İSTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF SCIENCE AND TECHNOLOGY

SIDE CRASH OF A VEHICLE AND DUMMY PERFORMANCE

M.Sc. Thesis by

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TAŞITLARDA YAN ÇARPIŞMA VE TEST MANKENİNİN PERFORMANSI

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ACRONYMS

ECE	: Economic Commission of Europe
EU	: European Union
EuroNCAP	: European New Car Assesment Programme
USNCAP	: United States New Car Assesment Programme
ATDs	: Anthropomorphic Test Devices
ARL	: Alderton Research Lab
GM	: General Motors
EUROSID	: European Side Impact Dummy
FTSS	: First Technology Safety Systems
SAE	: Society of Automotive Engineers
NHTSA	: National Highway Transport and Safety Administration
SID	: Side Impact Dummy
BIOSID	: Biofidelic Side Impact Dummy
EEVC	: European Experimental Vehicle Committee
RID	: Rear Impact Dummy
AIS	: Abbreviated Injury Scale
WSTC	: Wayne State Tolerance Curve
HIC	: Head Injury Criterion
RDC	: Rib Deflection Criterion
VC	: Viscous Criterion
PSPF	: Pubic Symphysis Peak Force
APF	: Abdominal Peak Force
kN	: Kilo Newton
UTS	: Ultimate Tensile Stress
HBS	: Hardness Brinell Steel
CAE	: Computer Added Engineering
CP	: Confirmation Prototype
FEM	: Finite Element Model
H-point	: Hip Joint Point

LF	: Lowest Front
LM	: Lowest Mid
LR	: Lowest Rear
MF	: Mid-Front
MM	: Mid-Mid
MR	: Mid-Rear
HF	: Highest Front
HM	: Highest Mid
HR	: Highest Rear

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LIST OF SYMBOLS

T_2	: Final time
T_1	: Initial time
A	: Resultant acceleration
a_x	: Acceleration in x direction
a_y	: Acceleration in y direction
a_z	: Acceleration in z direction
g	: Center of gravity
S	: Scaling factor
Y	: Chest deformation
Defconst	: Deformation constant
σij	: Cauchy stress tensor
x_j	: Displacement vector
b_i	: Body force
V_i	: Velocity of displacement
ρ	: Density
M	: Mass matrix
ν	: Velocity vector
F_{ext}	: External force vector
F_{int}	: Internal force vector
F_{bod}	: Body forces vector
Δt	: Time step according to Courant condition
Δl	: Characteristic element length
C	: Sound speed
σ	: Flow stress (Elastic and plastic components)
a	: Yield stress
b	: Hardening modulus
ε_p	: Plastic strain (True strain)
n	: Hardening exponent
c	: Strain rate coefficient
$\acute{\varepsilon}$	: Strain rate
$\acute{\varepsilon}_0$	: Reference strain rate
m	: Temperature exponent
T	: Temperature
T_{melt}	: Melting temperature

SIDE CRASH OF A VEHICLE AND DUMMY PERFORMANCE

SUMMARY

In this study first, some statistical informations about accidents in Turkey and some other countries in the world are given. Classifications of vehicles according to passenger or goods carrying and according to carriage capacities are stated. Vehicle legal homologation regulations for sale permissions are stated. Frontal, side, rear and pedestrian impact modes are explained. Legal rules which are valid for these types of crash are investigated. Dummies, which are used in crash simulation tests, are explained in details. Frontal crash test dummies, side crash dummies and rear crash dummies are investigated separately. Crash injury criteria which is created by the data collected from crash test dummies are investigated. Side crash finite element model analysis which was prepared according to European Union side crash regulation by using Hypermesh, M-Crash and Radioss softwares is compared with physical tst results. Due to comparison, good correlation of test and finite element models is achieved. Trustability and similarity of finite element model with physical test is approved. In correlated analysis, dummy crash injury parameters are calculated for various seating locations of dummy in finite element model. Different crash injury results are obtained for different seating positions. Reasons of these differences are stated. According to results obtained, advantages of using finite element in terms of time and cost save are stated.

TAŞITLARDA YAN ÇARPIŞMA VE TEST MANKENİNİN PERFORMANSI

ÖZET

Bu çalışmada, ilk önce Türkiye'deki ve dünyanın bazı ülkelerindeki kaza istatistiklerine yer verilmiştir. Araçların yolcu ile yük taşımasına göre ve ayrıca yük taşıma kapasitelerine göre sınıflandırılması yapılmıştır. Araçların yasal olarak onaylanabilmesi ve satılabilmesi için uyulması zorunlu bazı kriterler belirtilmiştir. Ön, yan, arkadan çarpma ve yaya ile çarpışma kaza tipleri ve bu kaza tiplerine göre geçerli olan yasal zorunluluklar incelenmiştir. Kazaları temsil eden çarpışma testlerinde kullanılan test mankenleri detaylı olarak anlatılmıştır. Önden çarpmada kullanılan test menkenleri, yandan çarpmada kullanılan test mankenleri, arkadan çarpma testlerinde kullanılan test mankenleri ayrı ayrı incelenmiştir. Test mankenleri üzerinden toplanan bazı bilgilere göre insanların kazalarda yaralanma miktarlarını tahmin edebilmek üzere belirlenmiş çarpışma yaralanma kriterleri incelenmiştir. Avrupa Birliği'ne bağlı ülkelerde geçerli olan yandan çarpma yasal zorunluluk kriterlerine göre yapılmış yandan çarpma testinin sonlu elemanlar yöntemiyle Hypermesh, M-Crash ve Radioss yazılımları ile hazırlanmış modelleri, gerçek test ile karşılaştırılmıştır. Karşılaştırma sonucunda gerçek test ve sonlu elemanlar modelinin benzerliği ve modelin güvenilirliği doğrulanmıştır. Elde edilen bu güvenilir modelde, yine sonlu elemanlar yöntemiyle modellenmiş olan test mankeni üzerinden değişik oturma pozisyonları için veriler toplanmış ve karşılaştırması yapılmıştır. Değişik oturma pozisyonları için farklı sonuçlar elde edildiği görülmüştür. Bu farklılıkların sebepleri üzerinde durulmuştur. Elde edilen sonuçlara göre sonlu elemanlar yöntemi kullanmanın zaman ve maddi kazanımlarının olduğu belirtilmiştir.

1. INTRODUCTION

According to the data from "World Report on road traffic injury preventation", which was produced by the collaboration with World Health Organisation and Worldbank, statistically 1.2 million people were died in traffic accidents worldwide in 2004. More than half of this number are young adults aged between 15 and 44. These people are often the breadwinners of their families. In addition, approximately 50 million people were injured and many of them became disabled which means they will not be able to live, work and play as they used to do. Nonetheless, traffic accidents are preventable and predictable. In high-income countries, some interventions such as,

- Enforcement of legislation to control speed
- Enforcement of legislation to control alcohol consumption
- Mandating the use of seat belts
- Mandating the use of crash helmets in motorcycles
- Safer design of vehicles
- Safer use of roads
- Safer use of vehicles

have contributed to significant reductions in traffic accidents, deaths and injuries in these accidents. For road safety, all sectors should fully engaged in responsibility, activity and advocacy [1].

According to a report which was released in 2006 by Turkey General Directorate of Highways, there were more than six hundred thousand reported traffic accidents in Turkey in 2005. Among these reported accidents approximately 4500 people were killed, in other words more than 12 people every day. Many of these accidents occured in urban traffic and resulted with damage to the vehicle only [2]. Reported number of accidents, deaths and injuries as a result of traffic accidents in Turkey between the years 2001 and 2005 is shown in Table 1.1 below.

Table 1.1: Number of accidents, deaths and injuries in Turkey between 2001 and 2005

		2001	**2002**	**2003**	**2004**	**2005**
Accidents	Urban	363258	362979	373531	436187	502682
	Highways	45879	44124	48771	58664	67737
	Rural	33553	32855	33365	42533	50764
	Total	442960	439958	455667	537384	621183
Deaths	Urban	1309	1215	973	1128	1159
	Highways	1645	1685	1845	1954	2056
	Rural	1432	1269	1148	1346	1310
	Total	4386	4169	3966	4428	4525
Injuries	Urban	62690	62202	59355	67693	77843
	Highways	31807	32023	35969	41988	46142
	Rural	21705	21820	21944	26548	30109
	Total	116202	116045	117268	136229	154094

Figure 1.1 shows fatality and injury numbers per 1000 accidents in Turkey between 2001 and 2005.

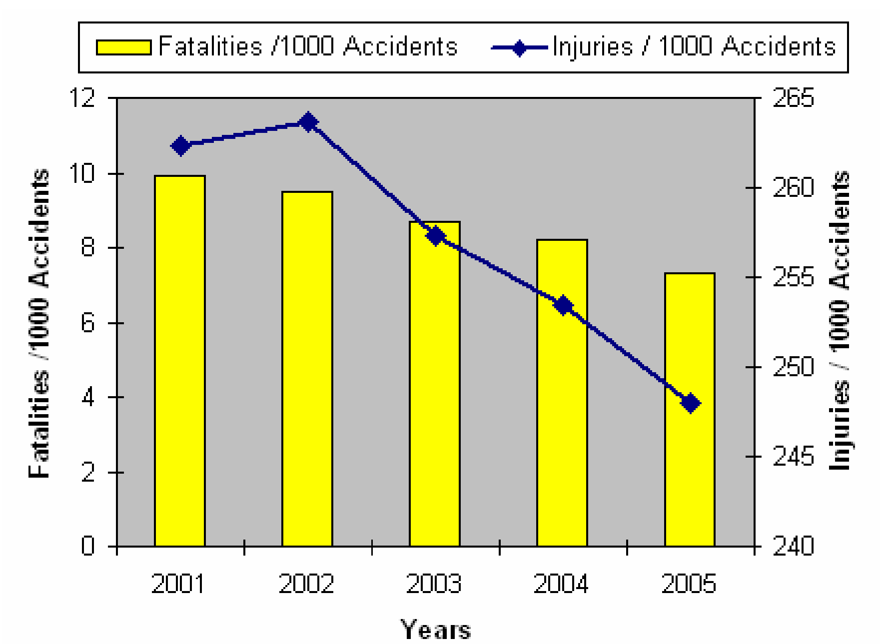

Figure 1.1 : Fatality and injury numbers per 1000 accidents in Turkey

Since the year 2002, deaths and injuries per 1000 accidents tend to decrease. This may be the result of some intervations such as speed limit legislation, alcohol controls, improvements in highways like double roads and also safer design of the vehicles. Accident distribution between years 2001 and 2005 due to type of collision, occurance location and percentage information are shown in Table 1.2 below [2].

Table 1.2: Accident distribution in 2005 according to types of collisions in Turkey

Type of collision	Accidents					
	Urban	**%**	**Rural and Highway**	**%**	**Total**	**%**
Head-on vehicle crash	20960	38.33	5342	23.65	26302	34.04
Rear-end crash	5222	9.55	2699	11.95	7921	10.25
Crash to stable vehicle	2216	4.05	419	1.86	2635	3.41
Crash to an object	4812	8.80	1424	6.93	6377	8.25
Crash to pedestrian	14877	29.47	1565	5.41	16098	20.83
Crash to animal	174	0.32	241	1.07	415	0.54
Rollover	2869	4.81	4329	19.17	7198	9.32
Lost of steering control	3151	5.76	6620	29.31	9771	12.64
People fall down from vehicle	363	0.66	118	0.52	481	0.62
Object fall down from vehicle	42	0.08	32	0.14	74	0.10
TOTAL	54686	100.00	22586	100.00	77272	100.00

Reasons of accidents and fault percantage values in Turkey between the years 2001 and 2005 are listed in Table 1.3 below.

Table 1.3: Reasons of the accidents in Turkey in the last 5 years (2001-2005)

Years	**Driver %**	**Pedestrian %**	**Passenger %**	**Vehicle %**	**Road %**
2001	96.82	2.38	0.16	0.32	0.32
2002	96.99	2.48	0.12	0.25	0.16
2003	97.29	2.16	0.13	0.25	0.17
2004	97.46	2.08	0.10	0.21	0.15
2005	97.68	1.98	0.05	0.15	0.14

Traffic statistics like accident numbers, death numbers, vehicle and population numbers of some countries in the year 2005 shown in Table 1.4 below [2].

Table 1.4: Traffic statistics of some countries for year 2005

Country	Accidents	Deaths	Vehicle	Population	Vehicle per 1000 people	Deaths per 100000 vehicle
Germany	354534	6613	53656000	82537000	650	12
Austria	43426	931	5114000	8118000	630	18
France	90220	6058	36198000	59625000	608	17
Polland	51078	5640	15899000	38191000	416	36
CZ Republic	27320	1447	4490000	10203000	441	32
Spain	99987	5399	25170000	42196000	597	22
Sweden	18365	529	4998000	8941000	559	11
Switzerland	23840	546	4888000	7318000	668	11
Japan	947993	8877	80970000	127619000	635	11
Korea	240832	7212	17519000	47925000	366	41
Portugal	41495	1546	5197000	10475000	496	30
Canada	156904	2766	18869000	31630000	597	15
Norway	7921	280	2752000	4577000	601	10
England	220079	3658	31950000	59554000	537	11
TURKEY	**83 788**	**4525**	**11146000**	**72065000**	**155**	**41**

According to data mentioned in Table 1.4 above, deaths per hundred thousand vehicle value is highest in Turkey and Korea. Vehicle per thousand people is lowest in Turkey in this table. Death ratio is highest in Turkey among all these countries. To lower death ratio in accidents, intervations mentioned on page 1 such as, legislation to control speed and alcohol consumption of drivers should be enforced. Use of seat belts should be commonized. Safer and modern roads should be constructed. Vehicles should be built safer.

2. VEHICLE CATEGORIES AND APPROVAL OF A VEHICLE

2.1 Vehicle Categories

Vehicles are divided into categories according to their usage purpose (passenger or goods carrying), number of wheels, number of passengers, amount of goods which they can carry or maximum speed they can reach. A common vehicle classification system is operated by the United Nations and the European Union, and this is widely applied in national law in Europe [3]. Vehicle categories according to usage purpose are shown in Table 2.1 below.

Table 2.1 : Vehicle categories and their descriptions

Category	Description
M	Motor vehicles with at least four wheels, or having three wheels when maximum weight exceeds 1 ton and used for the carriage of passengers
M1	With no more than eight seats in addition to driver's seat
M2	With more than eight seats in addition to driver's seat, and a maximum weight not in excess of 5 tons
M3	With more than eight seats in addition to driver's seat, and a maximum weight in excess of 5 tons
N	Motor vehicles with at least four wheels, or having three wheels when maximum weight exceeds 1 ton and used for the carriage of goods
N1	Vehicles used for the carriage of goods with a maximum mass not in excess of 3.5 tons
N2	Vehicles used for the carriage of goods with a maximum mass in excess of 3.5 tons but not exceeding 12 tons
N3	Vehicles used for the carriage of goods with a maximum mass exceeding 12 tons

2.2 Approval Of A Vehicle (Homologation)

Homologation is the certification of a product or specification to indicate that it meets regulatory standards. The product is a vehicle in this thesis. So, the vehicle must meet some regulatory standarts. Homologation is necessary for the legal sales of vehicles. Economic Commission of Europe, ECE, regulations are one of the most important regulatory for vehicles. Vehicles which are manufactured in European Union (EU), must satisfy the ECE regulations. After customs union agreement of Turkey with EU, ECE regulations adopted the Turkish market. Some of these ECE regulations are tough and force automotive manufacturers to design safer cars in terms of impact protection. Also regulations have been updated in a period of time and every couple of years they are becoming tougher and tougher. As a result of this, manufacturers will have to improve the crash performance of their new models. As can be easily seen on the chart on page 2, ratio of fatality per accident started to decrease beginning from year 2002 in Turkey. This may be the result of ECE regulations which are strictly started to be used in the vehicles which are sold in Turkish market. Some of the ECE regulations and their subjects for passenger cars can be seen in the Figure 2.1. Passenger cars ECE regulations and their descriptions can be seen in Table 2.2 below [4].

