 300mm above ground 1676mm width
Injury Criteria	TTI < 85 g (4-doors) TTI < 90 g (2-doors) Pelvis acceleration < 130 g	SIDIIs: HIC_{36} <1000, Lower spine acceleration<82kg Pelvic force<5.525kN ES-2re: HIC_{36} <1000 Chest deflection<44 mm Abdominal force<2.5 kN Pubic force<6 kN	See Table 3-6

Table 3-3: Moving deformable side impact at crab angle.

W is the wheelbase, TTI is the Thoracic Trauma Index.

Requirement	Euro NCAP	FMVSS 201
Vehicle velocity (on Flying floor)	29 km/h	29 km/h
Impact angle	Lateral @ 90 degree on fixed pole	Lateral @ 90 degree on fixed pole
Pole diameter	254 mm	254 mm
Dummy	1 ES-2 on impact side	1 US SID on impact side
Injury Criteria	Head : HIC_{36} ≤1000, a_{res} peak < 80 g Torax: Rib deflection≤42 [mm], Viscous criterion≤ 1.0 [m/s] Abdomen: Abdominal peak force ≤ 2.5 [KN] Pelvis: Pubic symphysis peak force ≤ 6 [kN]	Head HIC(d) < 1000

Table 3-4: Pole test.

HIC(d) is the head performance criterion, it is calculated from the HIC_{36} value, based on Equation (3-1):

$$HIC(d)=0.75446*HIC_{36}+166.4 \quad (3\text{-}1)$$

Requirement	FMVSS 214 new (Oblique Pole Test)	US NCAP
Vehicle velocity (on Flying floor)	32 km/h	32 km/h
Impact angle	Lateral @ 75 degree on fixed pole	Lateral @ 75 degree on fixed pole
Pole diameter	254mm	254mm
Dummy	1 ES-2re on impact side (50^{th} Oblique Pole Test) 1 SID IIs on impact side (5^{th} Oblique Pole Test)	1 SID IIs on impact side
Injury Criteria	SID IIs: HIC_{36} ≤1000 Lower spine acc. < 82g Pelvic Force < 5.525 kN ES-2 re: HIC_{36} ≤1000 Chest deflection < 44mm Abdominal Force < 2.5 kN Pelvis: Pubic symphysis peak forcce ≤ 6 [kN]	See Table 3-6

Table 3-5: Oblique pole test.

	ES-2re 50%	SID-IIs 5%
Head (HIC_{36})	$P_{head}(AIS3+) = \Phi(\frac{\ln(HIC15) - 7.45231}{0.73998})$ Where Φ = cumulative normal distribution	$P_{head}(AIS3+) = \Phi(\frac{\ln(HIC15) - 7.45231}{0.73998})$ Where Φ = cumulative normal distribution
Chest (rib deflection in mm)	$P_{chest-defl}(AIS3+) = \frac{1}{1 + e^{5.3895-0.0919*max.rib\ deflection}}$	
Abdomen (total abdominal force in N)	$P_{abdomen}(AIS3+) = \frac{1}{1 + e^{6.04044-0.002133*F}}$ Where F = total abdominal force (N) in ES-2re	
Pelvis (Force)	$P_{pelvis}(AIS3+) = \frac{1}{1 + e^{7.5969-0.0011*F}}$ Where F is the pubic force in the ES-2re in Newton	$P_{pelvis}(AIS2+) = \frac{1}{1 + e^{6.3055-0.00094*F}}$ Where F is the sum of acetabular and iliac force in the SID-IIs dummy in Newton
	$P_{joint} = 1 - (1 - P_{head}) \times (1 - P_{chest}) \times (1 - P_{abdomen}) \times (1 - P_{pelvis})$	$P_{joint} = 1 - (1 - P_{head}) \times (1 - P_{pelvis})$

Table 3-6: US NCAP side impact injury criteria [6].

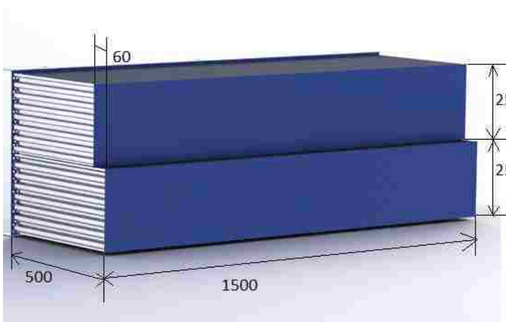
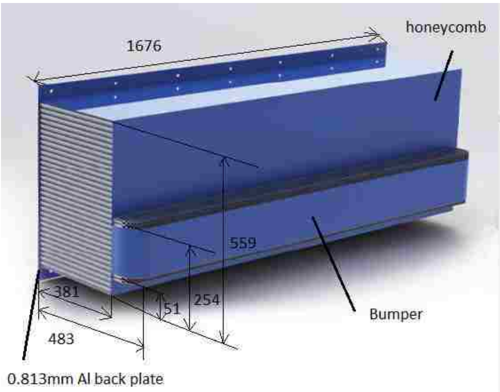
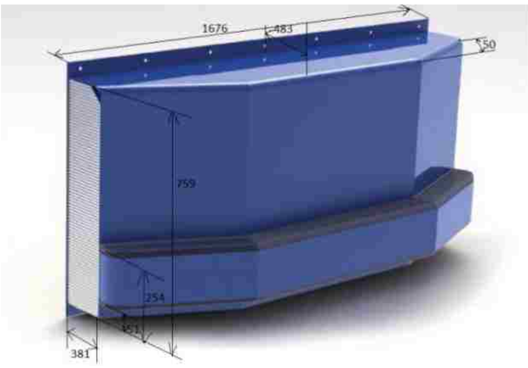
WG 13 barrier 	In Europe and China, the passenger vehicles on the road are mostly small vehicles with mass of less than 1400kg, the 950 kg WG 13 barrier was about the average mass of European vehicles at the time then when this regulation was developed. It is used for ECE-R95 and most other regulatory side impact and NCAP by most countries outside North America.
NHTSA barrier 	In North America, large vehicles with mass larger than 2200kg are more common [27]. 1368kg was the US average fleet mass of the vehicle when the rule was being developed.
IIHS barrier 	The IIHS barrier duplicates the front-end stiffness and large size of a heavy SUV.

Table 3-7: Different MDB used in side impact tests.

In the side impact test procedure, the MDB test simulates a colliding vehicle striking the side of the test vehicle. The specification of the deformable barrier, e.g. dimension, dynamic deflection characteristics, corresponds to those of the typical passenger vehicle. The mix of vehicle type varies considerably between global markets. The three different MDBs are shown in Table 3-7.

The test procedures of GB 20071-2006, CNCAP and ENCAP are the same with ECE-R95. The discussion in this section uses ECE-R95 to represent the four tests.

From Figure 3-2 and Figure 3-3, it is clear that the IIHS barrier has the highest weight, while the SINCAP barrier contains the highest kinetic energy.

Unlike the frontal test, the test dummies are harmonized to Hybrid-III family. There are five different dummies for side impact: EuroSID-1, EuroSID-2, EuroSID-2re, US-SID and SID-IIs.

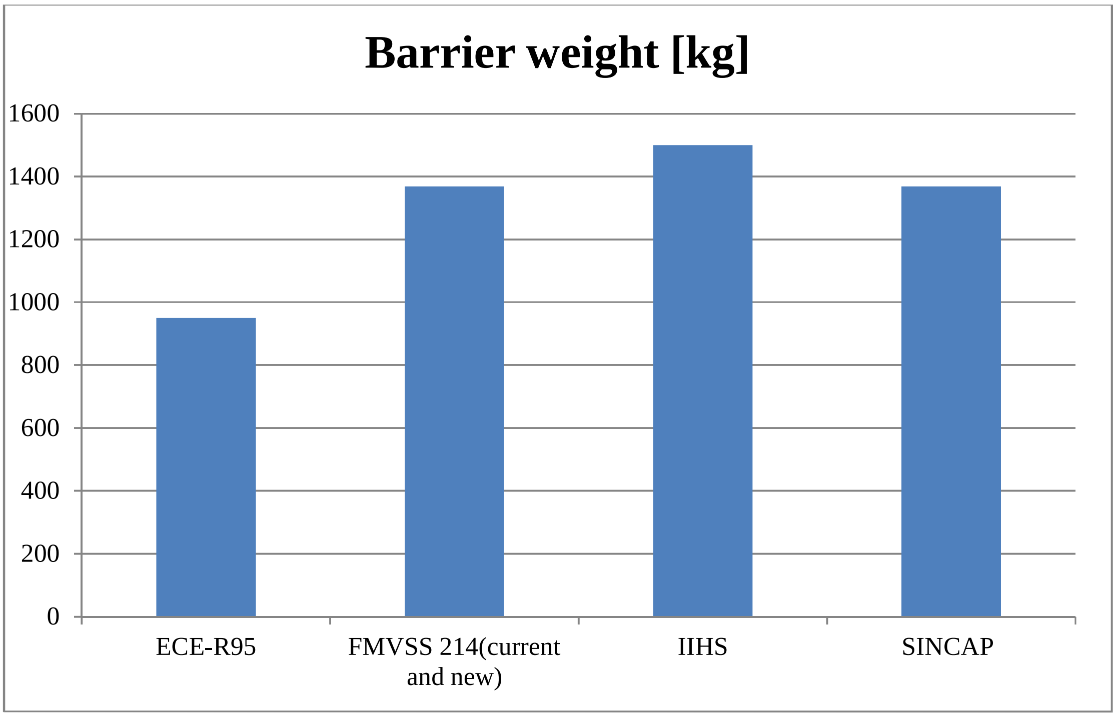


Figure 3-2: Comparison of the barrier weight in different MDB test.

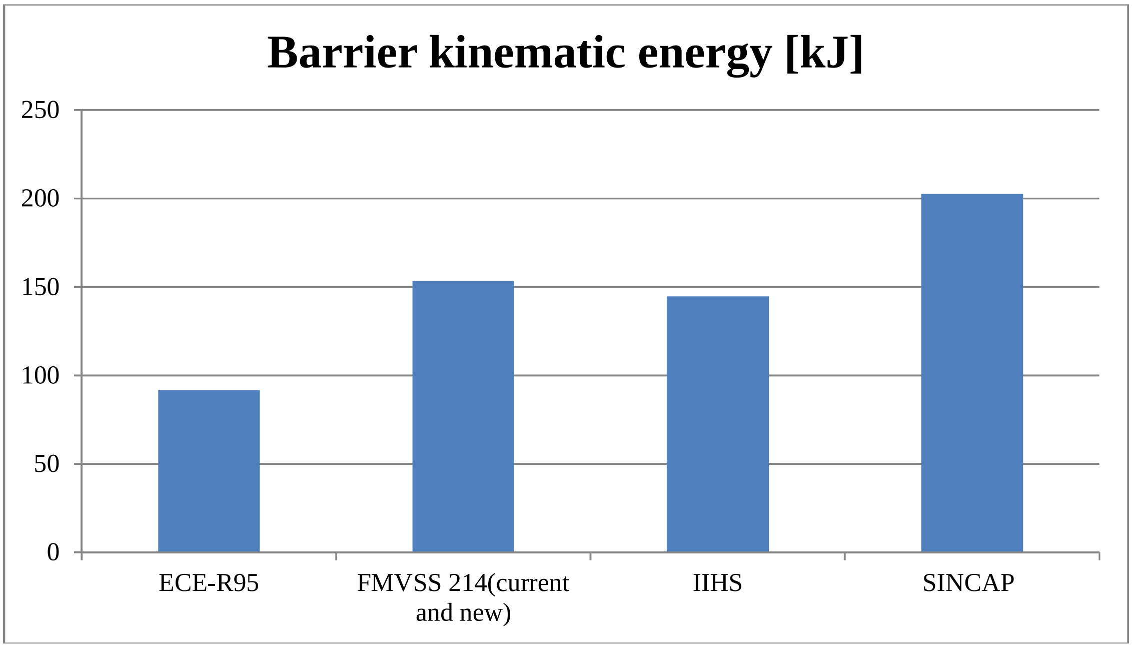


Figure 3-3: Comparison of the barrier kinetic energy in different MDB test.

The ES-1 was developed in the 1980s by the European Commission for side impact crash scenarios. It represents a 50th percentile adult male without lower arms. The head is from the Hybrid III 50th percentile dummy and the legs are from the Hybrid II 50th.

The ES-2 is the second generation of the ES-1 dummy. It is designed to address the important shortcomings of the ES-1 while bio-fidelity is maintained. NHTSA conducted extensive evaluation of the ES-2 dummy in various test configurations and concluded that the EuroSID-1 dummy's identified deficiencies were resolved in the ES-2. Many researchers have shown that the ES-2 dummy records higher rib deflections than the ES-1 [24].

The ES-2 back plate could get caught on some seat-back frames in side impact tests, therefore reducing rib deflections. To prevent this seat-grabbing interaction a rib extension kit was developed by NHTSA to enclose the gap of the rib cage between the ribs and back plate [28]. This design enhancement is called the ES-2re, as shown in Figure 3-4.

The US side impact dummy (US-SID) was developed in the U.S. by NHTSA at the same time as ES-1 was developed. It was originally developed for the FMVSS 214 test. The head, neck and neck bracket are from the Hybrid II 50th percentile male test dummy. Based on the ISO/TR9790 rating scale, the US-SID shows an unacceptable bio-fidelity. In the new FMVSS 214, the US-SID dummies were replaced by ES-2re in the front driver's seat and SID-IIs in the rear seat.

The anthropometry and mass of the SID-IIs are based on the Hybrid III-5th percentile female dummy and generally match the size and weight of a 12- to 13-year-old child. The SID-IIs head, neck and legs are based on the Hybrid III-5th percentile female dummy design.

		
ES-SID	US-SID	SID-IIs

Table 3-8: Different testing dummies used in side impact tests.

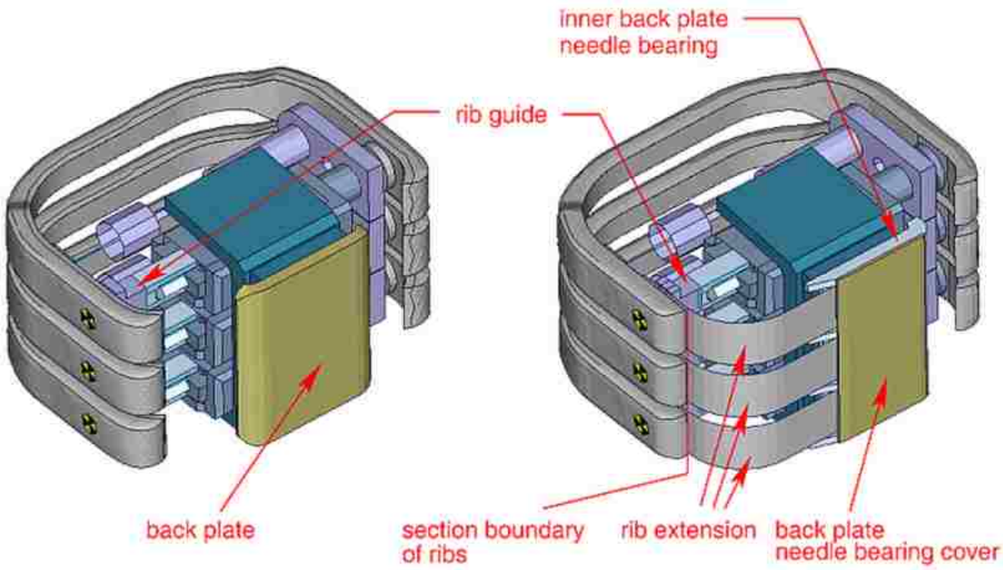


Figure 3-4: Differences between the ES-2 (Left) and ES-2re (Right) Rib module [28].

3.2 Energy management in side impact

Side impacts present a difficult problem for crash protection as there is little structure available between the occupant and the impacting vehicle or object. As Cesari and Bloch reported [29], by comparison, it is reported that the front of the vehicle can absorb two to five times as much energy as the side structure before injury occurs to the occupants of the vehicle. A major cause of serious injury during side collision is intrusion of the impacted door into the occupant [30]. The typical side impact test can be explained by the velocity profiles of Figure 3-5.

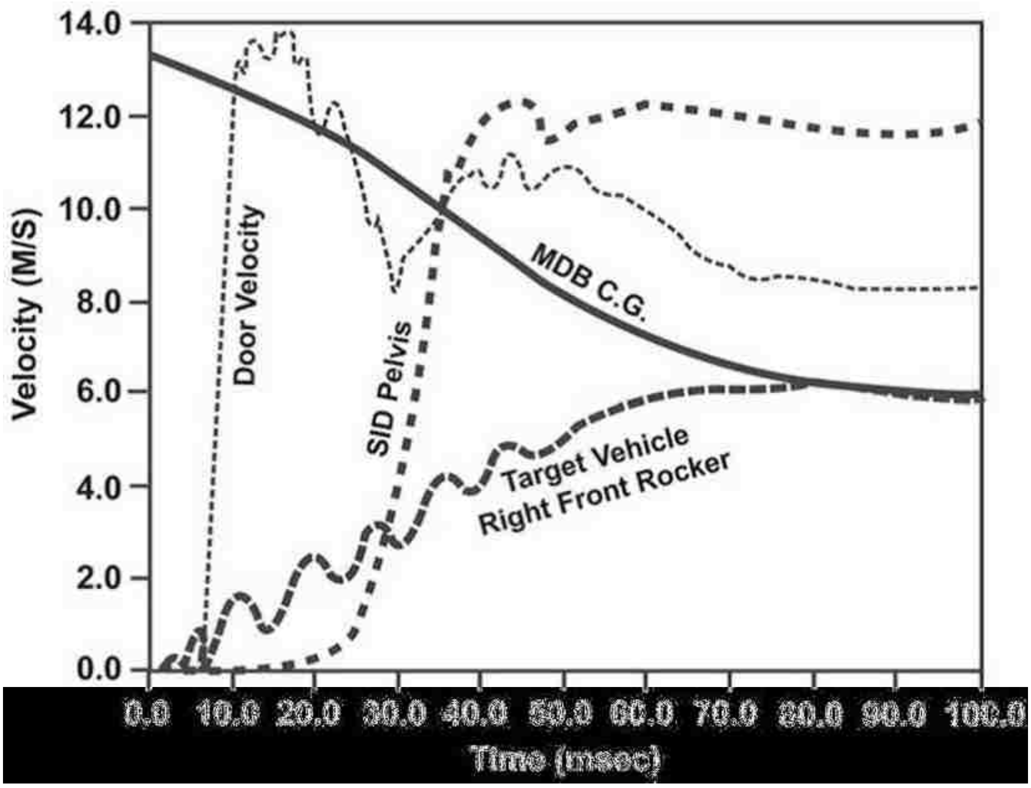


Figure 3-5: Typical vehicle profiles in side impact [31].

In Figure 3-5, all the velocity curves are obtained by the numerical integration of accelerometer data measured in the full vehicle side impact test. The door velocity is measured at the door inner panel armrest position. Before the MDB starts to contact the target vehicle, the vehicle is stationary. The MDB comes into contact with the vehicle at time 0 msec. A typical door intrusion velocity profile in a full-scale side impact test consists of three common characteristics: first peak, valley and second peak [32]. The first peak occurs immediately after the barrier contacts the door causing the door velocity to rapidly increase to its initial peak. The door velocity then decreases to its valley as the vehicle side structure transfers load to the main structure of the vehicle [33]. The second peak in door velocity is caused by stiffening of the barrier prior to slowing to its final velocity.

The exchange of energy between the vehicle, dummy and MDB takes place during the crash process. The primary energy exchange is between the MDB and the target vehicle until they achieve a common velocity. The second energy exchange takes place between the MDB and the door. The door quickly attains the high velocity of the MDB. Finally there is energy exchange between the intruding door and the stationary dummy when the door comes into contact with it. The dummy quickly accelerates in the lateral direction.

The dummy peak injury is mainly caused by the third energy exchange process. The input energy comes from the door intrusion velocity. The energy required to be dissipated by the vehicle interior and dummy is related to the door intrusion velocity. As shown in Figure 3-6, this incoming energy has three dissipation paths: the door padding material, the seat airbag and dummy injury. The door crush with its padding foam and the seat airbag are important energy absorbers during side impact. The rest of the energy is absorbed by the occupant. Injury criteria value is an interpolation of the energy quantity passing onto the occupant. The door trim stiffness and rigid parts layout in a door also have influence with occupant injury response.

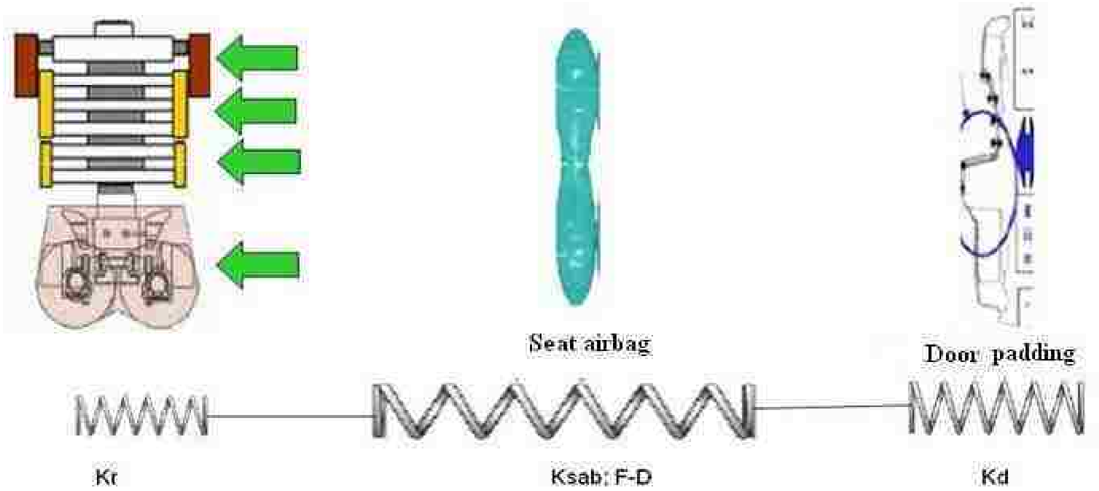


Figure 3-6: Three energy dissipation sources: door trim padding; seat airbag and dummy injury [34].

There are three main approaches to minimize the dummy injury [34]:

(1) Reduce the incoming energy from the door, minimize encroachment into the occupant zone by intrusion velocity reduction. These could be implemented by usage of the vehicle body side structure via efficient structural design or vehicle structure stiffness upgrade. Upgrading of vehicle side impact structure will reduce the door intrusion velocity profile, especially the peak intrusion velocity.

(2) Increase the energy dissipation through the padding system. Door padding material or seat airbag could absorb energy. The thickness of energy-absorbing padding and stiffness of padding material are important variables to optimise injury reduction.

(3) Proper design door trim stiffness and the rigid parts layout in a door, especially at the level of the beltline, armrest and pelvis.

The different impact configurations between MDB test and pole test lead to different energy dissipation procedures. From Figure 3-7, the comparison of the side impact contact area can be easily observed. In the pole side impact, the energy is centralized within a very narrow area, which leads to a similar amount of energy producing large intrusion velocity.

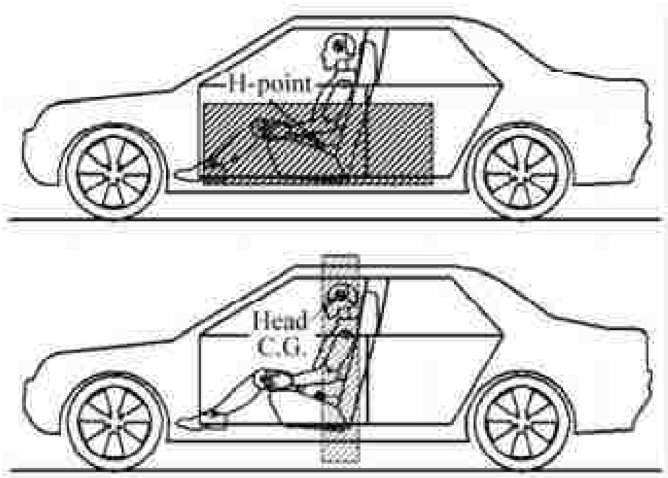


Figure 3-7: Side impact area [35].