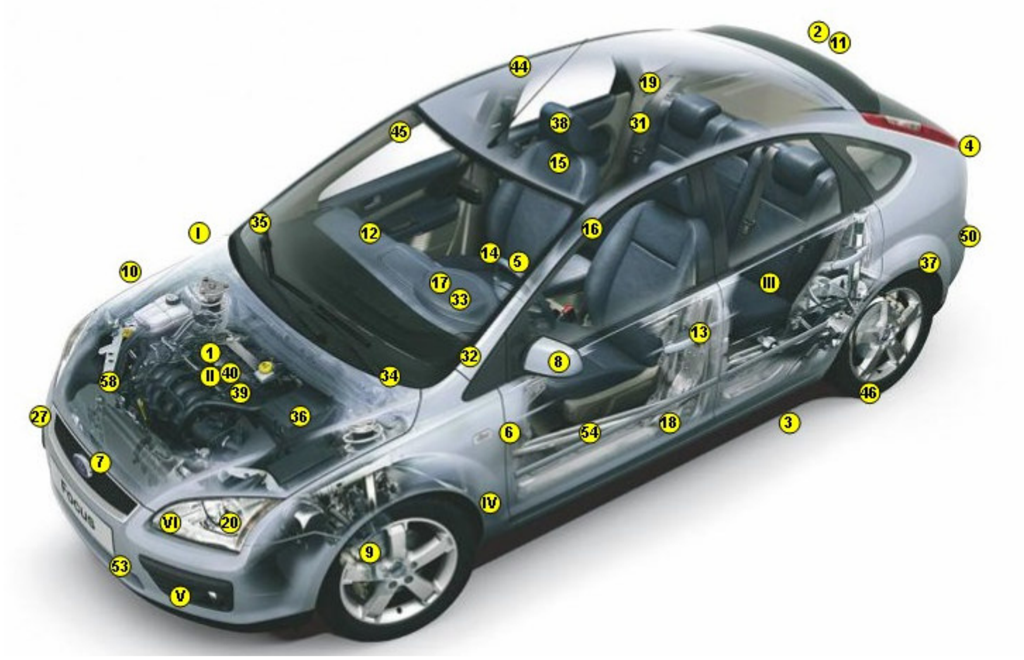

Figure 2.1 : ECE regulation numbers and locations for a passenger car

Table 2.2: ECE regulations for passenger cars

No.	Directive	Regulation	Subject
0	70/156/EEC	-	Whole Vehicle Type Approval - M1 only
1	70/157/EEC	ECE R51	Sound levels
2	70/220/EEC	ECE R83	Emissions
3	70/221/EEC	ECE R34 ECE R67 ECE R110	Fuel tanks / Rear underun protection Liquified petroleum gas - LPG Compressed natural gas - CNG
5	70/311/EEC	ECE R79	Steering effort
6	70/387/EEC	ECE R11	Door latches and hinges - M1 only
7	70/388/EEC	ECE R28	Audible warning
8	2003/97/EC	ECE R46	Rear visibility
9	71/320/EEC	ECE R13, ECE R13 H	Brakes
10	72/245/EEC	ECE R10	Electromagnetic compatibility
11	72/306/EEC	ECE R24	Diesel smoke
12	74/60/EEC	ECE R21	Interior fittings and interior impact - M1 only
13	74/61/EEC	ECE R18, ECE R97, ECE R116	Anti-theft
14	74/297/EEC	ECE R12	Protective steering - M1 only
15	74/408/EEC	ECE R17	Seat strength / Head restraints
16	74/483/EEC	ECE R26	Exterior projections - M1 only
17	75/443/EEC	ECE R39	Speedometer and reverse gear
19	76/115/EEC	ECE R14	Seat belt & Isofix anchorages
20	76/756/EEC	ECE R48	Installation of lighting
31	77/541/EEC	ECE R16	Seat belts & restraint systems
39	80/1268/EEC	ECE R84, ECE R101	CO2 emissions / Fuel consumption - M1
40	80/1269/EEC	ECE R85	Engine power
44	92/21/EEC	-	Masses and dimensions - M1 only
45	92/22/EEC	ECE R43	Safety glass
46	92/23/EEC	ECE R30, ECE R64	Tyres / Temporary spares
50	94/20/EC	ECE R55	Couplings
52	2001/85/EC	ECE R52, ECE R66	Bus construction - M2 only
53	96/79/EC	ECE R94	Frontal offset - M1 only
54	96/27/EC	ECE R95	Side impact - M1 only
58	2003/102/EC	-	Pedestrian protection - M1 only

Some of the ECE regulations and their subjects for commercial vehicles can be seen in the Figure 2.2. Commercial vehicle ECE regulations and their descriptions can be seen in Table 2.3 and Table 2.4 below [4].

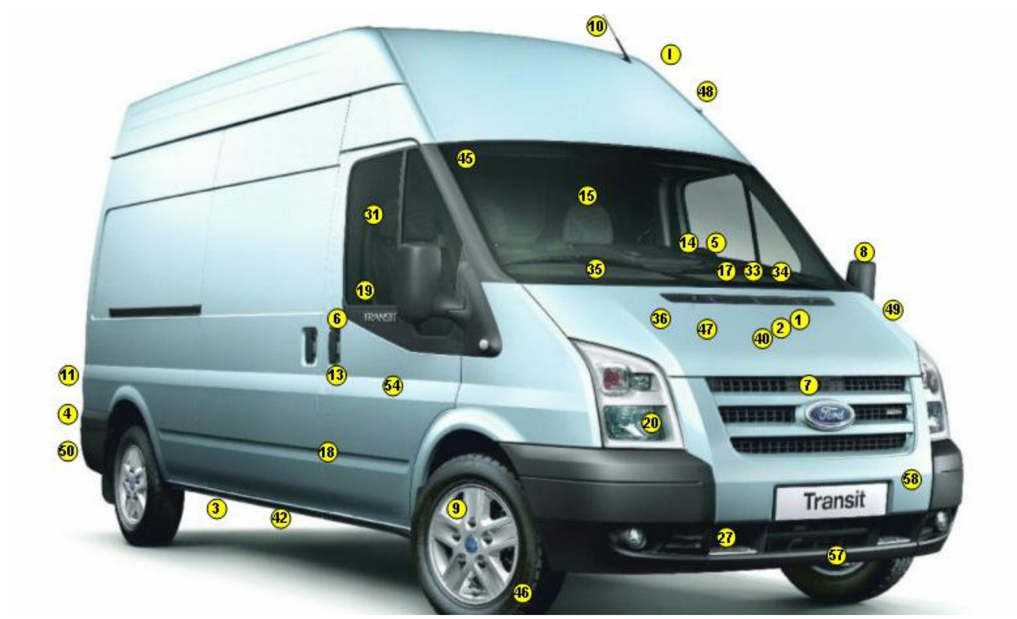

Figure 2.2 : ECE regulation numbers and locations for a commercial vehicle

Table 2.3: ECE regulations for commercial vehicles

No.	Directive	Regulation	Subject
1	70/157/EEC	ECE R51	Sound levels
2	70/220/EEC	ECE R83	Emissions
3	70/221/EEC	ECE R58 ECE R34 ECE R67 ECE R110	Rear underun protection - *N2, N3 only* Fuel tanks Liquified petroleum gas - LPG Compressed natural gas - CNG
4	70/222/EEC	-	Rear registration plate
5	70/311/EEC	ECE R79	Steering effort
6	70/387/EEC	ECE R11	Door latches and hinges
7	70/388/EEC	ECE R28	Audible warning
8	2003/97/EC	ECE R46	Rear visibility
9	71/320/EEC	ECE R13, ECE R13 H	Brakes
10	72/245/EEC	ECE R10	Electromagnetic compatibility
11	72/306/EEC	ECE R24	Diesel smoke
13	74/61/EEC	ECE R18, ECE R97, ECE R116	Anti-theft

Table 2.4: ECE regulations for commercial vehicles

No.	Directive	Regulation	Subject
14	74/297/EEC	ECE R12	Protective steering - *N1 only*
15	74/408/EEC	ECE R17	Seat strength / Head restraints
17	75/443/EEC	ECE R39	Speedometer and reverse gear
19	76/115/EEC	ECE R14	Seat belt & Isofix anchorages
20	76/756/EEC	ECE R48	Installation of lighting
31	77/541/EEC	ECE R16	Seat belts & restraint systems
34	Veh. shall be fitted with an adequate windscreen defrosting and demisting device		Defrost / Demist
35	Veh. shall be fitted with an adequate windscreen washing and wiping device		Wash / Wipe
40	80/1269/EEC	ECE R85	Engine power
42	89/297/EEC	ECE R73	Lateral underun protection - *N2, N3 only*
45	92/22/EEC	ECE R43	Safety glass
46	92/23/EEC	ECE R30, ECE R64	Tyres / Temporary spares
47	92/24/EEC	ECE R89	Speed limiter - *N2, N3 only*
48	97/27/EEC	-	Masses and dimensions
49	92/114/EEC	ECE R61	External projections of cabs
50	94/20/EC	ECE R55	Couplings
54	96/27/EC	ECE R95	Side impact - *N1 only*
57	2000/40/EC	ECE R93	Front underun protection - *N2, N3 only*
58	2003/102/EC	-	Pedestrian protection *N1 derived from M1 only*

ECE regulations mainly divided into 10 categories. These are;

- Braking
- Electrical Supply, Electromagnetic Compatibility, Radio and Telecommunications Equipment
- Emissions, Emission Control Equipment, Fuel Specifications, Fuel Consumption and Engine Power
- Impact Protection (Internal and External Bodywork, Front, Rear, Side and Rollover Protection, Doors and Locks)
- Lighting and Reflectors
- Noise

- Seats, Safety Belts, Head Restraints and Child Restraints
- Steering, Wheels, Wheel Guards, Tyres and Transmissions
- Visibility, Glazing, Mirrors, Washers, Wipers, Demisters and Defrosters
- Miscellaneous (Anti-theft protection, Fire risk prevention etc.)

Most of the items listed above are about vehicle components, systems and equipment approval. Among these groups, Impact protection regulations are directly about saving the life of driver, passenger or pedestrian. United Nations ECE Regulations for Impact Protection are listed below.

ECE No.	**Subject**
11	Door Latches and Retainers
21	Interior Fittings
26	External Projections
29	Occupant Protection in Cabs of Commercial Vehicles
32	Collision Structure Performance – Rear End
33	Collision Structure Performance – Front End
42	Bumpers Front and Rear
58	Underrun Device – Rear
61	External Projections – Commercial Vehicles – Forward of Rear of Cab
73	Lateral Protection – Goods Vehicles, Trailers etc
93	Underrun Device – Front – Category N Vehicles
94	Occupant Protection in Frontal Collision
95	Occupant Protection in Lateral (Side) Collision

Frontal impact, side impact and rear impact structural performance and occupant protection tests are regulatory in terms of ECE. In fact, pedestrian impact protection does not take part in ECE regulations, but vehicle manufacturers take pedestrian impact protection into consideration during vehicle design for prestige and advertisement purpose. Apart from the legal and necessary requirements, there are some non-official tests for the customers which have some expectations about safety performance of their vehicles. EuroNCAP (European New Car Assesment Program) and USNCAP (United States New Car Assesment Program) are mostly known special organisations to make consumers more conscious about safety performance of the vehicles sold in European and United States markets.

3. FRONT - SIDE - REAR AND PEDESTRIAN IMPACT MODES

3.1 Frontal Impact

ECE regulation number 94 is for the vehicles with regard to the protection of the occupants in the event of frontal collision. It is an obligatory regulation for the passenger cars, category M1, which do not exceed total mass of 2.5 tons. ECE-94 front impact regulation schema is shown in Figure 3.1 below [4].

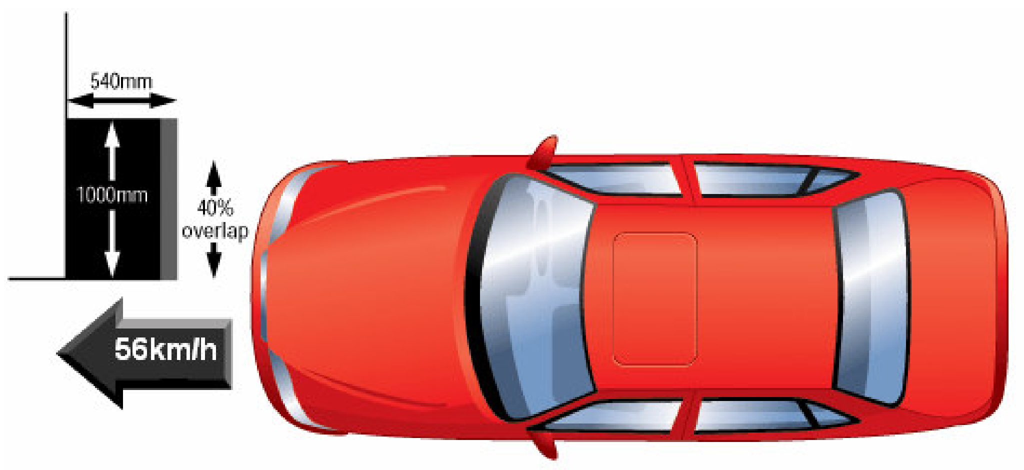

Figure 3.1 : 40% offset frontal crash with deformable barrier at 56km/h impact velocity [6]

In this crash mode, test vehicle's speed is 56km/h. Test vehicle hits to stationary deformable barrier which is mounted on a rigid wall at the end of a test track. Purpose of deformable barrier is simulating the real crash case. During real crash, hit car is absorbing energy as well. Vehicle width specified as distance between outer most right and left side planes of a vehicle excluding rear side mirrors, side marker lamps, tyre pressure indicators, direction indicator lamps, position lamps and flexible mud guards. 40% offset or overlap of the vehicle width is used for this regulation test which is statistically the most common improper overtaking accidents.

Data from crash test dummies which are sitting on the front seats of a vehicle is recorded. Dummies shall meet conditions like head injury criteria performance, neck injury criteria performance, chest deflection performance, femur and abdomen force performance criteria. Vehicle structural design and robustness are important as well to achieve through the front impact tests.

3.2 Side Impact

ECE regulation number 95 is for the vehicles with regard to the protection of the occupants in the event of a lateral collision. It is an obligatory regulation for the vehicles in category M1 and N1 where the seating reference point of the lowest seat is not more than 700mm from ground level. ECE-95 side impact regulation schema is shown in Figure 3.2 below [5].

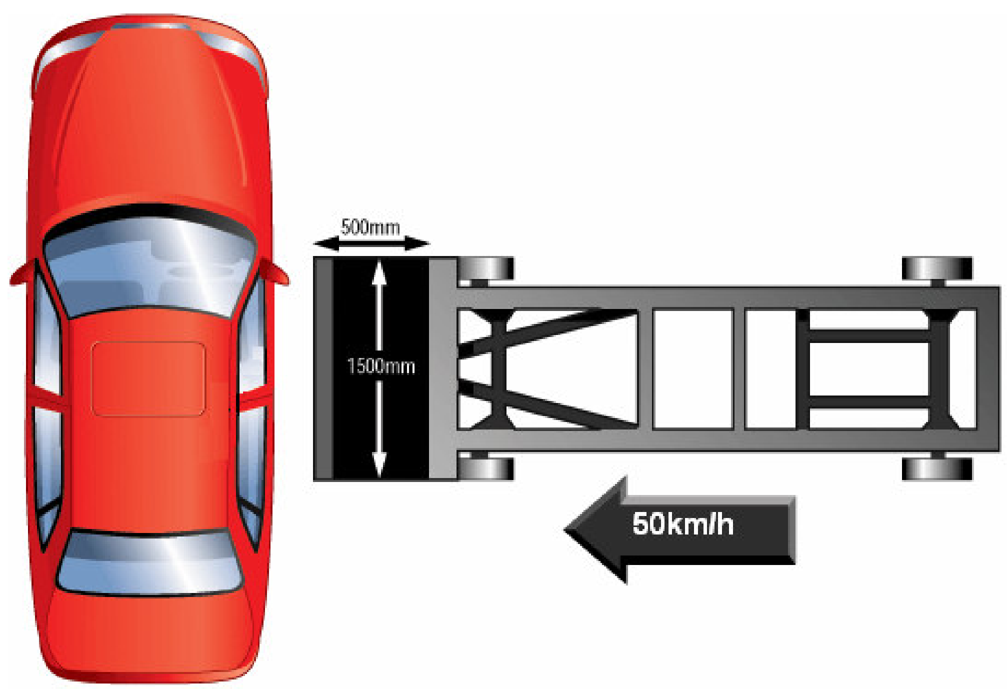

Figure 3.2 : Side crash with deformable barrier at 50km/h impact velocity [6]

In this crash mode, a trolley with a deformable part on the front with a speed of 50km/h towed into the test vehicle on the driver's side if there is not any asymmetric bodyside structures. If there are some differences for the sides of the vehicle design, test authority and manufacturer will agree and test will be carried out according to the worst case which can be the opposite side of driver but this case being considered as the least favourable. Total mass of the trolley and deformable barrier must be 950 -/+ 20kg.

Head injury criterion, rib deflection criterion, soft tissue criterion, pelvis and abdomen performance criteria must be less or equal to specified values which will be explained in the chapter 5, Crash Injury Criteria in detail.

3.3 Rear Impact

ECE regulation number 32 is for the vehicles with regard to the behaviour of the structure of the impacted vehicle in a rear-end collision. The behaviour of the passenger compartment is investigated in this regulation. ECE-32 rear impact regulation schema is shown in Figure 3.3 below [4].

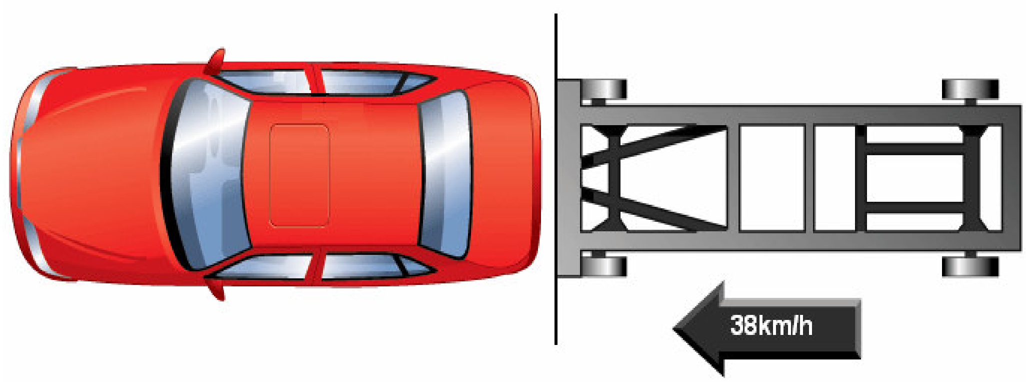

Figure 3.3 : Rear crash with rigid moving barrier at 38km/h impact velocity [6]

In this crash mode, a trolley with a rigid impactor part on the front with a speed of 38km/h crashed into the test vehicle. The impactor shall be made of steel with dimensions 2500mm wide and 800mm high. Total mass of trolley and impactor must be 1100 -/+ 20kg. The amount of longitudinal displacement of rearmost seat's reference point is measured after the test. It should not exceed a specific value for meeting the ECE regulation number 32. Fuel tank and fuel line's integrity is investigated after the test.

3.4 Pedestrian Impact

Pedestrian impact tests are not obligatory. Important vehicle manufacturers care about the results of pedestrian impact test of their products. Pedestrian impact test is arranged by EuroNCAP. Results of pedestrian impact test for all vehicles can be seen on EuroNCAP web page. This has a competitive meaning among vehicle manufacturers and force them to improve the design of their products in terms of regulations and NCAP tests. EuroNCAP pedestrian impact schema is shown in Figure 3.4 below [6].

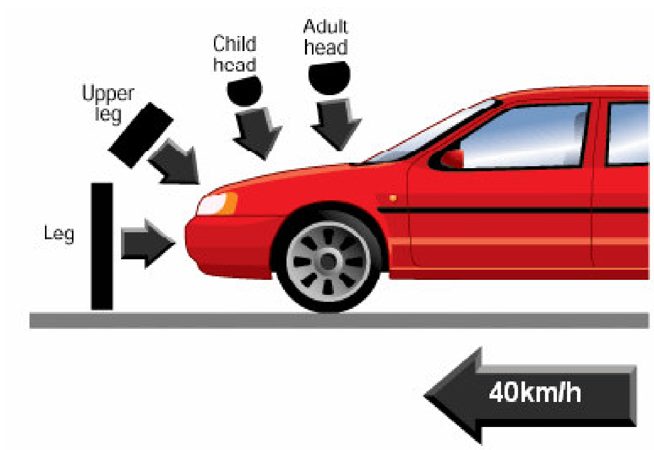

Figure 3.4 : Pedestrian Impact performance test at 40km/h impact velocity [6]

Test vehicle hits various child and adult test dummies at various locations at 40km/h test speed. According to the hit location of the head or any other vital organs, authorities rated the performance as good, adequate and marginal as can be shown on Figure 3.5 below [6].

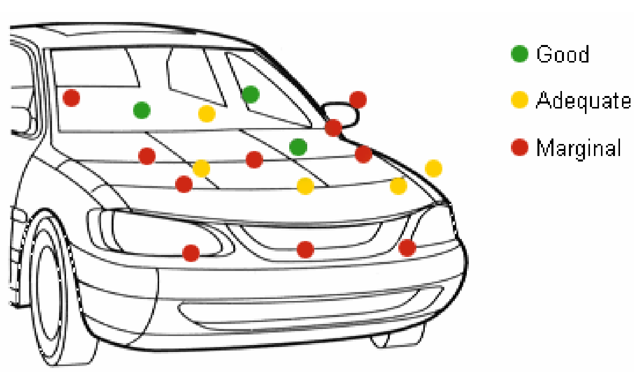

Figure 3.5 : Rate locations of a vehicle after pedestrian impact test [6]

4. CRASH TEST DUMMIES

Crash test dummies are anthropomorphic test devices (ATDs) and full scale represantatives of human beings. They have accordance with humans regarding geometry, dimensions, weight, gender, energy absorption and dissipation. The dummies' mechanical behaviours are very similar to human responses of velocity, acceleration and deformation in collision conditions. They are instrumented with various sensors to record data like speed of impact, crushing force, deformations and forces of body parts, torque of the body and deceleration rates during a collision. They are used for the development of new design and models of all types of vehicles varying from passenger cars to fighter airplanes [7].

4.1 Evolution Of Dummies

Through more than one hundred year history of the automobiles, safety has always been a critical issue. In fact, in 1930s when automobile was becoming a common part of a daily life, fatality rate was 15.6 per 100 million vehicle miles and were continuing to increase year by year. Current rate is approximately 1.8 per 100 million vehicle miles even there are millions of more cars on the road today. This impressive improvement is achieved by paying serious attention to safety and diligent efforts of car manufacturers to design safer cars by using the data collected from crash test dummies.

Before the invention of crash test dummies, effects of collision were investigated by using cadavers, volunteer testing and animal testing. Cadavers equipped with crude accelerometers, were straped into cars and used in head on collisions. However, working with cadavers presented many problems like moral and ethical issues related to working with dead human bodies. Reuse of cadaver was not always possible due to type of crash. Since no two cadavers were the same, consecutive test results could have major differences in same conditions. In addition to say that, specific limbs of dead body could be used only once. Also finding suitable and not wounded or not injuried dead body was difficult when crash testing became more usual.

In volunteer testing, researchers used themselves to serve as crash objects. There were examples like; propelling himself over 1010km/h speed on a rocket sled and stopped in less than a second. A professor whose name is Lawrence Patrick in United States, endured around 400 rides on a rocket sled for testing the sudden decceleration effects on human body. Also this professor and his students allowed themselves to be smashed in the chest with heavy metal pendulum, impacted in the face by pneumatically driven rotary hammers and sprayed with broken glass pieces to represent window implosion.

And the last category before invention of dummies is animal testing. Data collected from cadaver were not enough to see the survivability performance of the occupant. Because of this necessity and the shortage of suitable cadavers forced researcher to use animals in collision testing. Chimpanzees, bears, pigs and many useful animals were taken part in crash testing. As a matter of fact that animals were living and they felt pain during these tests. Animal rights groups protested these tests. Although finding suitable animal is easier than finding a cadaver, animals had not been using by any of the major automobile makers in crash tests since 1993. Protests and instrumentation difficulties were the major factors for ending live animal testing.

In the direction of experience and information gained from cadaver and animal testing, first human representative crash dummy “Sierra Sam” was created by Samuel W.Alderson at his Alderson Research Labs (ARL) and Sierra Engineering Coorperation to test aircraft ejection seats and pilot restraint performance in 1949. Sierra Sam had a human-like exterior shape and body weight. It had articulated limb joints. On the other hand, its stiffness is not biofidelic. Limited instrumentation facility and poor reproducibility were the disadvantages of this first dummy.

In the 1966, Alderson and Grumman produced a new dummy, which was called VIP (Very Important Person) series for crash tests which was suitable for both motor vehicles and aircraft. Alderson continued to produce new dummies. The following model was VIP-50 which was created specifically for GM and Ford. It had some common properties with Sierra Sam. Additive features were rubber neck, human shaped pelvis. It had a capability of measuring head and thoracic spine accelerations and femur loads. Disadvantages were the same as in Sierra Sam. In addition, repeatability of the results were poor.

“Sierra Stan” was the upgraded model of Sierra Sam, which was created in 1967. It had segmented neck and plastic shell for the rib cage. Neck bending response was poor in this dummy series. Sierra Stan was found unreliable and unstable by GM.

GM safety engineers combined the best features of VIP series and Sierra Stan and Hybrid-I was created in 1971. Hybrid-II was introduced in 1972 which is much more sophisticated than Hybrid-I with improved shoulder, spine and knee responses. Hybrid-I and Hybrid-II were still not suitable for developing and testing seat belt designs.

GM researchers produced Hybrid-III series in 1976 which is also still using by major automobile companies today. Hybrid-III has a human-like shape and body weight. It has biofidelic response for head, neck, chest and knee. It can be instrumented extensively. It has a human-like automotive seated posture. It has excellent repeatability, reproducibility and durability.

In 1979, American National Highway Transportation Safety Administration and University of Michigan Transportation Institute produced new side impact dummy. It was derived from Hybrid-II dummy with new thorax (chest) design for side impact loading. In 1989, EUROSID-I and BIOSID were created with modifications due to side impact conditions on Hybrid-III series. Small female, large male, children and baby dummies were developed and produced in crash test dummy’s historical devlopment. Improvements on dummies are still going on to take better results during crash tests [7].

4.2 Types Of Dummies

Crash test dummies can be classified according to type of crash, their size, gender and age. Adult dummies has 3 main sizes as follows: 5th percentile female, 50th percentile male and 95th percentile male. 50th percentile male dummy represents the median sized male in the U.S. population. It is bigger than half of the male population and smaller than the other half. If this dummy could stand upright, it could be around 1.75m tall and 78 kg in weight. This is the most common and popular dummy used in crash testing facilities. Child dummies represent different ages. Heights and weights of child dummies are approximate median values of the specified age groups, without regard to gender. There are some companies producing crash test dummies. First Technology Safety Systems (FTSS) company is one of the largest creator of sophisticated dummies in the world [8].

4.2.1 Frontal crash test dummies

5th percentile hybrid-III female dummy represents the smallest segment of the adult population and derived from scaled data from the hybrid-III 50th percentile dummy. If she could stand upright, she could be around 1.52m tall and 47kg in weight. The year 1988 is the first production date and it was upgraded in 1991 to evaluate seat belt submarining. It was upgraded again in 1997 to see the performance of airbags on drivers which are sitting closer to steering wheel. The FTSS 5th percentile hybrid-III female dummy has ability to measure the thorax Viscous Criterion. The FTSS 5th percentile hybrid-III female dummy is shown in Figure 4.1 below.

Figure 4.1 : First technology systems 5th percentile hybrid-III female dummy

50th percentile hybrid-III male dummy is the most common used crash test dummy in the world for the evaluation of automotive safety restraint systems in frontal crash testing. Originally developed by General Motors, the hybrid III 50th design is now maintained and developed by FTSS in conjunction with the Society of Automotive

Engineers' (SAE) Biomechanics Committees and the National Highway Transport and Safety Administration (NHTSA). The dummy is a regulated test device in the USA Code of Federal Regulations and also in the European ECE Regulations. If he could stand upright, he could be around 1.78m tall and 78kg in weight. It has satisfactory and good biofidelity, a measure of how well the dummy simulates the forces and motions of a human, and instrumentation capability. This dummy can also be used in many non-automotive applications such as wheelchairs, medical and sport equipment design. The FTSS 50th percentile hybrid-III male dummy is shown in Figure 4.2 below.

Figure 4.2 : First technology systems 50th percentile hybrid-III male dummy

95th percentile hybrid-III male dummy represents the largest segment of the adult population. If he could stand upright, he could be around 1.88m tall and 102kg in weight. The biomechanical impact responses are derived from hybrid-III 50th dummy by scaling the functions. Originally developed in 1988, the dummy is used worldwide for the evaluation of automotive and military safety restraints and particularly for seat belt integrity testing. The FTSS 95th percentile hybrid-III male dummy is shown in Figure 4.3 below [8].

Figure 4.3 : First technology systems 95th percentile hybrid-III male dummy

4.2.2 Side crash test dummies

SID (Side Impact Dummy), EUROSID-1 (European Side Impact Dummy Version-1) EUROSID-2 (European Side Impact Dummy Version-2) and BIOSID (Biofidelic Side Impact Dummy) are four commercially available 50th percentile adult male side impact dummies. SID-IIs is also available representing 5th percentile female or 12-13 age child with its weight and sizes. 50th percentile adult male EUROSID-1, BIOSID and SID dummies are shown in Figure 4.4 below.