<u>3.3 Focus of the research</u>

From this analysis, three important factors were identified that could contribute to occupant response either during a MDB impact test or pole test: the door intrusion velocity, door trim component force-displacement response behaviour and seat airbag stiffness. How will the occupant injury response vary by a 20% variation in the three factors? How can manufacturers comply with the MDB test and pole test by manipulating these three factors? A generic vehicle was chosen to study these in detail. Since the occupant protection performance in all the rating system have complicated calculation methods, it's difficult to use four-star or five-star as the design target. In this study the occupant injury protection is mainly focused on the regulation requirement. There are 5 regulatory side impact tests existing in Europe, U.S. and China: ECE-R95, GB 20071-2006, FMVSS 214 MDB, 5^{th} oblique pole test and 50^{th} oblique pole test.

The finite element analysis (FEA) method was used to investigate the relationship between the design variables and the occupant response in both MDB test environment and pole test environment. The finite element model was based on Heidelberg buck sled test set-up. The crash simulation utilized the LS-DYNA explicit code.

4. NUMERICAL MODEL DEVELOPMENT

4.1 Heidelberg buck sled test method

The Heidelberg buck sled is a simplified test system used to realistically simulate the kinematics of a full-scale side impact crash test, and reproduce the key conditions present in full scale tests. It is suitable to assess the effects of airbag and door trim stiffness. The sled system uses impact pulse from a full vehicle test to generate the velocity change between the door and the occupant.

Figure 4-1: Heidelberg buck pole sled test set-up. [36].

The 5th pole sled test pre-test set up is shown in Figure 4-1. The test system contains a frame on which a deformed door is mounted, a seat back form fixed on the pole acts as a side window curtain is used to protect the head. Next to the door is a bench, in which an unbelted dummy sits. The door and bench are placed on a sled which runs on linear rails. When a pulse is applied, the door moves along the linear rails towards the dummy, once the seat bench is impacted by the door, the dummy will slide across the seat due to inertial force and contact the door trim at the predefined velocity setting, similar to its action during a full-scale impact. The dummy's injury responses are measured.

The main goal of the pre-test preparation is to control the relative timing of body contact with the vehicle door [36]. Lateral dummy positioning (impact direction) relative to the door trim panel can be adjusted so that dummy-to-trim contact time in the velocity-time trace can be matched between the sled and full vehicle tests. The dummy offset is the area under the sled velocity pulse before reaching the peak velocity. For this test, the dummy shoulder is approximately 305 mm (12 inches) away from the door trim.

Figure 4-2: Pole sled test pulse correlation.

In Figure 4-2, the dark line represents door intrusion velocity on the vehicle beltline which is close to the dummy thorax in a full vehicle 5th oblique pole test. It is obtained from the numerical integration of the acceleration measured in the physical full scale vehicle test by an accelerometer. The acceleration is filtered by the filter type SAE CFC 180, in accordance to SAE J211 [37]. CFC is the abbreviation for channel frequency classes (CFC) and 180 is the value of frequency in hertz. The door in the sled test model is taken from the same vehicle as tested in the full vehicle test. The red line is the applied sled pulse.

For better correlation with the full vehicle test, two parameters need to match between the sled test and full vehicle test: the peak door velocity and the dummy-to-trim contact timing. Since the critical time period for a side impact event is ~20ms after door intrusion peak velocity, the peak dummy injury occurs in this period. Therefore it is more crucial for the sled test pulse to achieve the full test's peak velocity, while the initial slope is not critical. In addition to matching the peak velocity and door-to-trim contact timing between the full test and sled test, it is also important that the deceleration of the sled after dummy contact matches what is observed in the full vehicle test.

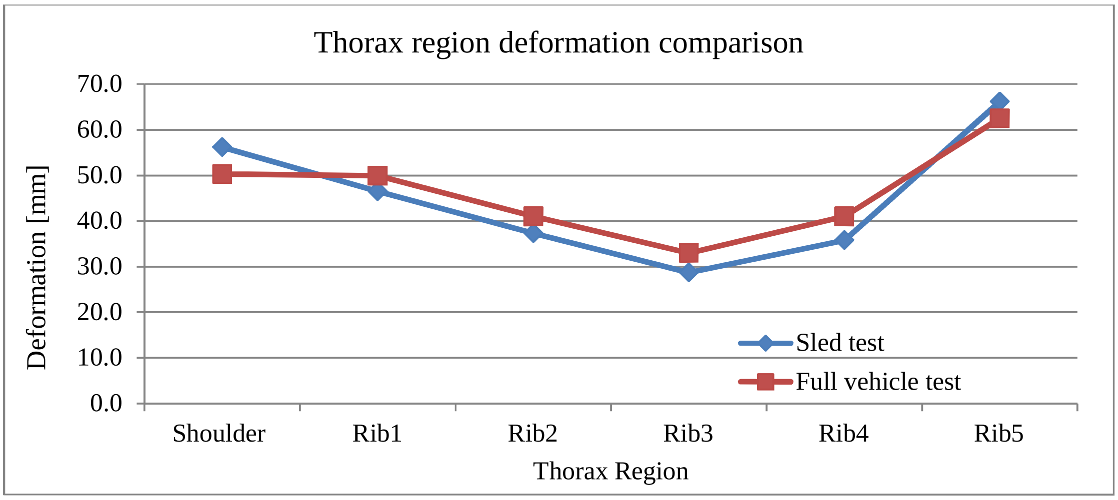


Figure 4-3: Sled test to full vehicle test thorax injury correlation.

From Figure 4-3, the SID-II dummy thorax injury response digital value correlations are considered adequate between sled test and full vehicle test.

The Heidelberg buck sled test for simulation of the MDB test environment is similar to the pole sled test, except the deformed door is substituted by a non-deformed door.

4.2 Finite element model development and validation

The FE pole sled model was based on the specifications and procedure adopted by the Heidelberg buck sled system. The FE side impact sled model was comprised of the deformed door, bench, and dummy.

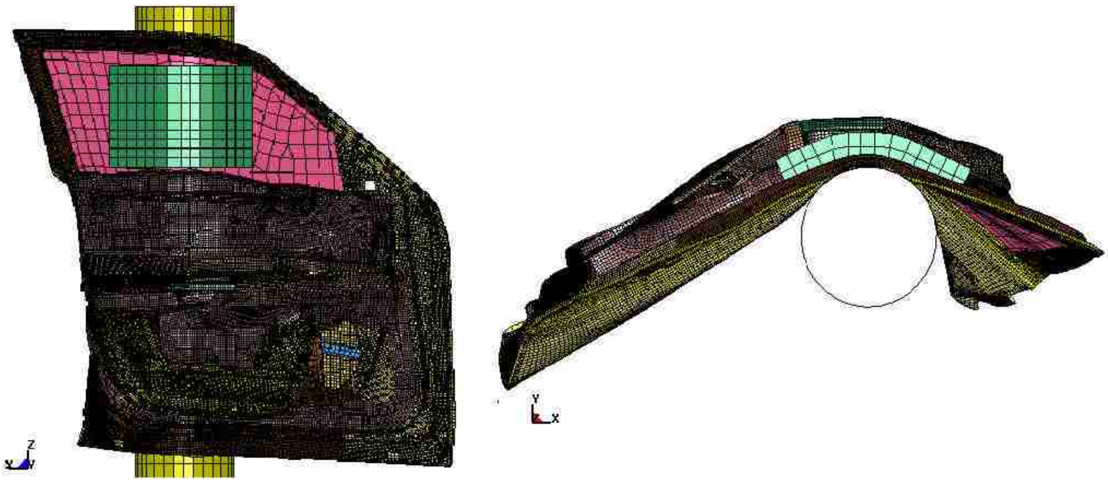


Figure 4-4: Deformed door discretizing.

The deformed door is modeled on the intrusion profile obtained from the full-scale vehicle test. The door inner is modeled with *Mat 24 [38]. Foam for head protection and door inner are held against the rigid pole with extra nodes.

As indicated in Figure 4-5, the accelerometer in the dummy thorax is used to measure the lower spine acceleration. Pelvic force is the sum of the acetabula and iliac force measured by the load cell. All these values are output in ASCII files. Dummy head acceleration is measured by an accelerometer located in the head center of gravity position, to measure the nodal displacement, velocity and acceleration values.

HIC_{36} value is the standardized maximum integral value of the head acceleration. It is calculated based on Equation (4-1):

$$HIC_{max} = \left\{ \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a_{resultant} dt \right]^{2.5} (t_2 - t_1) \right\} \quad (4\text{-}1)$$

where,

resultant head acceleration $a_{resultant} = \sqrt{a_x^2 + a_y^2 + a_z^2}$.

t_1, t_2 are the start and stop times of the integration, which are selected to give the largest HIC value. For the HIC_{36} analysis, t_1 and t_2 are constrained such that $(t_2\text{-}t_1) \leq 36$ ms.

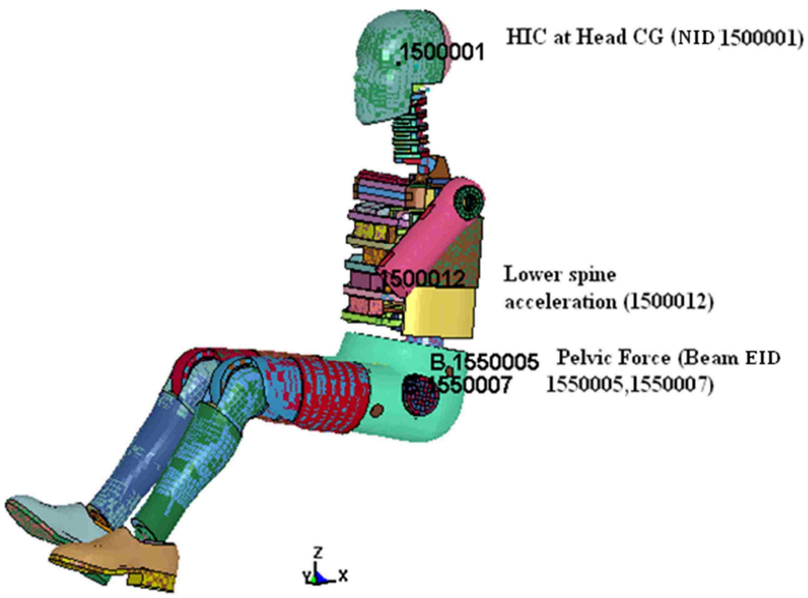


Figure 4-5: FE model of 5th dummy and injury response acquisition.

A seat plate was generated for supporting the dummy in Z direction. *CONTACT_AUTOMATIC_SURFACE_TO_SURFACE contact algorithm is used to define the contact between dummy to seat plate and dummy to door. The whole FE model for simulating the pole sled test is shown in Figure 4-6.

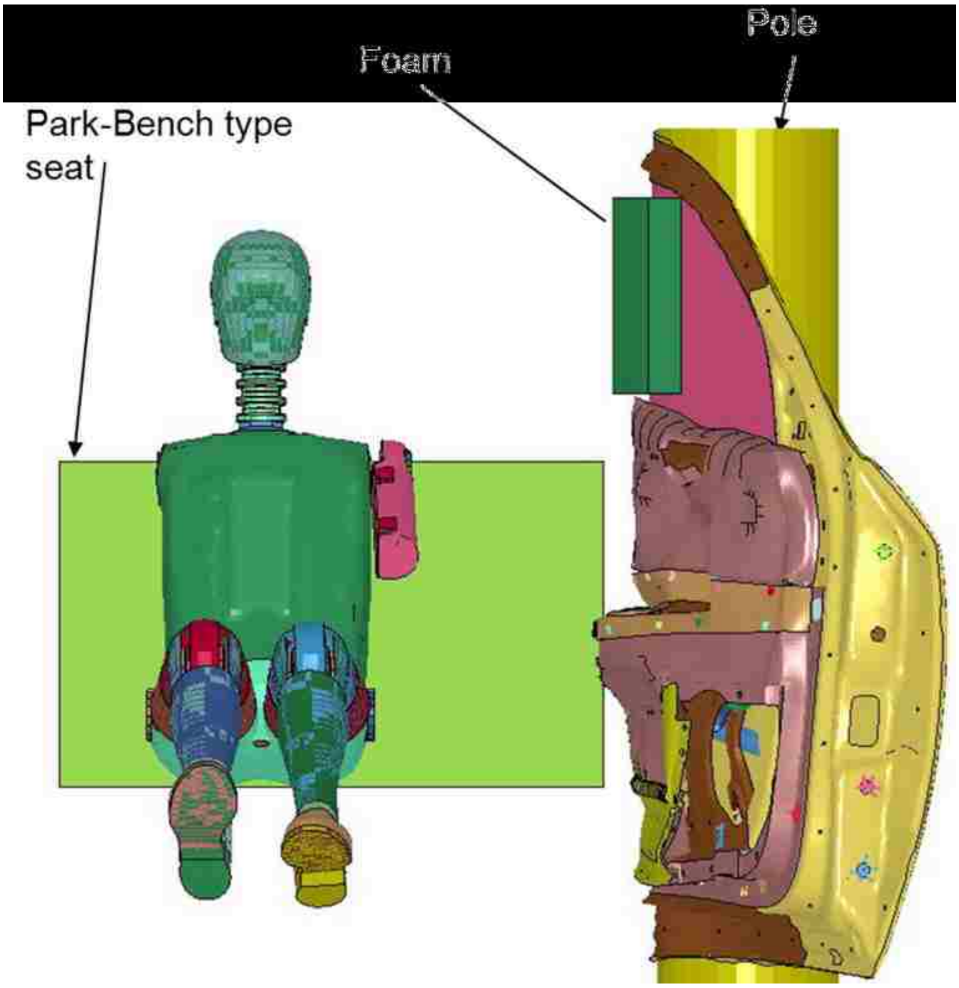


Figure 4-6: FE model of pole sled test.

The difference between the FE model and the Heidelberg buck sled system is that instead of using the velocity pulse on the door and bench fixture, in the FE model the dummy moves towards the door, using the sled pulse peak value as the dummy initial velocity to represent the relative velocity between the dummy and the door trim at the instant dummy starts to contact the door. The dummy's initial velocity is defined by *INITIAL_VELOCITY. In this case the dummy lateral position will not affect the injury response. Less simulation time is required if the dummy is closer to the door. The dummy H-point position is such that the 5^{th} rib is the likely target of the door armrest. In the baseline model, the dummy initial velocity is set to 8.94 m/s (20 mph) in the y-direction towards the door trim.

The simulations were performed using the LS-DYNA non-linear explicit finite element code. The models were run by the LS-DYNA code version MPP971 R4.2.1. on the Chrysler 48 parallel computer platform. The total simulation time for each model is 80 milliseconds to capture the main impact events. Approximate computation time to run 80ms using 12 processors was about 1 hour 40 minutes for a model with the SID-IIs dummy.

Figure 4-7 to Figure 4-9 show the occupant side impact response histories of the sled test and FE simulation at 25ms, 30ms and 45ms. In Figure 4-7, the interaction of the door trim with the dummy torso is similar. Similar interaction of the head with the foam can also be observed in this figure. In Figure 4-8, the kinematics of the dummy head, arm and torso are closely matched between the FE simulation and the test. In Figure 4-9, a slight difference of the head and foam relative position between test and simulation can be observed, it is mainly for the reason that the thickness of the foam in FE model is not the same as that in the sled test. Since the HIC value was not monitored in this study, this difference won't influence the accuracy of the FE model.

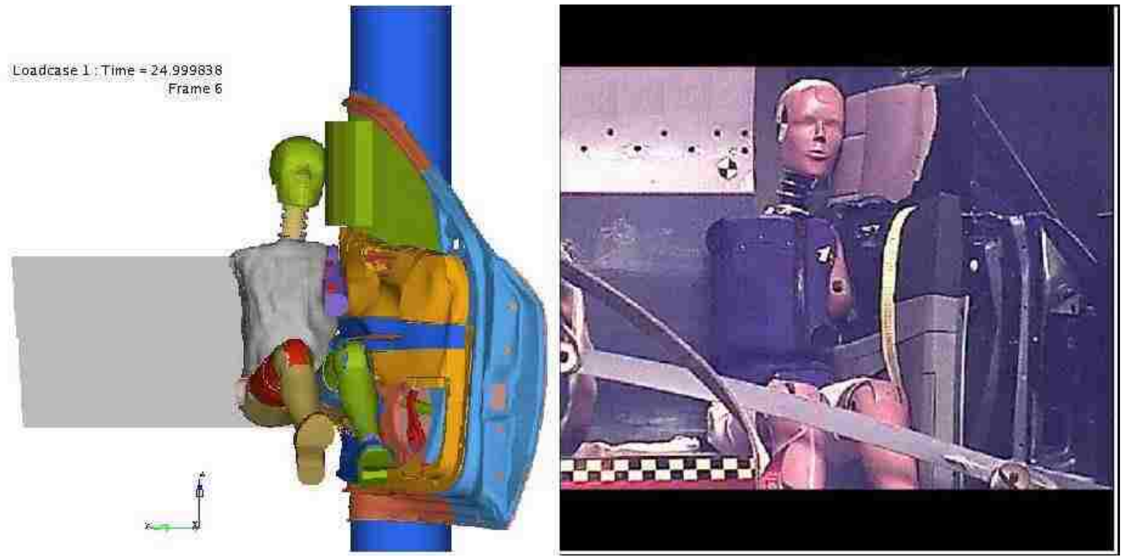


Figure 4-7: Kinematics comparison of the pole test at t = 25 ms (1).

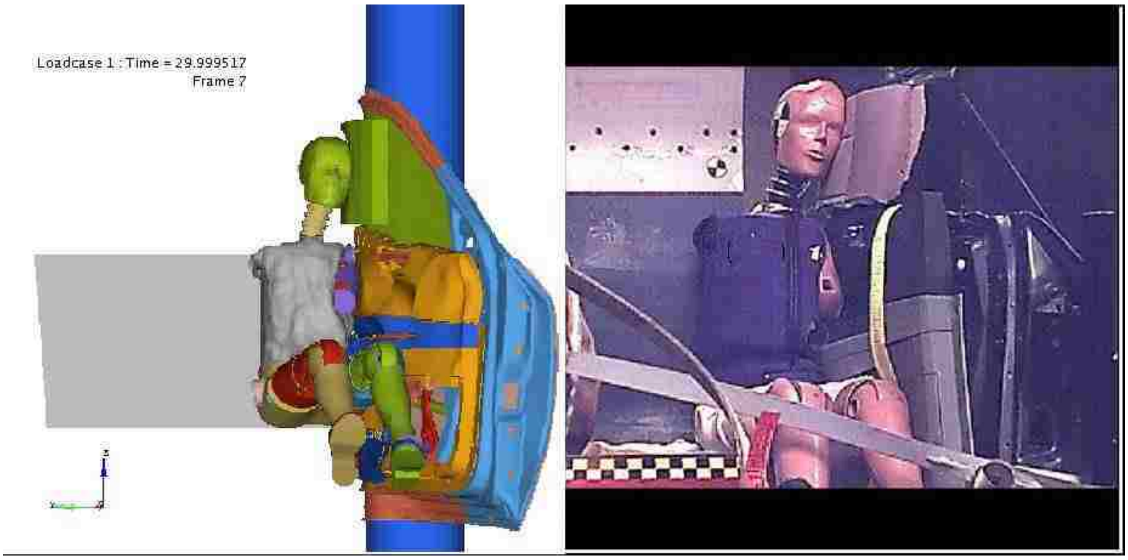


Figure 4-8: Kinematics comparison of the pole test at t = 30 ms (2).

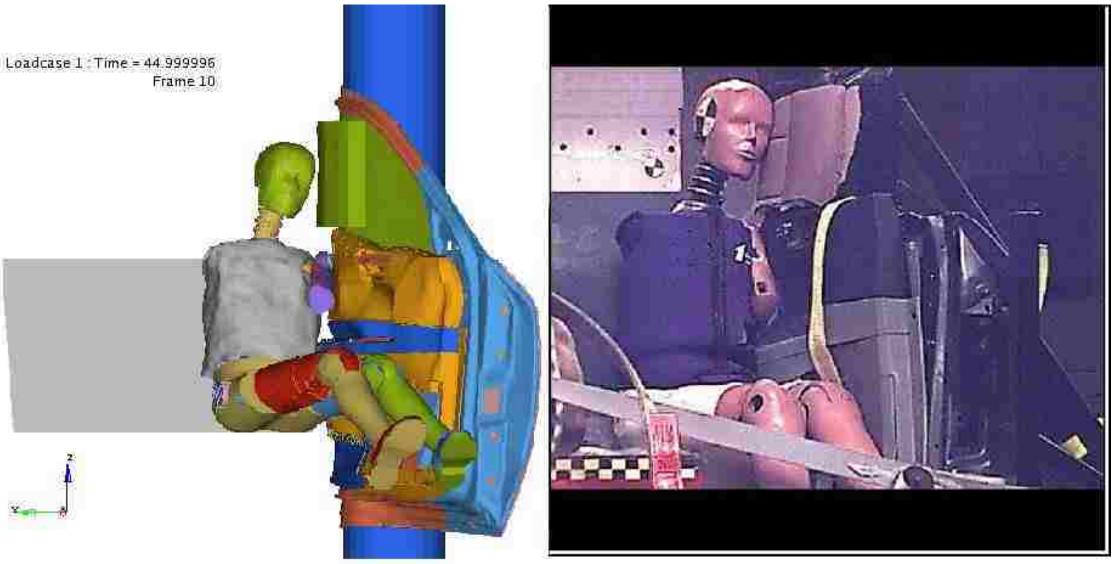


Figure 4-9: Kinematics comparison of the pole test at t = 45 ms (3).

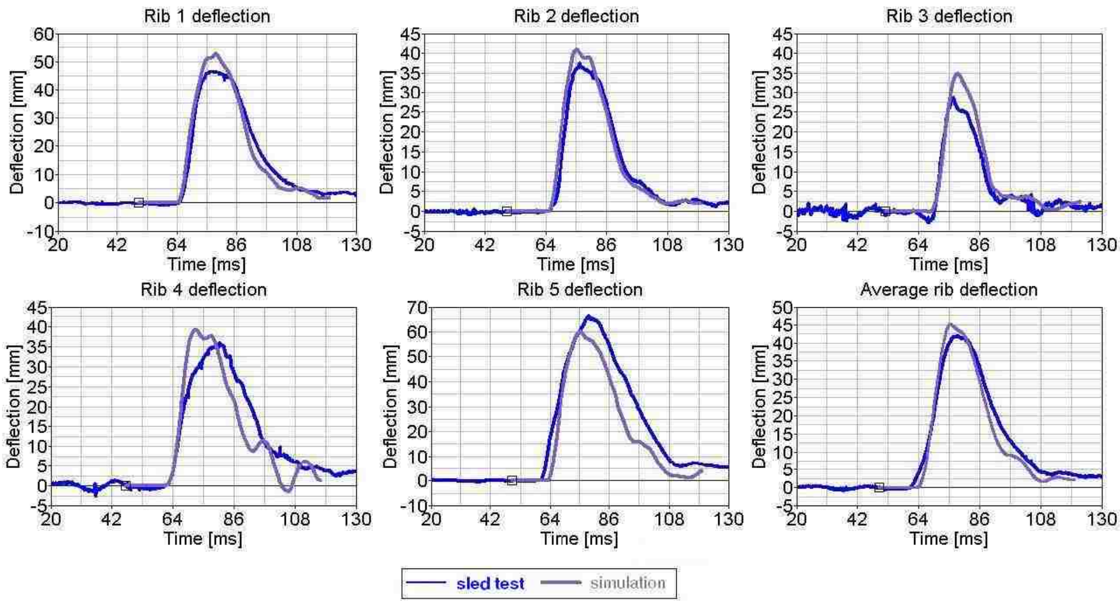


Figure 4-10: Comparison of the rib deflection between 5th oblique pole sled test and simulation results.