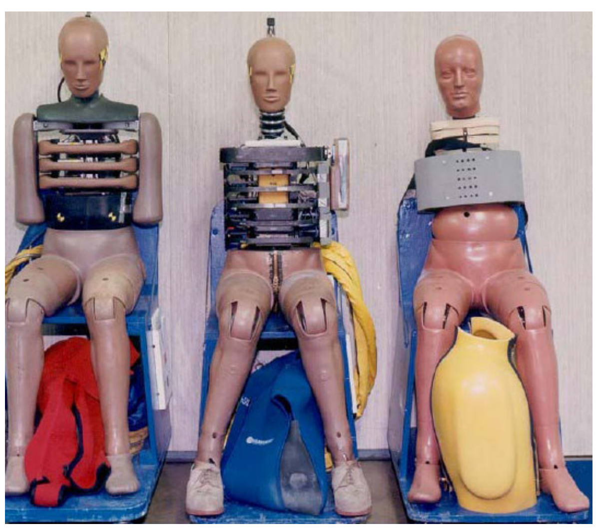

Figure 4.4 : EUROSID-1, BIOSID, SID 50th percentile adult male side impact dummies

The European Side Impact Dummy, EuroSID-1, was developed for lateral impact crash simulations. EuroSID-1 is a regulatory test device in the European Regulation for Side Impacts, ECE-95 regulation.

EuroSID-1 represents a 50th percentile adult male. European research laboratories working under the auspices of the European Experimental Vehicle Committee (EEVC) is responsible for constructing this dummy. The final specification for EuroSID-1 was established by EEVC in April 1989 [8].

4.2.2.1 Specifications and part details of Eurosid-1 dummy

EuroSID-1 basically consists of a metal and plastic skeleton, covered by flesh simulating skiny materials. The total body mass is 72 kg. Parts of the dummy are head, neck, chest, shoulder, arms, abdomen, pelvis, legs and suit.

The head is made of aluminium and covered with rubber flesh feeling material. Three accelerometers are located inside of it and each of them provides force and acceleration data which the brain would be subjected in a crash.

The neck consists of metal discs and rubber elements. It has connection with special joints to head and chest to represent a realistic motion of the head relative to the chest. Closer view of side impact dummy neck is shown in Figure 4.5 below.

Figure 4.5 : Closer view of side impact dummy neck

Flesh-simulating foam covered three seperate ribs are attached to a rigid steel spine box. Inside these ribs, springs and dampers are located to record compression of the chest and the velocity of this compression during lateral impact. General view of side impact dummy chest is shown in Figure 4.6 below.

Figure 4.6 : General view of side impact dummy chest

Shoulder part is designed to allow the arms to move realistically and expose the ribs to direct impacts.

Arms are represented as flesh simulating foam and a PVC skin covered on a plastic skeleton. Only the upper arm exists. There is not any instrumentation inside the arms because movement of the arms are not similar in each crash case. In a crash test, the arms flail around in an uncontrolled way.

Abdomen is represented with metal casting. There is a foam on this metal casting which is simulating a mass-carrying flesh.

Pelvis part is made up of two plastic wings connected by a metal sacrum and covered with flesh simulating foam and a PVC-skin. Lateral forces are recorded from pelvis structure that may result in fractures or hip-joint dislocation.

Legs are represented as a metal skeleton covered by flesh-simulating foam and plastic skin.

There is a rubber suit on EUROSID dummy to cover the shoulder, chest, abdomen and pelvis during an impact.

EUROSID dummy chest and abdomen structures can be rotated 180 degrees and it can be used for left-hand side impacts as well as for right-hand side impacts. 50th percentile EUROSID-1 adult male side impact dummy is shown in Figure 4.7 below.

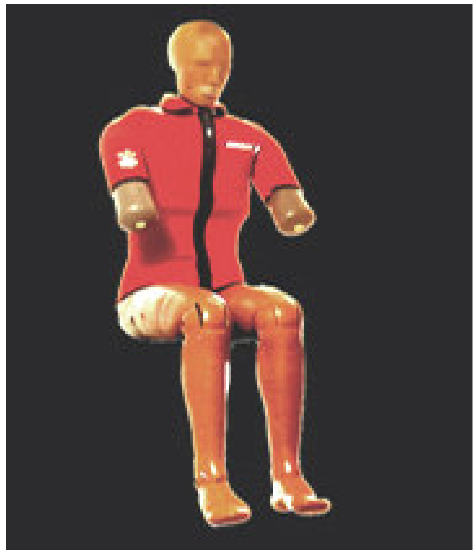

Figure 4.7 : EUROSID-1 50th percentile adult male side impact dummy

EUROSID-2 is modified version of EUROSID-1. Shoulder part has rounded edges. In thorax region, more stiff spine box is used. Ribs with ball bearings against stick and slip affect is used. To locate these roller bearings, back plate has been redesigned. EuroNCAP has been using EUROSID-2 since 2003 for lateral impact tests [9].

SID and BIOSID are used in America and Canada to meet these region's regulatory tests. They have similar properties with EUROSID dummies. Main purpose is measuring lateral impact's effect on ribs, pelvis, thoracic spine and head in each type crash dummy series. SID dummy series have no arm or shoulder structure which was created by Highway Safety Research Institute at the University of Michigan, under contract to the National Highway Traffic Safety Administration, SID is usually used in head airbag in side impact test according to FMVSS 571.201 (Federal Motor Vehicle Safety Standards) in United States.

BIOSID was developed by General Motors, in cooperation with the Society of Automotive Engineer's (SAE) Human Biomechanics and Simulation Standards Committee after internal evaluations of SID and EUROSID dummies. It is biofidelic side impact dummy. Rib deflection is measured by six rib elements. BIOSID has additional measurement capability.

Also a dummy which is a harmonization of all side impact dummies, WorldSID was created in 2004. It has been financed by the US-American, European and Asia-Pacific Automotive Industries. It has capability of replacing all existing Side Impact dummies in the market. Biofidelity of WorldSID is better than EUROSID and SID dummies. But its price is approximately 300.000 € which is 4 or 5 times higher than those of usual side impact dummies [7].

4.2.3 Rear crash test dummies

As a result of Brite-Euram Whiplash project, a rear impact dummy has been developed by the efforts of TNO Crash Safety Centre. RID2 is revised model of Hybrid-III dummy. With the RID2 conversion package, the Hybrid-III can be transformed into a rear-end impact dummy. For evaluating the seat and restraint system performance, it is highly recommended to use a RID dummy in rear impact conditions. Rear impact dummy is shown in Figure 4.8 below.

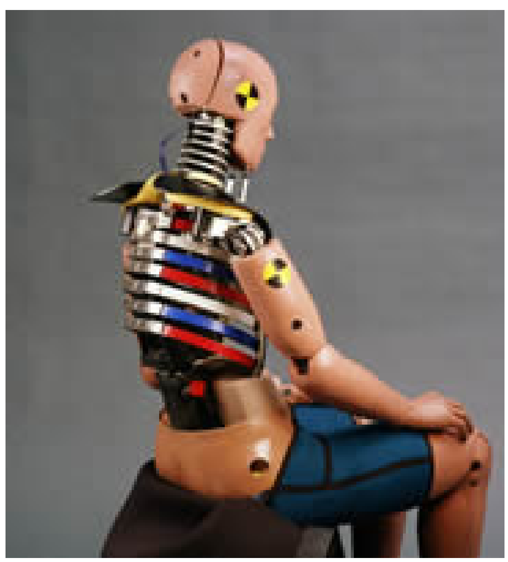

Figure 4.8 : RID2 rear impact dummy

Approximately 60.000-80.000 € is required to build each of these anthromorphic test devices with their accelerometers, load cells and basic instrumentations [7].

5. CRASH INJURY CRITERIA

Dummies cannot simulate injuries, but rather they are used for generating numerical data like force, acceleration and velocity during crash tests. Severity of the injuries is classified after processing the data which are collected from crash test dummies with the help of injury biomechanics. Knowledge of human tolerance to impact is required for evaluating the measurements on dummies. Categorizing injuries is a quite complex issue. Injury parameters can be used for classification. An injury parameter is a physical parameter or function of many physical parameters that correlates good with the injury of the body region. There is not any single classification coding scheme which has achieved universal acceptance. The Abbreviated Injury Scale (AIS), which is developed by the Association for the Advancement of Automotive Medicine, is the most widely used anatomic injury severity scale in the world. The AIS classifies injuries by body part, specific lesion, and severity on a 6-point scale in terms of the threat to life of a single injury.

AIS levels of injuries categorized as;

0 – No injury,

1 – Minor,

2 – Moderate,

3 – Serious,

4 – Severe,

5 – Critical or life threatening,

6 – Maximum injury (fatality).

The scale is ordinal, meaning that, an AIS 2 injury is greater than an AIS 1 injury, but AIS 2 is not twice as much as AIS 1 [10].

Biomechanical engineers need injury criteria to describe the relationship between one or more physical parameters and the injury. These injury criteria usually take the form of a simple mathematical expression, a force or an acceleration level. For defining injury parameters, usually Latin terms are preferred. Human skeleton system schema shown in Figure 5.1 below will help to understand the exact location of an injury on the body.

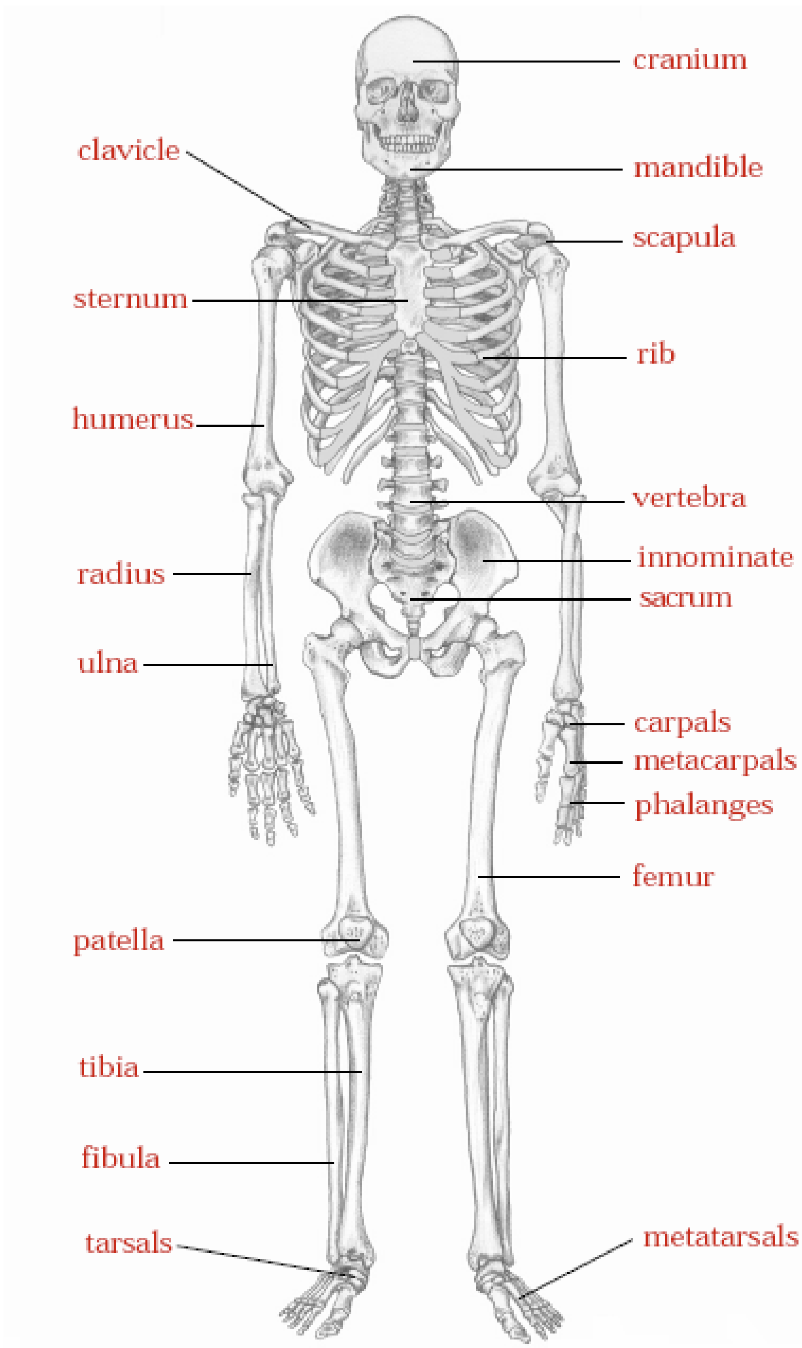

Figure 5.1 : Human skeleton system schema

5.1 Head Injury Criterion (HIC)

The principal concern in head injury is brain injury. Wayne State Tolerance Curve (WSTC) is one of the first attempts to define tolerance of the brain to linear acceleration. Nature of the skull is such that, brain can tolerate higher accelerations if the duration of the pulse is shorter. Human head can tolerate 80g acceleration values if the duration of pulse is 3 miliseconds. The mathematical calculation of HIC value is based on the equation given below:

$$HIC = \max\left[\left[\frac{1}{T_2 - T_1}\int_{T_1}^{T_2} A(t).dt\right]^{2.5} .(T_2 - T_1)\right] \qquad \textbf{(5.1)}$$

$$A = \sqrt{(a_x)^2 + (a_y)^2 + (a_z)^2} \qquad \textbf{(5.2)}$$

where A(t) is the head acceleration measured at the head's centre of gravity in g value ($g = 9.81\ m/s^2$) during the test or simulation time. T_1 and T_2 are the initial and final times (in second) of the interval during which the HIC reaches its peak value and also (T_2 - T_1) states the duration of the impact pulse. Max in the formula above represents integral sum during a 36ms interval in acceleration-time curve in which the integral is the highest. Exponent value 2.5 was taken from WSTC, which could be approximated by a straight line with a negative slope of 2.5 if it were plotted on a log-log scale. For practical reasons, the maximum time interval (T_2 - T_1) which is considered to give appropriate HIC values was set to 36miliseconds [ms]. 1000 is specified as the maximum HIC_{36} value in tolerance limits for side crash tests. In some regulations, HIC_{15} is also calculated in 15ms time interval for simulating harder head impacts. Maximum acceptable HIC_{15} value is 700. HIC only considers linear acceleration, but in most head impacts both linear and angular accelerations exist. No validated injury criterion for angular acceleration is currently available. Also, HIC is only valid for hard contact, thus the time duration of the impact is limited. Despite these handicaps, HIC is the most common used criterion for head injury classification, especially in pass or fail tests. If there is no head contact, this criterion is fulfilled [10].

5.2 Rib Deflection Criterion (RDC)

The ribs are long and curved bones of the human body which created the rib cage. The human rib cage is located within the thoracic (chest) area. Both males and females have 24 ribs, 12 on each side of thoracic cavity. Seven of the ribs from the top of rib cage have connectivity with sternum in front and known as true ribs. Eighth, ninth and tenth ribs, which are known as false ribs, are attached together in front of the cartilaginous portion of the next rib above. The eleventh and twelfth ribs are not attached in the front and are called floating ribs. Rib cage schema of human body is shown in Figure 5.2 below.

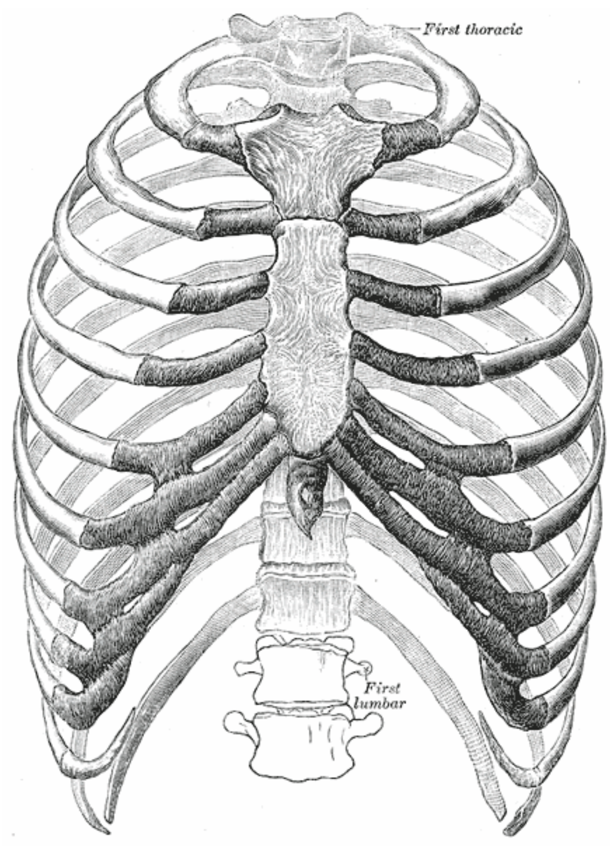

Figure 5.2 : Rib cage schema of human body

Rib deflection criterion is the criterion for the deflection of the ribs, expressed in mm, in a side impact collision. In ECE-R95 Side crash regulation, max Rib deflection is set to 42mm, which is assumed as internal bleeding start for the vital organs located inside chest cage. Rib deflection is measured from the spring-piston system located laterally in dummy chest cage.

Rib deflection measurement pistons on side crash dummy are shown in Figure 5.3 below.

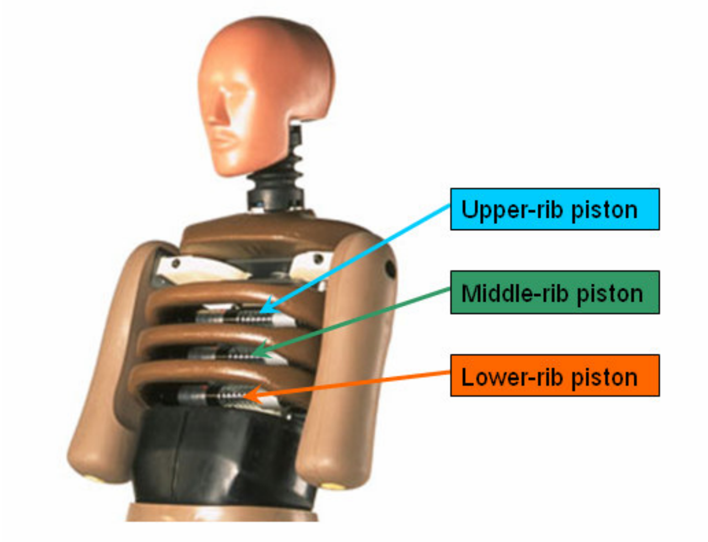

Figure 5.3 : Rib deflection measurement pistons on side crash dummies

5.3 Viscous Criterion (VC)

Viscous criterion is an injury criterion for the chest (thorax) area. The VC value [m/s] is the maximum value of the multiplication of the thorax deformation speed and the thorax deformation. Both quantities are determined by measuring the acceleration of bony structures like the ribs for side impact and the spine or chest deflection measurement for frontal impact. Inside chest cage structure, vital organs hearth and lungs exist. These organs are made of soft tissues. In fact, viscous criterion is important and measured for these organs. Viscous criterion is proposed as a predictor for injury risk. For that reason, the second common name of viscous criterion is Soft Tissue Criterion. The mathematical calculation of the VC value is based on the equation given below:

$$VC = S.\frac{Y}{Defconst}.\frac{dY}{dt} \qquad \textbf{(5.3)}$$

where:

S = Scaling factor **(5.3a)**

Y = Chest deformation [m] **(5.3b)**

Defconst = Deformation constant, i.e., depth or width of half the rib cage **(5.3c)**

dY/dt = Deformation velocity **(5.3d)**

Scaling factor and deformation constant according to dummy types are shown in Table 5.1 below.

Table 5.1: Scaling factor and dummy constants

Dummy Type	Scaling Factor	Deformation Constant
Hybrid III, male 95%	1.3	254mm
Hybrid III, male 50%	1.3	229mm
Hybrid III, female 5%	1.3	187mm
BioSID	1.0	175mm
EuroSID-1	1.0	140mm
ES-2	1.0	140mm
SID-IIs	1.0	140mm

Analyses and experiments on human cadavers show that, during a frontal impact, occupant whose VC value reaches to 1.3 m/s has a 50% chance of severe thoracic injury (AIS > 4). This is also valid for frontal collisions. In both crash types (side and front) 1.0m/s soft tissue criterion is selected as reference value for human tolerance [10].

5.4 Pelvis Performance Criterion

The bony structure which is located at the base of the spine is called Pelvis. The pelvis incorporates the socket portion of each leg. Pelvis is made up of three main bones which are; ilium, ischium and pubis. In the frontal location of the pelvis structure, pubis bones are coming together and this location is called symphysis pubica. The pelvis structure protects the digestive and reproductive organs on the body. Many large nerves and vessels pass through it to supply the legs. Pelvis structure is also provides a connection between axial skeleton and legs. Pelvis structure is shown in Figure 5.4 below.

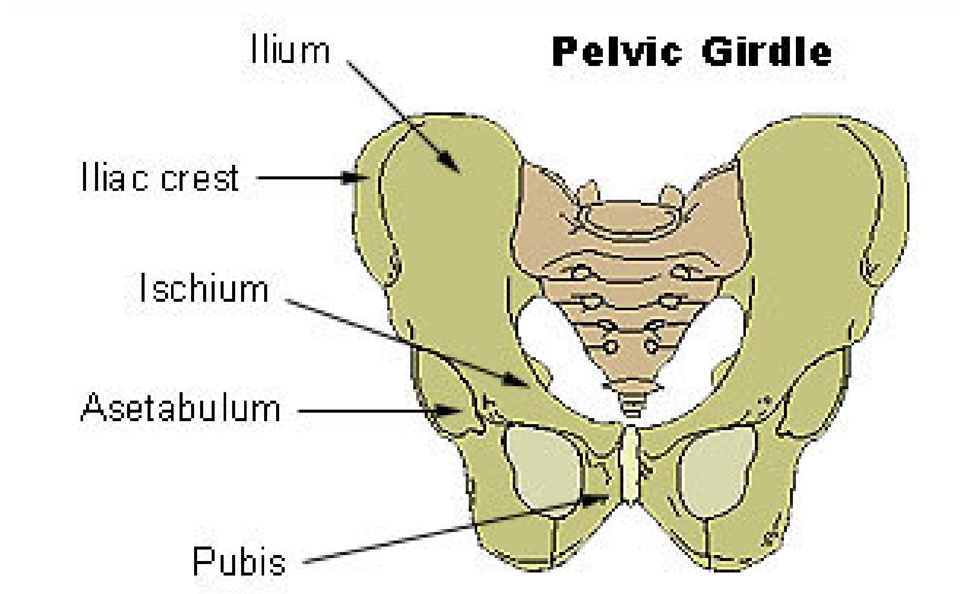

Figure 5.4 : Pelvis structure

The pubic symphysis peak force (PSPF) criterion is the maximum measured force by a load cell located at the pubic symphysis of the pelvis, which is expressed in kN [10].

5.5 The Abdomen Performance Criterion

Human abdomen is part of the body between pelvis and thorax (chest). Abdomen is seperated from throax by throacic diaphragm and seperated from pelvis by pelvic brim. Stomach, intestines, liver, pancreas and spleen is located behind abdomen area.

Abdominal peak force (APF) is the criterion for European side impact regulation. APF is the maximum value of the sum of three forces in kN that are measured on the impact side by a load cell located in abdominal part of the side crash dummy, which is expressed in kN [10].

$$APF = \mathbf{max} \mid F_y front + F_y middle + F_y rear \mid \quad \textbf{(5.4)}$$

5.6 ECE-95 Requirements

According to injury criteria mentioned above, ECE regulations have set targets and limits for side impact crash test. ECE-95 side impact regulation injury criteria limit values are;

- The head injury criterion (HIC) shall be less than or equal to 1000
- The thorax performance criteria shall be:

  a) Rib Deflection Criterion (RDC) less than or equal to 42 mm.

  b) Soft Tissue Criterion (VC) less or equal to 1.0 m/sec.
- The pelvis performance criterion shall be:
- Pubic Symphysis Peak Force (PSPF) less than or equal to 6 kN.
- The abdomen performance criterion shall be:
- Abdominal Peak Force (APF) less than or equal to 2.5 kN internal force, equivalent to external force of 4.5 kN [5].

6. SIDE CRASH OF A VEHICLE

Lateral collisions are the second most common type of crash to cause serious injuries or fatality (According to AIS ranking 3 to 6). The relative frequency for side crash is 20% among all types of crashes and accounts as far as 50% of the total number of accidents causing serious or fatal injuries.

6.1 ECE-95 European Side Impact Test

The European side impact test simulates a stationary vehicle hit by another vehicle at 50 kph. Test is performed by a deformable barrier of 950kg in mass. ECE-95 European side impact test schema is shown in Figure 6.1 below.

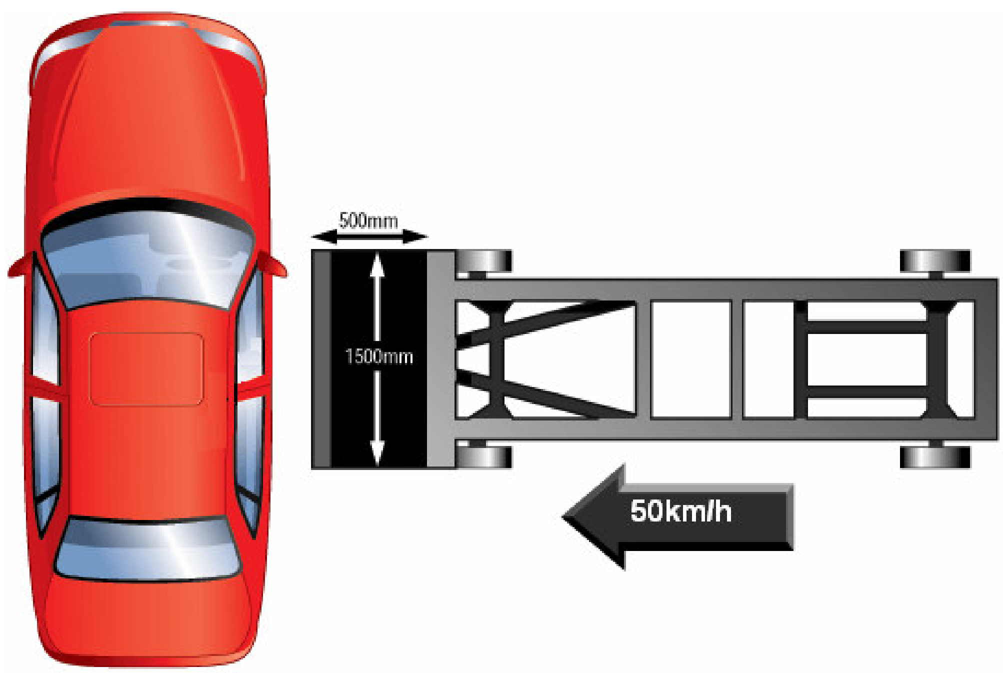

Figure 6.1 : European ECE-R 95 Side Crash test procedure from driver side [6]

As the car manufacturers in Turkey are producing vehicles according to standards for European Union, ECE regulation will be the base for this study. Side crash test and simulation will be done according to ECE Regulation number 95 [5].

6.1.1 ECE-95 European side impact test procedures:

Purpose of lateral impact is to observe the behaviour of the structure of the passenger compartment of M1 and N1 categories (See chapter 2). Passenger compartment means the space for occupant accomodation bounded by roof, doors, floor, side walls, glasses and bulkhead. Bulkhead is a panel used in N category vehicles to seperate the cargo compartment from passenger compartment.

The test will be done on the driver's side if there is not any unsymmetric structure for both sides of the vehicle, if there is an unsymmetric geometry to affect the side crash performance of the vehicle, test authority will decide the impact side of the test with the information given by the manufacturer. But, usually impacting from the opposite side of the driver's side is the least favourable method for testing. In normal conditions, the manufacturer prepares a document showing incompatibilites for both sides and test authority performs the test from driver's side by taking this document into consideration [5].

The three dimensional reference system for a vehicle is defined by three orthogonal planes established by the manufacturer (See Figure 6.2). The coordinates of the reference seating point and vehicle attitude measurement is performed by positioning the vehicle according to supporting plane shown in the same figure (Figure 6.2) below.

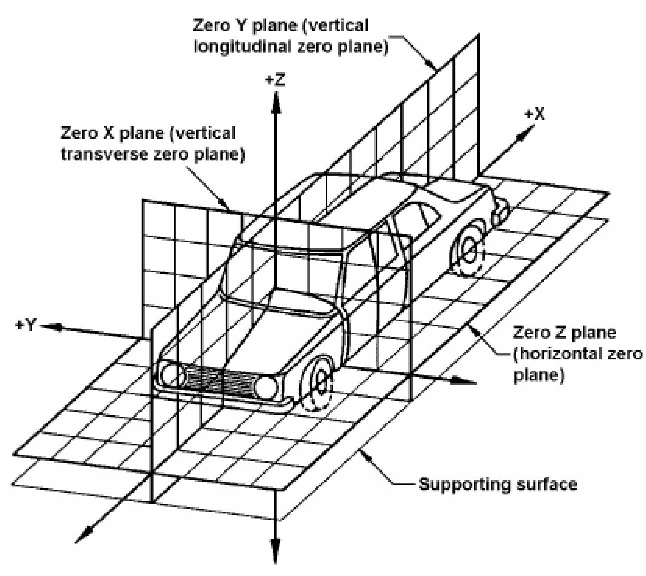

Figure 6.2 : Three dimensional reference system for a vehicle

6.1.1.1 Before test

Test area shall be large enough to let the vehicle and mobile deformable barrier to move safely after the impact occured. Also, test floor will be flat, uncontaminated and representative of a normal and dry road surface. The vehicle which is tested will be stationary in neutral gear and parking handbreak is disengaged. The mobile deformable barrier with a mass of 950 kg will hit the test vehicle at a speed of 50 -/+ 1 kph. However, the impact speed is measured as more than 51 kph and if the vehicle satisfies all of the items in the regulation, test result will be pass. But, if the impact speed is lower than 49kph, new test will be performed. Test vehicle shall be representative of a series production and include all the options normally fitted on the vehicle. Fuel tank will be filled with colourful liquid representing 90% of the mass of the full fuel load of the tank. Colourful liquid must be inflammable material to prevent the fire risk during or after test. And the colour of fuel represanting liquid is different to investigate the leakage of fuel if any leakage occured after the test. The side windows at least on the impact side shall be closed before the test. The doors shall be closed but not locked. If the seats are adjustable, fore-aft location and height location of seat will be adjusted to mid-mid point. If steering wheel is adjustable, all adjustments are positioned to their mid-travel locations [5].