Good correlation is observed in Figure 4-10 for the rib injury response between the simulation and the sled test. Therefore, the pole sled test FE model can be applied to investigate the effect of various input conditions on occupant injury response.

Similarly, the FE sled model of MDB test can be developed through the same procedure. The model includes a non-deformed door (Figure 4-11), ES-2re dummy (Figure 4-12) and a seat plate. The dummy position is adjusted so that the abdomen region aligns with the door armrest. The non-deformed door inner part is modeled as a rigid body and constrained for all degrees of freedom. Since the rigid material model won't absorb energy during the dummy and door impact, the present of the rigid door is to simulate the worst case scenario of the side impact. The door trim parts which are mounted on the rigid door inner are modeled with the vehicle door trim material properties. The HIC_{36} value is not a critical injury criterion for either the MDB test or the pole test, because the solution for head protection is well known by manufacturers. For this reason, the door window is not modeled. The HIC_{36} value is not taken into consideration in this study.

Figure 4-11: Non-deformed door discretizing.

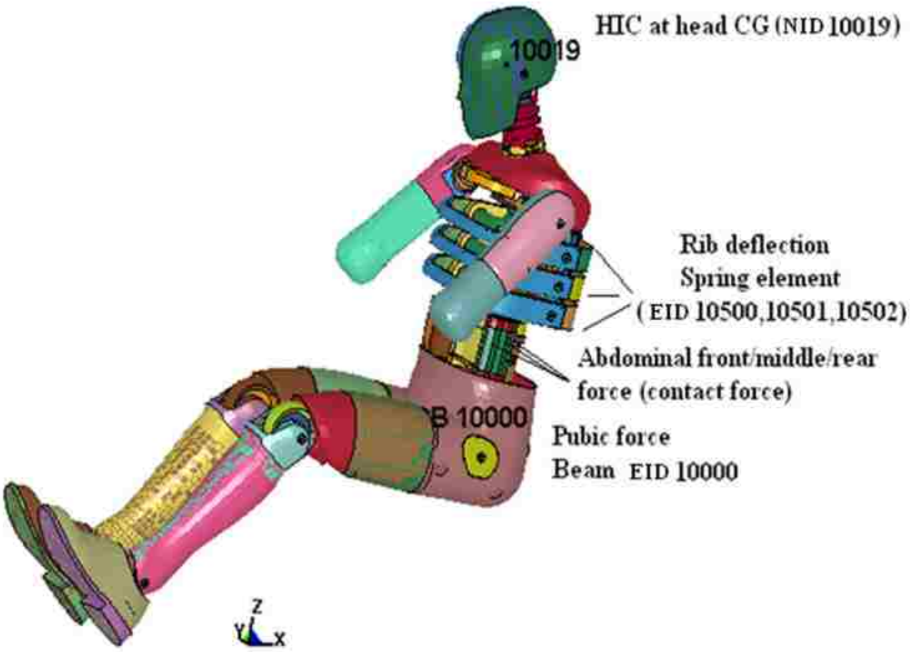


Figure 4-12: FE model of 50th dummy and injury response acquisition.

As shown in Figure 4-12, spring elements are positioned at the dummy's thorax area to measure the rib deflection values. A beam element is positioned to measure the public symphysis force. Three contacts in the abdomen area are used to measure the abdominal force. All these values are output in ASCII files. Rib viscous criterion is calculated based on Equation (4-2) [39]:

$$C_{(t)} = \frac{D_{(t)}}{0.14}, V_{(t)} = \frac{8[D_{(t+1)} - D_{(t-1)}] - [D_{(t+2)} - D_{(t-2)}]}{12\delta t} \quad (4\text{-}2)$$

where,

$D_{(t)}$ = rib deflection at the moment t, [m].

δt = rib deflection measurement time step, [s].

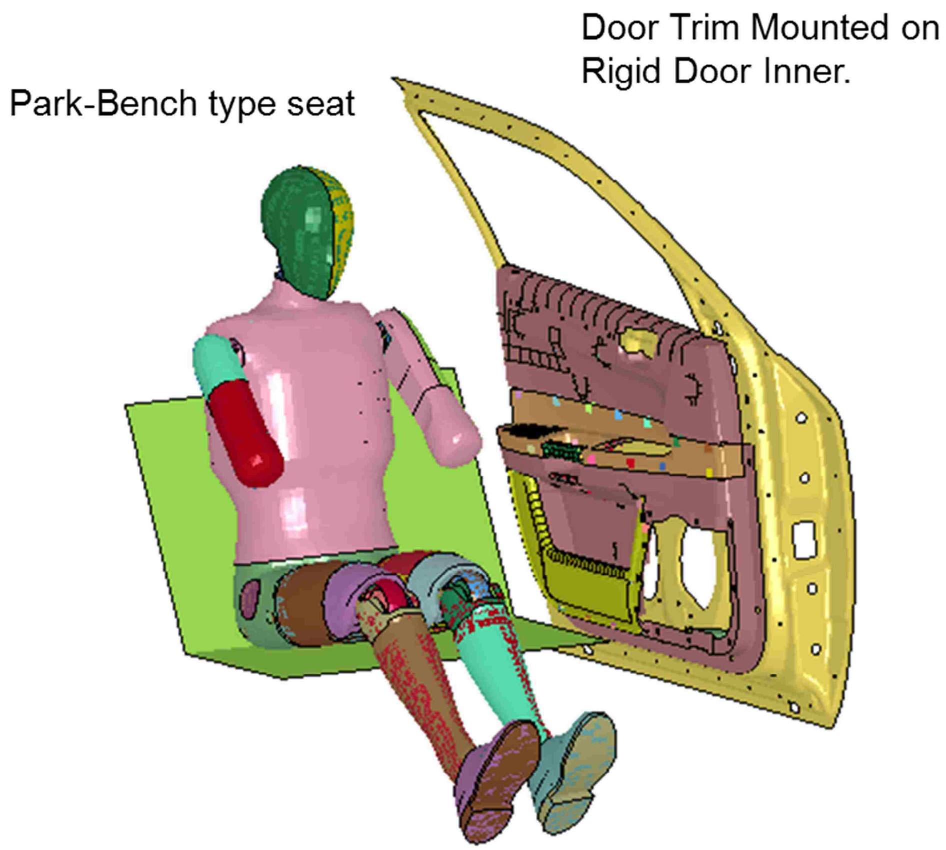


Figure 4-13: FE model of sled for MDB test.

The maximum available dummy initial velocity is 7.6 m/s (17 mph). For the model with dummy initial velocity 8.046 m/s (18 mph), a negative volume problem will arise at the shoulder area of the dummy. This numerical instability is evidence that there is a need for structural enhancement to reduce the intrusion velocity for vehicle which has a door intrusion velocity greater than 7.6 m/s, otherwise without a seat airbag, it will result in the occupant injury response exceeding the injury criteria requirement in the physical sled test. For this reason, the baseline test condition used 7.6 m/s as the dummy initial velocity. The value of the dummy initial velocity could interpolate either to different vehicle side structure stiffness under the same impact test condition, or the same vehicle structure under different side impact tests.

The model summary of these two tests FE models are list in Table 4-1.

	MDB test environment	**Side pole test environment**
Dummy	ES-2re (50th male)	SID-IIs (5th female)
Dummy and seat location	Middle height Full down (Armrest align with the abdomen of the ATD)	Full forward Mid-track (Armrest align with 4th or 5th ribs of the ATD)
Dummy response evaluation	Rib deflection Rib viscous criterion Abdominal force Pubic force	Lower spine acceleration Pelvic force

Table 4-1: The model summary of the MDB and pole sled test models.

The sled model in Figure 4-13 takes approximately 2 hours 40 minutes computation time to run 100ms using 12 processors. This model can simulate the occupant environment of any MDB crash tests. For IIHS test, the test dummy must be replaced by a SID-IIs dummy. For European and Chinese side impact test, the test dummy is ES-1 or ES-2. Since the ES-2re dummy are more strict in measuring rib deflection, using ES-2re dummy to evaluate the dummy injury performance according to European and Chinese test requirement won't change the relationship between the design variables and dummy injury.

5. NUMERICAL MODEL SIMULATION RESULTS

5.1 Simulation of side impact sled tests

Under the baseline test condition, the door intrusion velocity profile has a peak value of 7.6 m/s and no seat airbag (SAB). Hyperview with Impact/CAE application developed by Altair Engineering was used for the post-processing. The occupant injury responses were compared both to ECE-R95 and FMVSS 214 test requirements.

5.1.1 Baseline condition results

Figure 5-1 shows on animation sequence of the side impact MDB sled test under the baseline condition at t= 0ms, t= 20ms, t= 45ms and t= 65ms. The dummy contacted with door trim at t= 20ms.

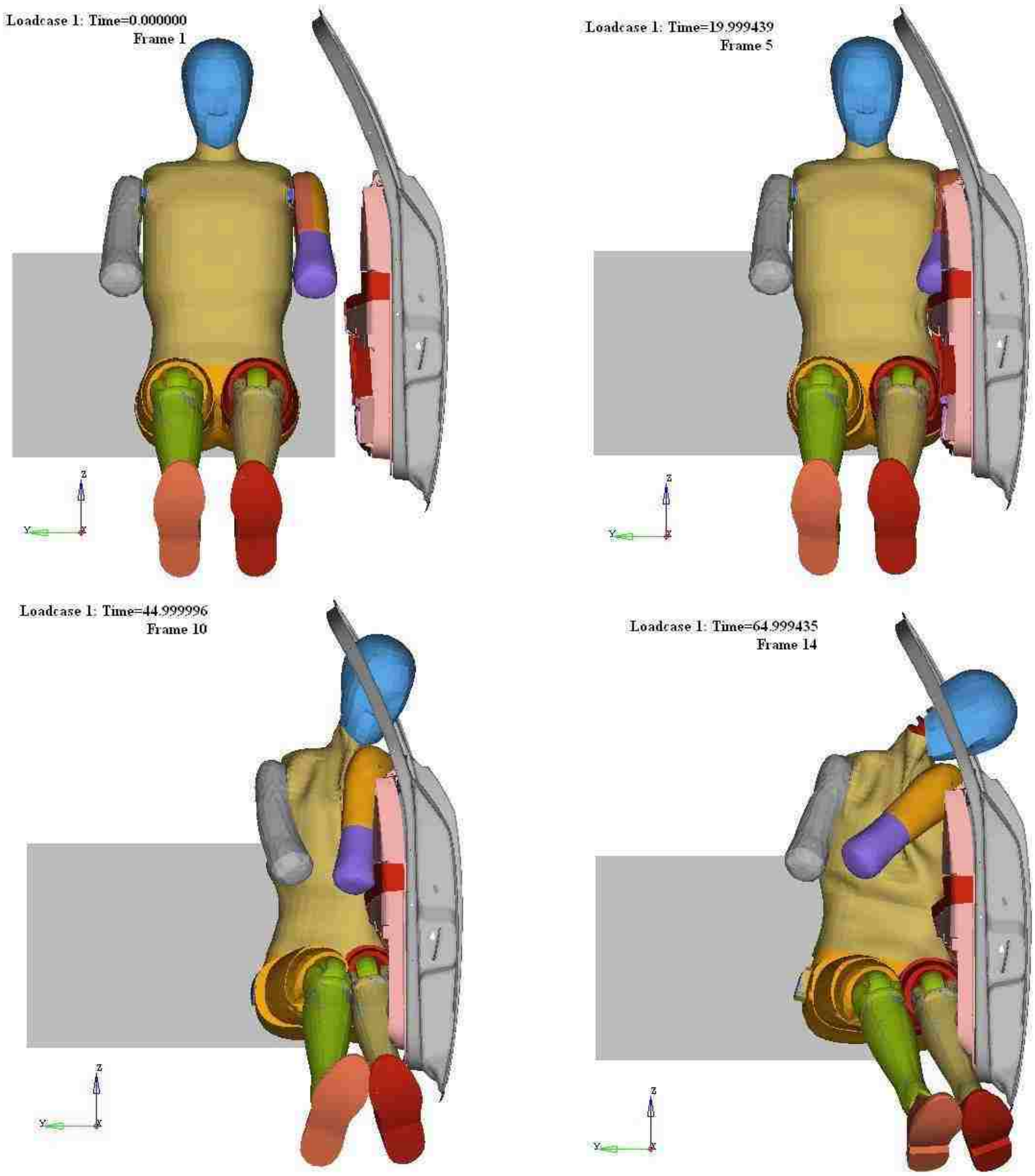


Figure 5-1: Impact sequence of side impact sled test simulation.

In Figure 5-2, the red line represents the FMVSS 214 requirement for the rib deflection, the green line represents the 80% of the regulatory limit. The maximum deflection for each rib all occur at the same moment. The upper rib shows the maximum deflection. Besides the maximum rib deflection, the thorax region injury requirement ECE-R95 also contains the rib viscous criterion which must to be less than 1m/s. The viscous criterion focuses on soft tissue injury and is determined as the peak of the product of velocity of deformation and the instantaneous chest compression. As shown in Figure 5-3, the maximum viscous criterion is also imposed on the top rib which suffers the maximum rib deflection.

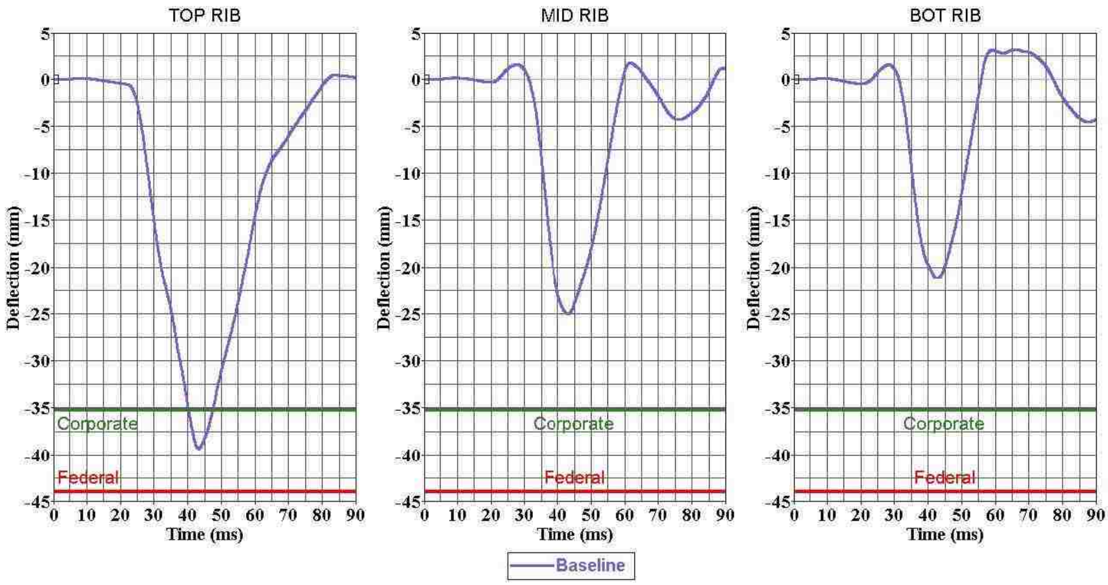


Figure 5-2: Rib deflection history for baseline condition in MDB sled test.

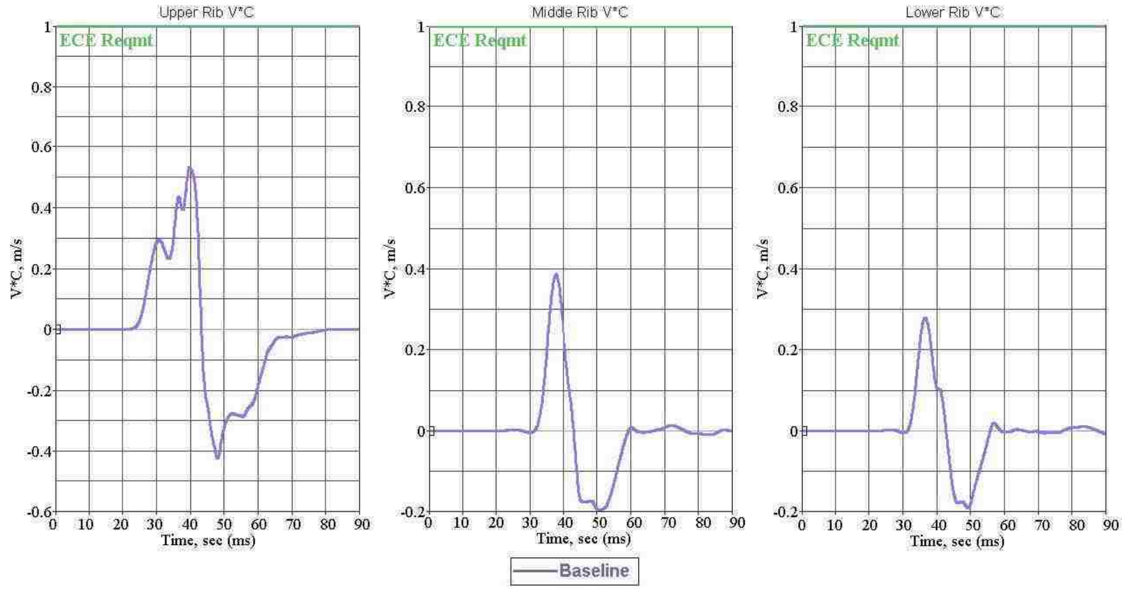


Figure 5-3: Viscous criterion history for baseline condition in MDB sled test.

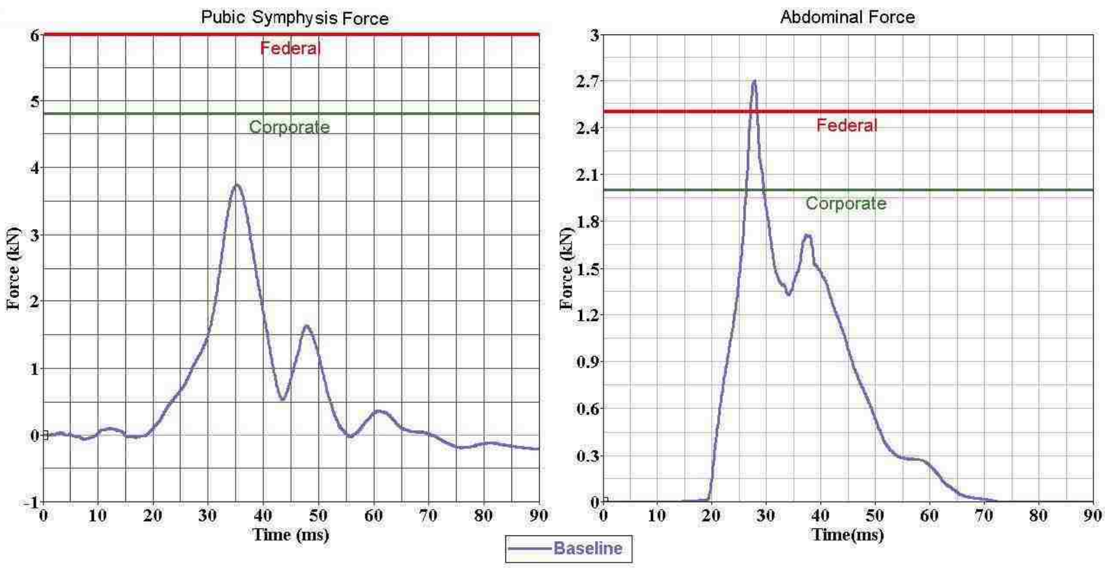


Figure 5-4: Pubic symphysis force and abdominal force histories for baseline condition in MDB sled test.

In Figure 5-4, the pubic symphysis peak force is under the 80% of the regulatory requirement. The abdominal force exceeds the requirement at the time period 26ms to 29ms.

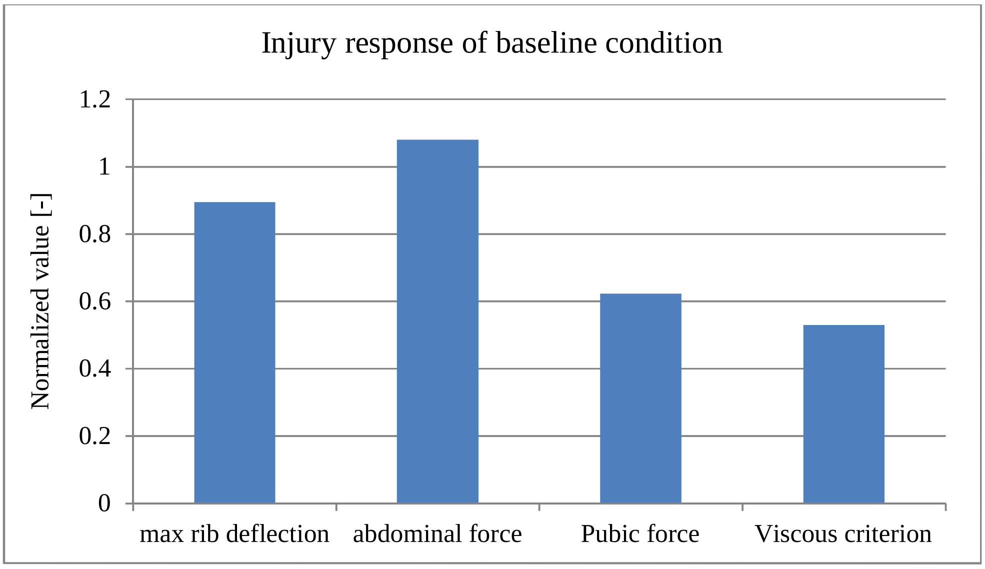


Figure 5-5: Injury response of baseline condition.

Figure 5-5 shows that, the maximum rib deflection and abdominal force are two critical injury criteria. Regardless of which side impact test configuration is applied, for a vehicle without a seat airbag (SAB) and door peak intrusion velocity exceeding 7.6 m/s, the abdominal force will exceed the requirement. Without the SAB between the dummy and the door trim, the abdomen area will directly come into contact with the door armrest at a high velocity.

5.1.2 The effect of reducing door intrusion velocity

The variation of door intrusion velocity in FE model was realised by changing the dummy initial velocity value. The dummy injury response under the test condition of 6.7 m/s (15 mph) door peak intrusion velocity is compared with the baseline results in Figure

5-6 and Figure 5-7. All three peak rib deflections are lower than the 80% regulatory limit when the door velocity is 6.7 m/s. The peak value of each rib deflection is reduced. (Figure 5-6) The frontal, middle and rear abdominal force peak values were also reduced by decreasing the door intrusion velocity. As a result the abdominal force can meet the requirement. (Figure 5-7)

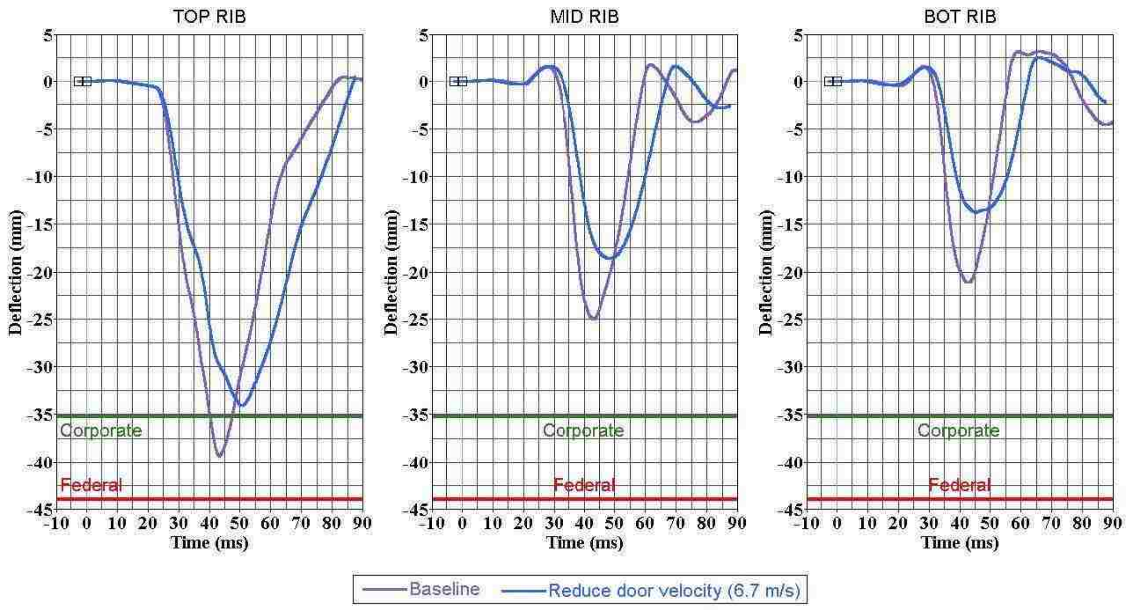


Figure 5-6: Rib deflection variation for reducing door intrusion velocity to 6.7 m/s.

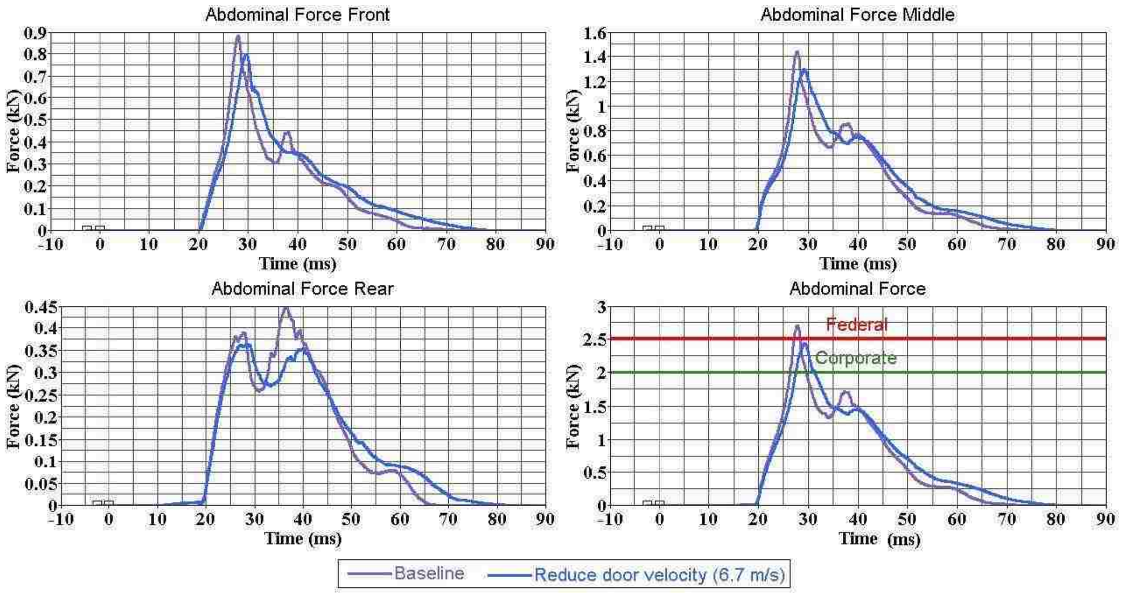


Figure 5-7: Abdominal force variation for reducing door intrusion velocity to 6.7 m/s.

It is obvious that less door intrusion velocity gives less input energy. To find out how the door intrusion velocity will contribute to each injury criteria, different door velocity starts from 7.6 m/s (17 mph) to 5.36 m/s (12 mph) were simulated. The results are listed in Figure 5-8.

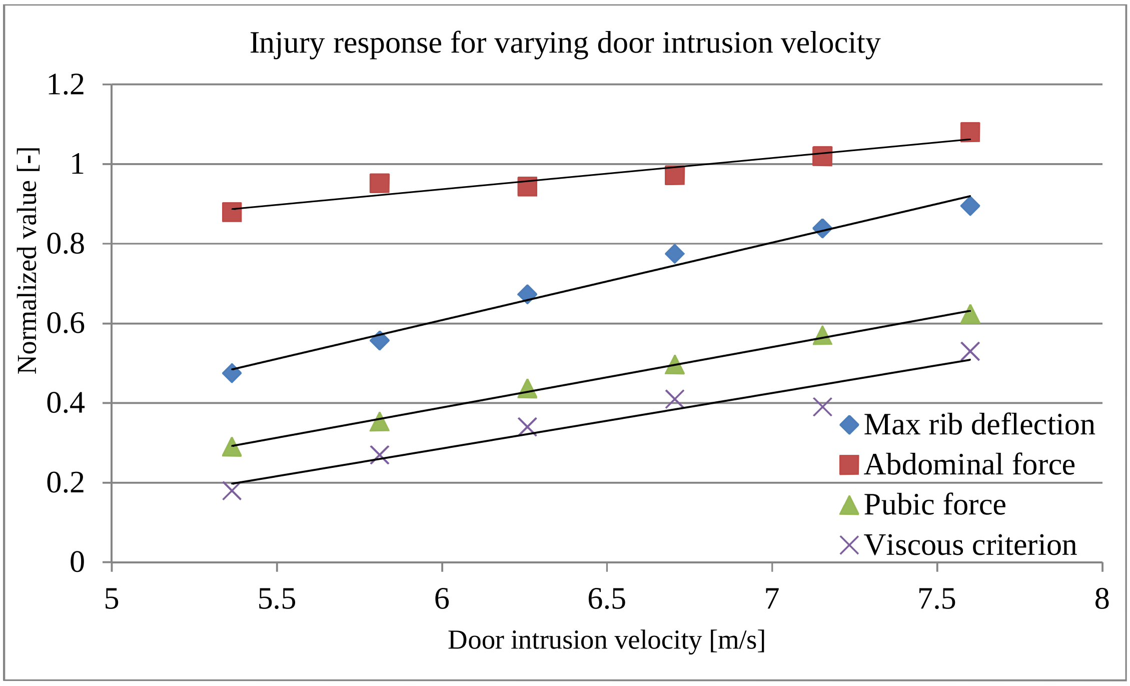


Figure 5-8: Injury response for varying door intrusion velocity.

The maximum rib deflection, rib viscous criterion, abdominal force and pubic force all showed a linear relationship with door intrusion velocity. The linear regression analysis was performed to determine the regression coefficients for the three injury criteria by the least squares method.

Maximum rib deflection = 0.195door velocity - 0.5613, R^2 = 0.9852 (5-1)

Viscous Criterion = 0.1393 door velocity - 0.5498, R^2 = 0.9309 (5-2)

Pubic symphysis peak force = 0.1519 door velocity - 0.523, R^2 = 0.9971 (5-3)

Abdominal force = 0.0787door velocity + 0.4643, R^2 = 0.9198 (5-4)

From Equation (5-1) to Equation (5-4), it is clear that the door velocity reduction mainly contributes to the reduction of the maximum rib deflection while it has the least effect on the abdominal force. Reducing door intrusion velocity may not be considered as an effective strategy for reducing abdominal force.

5.1.3 The effect of varying door trim component stiffness

The door trim force-displacement responses at the level of pelvis, abdomen and thorax regions can be obtained from a drop tower test. The stiffness variation can be implemented by changing components thickness, change of component geometry or substituting with another material. In the FE model, the door trim component stiffness variation was implemented by scaling up or down the material mechanical property.

There are four different materials modeled with two material types for door trim material in this FE model: *Mat 01 for the door handle, *Mat 24 for the other components. For material modeled with *Mat 24, the elastic modulus and stress-strain curve was increased or reduced up to 20% of the baseline value. For the material modeled with *Mat 01, only the elastic modulus was scaled. (Figure 5-9).

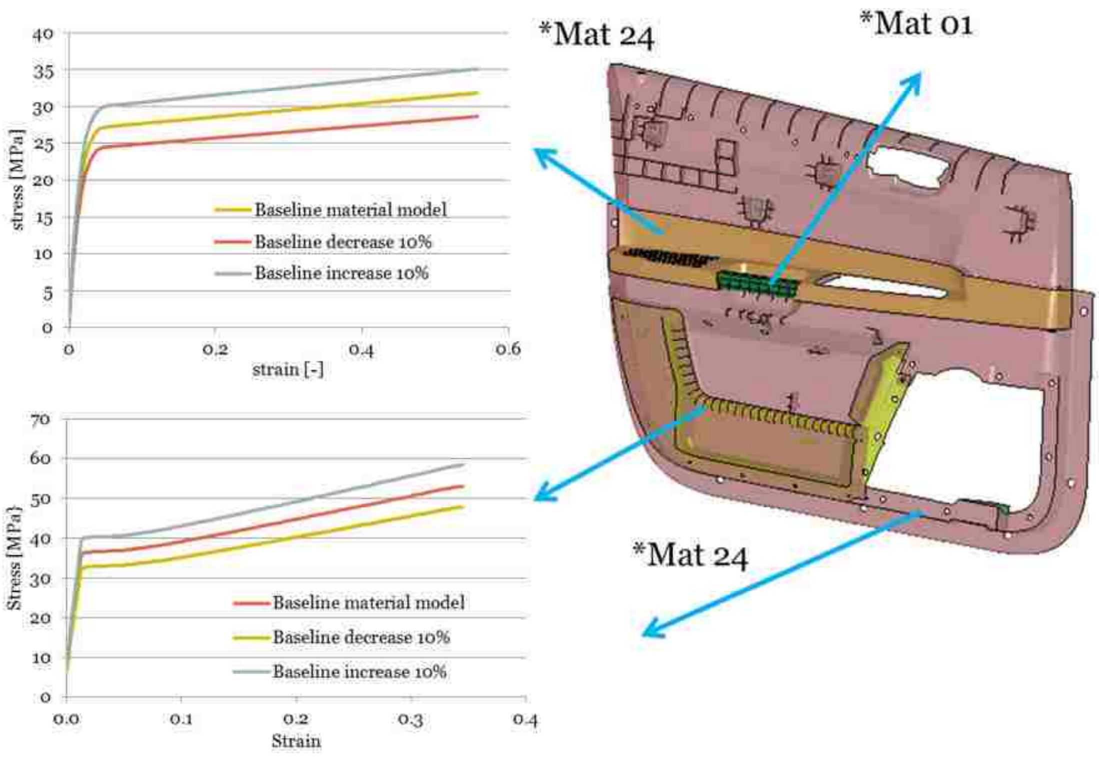


Figure 5-9: Door trim material stress-strain curves.

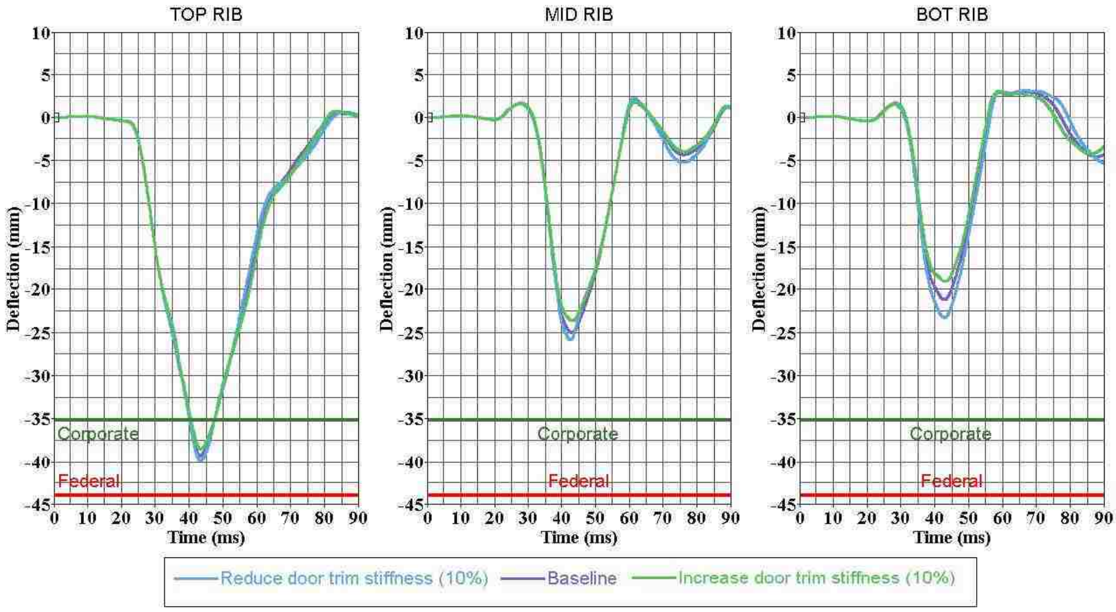


Figure 5-10: Rib deflection variation for varying door trim material properties.

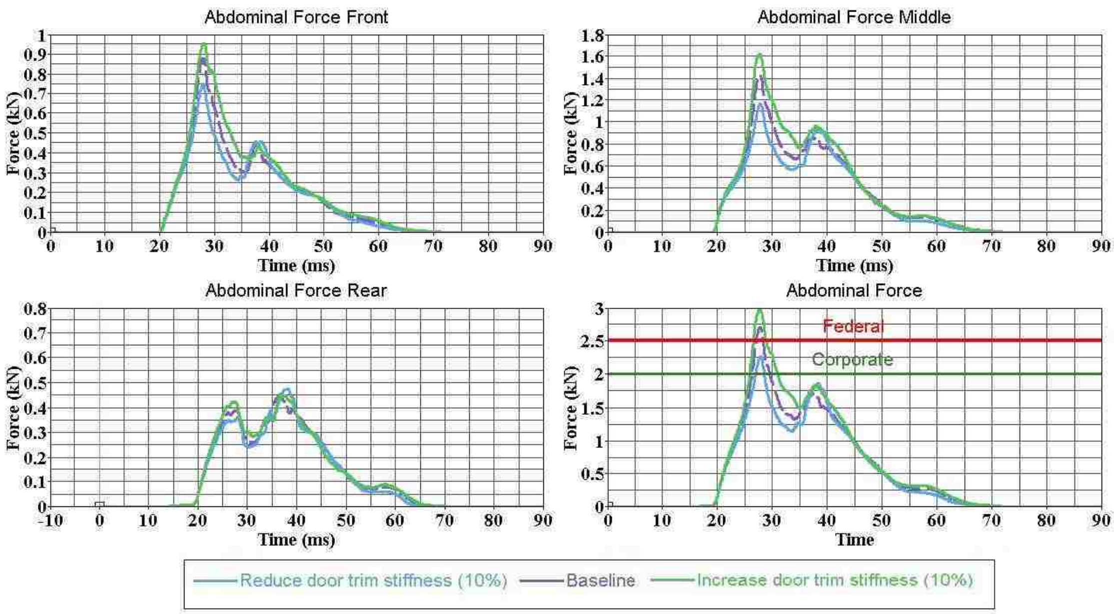


Figure 5-11: Abdominal force variation for varying door trim material properties.

Figure 5-10 shows that the reduction of material stiffness increased the rib deflection slightly. The opposite variation trend can be observed from Figure 5-11, as the door trim material stress-strain curve scale down by 10%, the abdominal force becomes less than the requirement. These trends are shown in Figure 5-12. The abdominal force decreases when the door trim material stress-strain response is scaled down, in comparison, the injury in the thorax region becomes more severe. Compared to the abdominal force, the thorax rib deflection shows insignificant sensitivity to material stiffness variation for the material and change range used in this study. This might because the baseline model door trim component stiffness was designed for the rib deflection optimization. The pubic symphysis peak force is shown to independent of the material property in Figure 5-12.

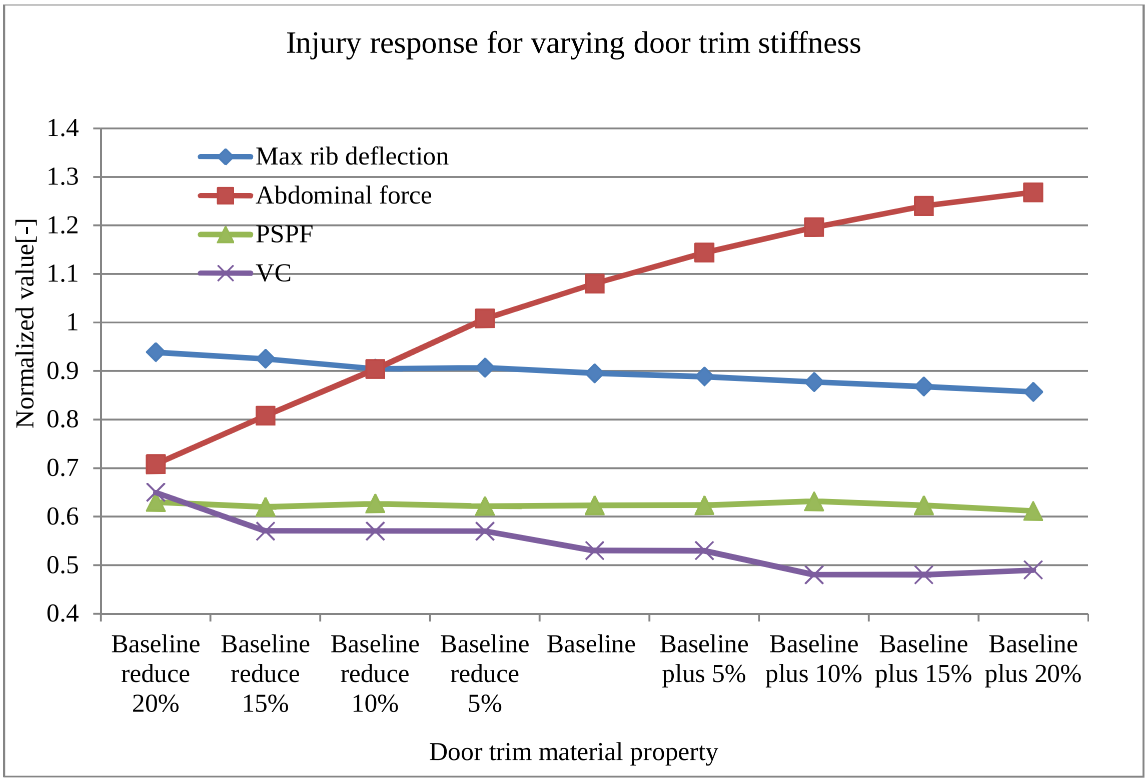


Figure 5-12: Injury response for varying door trim stiffness.

5.1.4 The effect of seat airbags

A seat airbag was added into the original FE model by *INCLUDE. The position of the airbag is such that it could cover the dummy pelvis and torso regions after being deployed. The airbags have one vent hole on the side of the bag. The hole controls the release of gas as the occupant compresses the bag during the impact. Increasing the vent hole size will result in diminishing airbag inner pressure and finally affect occupant-to-bag loading. Proper design of seat bag vent hole is important to minimize the passenger's injury. In addition, a vent hole is essential to ensure the range space for passengers [40].

The airbag stiffness changes during the entire deployment process. The contact time between the dummy thorax and the airbag affects the injury response. For this reason, the dummy lateral position was adjusted so that the rib deflection start time could be matched between the simulation and full vehicle test (~10ms). The contact between the door to airbag and dummy to airbag were modeled with an algorithm called *CONTACT_AUTO_SURFACE_TO_SURFACE. For the model with SAB, the approximate computation time for 100 milliseconds with 12 processors increased to 3 hours 40 minutes.

Figure 5-13 shows an animation sequence of the side impact MDB sled test with SAB at t= 0ms, t= 10ms, t= 50ms and t= 65ms. The SAB deployed at the same time as the dummy started to move toward the door trim. At t= 10ms, the dummy torso contacted the airbag. The airbag was compressed by the dummy until the air inside totally leaked out.

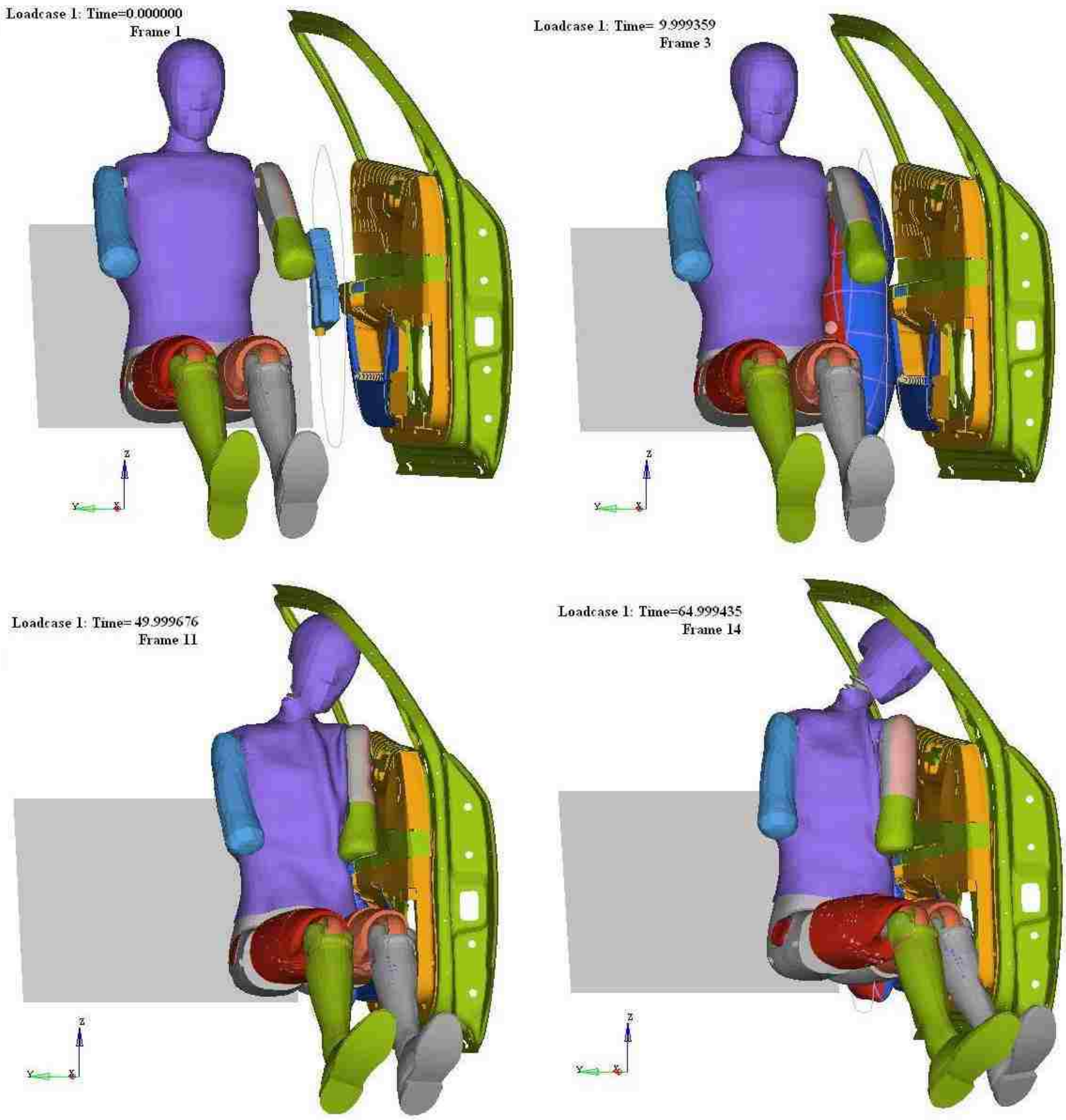


Figure 5-13: Impact sequence of side impact sled test simulation with SAB.