6.1.1.2 After test

After the impact, it shall be possible to open the sufficient number of doors to take the dummy outside from the vehicle without using any tools. None of the doors will open during the test. None of interior device or components will become detached in such a way to increase the risk of injury because of sharp or jagged edges occured in detaching. Ruptures and tears are acceptable if they do not increase the risk of injury after the test was performed. If there is a continuous leakage of liquid from fuel system, the amount of liquid shall not exceed 30grams/minute [5].

6.1.2 ECE-95 European side impact dummy procedures

The side impact dummy (EuroSID) shall be fitted in the front seat on the impact side of the vehicle. Seat belts or restraint systems will be adjusted to fit the dummy according to vehicle manufacturer’s directives on front seat. The dimensions and masses of the side impact dummy should represent 50% percentile adult male without lower arms. Front view of side impact dummy sketch shown in Figure 6.3 below. Part details of side impact dummy are shown from Figure 6.4 to Figure 6.8 below. Side impact dummy component numbers and details are shown in Table 6.1 below [5].

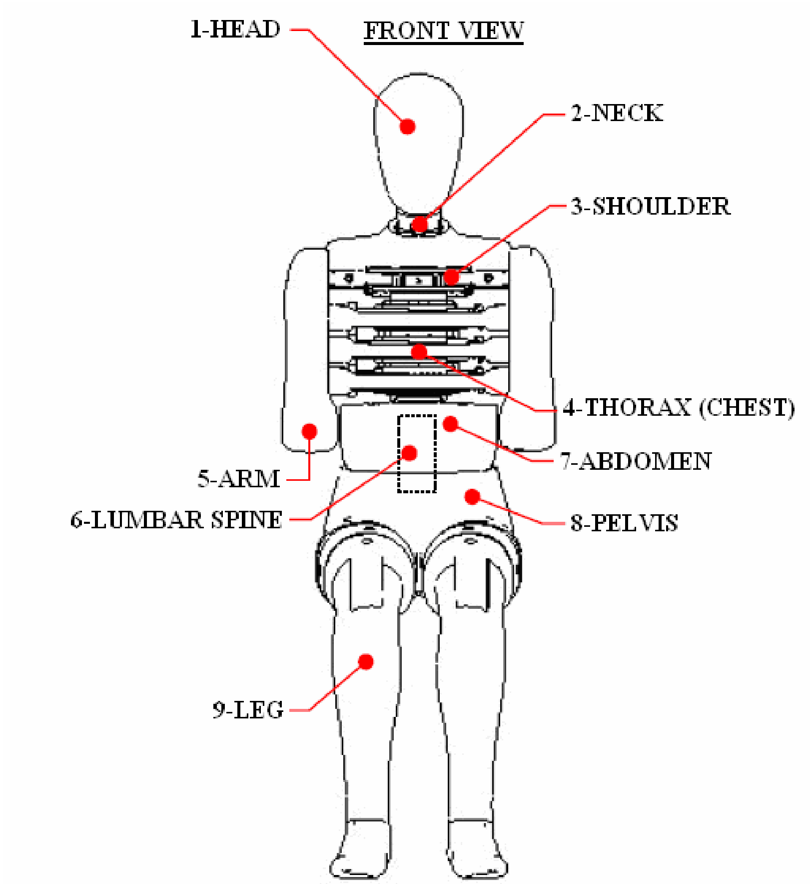

Figure 6.3 : Front view of side impact dummy sketch

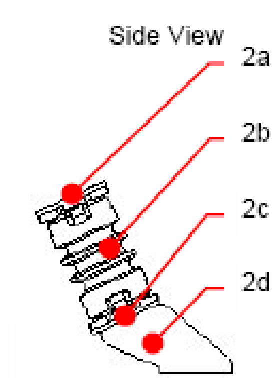

Figure 6.4 : Side view of side impact dummy neck part

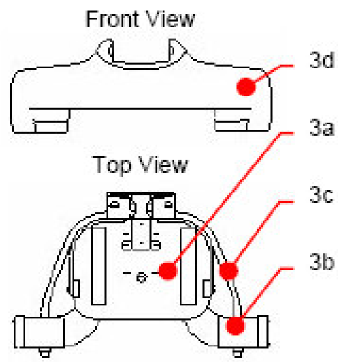

Figure 6.5 : Front and top views of side impact dummy shoulder part

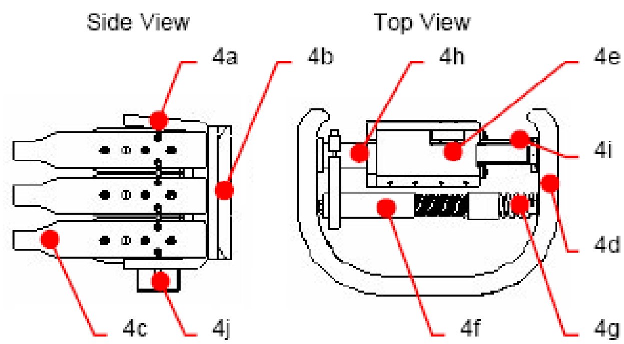

Figure 6.6 : Side and top views of side impact dummy thorax part

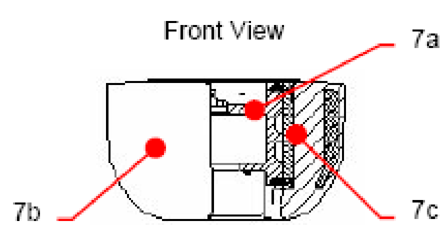

Figure 6.7 : Front view of side impact dummy abdomen part

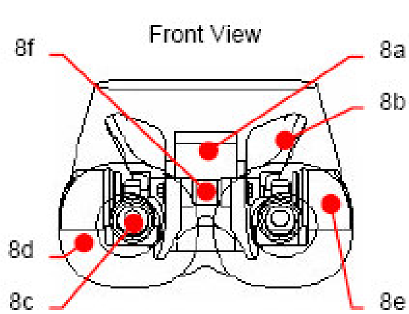

Figure 6.8 : Front view of side impact dummy pelvis part

Table 6.1: Side impact dummy component numbers and descriptions

Part	No	Description
1		**HEAD**
2		**NECK**
	2a	Head-neck interface
	2b	Central section
	2c	Neck-thorax interface
	2d	Neck bracket
3		**SHOULDER**
	3a	Shoulder box
	3b	Clavicle
	3c	Elastic cord
	3d	Shoulder foam cap
4		**THORAX (CHEST)**
	4a	Thoracic spine
	4b	Back plate
	4c	Rib module
	4d	Rib bow covered with flesh
	4e	Piston-cylinder assembly
	4f	Damper
	4g	Stiff damper spring
	4h	Tuning spring
	4i	Displacement transducer
	4j	T12 load cell
5		**ARM**
6		**LUMBAR SPINE**
7		**ABDOMEN**
	7a	Central casting
	7b	Foam covering
	7c	Force transducer
8		**PELVIS**
	8a	Sacrum block
	8b	Iliac Wings
	8c	Hip joint assembly
	8d	Flesh covering
	8e	H-point foam block
	8f	Force transducer
9		**LEG**

6.1.3 General specifications of mobile deformable barrier

The mobile deformable barrier includes both impactor and trolley. Total mass of barrier shall be 950kg -/+ 20kg. Wheelbase of the trolley shall be 3000mm -/+ 10mm. The ground clearance of the impactor shall be 300mm -/+ 5mm measured in static conditions from the lower edge of the lower front plate before the impact [5].

6.1.4 General specifications of impactor

The impactor consists of six single blocks of aluminium honeycomb, which have been processed in order to give a progressively increasing level of force with increasing deflection. Front and rear aluminium plates are attached to the aluminium honeycomb blocks. General view of plascore progressive impactor is shown in Figure 6.9 below [5].

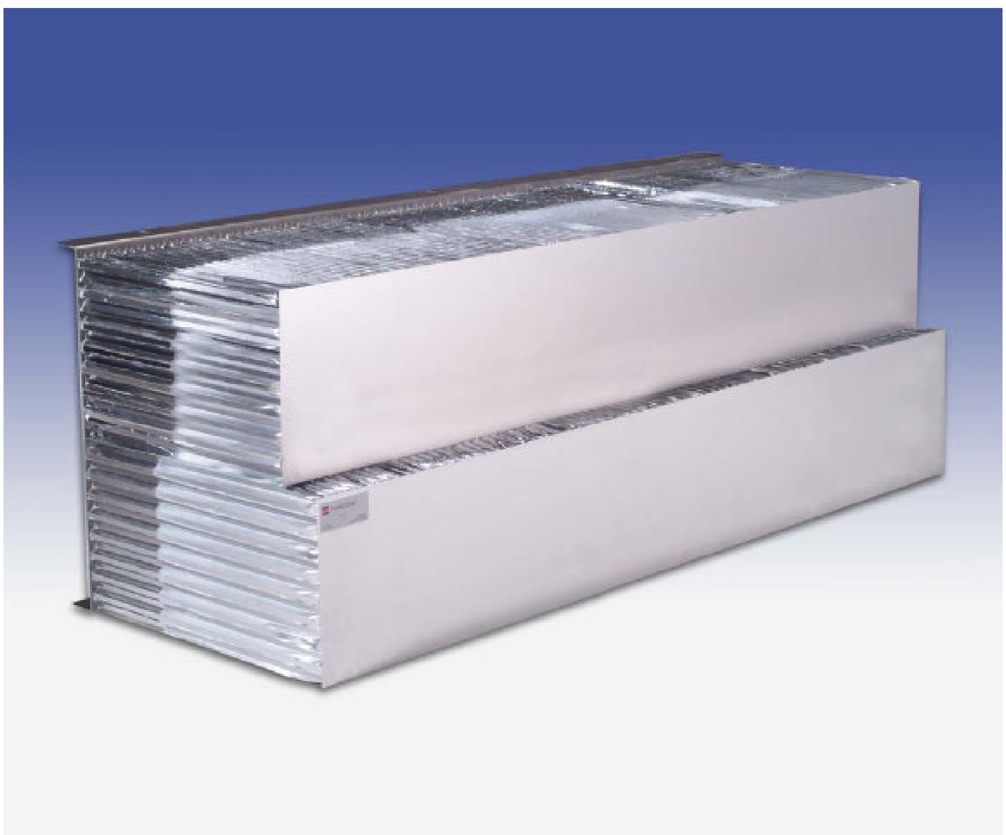

Figure 6.9 : Plascore progressive impactor

6.1.4.1 Honeycomb blocks

The impactor consists of 6 joined zones whose forms and positioning are shown in Figures 6.10 and 6.11 below. The zones are defined as 500 ± 5 mm x 250 ± 3 mm in Figures 6.10 and 6.11. 500 mm should be in the W direction and 250 mm in the L direction of the aluminium honeycomb construction.

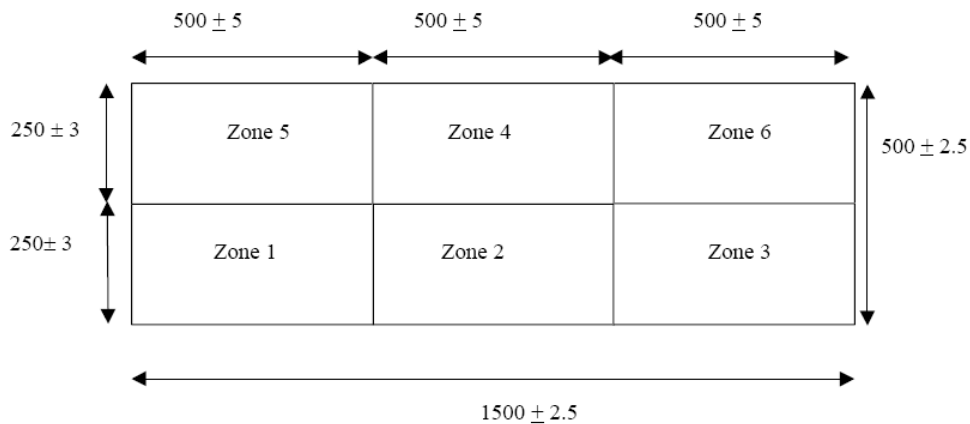

Figure 6.10 : Design of impactor (Front View)

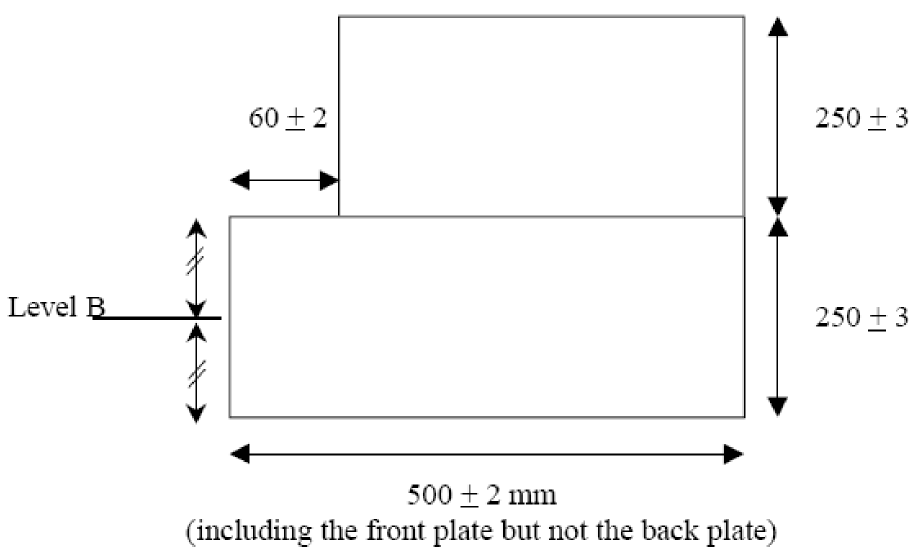

Figure 6.11 : Design of impactor (Side View)

Honeycomb construction is shown in Figure 6.12 below.

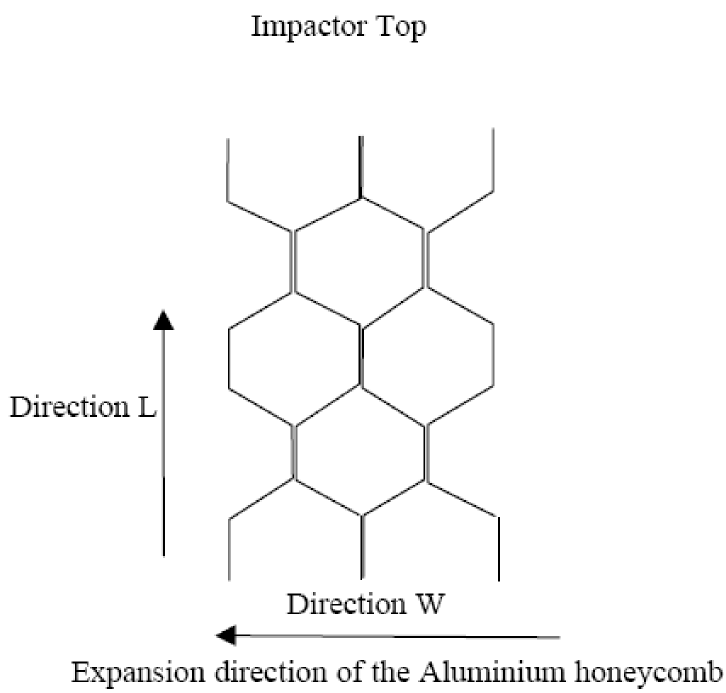

Figure 6.12 : Aluminium Honeycomb Orientation (Top View)

The impactor is divided into 2 rows. The lower row shall be 250 ± 3 mm high, and 500 ± 2 mm deep after pre-crush, and deeper than the upper row by 60 ± 2 mm. The pre-crush shall be performed on the surface of the honeycomb to which the front sheets are attached. Blocks 1, 2 and 3 shall be crushed by 10 ± 2 mm on the top surface prior to testing to give a depth of 500 ± 2 mm. Blocks 4, 5 and 6 shall be crushed by 10 ± 2 mm on the top surface prior to testing to give a depth of 440 ± 2 mm [5].