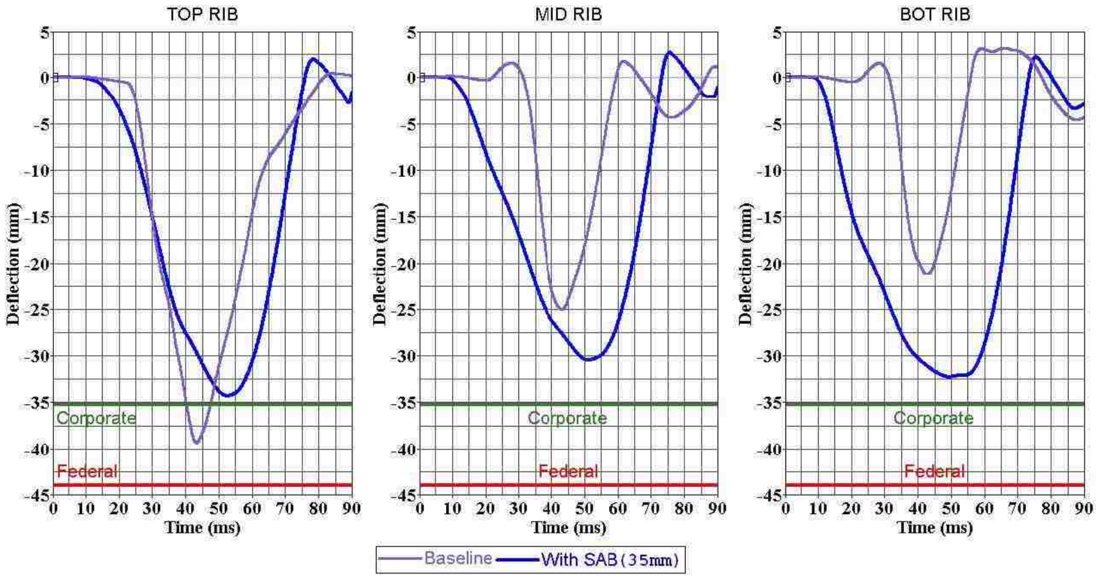


Figure 5-14: Rib deflection variation for adding a 35mm vent SAB.

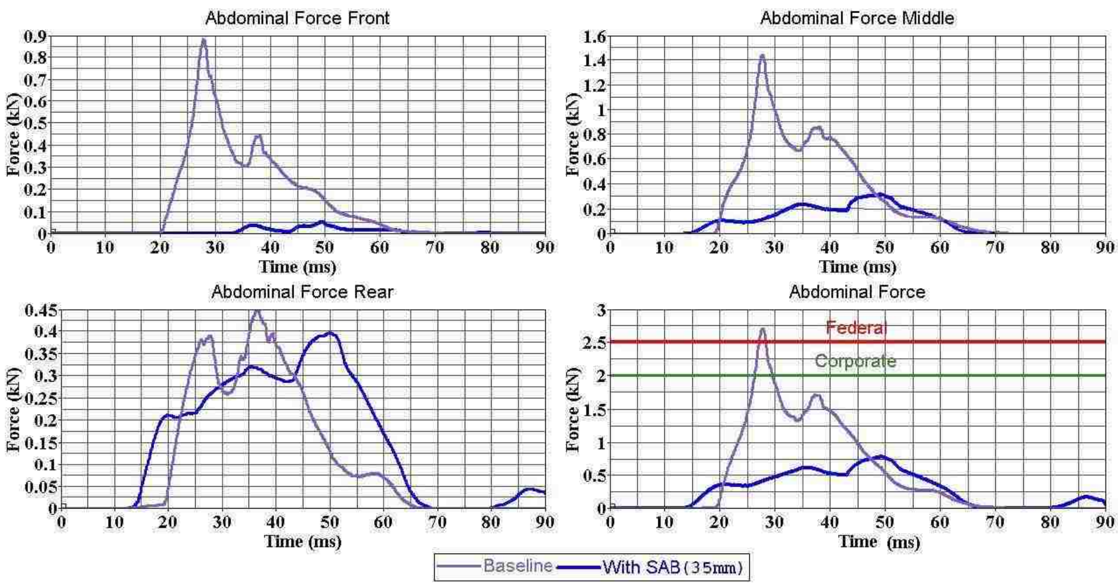


Figure 5-15: Abdominal force variation for adding a 35mm vent SAB.

Figure 5-14 shows that the maximum rib deflection is reduced by 5 mm with a SAB, while the middle and lower rib deflection is increased. The SAB gives a more uniform thorax deformation and broadens the rib deformation time period. One effect of the SAB is to redistribute the impact load on the thorax of the test dummy. The three rib deflections are under the 80% of regulatory limit. Figure 5-15 shows that the abdominal force is reduced to less than 1 kN by the addition of a SAB. The reduction of abdominal force is significant with a SAB. Compared to structure enhancement, adding a SAB is more effective in reducing abdominal injury.

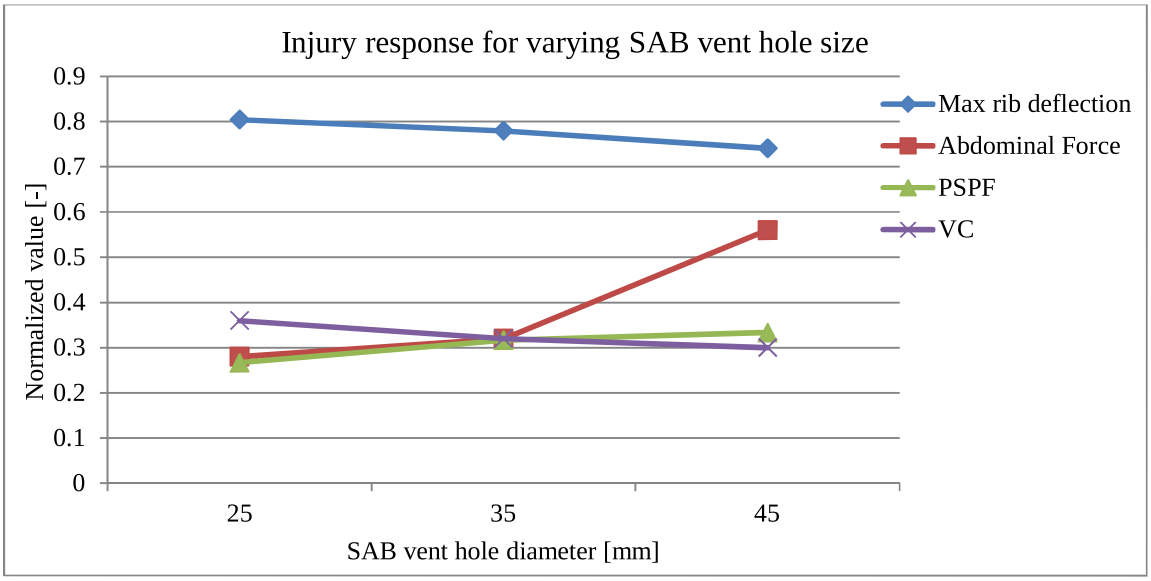


Figure 5-16: Injury response by adding an SAB with different vent hole sizes.

In Figure 5-16, when the SAB vent hole size is changed, the rib deflection and viscous criterion shows an opposite trend compared with abdominal force and pubic force. To compare the occupant injury response by applying SAB with 25 mm, 35 mm and 45 mm vent hole diameter: with a 45 mm vent hole size, the SAB is too weak to protect the abdomen area and the occupant abdomen area may hit the armrest after the airbag bottoms out; with a 25 mm vent hole size, the SAB is too stiff for the thorax region and tends to increase the maximum rib deflection.

5.2 Simulation of the pole sled test

For the pole sled test, under the baseline test condition, the door intrusion velocity was 8.94 m/s with no SAB. The occupant injury responses were compared to the FMVSS 214 5^{th} oblique pole test requirement.

5.2.1 Baseline condition result

Figure 5-17 shows an animation sequence of the sled pole test under baseline conditions at t= 0ms, t= 25ms, t= 35ms and t= 60ms. The dummy contacted the door trim at t= 20ms. At t= 35ms the dummy started to bounce back due to the high initial impact velocity. The major interaction of the dummy and door trim was concentrated in the time period from t= 25ms to t= 35ms.

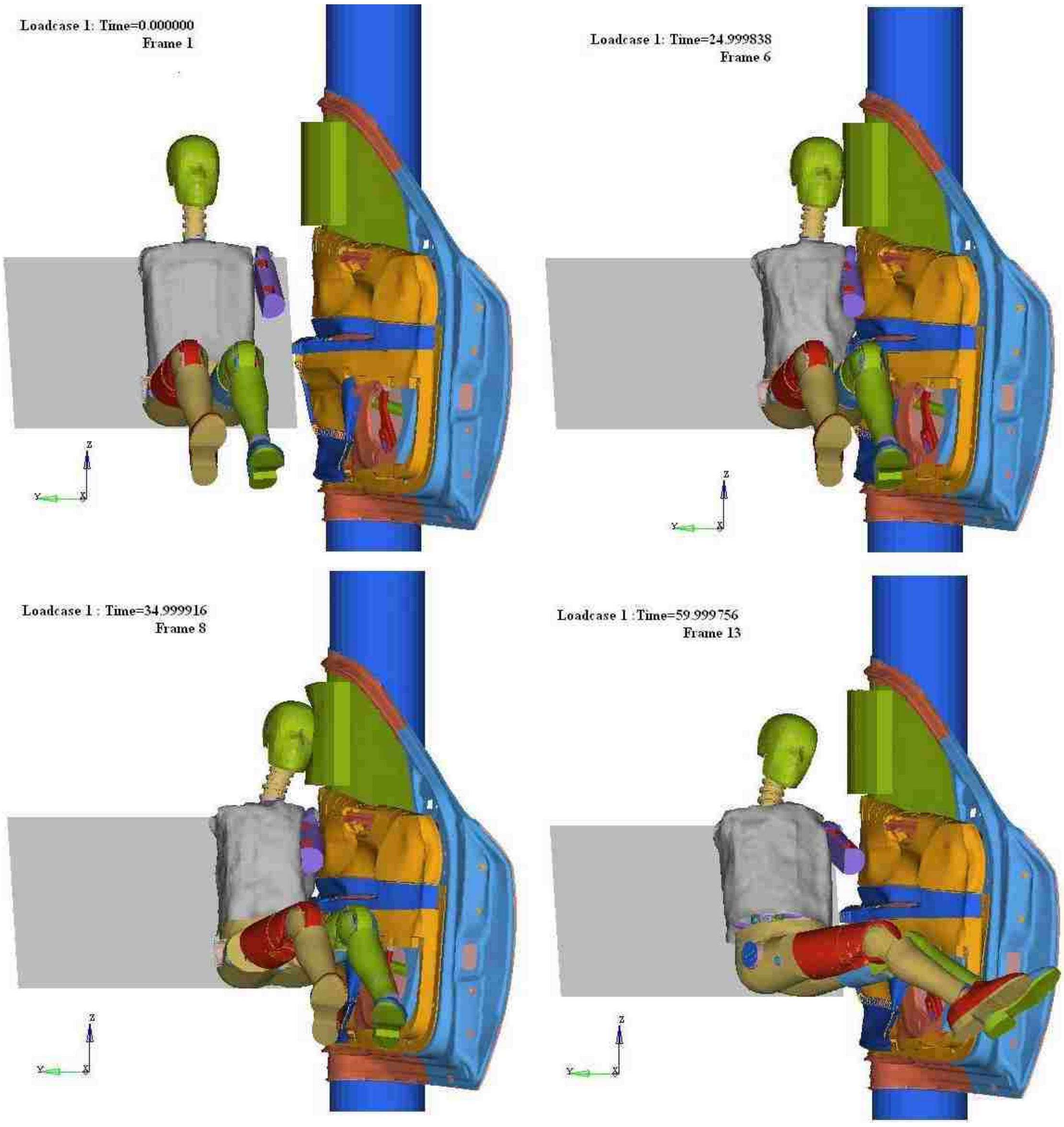


Figure 5-17: Impact sequence of the pole sled test simulation.

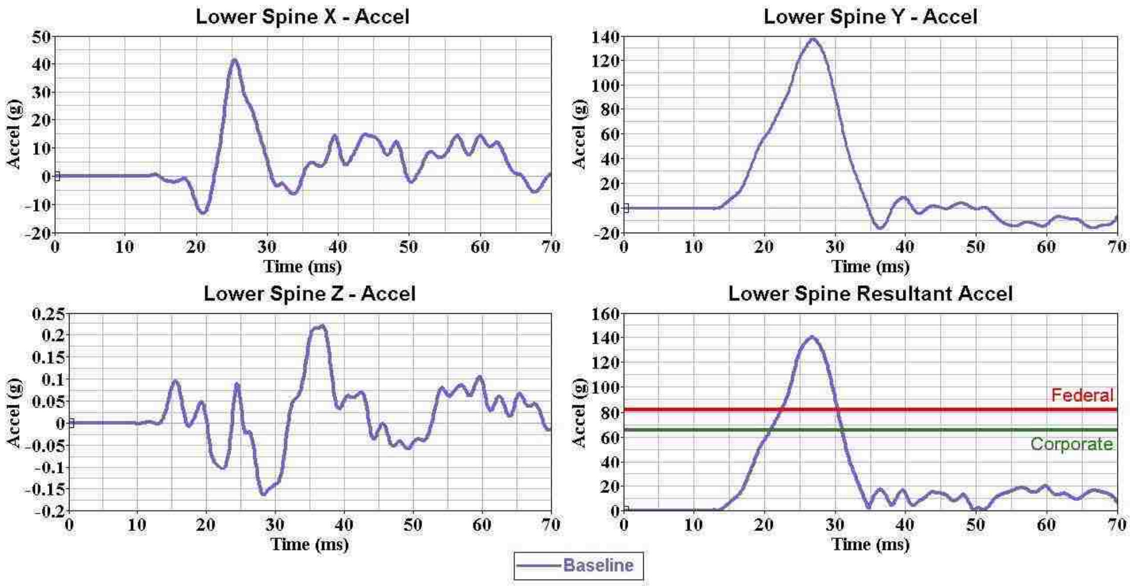


Figure 5-18: Lower spine acceleration for baseline condition (Filtered by CFC 180).

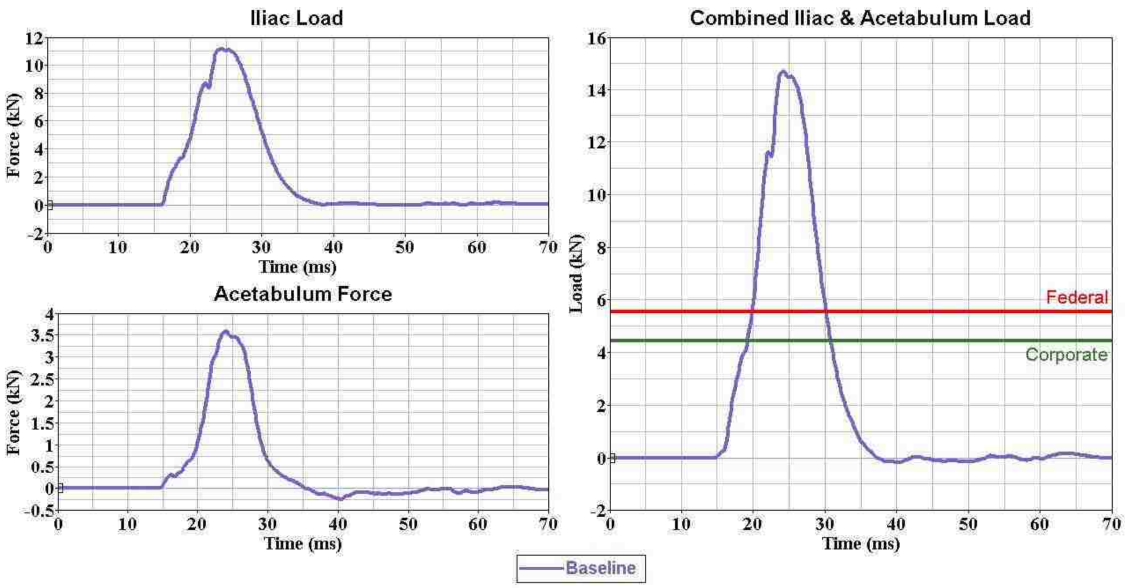


Figure 5-19: Pelvic force for baseline condition.

In Figure 5-18 and Figure 5-19, both the lower spine acceleration and pelvic force in the baseline condition dramatically exceeds the requirements.

5.2.2 The effect of reducing door intrusion velocity

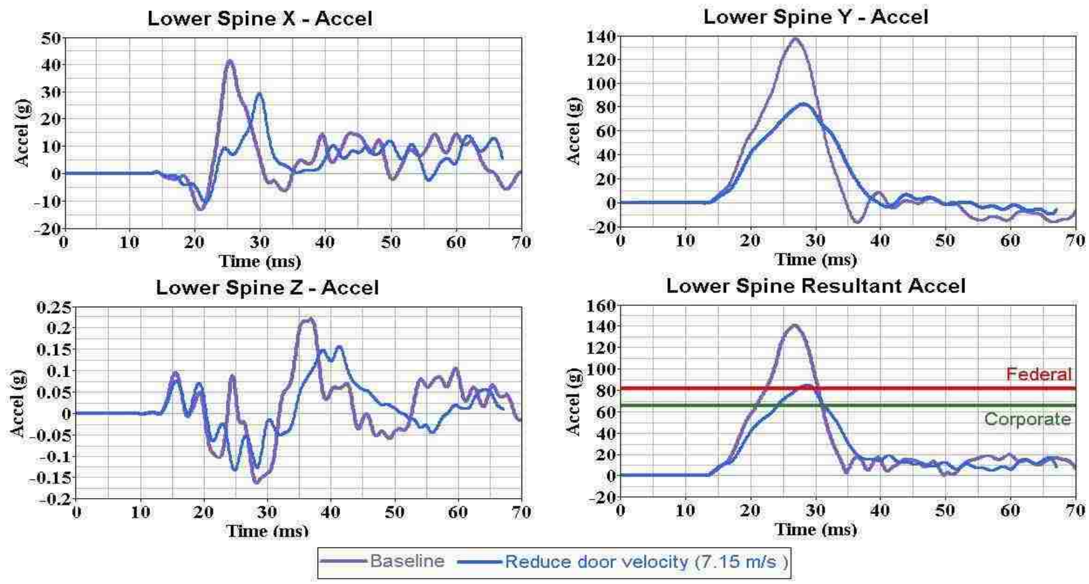


Figure 5-20: Lower spine acceleration variation for reducing door intrusion velocity to 7.15 m/s.

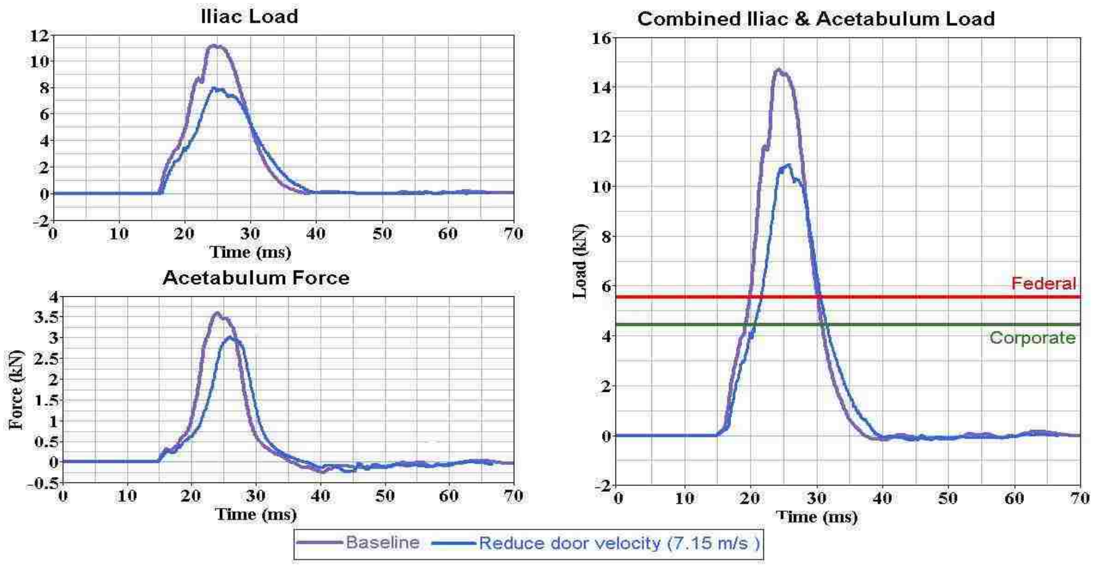


Figure 5-21: Pelvic force variation for reducing door intrusion velocity to 7.15 m/s.

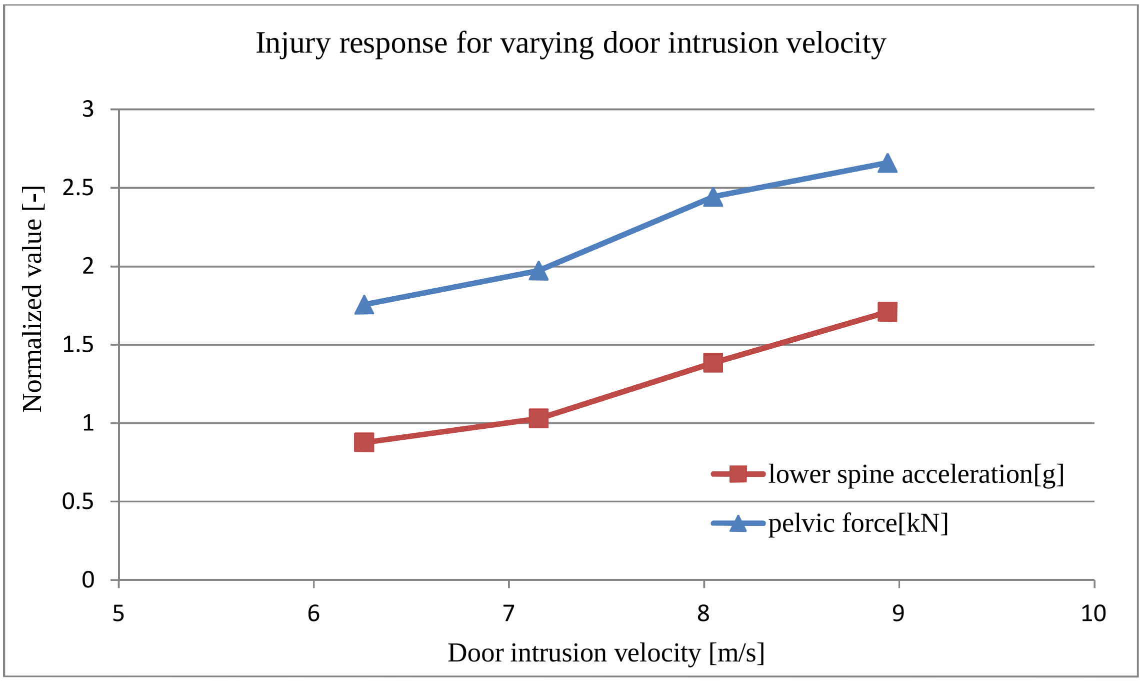


Figure 5-22: Injury response for varying door intrusion velocity.

From Figure 5-22, both the lower spine acceleration and pelvic force shows dependence on the door intrusion velocity. Even when reducing the door intrusion velocity by 20%, from 8.94 m/s (20 mph) to 7.15 m/s (16 mph), the pelvic force is still above the limitation. On the other hand, during the pole impact the intrusion area is small, and therefore the upgrade of the vehicle side structure has a limited effect on the reduction of the door intrusion velocity. So reducing the door velocity may not be a proper solution to ensure compliance with the 5^{th} oblique pole test requirement.

In this sled test model, the door is pre-deformed in a certain deformation profile taken from a full vehicle test. In reality, upgrading the vehicle structure will reduce the door intrusion, and this will result in less severe thorax and pelvic injury. While in the sled simulation, the door intrusion profile variation because of the reduction of intrusion velocity was not taken into account. This might lead to an over-estimate of the occupant injury response.

5.2.3 The effect of varying door trim component stiffness

The implementation of door trim component stiffness variation in this model was the same as for the side impact sled model. The material elastic modulus and stress-strain curve was scaled up and down up to 20%.

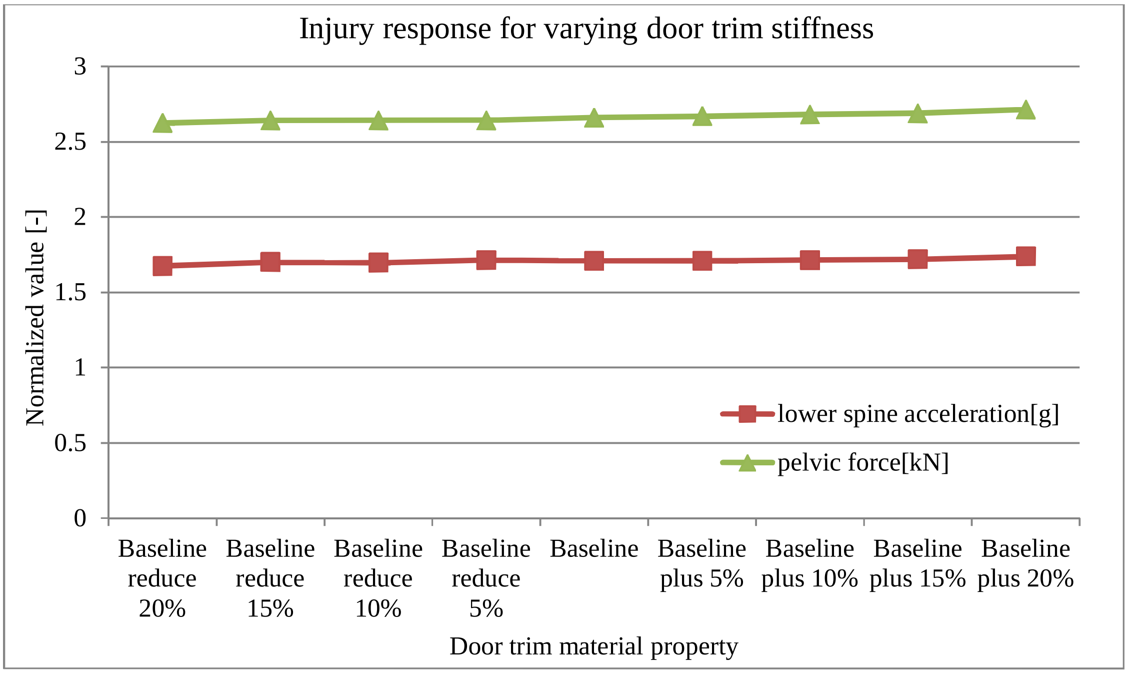


Figure 5-23: Injury response for varying door trim stiffness.

The Figure 5-23 clearly shows that for the oblique pole test, the dummy injury response does not depend on the door trim component stiffness. The reason could be that in the oblique pole test, the door intrusion area is quite narrow, the contact area between the dummy and door trim is limited, so the injury response does not vary with the door trim component stiffness.

5.2.4 The effect of seat airbags

Seat airbags (SAB) with different vent hole size were added into the original FE model by *INCLUDE. The dummy lateral position is adjusted so that the injury starting time can be matched between the simulation and full vehicle test (~10ms). The position of the airbag is such that it covers the dummy pelvis and torso regions after deployment. Contact between the door to airbag and dummy to airbag are modeled with *CONTACT_AUTO_SURFACE_TO_SURFACE. For models with SAB, the approximate computation time for 80 milliseconds with 12 processors increases to 2 hours 30 minutes.

Figure 5-24 shows animation sequence of the pole sled test with SAB at t= 0ms, t= 10ms, t= 45ms and t= 60ms. The airbag absorbs the dummy's kinetic energy during impact, and no bounce can be observed before t= 60ms.

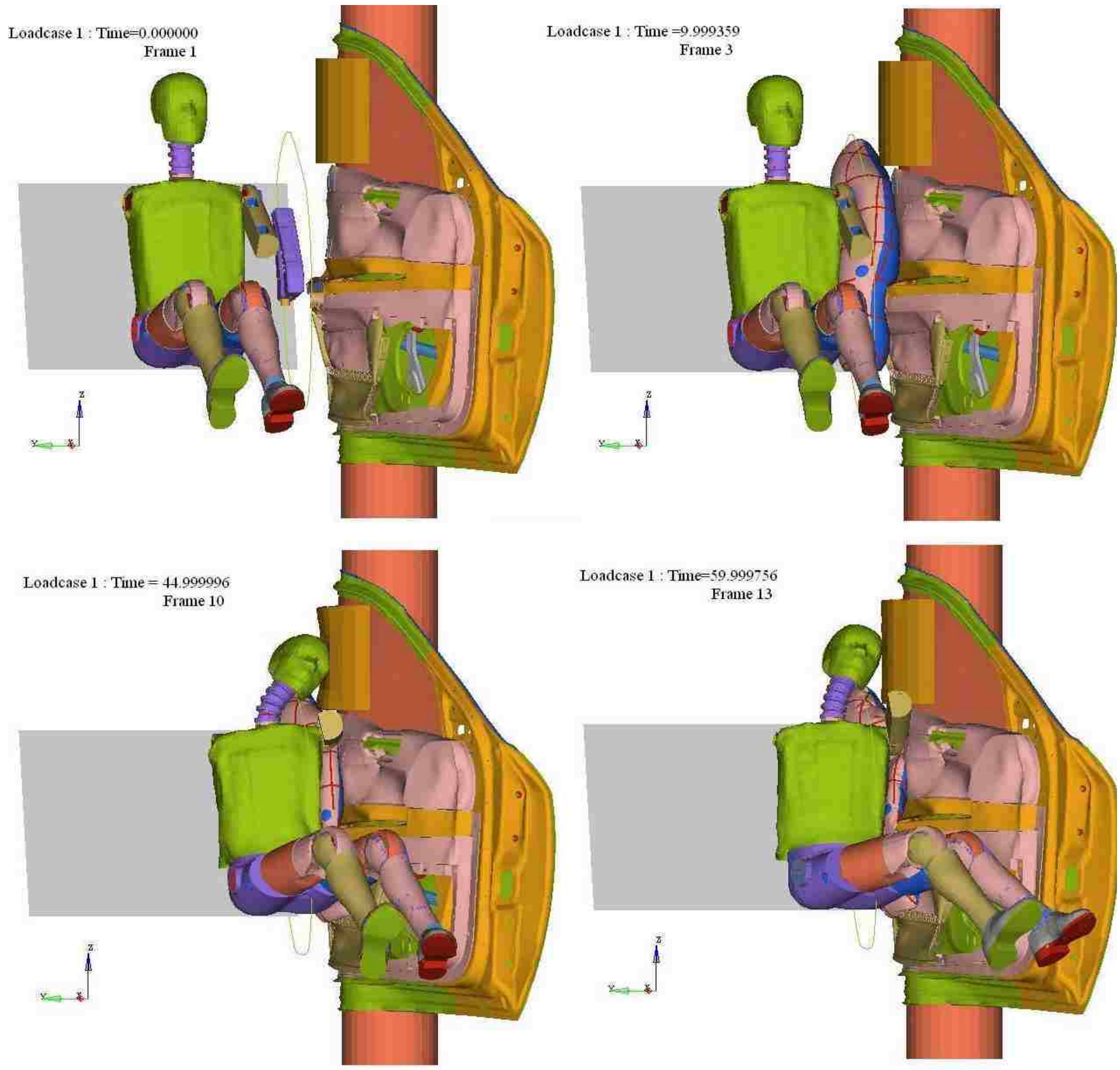


Figure 5-24: Impact sequence of pole sled test simulation with SAB.

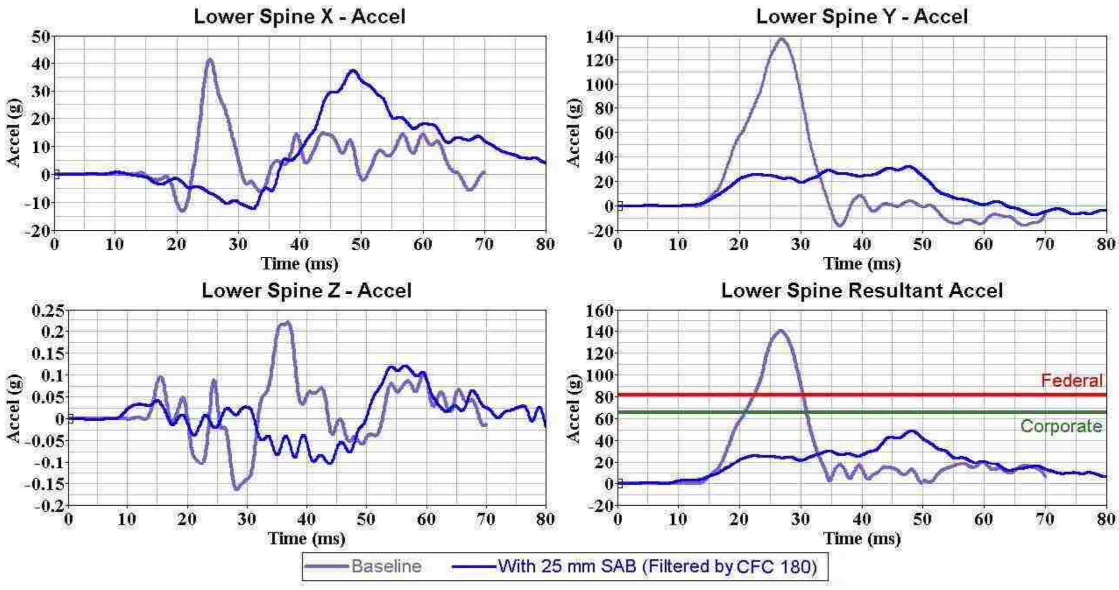


Figure 5-25: Lower spine acceleration variation for adding a 25mm vent hole SAB.

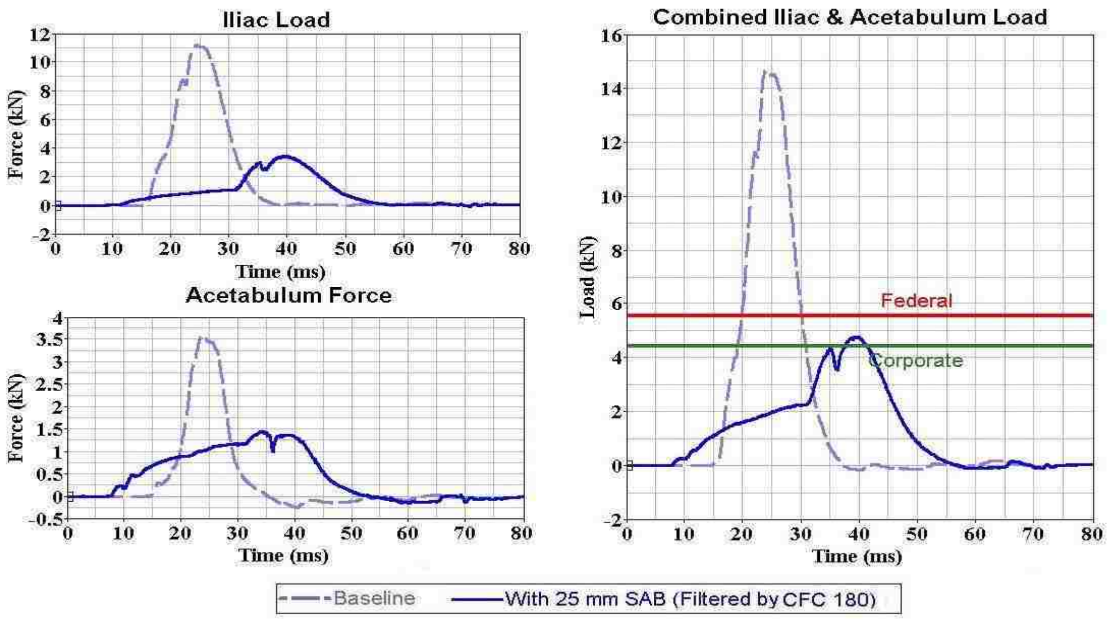


Figure 5-26: Pelvic force variation for adding a 25mm vent hole size SAB.

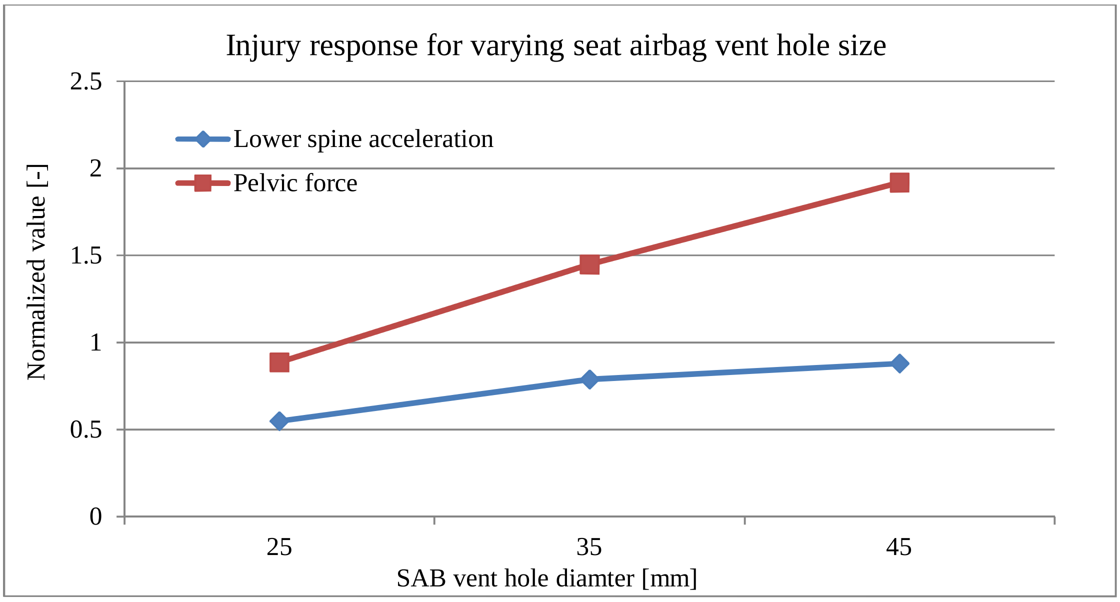


Figure 5-27: Injury response by adding SAB with different vent hole size.

In Figure 5-27, both lower spine acceleration and pelvic force decrease when the SAB has a smaller vent hole size, which means higher inner pressure. For a SAB with a 25mm vent hole diameter, the two injury responses can meet the requirement. One reason for this could be that a smaller vent hole size results in a higher airbag pressure. With the higher inner pressure, the airbag can generate a sufficient reaction force toward the dummy when the dummy impacts the airbag, so as to push the dummy's torso away from the door trim. In this way the occupant injury protection was improved.

5.3 Proposed solution to comply with regulatory requirement

Based on the information gathered from the studies performed on the intrusion velocity, door trim stiffness and the seat airbag, side impact safety is highly dependent on the variation in these factors.

5.3.1 Summary of the findings from simulation studies

In the MDB tests, rib deflection and abdominal forces are two critical injury criteria in a vehicle without SAB. The most effective method of reducing abdominal force is by using SAB and optimizing the door trim component stiffness. The most effective method to reduce rib deflection is to reduce the door intrusion velocity which means a structural enhancement. Compared to abdominal force, rib deflection is more difficult to control. There is a compromise between reducing the injury in the abdominal area and the thorax area. Reducing the door trim component stiffness can reduce the abdominal force but increases the rib deflection and viscous criterion at the same time. The same trend is observed from varying the seat airbag vent hole size.

For the 5^{th} pole test, the injury was severe due to the high intrusion velocity. The pelvic force is the most critical injury criteria. Countermeasures like door trim component stiffness variation that are effective in injury reduction in MDB test may not reduce the injury in the oblique pole test due to the narrow and localized loading. An effective method to reduce the pelvic force and lower spine acceleration is by optimizing the restraint system, it may be more crucial than countermeasures on the vehicle structure itself.

For a vehicle to comply with both ECE-R95 and FMVSS 214, a possible solution could be first to develop the restraint system under the oblique pole test condition. Assuming the vehicle side structure has no contribution to door intrusion velocity. A vehicle with weak side structure could have a similar door intrusion velocity to the vehicle impact speed. During the pole test, the vehicle impacts a fixed rigid pole at 8.94 m/s with a 75 degree crab angle, so the restraint system can be developed on a sled model with 8.94 m/s door intrusion velocity. Once the restraint system is developed, the vehicle should be tested with this restraint system on the MDB sled test. The door intrusion velocity value could be obtained from the full vehicle test results or could start from 7.6 m/s as a baseline if no available full vehicle test data exists. If the maximum rib deflection does not meet the target requirement and the abdominal force is far lower than the requirement, the door trim component stiffness can be increased to reduce the rib deflection. This countermeasure reduces the rib deflection by sacrificing abdomen region protection. If this solution is not effective, or if the maximum rib deflection exceeds the requirement and the abdominal force is close to the requirement, a door intrusion velocity reduction is needed. As the door intrusion velocity reduces, both rib deflection and abdominal force will also decrease. Once the maximum rib deflection value meets the requirement, this door intrusion velocity could be used as the structure design target. The vehicle side structure needs to be enhanced so that under both ECE-R95 MDB test condition and FMVSS 214 MDB test condition, the measured door intrusion velocity on the vehicle upper beltline will be lower than this target value. We can summarize these steps in the flowchart shown in Figure 5-28.

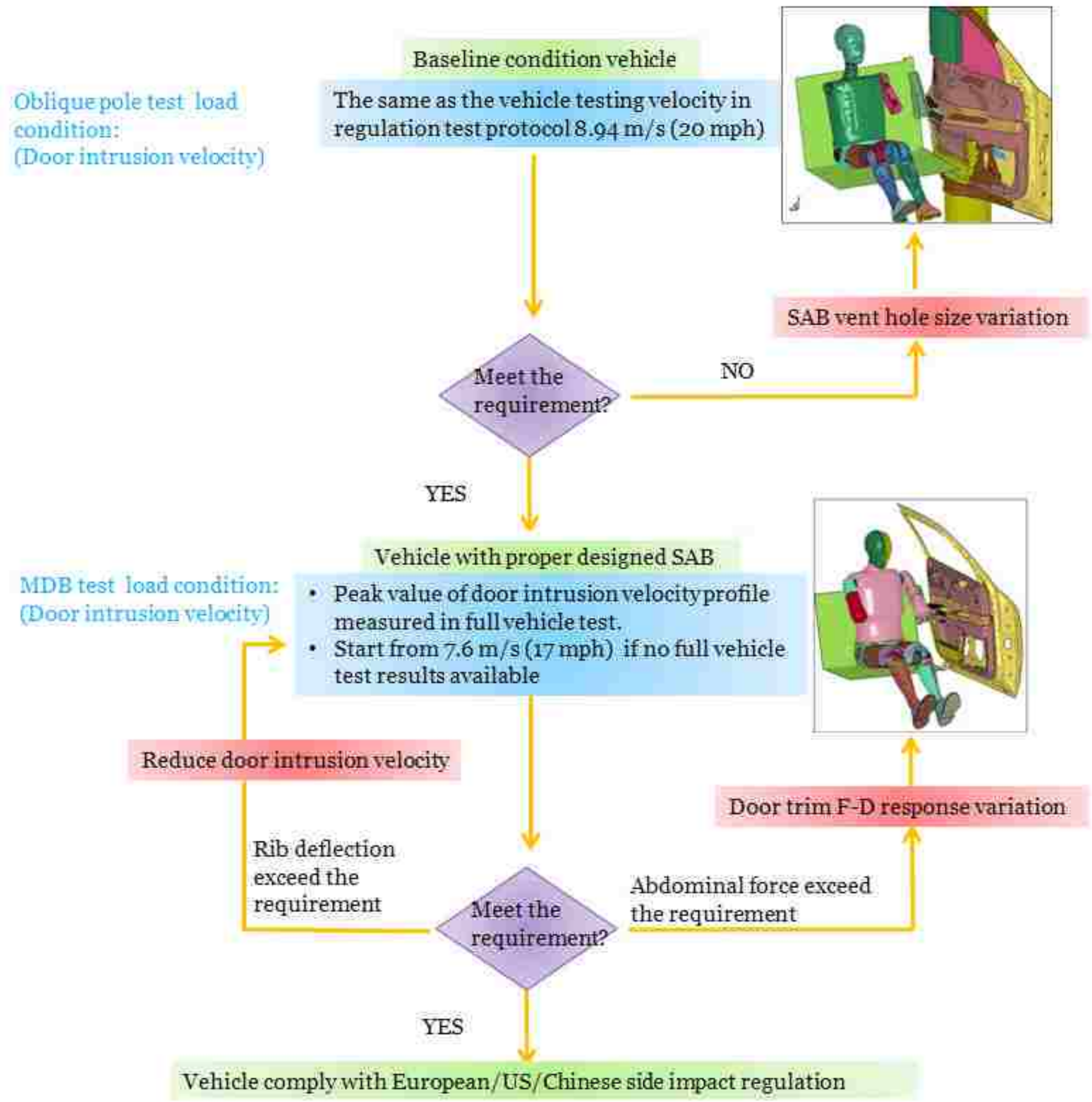


Figure 5-28: Design flow for vehicle to comply with MDB test and pole test.

5.3.2 Proposed solution

By applying the design flow shown in Figure 5-28, for the selected baseline vehicle to satisfy the FMVSS 214 5th oblique pole test, a 25 mm SAB is needed. From Figure 5-16, it was shown that with a 25 mm vent hole size SAB, regardless of which MDB test is performed, if the vehicle door intrusion velocity is 7.6 m/s or higher, the maximum rib deflection will exceed 80% of the regulatory limit. If the rib deflection needs to be lower than 80% of the regulatory limit for a robust design, the door intrusion velocity must be controlled by structural enhancements to achieve a lower value.

A combination effect of adding a 25 mm vent hole size SAB to the vehicle and lowering the door intrusion velocity to 6.7 m/s by structural enhancement was studied. The 6.7 m/s door intrusion velocity was under the MDB side impact test load condition. Assuming the structure update was not affected by the intrusion velocity in the oblique pole test, the intrusion velocity remained unchanged in the sled simulation.

The comparison between the baseline condition and the improved condition is listed in Table 5-1. The injury response comparison between the baseline condition and the improved condition for MDB sled test is shown in Figure 5-29 and Figure 5-32, the comparison for the pole sled test is shown in Figure 5-33 and Figure 5-34.

	Door intrusion velocity		**Door trim stiffness**	**SAB**
	MDB test load condition	**Pole test load condition**		
Baseline	7.6 m/s	8.94 m/s	Vehicle original door trim	No SAB
Improved	6.7 m/s	8.94 m/s	Vehicle original door trim	25 mm vent SAB

Table 5-1: Comparison of the baseline condition and the improved condition.