6.1.4.2 Material characteristics of impactor

The cell dimensions shall be 19 ± 10% for each block (See Figure 6.13).

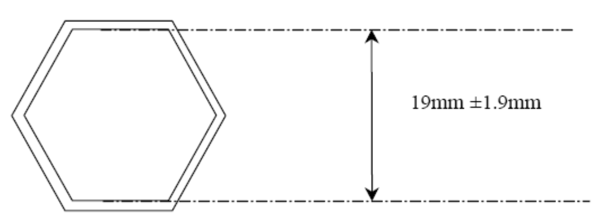

Figure 6.13 : Dimension of Aluminium Honeycomb Cells (Top View)

The cells shall be made of 3003 aluminium for the upper row (Zone 4, 5, 6). The cells shall be made of 5052 aluminium for the lower row (Zone 1, 2, 3).

6.1.4.3 Front plates

The dimensions of the front plates are 1500 + 1mm wide and 250 + 1mm high.The thickness is 0.5 ± 0.06 mm (0.02"± 0.002"). When assembled the overall dimensions of the impactor shall be 1500 ± 2.5mm wide and 500 ± 2.5mm high. The upper edge of the lower front plate and the lower edge of the upper front plate shall be aligned within 4mm (0.157"). The front plates are manufactured from aluminium of series Al Mg 2.5 (5052) with elongation =12%, and a UTS = 228 N/mm2 (33 ksi) [5].

6.1.4.4 Back plate

The geometrical detail for back plate is shown in Figure 6.14. Attachment of backplate to ventilation device and trolley back plate is shown in Figure 6.15. The back plate shall consist of a 3 mm (0.118") aluminium sheet. The back plate shall be manufactured from aluminium of series Al Mg 2.5 (5052) with a hardness of 60 HBS. This plate shall be perforated with holes for ventilation (See Figure 6.14).

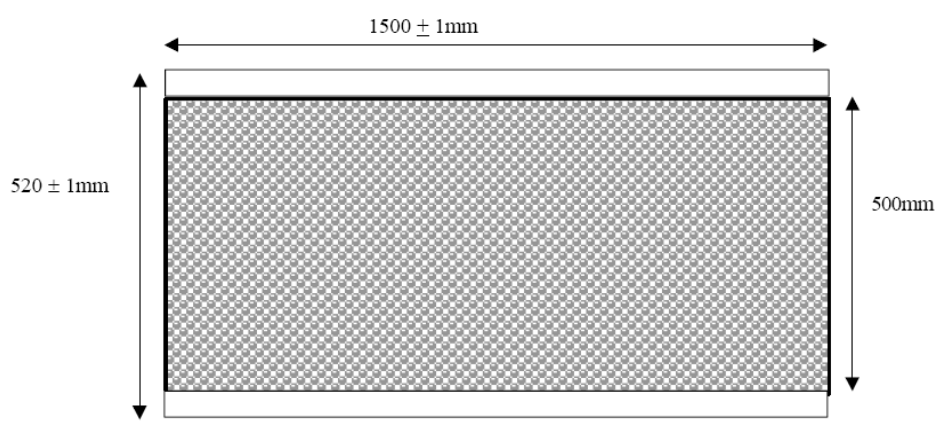

Figure 6.14 : Design of the back plate (Front View)

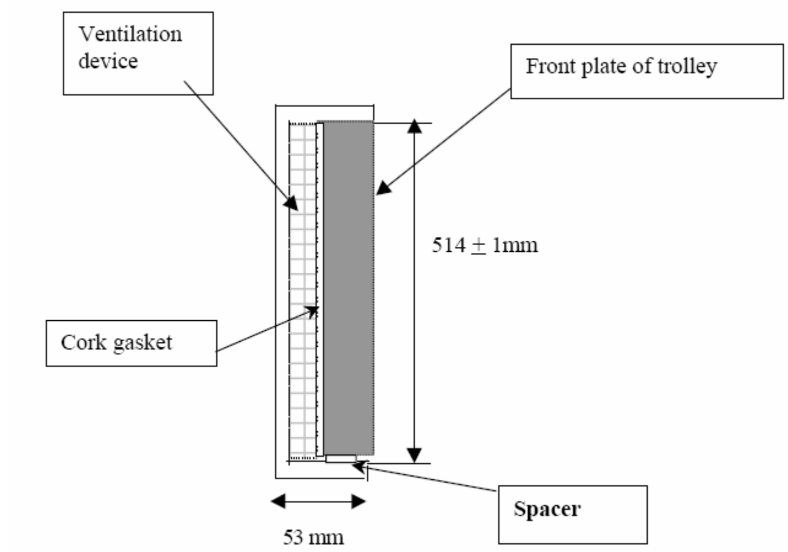

Figure 6.15 : Attachment of backplate to ventillation device and trolley back plate (Side View)

6.1.4.5 Impactor attachment

Six metric 8 bolts are used for the fitting of the impactor on the trolley. Nothing shall be larger than the dimensions of the barrier in front of the wheels of the trolley. Appropriate spacers must be used between the lower back plate flange and the trolley face to avoid bowing of the back plate when the attachment bolts are tightened [5].

7. FINITE ELEMENT USAGE AND IMPORTANCE

Automotive safety has been studied since the first fatality occurance on a motor vehicle in 1889. Occupant safety has been rising and become an important decision criteria for customers among all the performance criterion and specifications of ground transportation vehicles. Nowadays, transportation safety studies focus on crashworthiness, crash avoidance, driver performance and constructing safer highways. “Crashworthiness” term has a meaning that providing measure of vehicle’s structural ability to plastically deform and yet maintain a sufficient survival space for its occupants during crashes involving reasonable deceleration loads. Restraint systems like seat belts and occupant packaging can be helpful factors for reducing severe injuries and fatalities. Crashworthiness evaluation is achieved by both several tests and analytical methods.

In the early phases of automotive history, vehicle bodies were manufactured from wood which can only avoid vehicle deformations restrictively in terms of crashworthiness. Over the years, the body structures designed to obtain progressive crush zones to absorb some of the kinetic energy by plastic deformations. Today, vehicle bodies are built from stamped steel panels. Designers take care about maintaining integrity of the passenger compartment and controlling the crash deceleration pulse to stay below the limit of human tolerance when they are creating the vehicle body structure. Therefore, the purpose of crashworthiness is as follows: An optimized vehicle structure that can absorb some of the crash energy by controlled vehicle plastic deformations and also minimize the crash loads which are transferred to the vehicle occupants by using restraint systems.

In the beginning of automotive history, structural design could be done by extensive testing and experience. Available analytical tools for calculating the strength of materials were rare and engineers could not estimate the overall crashworthiness until a vehicle prototype was built and tested. To ensure the crashworthiness and satisfy the local and also international regulations, the manufacturer may test approximately 100 prototype vehicles, with each early prototype costing around $500.000. In recent years requirements like safety regulations, fuel economy, low cost of manufacturing and reduction in design cycle time have provided a momentum for the development of mathematical tools for crashworthiness evaluations which is more effective and useful than simple strength of material calculations.

With the improvements in computer technology and success of finite element techniques in crash simulation, new vehicle development approach at most of the vehicle manufacturer companies has become a Computer Aided Engineering (CAE) leaded process. CAE is effectively used to provide directions for Confirmation Prototype (CP) design and to guide prototype development to meet front impact, side impact, rear impact, roof crush and interior head impact requirements. Even with the increasing regulatory requirements, the number of crash prototypes needed for safety development is becoming smaller. With preceding CAE evaluation, prototype tests are becoming more successful every time. Numbers of component and sled tests are decreasing rapidly.

Use of CAE in the automotive industry has becoming more popular day by day and CAE allows design community to try many alternatives simultaneously compared to prototype testing cost and timing. CAE usage results in better engineered and lower costed product development.

Safety CAE has a major and also very critical role in product development process to provide integrated design directions during product development phases. CAE ensures that all new vehicles meet local and necessary global safety requirements.

In spite of the enormous progress succeeded in crashworthiness simulations of vehicle structures from components to detailed finite element models with millions of elements and degrees of freedom, using highest technology and techniques in computational mechanics and super computers, final crashworthiness assessment still depends on laboratory tests. This is also valid in vehicle certification [11, 12].

8. FINITE ELEMENT MODELING IN SIDE CRASH TEST

8.1 Mathematical Model Of Crash Simulation With Radioss Software

Radioss is a finite element software produced by Mecalog Group. Radioss uses explicit or implicit time integration scheme with a Lagrangian, Eulerian or an arbitrary Euler-Lagrange formulation. It allows mechanical, structural, fluid mechanics or fluid-structure interaction problems resolution, under dynamic or static solicitations. The structures can be subjected to large strains, large displacements and large rotations by using the material's non-linear behaviours. Radioss has a high level and efficient parallelism and it obtains exactly the same results regardless of processor numbers in terms of performance and compatibility. Technically, Radioss is an efficient software regarding material laws. Radioss allows to deal with all the structure mechanics, fluid and fluid-structure interaction problems [13].

8.1.1 Method

Radioss solves the momentum equation during analysis:

$$\frac{\partial \sigma_{ij}}{\partial x_j} + \rho b_i = \frac{\partial v_i}{\partial t} \qquad \textbf{(8.1)}$$

Where;

σ_{ij} = Cauchy stress tensor **(8.1a)**

b_i = Body force **(8.1b)**

x_j = Displacement vector **(8.1c)**

v_i = Velocity of displacement **(8.1d)**

ρ = Density **(8.1e)**

When finite element method is used to solve the momentum equation, the equation is formulated as a system of ordinary differential equations,

$$M\left\{\frac{dv}{dt}\right\}=\{F_{ext}\}-\{F_{\text{int}}\}+\{F_{bod}\} \tag{8.2}$$

Where;

M = Mass matrix **(8.2a)**

v = Velocity vector **(8.2b)**

F_{ext} = External force vector **(8.2c)**

F_{int} = Internal force vector (stress divergence vector) **(8.2d)**

F_{bod} = Body forces vector **(8.2e)**

The equation is solved in the time domain by using central difference method in explicit integration.

$$v_{t+\frac{\Delta t}{2}}=v_{t-\frac{\Delta t}{2}}+\frac{dv}{dt}\Delta t$$

(8.3)

$$x_{t+\Delta t}=x_t+v_{t+\frac{\Delta t}{2}}\Delta t$$

(8.4)

Δt is time step and according to Courant condition,

$$\Delta t\leq\frac{\Delta l}{C} \tag{8.5}$$

Where; Δl is characteristic element length and C is sound speed [14].

8.2 Finite Element Model Description

The finite element model represents a right-hand drive light commercial vehicle's ECE R-95 50km/h side impact test. Test is performed by crashing the moving deformable barrier at a velocity of 50km/h into a stationary vehicle. The vehicle includes the driver dummy and mass of the vehicle is adjusted to match the mass of a production level vehicle with all accessories. Finite element model's front and rear axle loads are the same with test vehicle's axle loads. Data is collected from the dummy and vehicle itself. Collected data are processed and injury criteria are calculated as mentioned in crash injury criteria section.

The finite element model of light commercial vehicle shown in Figure 8.1 and Figure 8.2 is created by using "Altair Hypermesh" and "Mecalog M-Crash" preprocessor softwares [15, 16]. Model contains 693811 nodes and 695757 elements. All structural parts are modeled as surface generated by triangular and quadrilateral shell elements. Solid elemets are used for the thick parts which are not suitable for shell type element mesh. All connectivity parts like; bolts, spotwelds, arcwelds and adhesives are modeled using spring, beam, truss and rigid body type one dimensional elements.

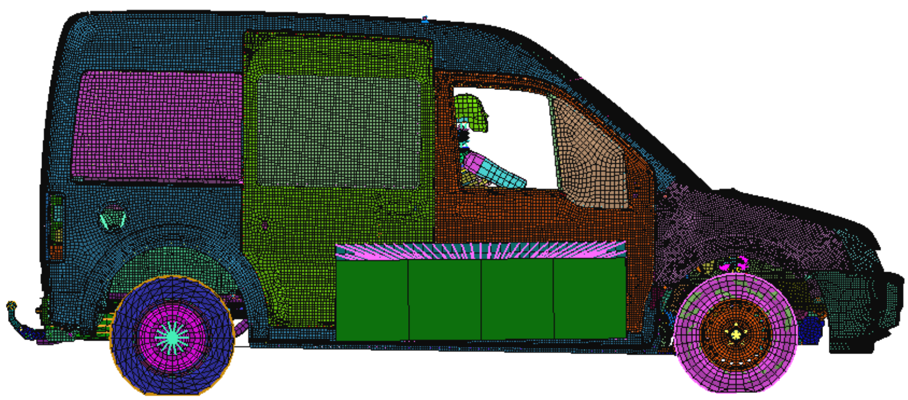

Figure 8.1 : Finite element model side view

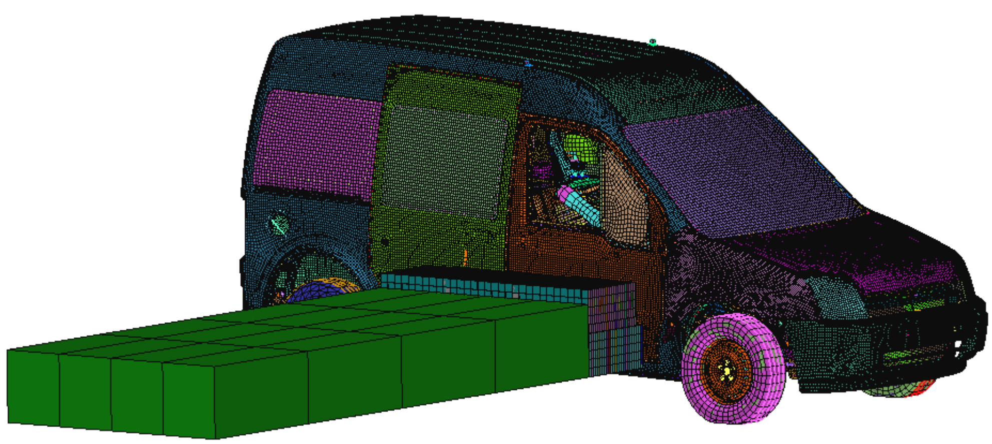

Figure 8.2 : Finite element model isometric view

8.2.1 Modeling of structural items

All structural and critical energy absorbing parts are modeled in details. In side impact case; front door, underbody floorpan, dash & cowl, and side load door are the most energy absorbing parts on the vehicle as shown in Figure 8.3, Figure 8.4, Figure 8.5, Figure 8.6 and Figure 8.7. Other parts like; hood, bumper, fender, rear cargo doors and 3rd row seat, which have not big affect on crash resistance also included into the model to get the proper mass distrubution in terms of axle loads and center of gravity to get better correlation in analysis according to physical test.