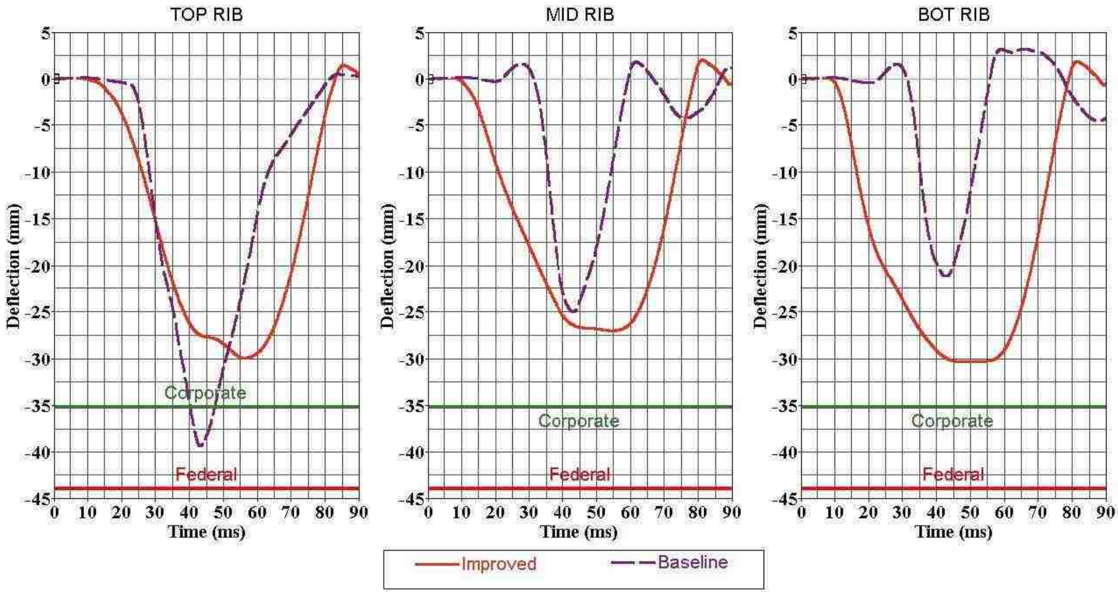


Figure 5-29: Rib deflection improvement of MDB sled test.

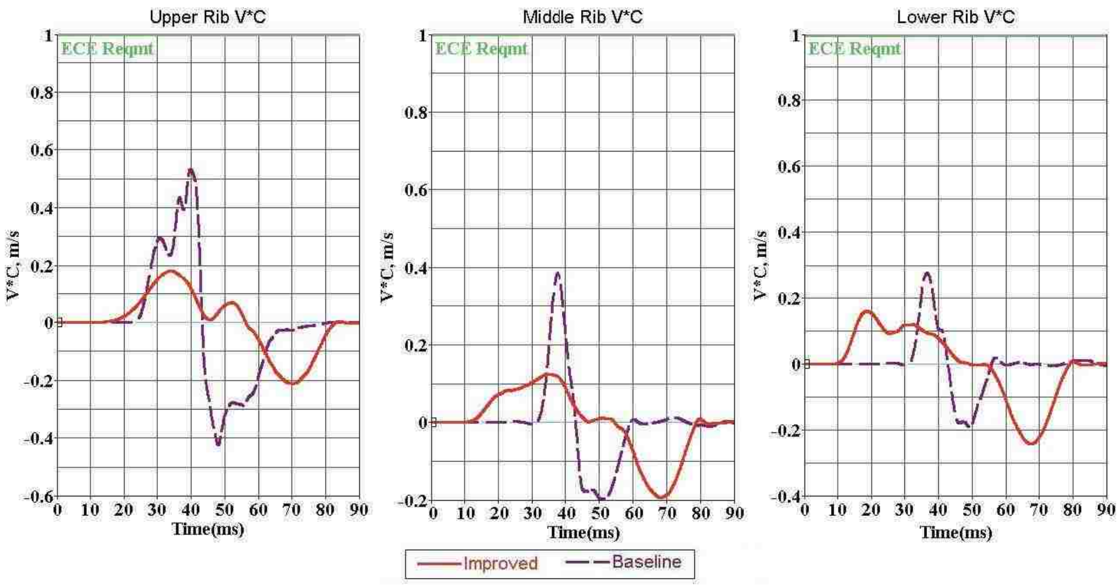


Figure 5-30: Rib viscous criterion improvement of MDB sled test.

Figure 5-29 shows that with the improved condition, the maximum rib deflection is reduced from 40 mm to 30 mm. This improvement is the result of adding a 25 mm seat airbag and limiting the door intrusion velocity to lower than 6.7 m/s under MDB test condition. The rib injury was distributed to other ribs by adding a SAB. More severe rib deflection can be observed on middle and bottom ribs. Figure 5-30 shows that three rib viscous criterions are all reduced after vehicle improvement.

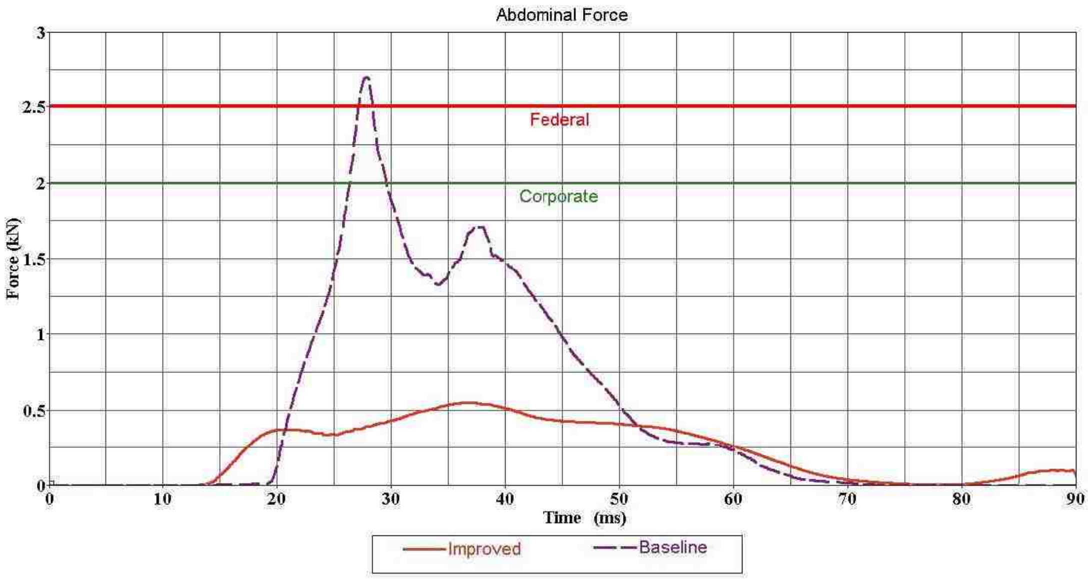


Figure 5-31: Abdominal force improvement of MDB sled test.

Figure 5-31 shows that the sharp peak value in the baseline condition vanished after adding SAB and structure updating. With the improved condition, the maximum abdominal force is reduced from 2.7 kN to 0.55 kN.

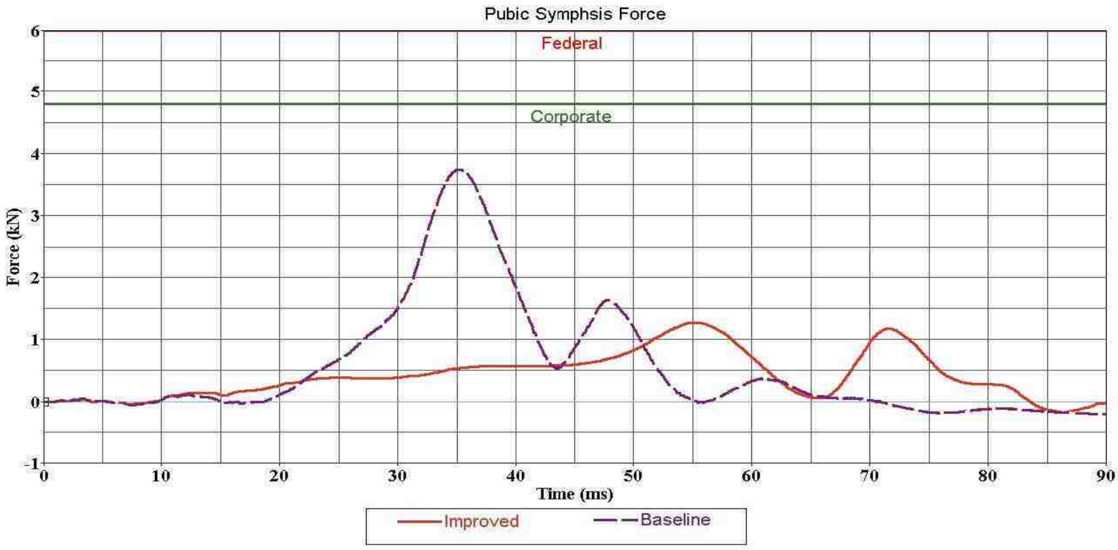


Figure 5-32: Pubic protection improvement of MDB sled test.

Figure 5-32 shows that the peak of pubic force is postponed in the improved condition. The peak value is reduced from 3.7 kN to 1.4 kN.

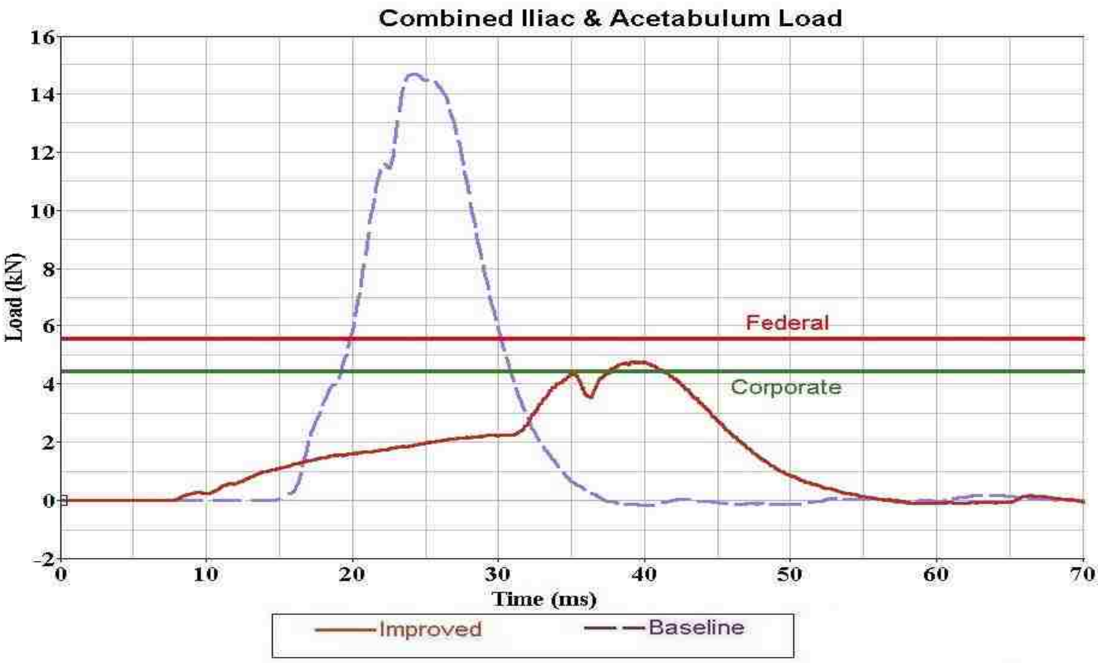


Figure 5-33: Pelvis protection improvement in 5th pole sled test.

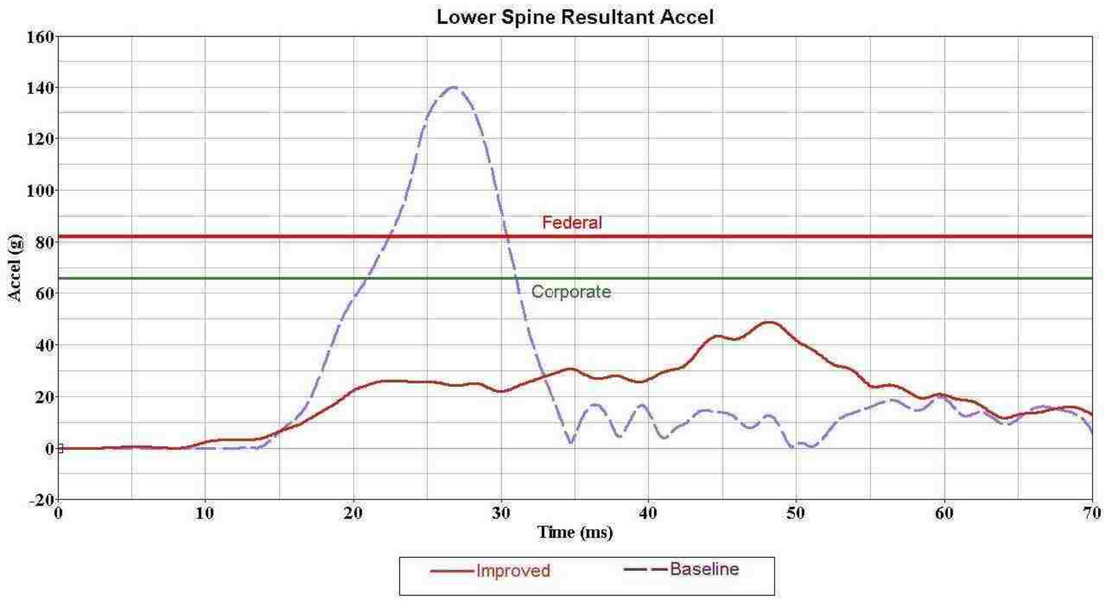


Figure 5-34: Lower spine protection improvement in 5th pole sled test.

In Figure 5-33 to Figure 5-34, the proposed countermeasure effectively improved the occupant protection performance in the oblique pole test. The improvement mainly results from the adding a SAB.

An airbag with different vent hole size can be purchased from suppliers. The challenge for engineers will be how to limit the door intrusion velocity under 6.7 m/s in MDB test. Some possible design solutions to lower the door intrusion velocity are discussed in Chapter 6.

6. SIDE STRUCTURE ENHANCEMENT

6.1 Door intrusion velocity analysis

In a full scale vehicle side impact test, the value of the door intrusion velocity is obtained by the numerical integration of the measured acceleration on the front door beltline of the impacted side. The intrusion velocity is a function of either the type of applied MDB test procedure or the vehicle side structure stiffness.

6.1.1 The effect of different MDB test procedures

As described in Chapter 2, the moving deformable barriers in ECE-R95 and FMVSS 214 are of different weight and height. The kinetic energy of the FMVSS 214 barrier is higher than that of ECE-R95. The barrier width is also different. The FMVSS 214 test barrier is 100 mm wider than ECE-R95 barrier and the kinetic energy of the former is 1.67 times of the latter. Figure 6-1 is a comparison of the frontal door beltline intrusion velocity measured from the same vehicle under two different MDB test conditions. It is obvious from this figure that under ECE-R95 test conditions, the rate of increase of vehicle intrusion velocity at the initial time period is lower than that of FMVSS 214 and also the peak intrusion velocity under ECE-R95 load conditions is lower compared to that of FMVSS 214.

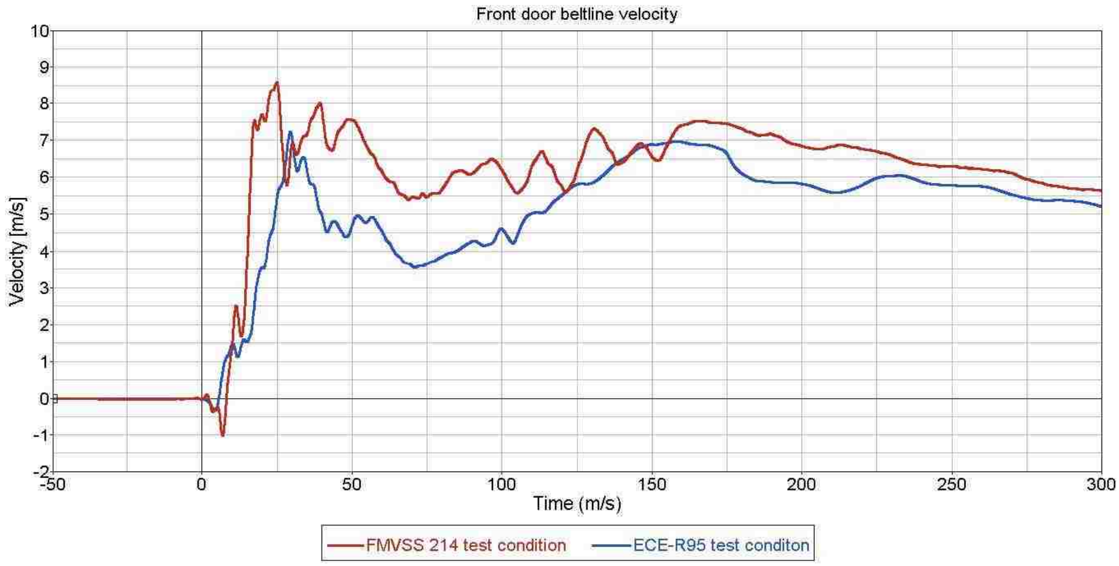


Figure 6-1: The effect of different test procedures on door intrusion velocity profile.

6.1.2 The effect of different side structure

In a typical MDB test, the important events influencing injury occur very early in the impact as listed in Table 6-1. If the impact starts with MDB contact with the vehicle at time 0, the door hits the occupant at between 15 and 25 ms. In Figure 6-2, it can be observed that the door peak intrusion velocity is also in this time period.

Figure 6-2 shows the effects of structural upgrading based on hypothetical simulation and the results of an upgraded experimental vehicle [31]. The comparison of the curve between the baseline and after structural upgrading can reflect the general trends. From 0 to 10 ms, the door intrusion velocity rises at a similar rate. The most significant effect of structural upgrading would be the reduction of door peak intrusion velocity.

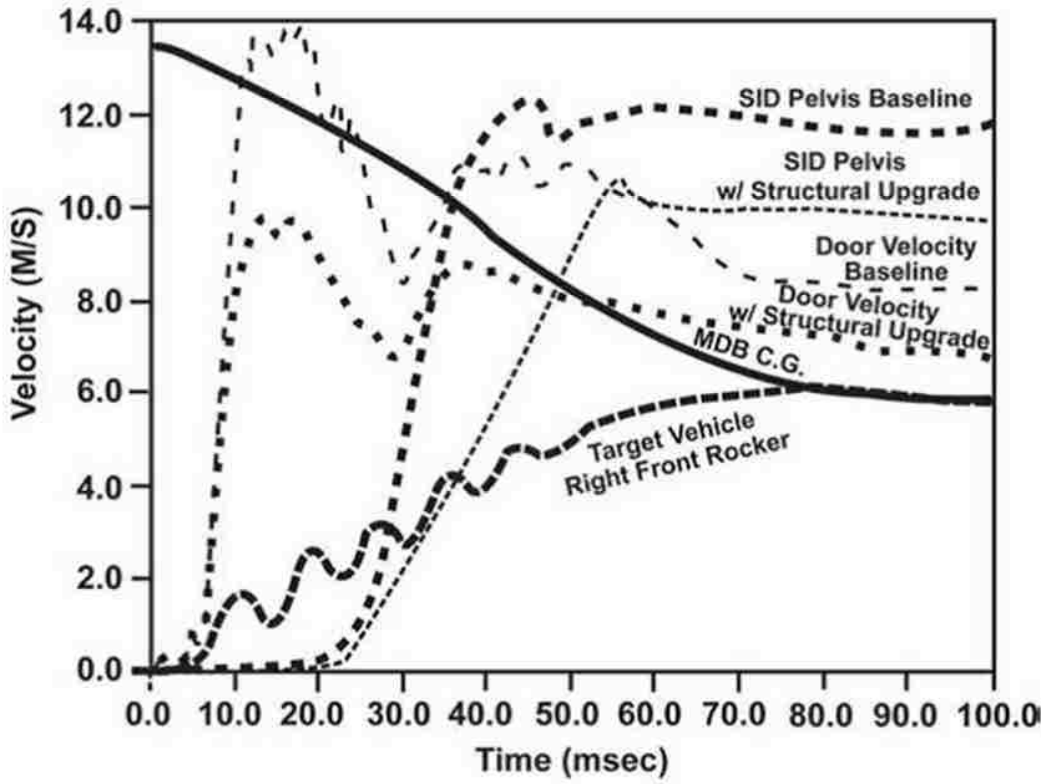


Figure 6-2: Effects of a hypothetical structural upgrade [31].

0 msec	MDB contacts car
15-25 msec	Door contacts dummy
25-30 msec	Max rib acceleration
25-30 msec	Max viscous criterion
30-35 msec	Max spine acceleration
35-50 msec	Max chest compression
80-130 msec	Main body of car moved sideway
70-100 msec	Max sideway velocity of C.G of the car

Table 6-1: Time history of a typical MDB test [41].

6.1.3 Possible solution for side structure upgrading

Most of the improvements on the body structure side apertures can be obtained through the critical components material reinforcement, redesign of the cross section and thickness variation. Critical components which contribute to the vehicle side structure stiffness are B-pillar, roof structure, door sill, and side impact bar, floor structure [42]. A Toyota Yaris model year 2010 was chosen to better illustrate these critical components by disassembling the vehicle structure in Hyperview [43].

The B-pillar provides the basic resistance to side impact. The structural behaviour of the B- pillar during a side collision will influence the upper door velocity [44]. The B-pillar is usually made from high strength material with appropriate thickness. B-pillars are typically composed of 5 parts, as shown in Figure 6-3:

- The most external part of the B-pillar is integrated with the vehicle side skin panel. This solution is adopted by most automotive companies. For manufacturing purposes, this skin has low strength and low thickness. This part has very limited effect during side impact.
- The second and third parts are the main structural parts which resist the side impact. Their thickness is greater than that of other parts.
- The fourth part is the bracket at a lower position.
- The fifth part is the trim for mounting the interior.

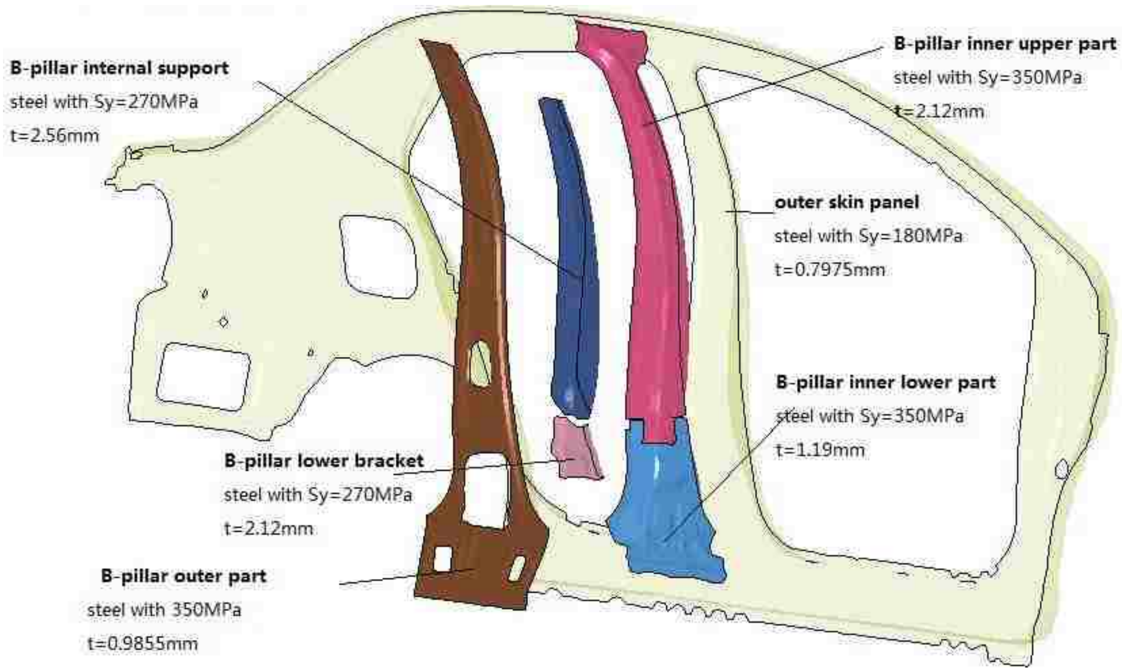


Figure 6-3: B-pillar components of Yaris.

Figure 6-3 shows the B-pillar components of Yaris. The thickness in the upper area is greater than that of the lower part. During side impact more energy will dissipate from the lower part of the B-pillar, the intrusion of the upper part will be minimized. This design was supported by the research findings of the Transport Research Lab in 1995. Certain structural upgrading of the vehicle body side structure could lead to an undesirable intrusion profile of B-pillar and door by tilting inboard at the 'waistline' and concentrating the impact load on the occupant in the thorax region [41]. A more desirable crush pattern for the B-pillar and door is to remain upright during side impact for a more evenly distributed impact loading on the occupant, as shown in Figure 6-4.

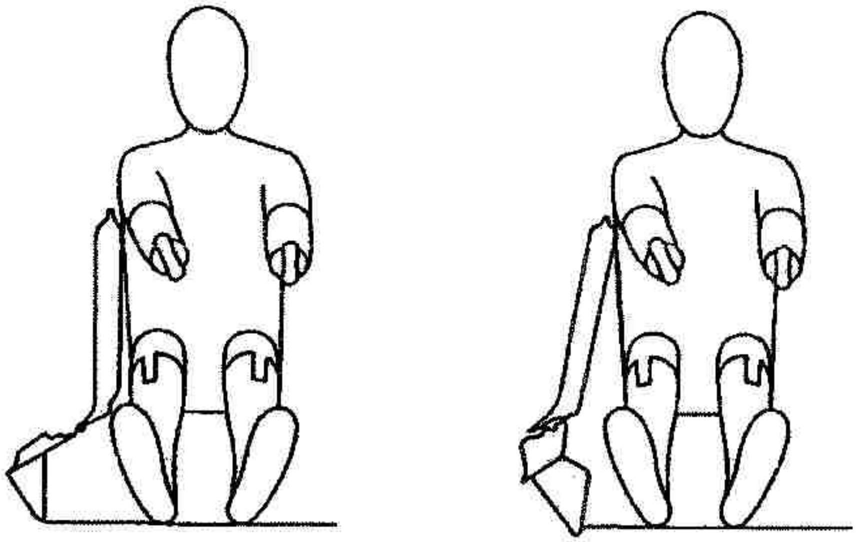


Figure 6-4: Door vertical intrusion profile: door tilting in (right) and door remaining upright (left) [41].

The roof panel contributes less to the vehicle's crash resistance than the roof cross-member during a side impact. Both the thickness and the strength value of the cross member are smaller than those of the roof rail. The proper deformation of the roof can reduce the energy absorbed by the B-pillar and the door sill.

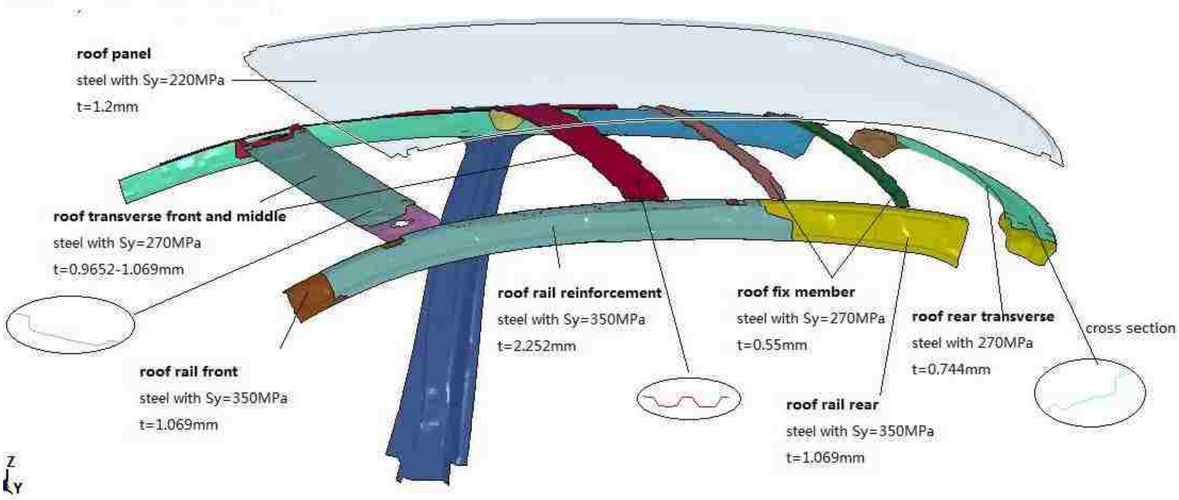


Figure 6-5: Roof structure components of Yaris.

The roof of the Yaris in Figure 6-5 has several cross members. One of them is located at the position of the B-pillar end, and is made from 350MPa high strength steel, with a 2.25mm initial thickness. This member will support the upper part of the B-pillar during side impact and reduce the intrusion of B-pillar. The cross section of the front and rear transverse is U shaped, while the middle transverse has a W shape cross section, and larger thickness. In this case the stiffness of the roof in the middle is greater than the front and rear, so that energy is absorbed farther away from the B-pillar position.

Due to the door sill low position, it will not be hit by the MDB. Nevertheless, the door sill contributes to the body stiffness since it is a main load path, to transmit the load to the A-pillar and the C-pillar. Meanwhile, the door sill plays an important role in the side pole impact. Improving the door sill is an effective way to increase the stiffness of the vehicle side structure.

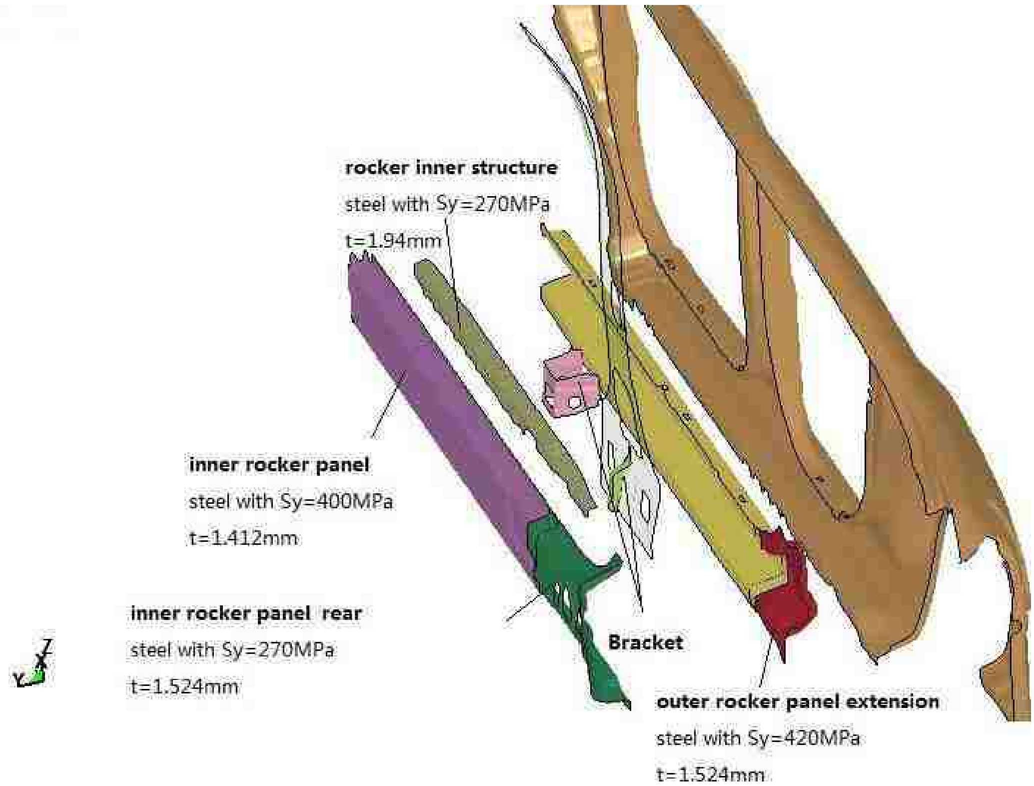


Figure 6-6: Door sill structure components of Yaris.

The Yaris door sill consists of several main components as shown in Figure 6-6.The outer rocker and inner rocker are connected to the end of the B- pillar. With the inner structure, the door sill stiffness is enhanced further. The brackets inside the rocker can improve the door sill bending strength. This will leave more space for the occupant during a side collision.

The side impact bar’s main function is to reduce the depth of door intrusion into the passenger compartment. It can effectively disperse strike energy input to the A-pillar and B-pillar. Mounting position, shape and material are factors that dominate the effectiveness of protection afforded by the side impact bar [42].

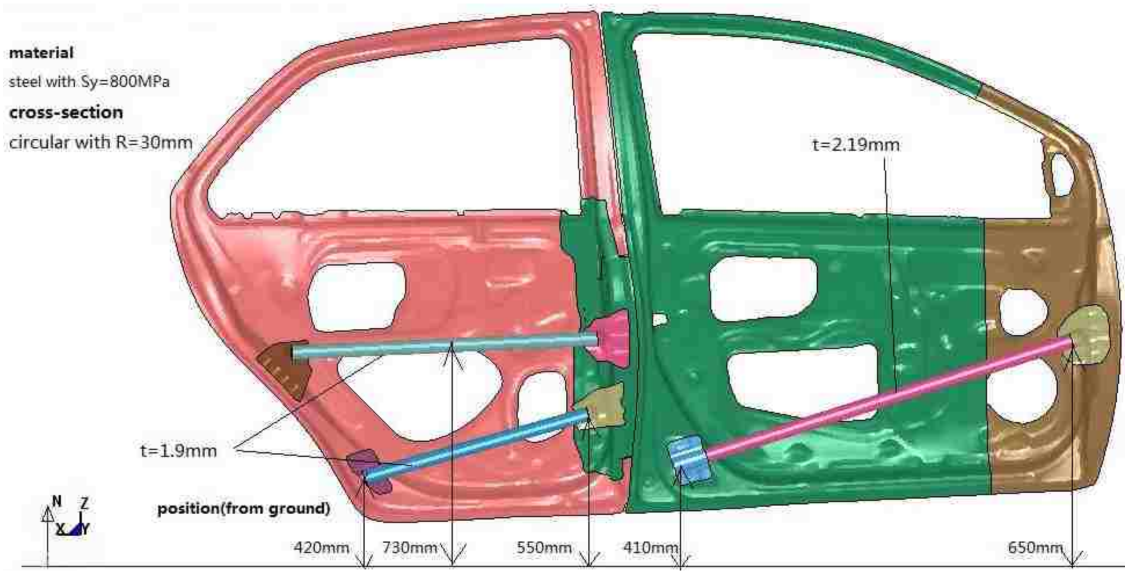


Figure 6-7: Side impact bars of Yaris.

As shown in Figure 6-7 there are two side impact bars with circular cross section mounted on the front door and one is mounted on the rear door of the Yaris. The material of the side impact bar is ultra-high strength steel with 800MPa yielding strength.

In order to avoid large deformations of the floor during side impacts, the cross member in the floor structure is important. The floor panel is further strengthened by the seat bracket. During a side impact the part that absorbs the most energy is the floor tunnel.

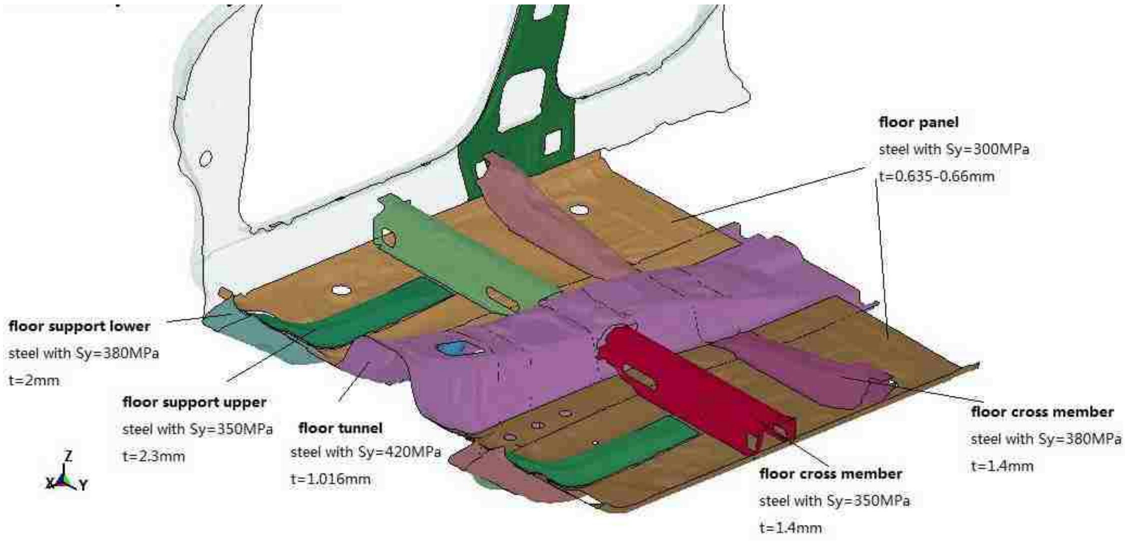


Figure 6-8: Floor structure components of Yaris.

The floor panels of the Yaris are connected by the floor tunnel as shown in Figure 6-8. The tunnel is the main deformation part of the floor during side impact, both the strength of tunnel material and the thickness are greater than those of the floor panel.

However, the approach for improving side impact occupant protection through the use of vehicle body structure reinforcement will add structural weight. The additional weigh to achieve this effect is enormous. Steel reinforcements heavily contribute to increased vehicle weight, CO_2 emissions requirements drive towards lighter vehicle construction. The additional weight is estimated at more than 18kg for a 2-door compact vehicle. [45].

7. CONCLUSION

7.1 Conclusion

This study was performed to provide a design methodology for a vehicle to comply with the different side impact crash regulations and rating tests in Europe, North America and China. A detailed comparison among different side impact tests was done. The side impact tests were divided into two categories: MDB test and pole test. Each one leads to a different design strategy.

After analysis of the energy management of side impacts, three possible design factors were selected to study the relationship of vehicle design factors and occupant protection performance under different test processes: door intrusion velocity, door trim components stiffness and the seat airbag.

The occupant injury response variation for these three design factors was investigated using the finite element method. The reason for using a sled test is that it provides the flexibility to vary the influential factors on occupant safety. The FE model was developed based on the Heidelberg buck sled test set up using LS-DYNA explicit code. The FE model for pole sled test baseline model was correlated with the Heidelberg buck sled test and full vehicle test. Good correlation was observed for the thorax injury. The FE model for MDB sled test was developed in the same way.

The simulation input metrics consisted of the variation of each design factor between upper and lower bounds. It was found that reducing door intrusion velocity will reduce occupant injury during side impact. The door trim component stiffness and seat airbag vent hole variation gave a compromise between thorax protection and abdominal region protection. The pole sled test under new FMVSS 214 oblique pole load condition showed a challenge in meeting the pelvic force requirement. A proper restraint system was found to be an effective solution to enable the vehicle to comply with oblique pole impact requirement.

To comply with different side impact regulations, a possible method would be to first develop the restraint system under the oblique pole impact load condition, then test the vehicle with this restraint system under MDB test procedure. If the thorax region injury exceeds the requirements, the countermeasure would be to increase door trim component stiffness or side structure enhancements could be applied. The selection of the two solutions depends on the abdominal area injury response. The implementation of structural enhancements would be to redesign the critical components, by either changing the geometry or altering the material or both.

7.2 Recommendations for future work

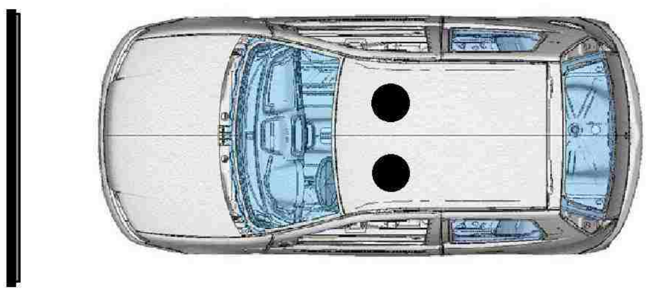
The sensitivity of main design factors to occupant injury response is the focus of the regulatory injury criteria. The oblique pole occupant injury response is only studied using a SID-IIs dummy. The future work for this investigation includes developing a 50th sled pole test model and evaluating the sensitivity of the main design factors to this ES-2re dummy injury response under oblique pole test loading conditions. To add the side impact rating test to the study, a SID-IIs dummy in the MDB sled test model must be developed to simulate the IIHS side impact test. Based on Table 7-1, a simple change to the door fixture, substituting the dummy, adjusting the seat position, and changing the dummy initial velocity can generate different side impact test.

Dummy / Door fixture	ES-2re dummy	SID-IIs dummy
Un-deformed door	ECE-R95/ECAP/ GB 20071-2006/ CNCAP FMVSS 214 US NCAP	IIHS
Deformed door merging with pole	FMVSS 214/US NCAP(50th oblique pole) ENCAP	FMVSS 214/US NCAP(5th oblique pole)

Table 7-1: Sled test set-up for different side impact test procedures.

This study started from a generic vehicle which was not benchmarked against an actual vehicle. The conclusions and general design methods drawn from this study can therefore be applied to any vehicle. In future work, a full vehicle model can be used to study the overall compliance with existing side impact rating tests by applying this design method.

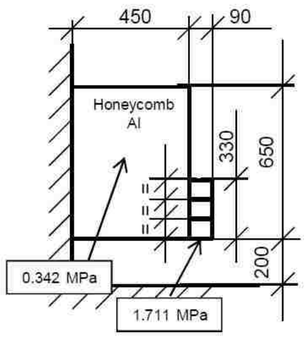
Appendix A: China crash regulations

Configuration **Front full-overlap test**	**Name** **GB 11551-2003**	**Type of test** **Homologation**
Set-up of test:	Set-up of test: 	

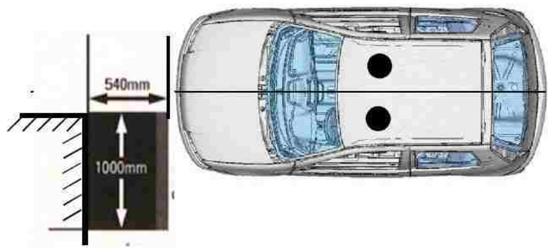
Impact of velocity: 50 km/h	Requirement : <u>Biomechanical:</u>
Description of obstacle: Rigid barrier Full overlap 0 grade inclination	Head — Head performance criterion (HPC)≤1000
Type of load: 2 Hybrid-III 50% I Hybrid-II if no restrain system on the rear row Tank up to 90%(with H_2O)	Chest — Sternum deflection in compression (Thorax performance criterion ThPC)≤ 75mm Femur — Axial load (Femur force criterion FPC)≤ 10 kN
Purpose of test: Stress on the occupants Sealing fuel system Structural behaviour of the vehicle Possibility of rescue	Structure: In the first 5 minutes, fuel leakage ≤ 30 g/min

Configuration **Frontal**	**Name** **GB 11511-2007**	**Type of test** **Homologation**

Set-up of test: ODB lateral view



Set-up of test: Offset deformable barrier+ vehicle



Impact of velocity: 56 km/h

Description of obstacle:

OBD offset: 40%
0 grade inclination

Type of load:
Two Hybrid III
Tank up to 90%(with H_2O)

Purpose of test:

Stress on the occupants
Sealing fuel system
Structural behaviour of the vehicle
Possibility of rescue

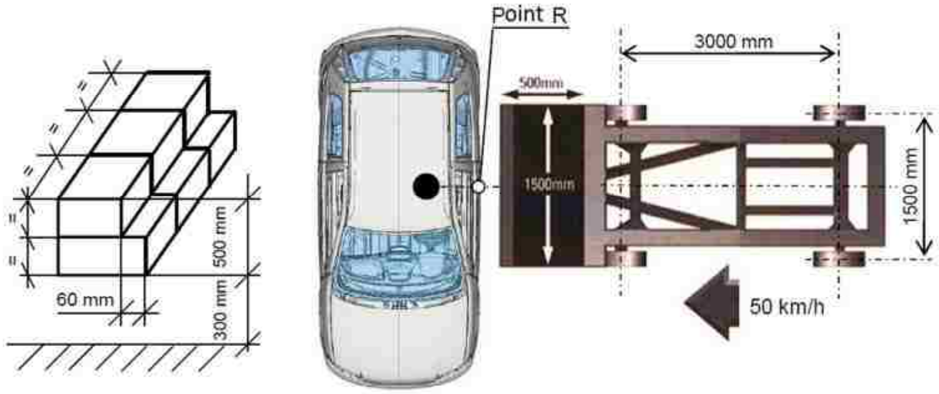
Requirement :
<u>Biomechanical:</u>

Head	HPC≤ 1000, $a_3$ms<80 g
Neck	Traction, below the limitation curve 3.3 kN@0 ms; 2.9 kN@ 35 ms;1.1 kN@≥60 ms Shearing, below the limitation curve 3.1 kN@0 ms ; 1.5 kN@25-35 ms; 1.1 kN@≥ 45 ms Bending moment: My <57Nm in extension
Chest	Thorax compression criterion (ThCC) ≤ 50 mm Viscous Criterion (VC)≤ 1.0 m/s
Femur	Axial force, below the limitation curve 9.07 kN@0 ms; 7.58 kN@ ≥ 10 ms
Knee	Displacement <15 mm
Tibia	Tibia compression force criterion (TCFC) ≤ 8 kN Tibia index (TI) ≤ 1.3

Structure:

In the first 5 minutes, fuel leakage ≤ 30 g/min

Steering wheel	Upward vertical displacement ≤ 80 mm Backward horizontal displacement ≤ 100 mm

<table>
<tr><th colspan="2">Configuration
Side impact</th><th>Name
GB 20071-2006</th><th>Type of test
Homologation</th></tr>
<tr><td colspan="4">Set-up of test: MDB+ vehicle

</td></tr>
<tr><td colspan="2">Impact of velocity: 50 km/h</td><td colspan="2" rowspan="4">Requirement :

<u>Biomechanical:</u>
<table>
<tr><td>Head</td><td>Head performance criterion ≤ 1000</td></tr>
<tr><td>Chest</td><td>Rib deflection ≤42 mm
Viscous criterion ≤ 1.0 m/s</td></tr>
<tr><td>Abdomen</td><td>Abdominal peak force (APF) ≤ internal force of 2.5 kN(equivalent of 4.5 kN external force)</td></tr>
<tr><td>Pelvis</td><td>Pubic symphysis peak force (PSPF) ≤ 6 kN</td></tr>
</table>
Structure:
In the first 5 minutes, fuel leakage ≤ 30 g/min</td></tr>
<tr><td colspan="2">Description of obstacle:
Mobile deformable barrier(MDB)
Mass of 950Kg
Impact perpendicular on the driver’s side (X-axis centered on the R-point)</td></tr>
<tr><td colspan="2">Type of load:
One Euro-SID-1
Tank up to 90%(with $H2O$)</td></tr>
<tr><td colspan="2">Purpose of test:

Stress on the occupants
Sealing fuel system
Structural behaviour of the vehicle
Possibility of rescue</td></tr>
</table>

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