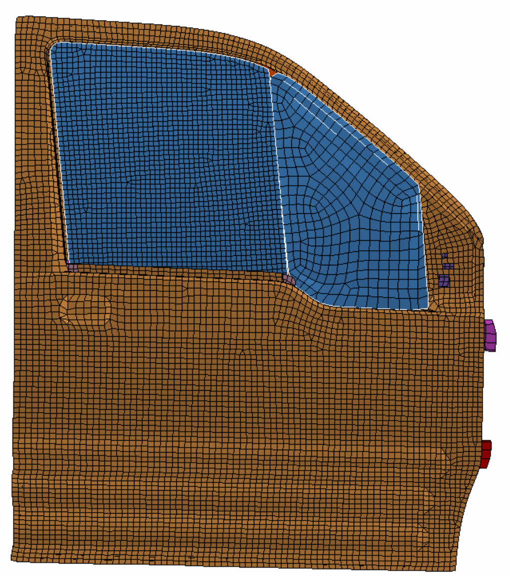

Figure 8.3 : Front right door (Side View)

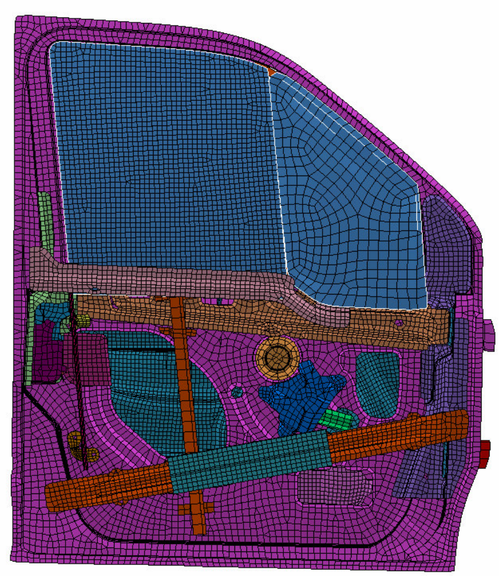

Figure 8.4 : Front right door without outer panel (Side Outer View)

Strainer system inside door assembly can be seen in Figure 8.4. This system increase the stiffness of door and this will help lower the door intrusion values. Element mesh size in energy absorbing parts was chosen around 10mm. Element size smaller than 4mm was not used in the model to avoid small time step problem during analysis run.

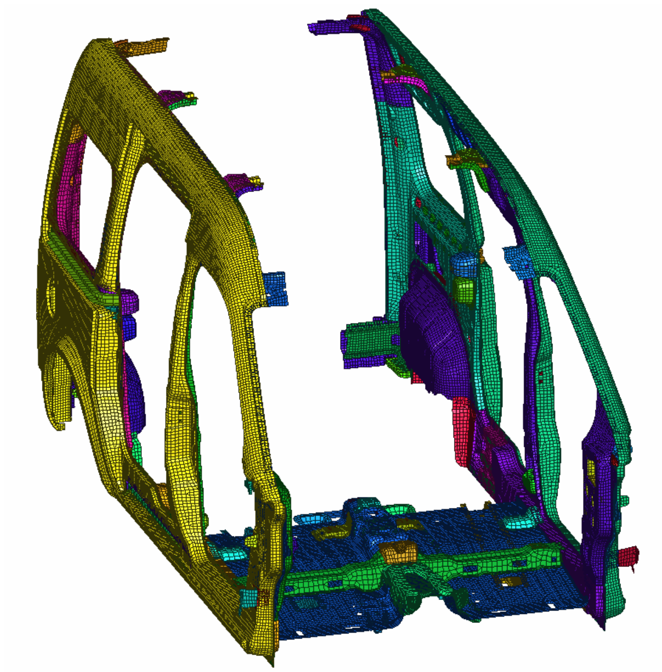

Figure 8.5 : Underbody front floor pan with bodysides (Angular View)

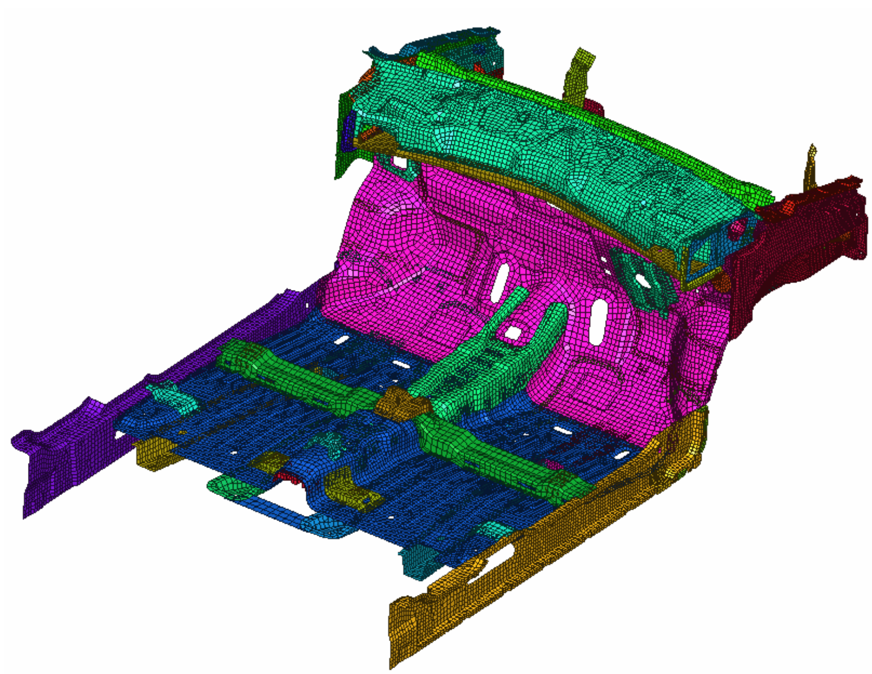

Figure 8.6 : Underbody floor pan with dash & cowl (Angular View)

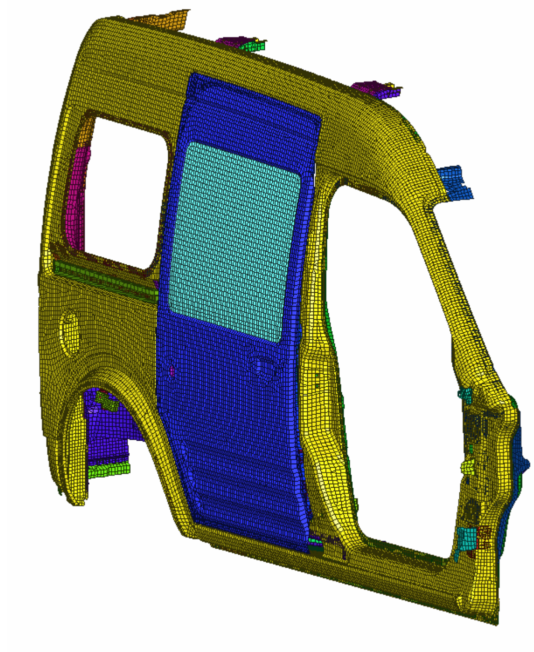

Figure 8.7 : Side load door with bodyside (Angular View)

8.2.2 Material models in analyses

In high speed crash testing like side crash at 50 km/h, some of vehicle parts especially close to impact zone experience big deformations and strain-hardening behaviour can be observed on metarials. Correct definition of strain-hardening in plastic (permanent) deformation is necessary. For many plasticity problems, the hardening behaviour of the material can be characterized by the stress-strain curve of the material.

Johnson-Cook material model is one of the most common used material model in Radioss material database. In this material model, material behaves as linear elastic when the equivalent stress is lower than the yield stress. For higher values of stress, the material behaviour is plastic. This material is applicable to shell, beam, truss and brick element types in Radioss. Mathematical equation of this material model can be defined as:

$$\sigma = \left(a + b\varepsilon_p^n\right)\left(1 + c\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\left(1 - T^{*m}\right) \quad \textbf{(8.6)}$$

Where:

σ = Flow Stress (Elastic + Plastic Components) **(8.6a)**

a = Yield Stress **(8.6b)**

b = Hardening Modulus **(8.6c)**

ε_p = Plastic Strain (True Strain) **(8.6d)**

n = Hardening Exponent **(8.6e)**

c = Strain Rate Coefficient **(8.6f)**

$\dot{\varepsilon}$ = Strain Rate **(8.6g)**

$\dot{\varepsilon}_0$ = Reference Strain Rate **(8.6h)**

m = Temperature exponent **(8.6i)**

$$T^* = \frac{T-298}{T_{melt}-298} \qquad \textbf{(8.6j)}$$

Where T_{melt} is the melting temperature in Kelvin. Test room temperature is assumed as 25°C (298°K). Usually, temperature factor is omitted in the equation.

In Figure 8.8 stress-strain curve for Johnson-Cook material law is shown. Material stress increases an stays constant till its maximum plastic strain value. After this strain value rupture is occured and rupture is simulated by deleting the element of which reaches its maximum plastic strain value [13].

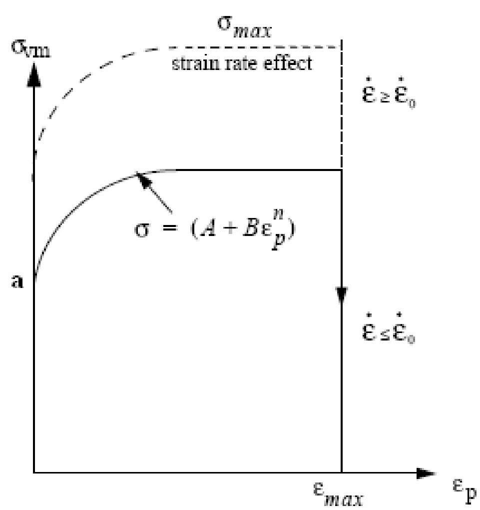

Figure 8.8 : Stress-Plastic strain curve

In finite element model, generic material data, which is shown in Table 8.1, were used. Generic material data is produced through specimens which were obtained from sheet metals. Sheet metal suppliers performed tensile testing to obtain the material data. However, sheet metals are drawn to produce vehicle parts. During deep drawing process, parts undergo strain hardening and crush performance of vehicle parts are better than the parts modeled in finite element model. As a result, vehicle's real test performance is better than finite element model simulation. Some difference can be observed in post-crash displacements between physical test and finite element model.

Table 8.1: Generic material data obtained from sheet metal suppliers

Steel Type	a	b	n	c	$\dot{\varepsilon}_0$
Mild steel	0.170	0.196	0.45	0.0683	$1x10^{-6}$
ZSTE180	0.218	0.334	0.45	0.0265	$1x10^{-6}$
ZSTE220	0.258	0.334	0.45	0.0265	$1x10^{-6}$
ZSTE260	0.287	0.400	0.50	0.0265	$1x10^{-6}$
ZSTE300	0.332	0.468	0.64	0.0275	$1x10^{-6}$
ZSTE340	0.363	0.482	0.70	0.0295	$1x10^{-6}$
ZSTE380	0.389	0.482	0.70	0.0295	$1x10^{-6}$
ZSTE420	0.429	0.638	0.57	0.0209	$1x10^{-6}$
DP600	0.640	2.000	0.80	0.0200	$1x10^{-3}$
DP800	0.800	0.671	0.25	0.0200	$1x10^{-3}$
BORON	1.113	9.402	0.93	0.0200	$1x10^{-3}$

8.2.3 Modeling of deformable barrier

The progressive deformable barrier ,which is used in crash simulation, is obtained from the Mecalog M-Crash barrier database [16]. In deformable barrier model, solid element is prefered instead of shell element for modeling of honeycomb structure. Solid element is chosen to prevent excessive hourglass internal energy generation. Modeling the honeycombs with shell elements make structure stiffer than it used to be. Angular and side views of progressive deformable barrier are shown in Figure 8.9 and Figure 8.10 below.

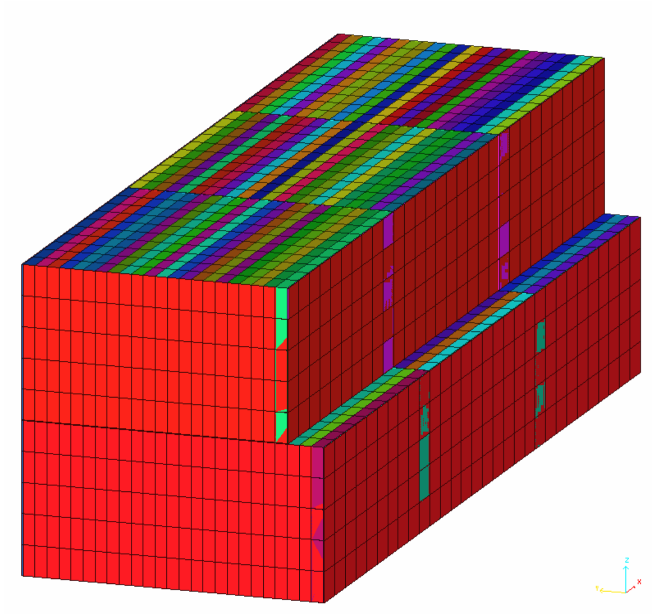

Figure 8.9 : Angular view of progressive deformable barrier finite element model

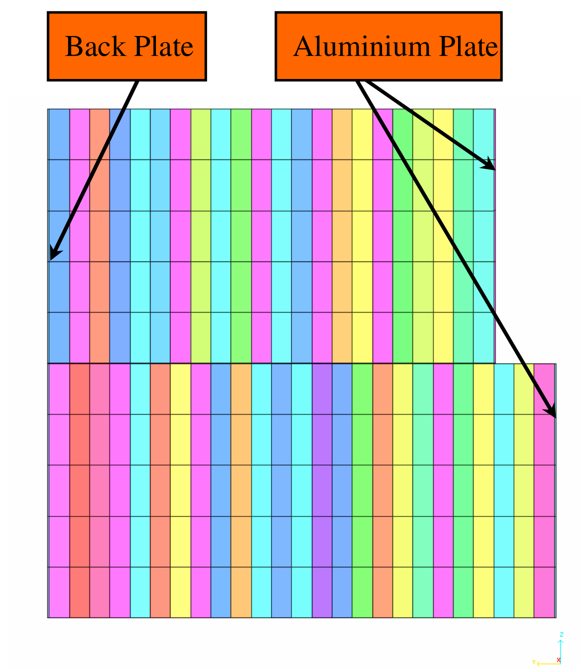

Figure 8.10 : Side view of progressive deformable barrier finite element model

8.2.4 Modeling of side crash dummy

The Eurosid-II dummy used in the analysis is obtained from the Mecalog M-Crash database [16]. In dummy model; shell, solid, spring and rigid body elements are used. Dummy positioned in vehicle according to seat back angle and seat height. Dummy crash performance is calculated by using the data obtained from the accelerometers and load cells instrumented on the dummy in terms of crash injury criteria. Angular view of Eurosid-II dummy finite element model is shown in Figure 8.11 below.

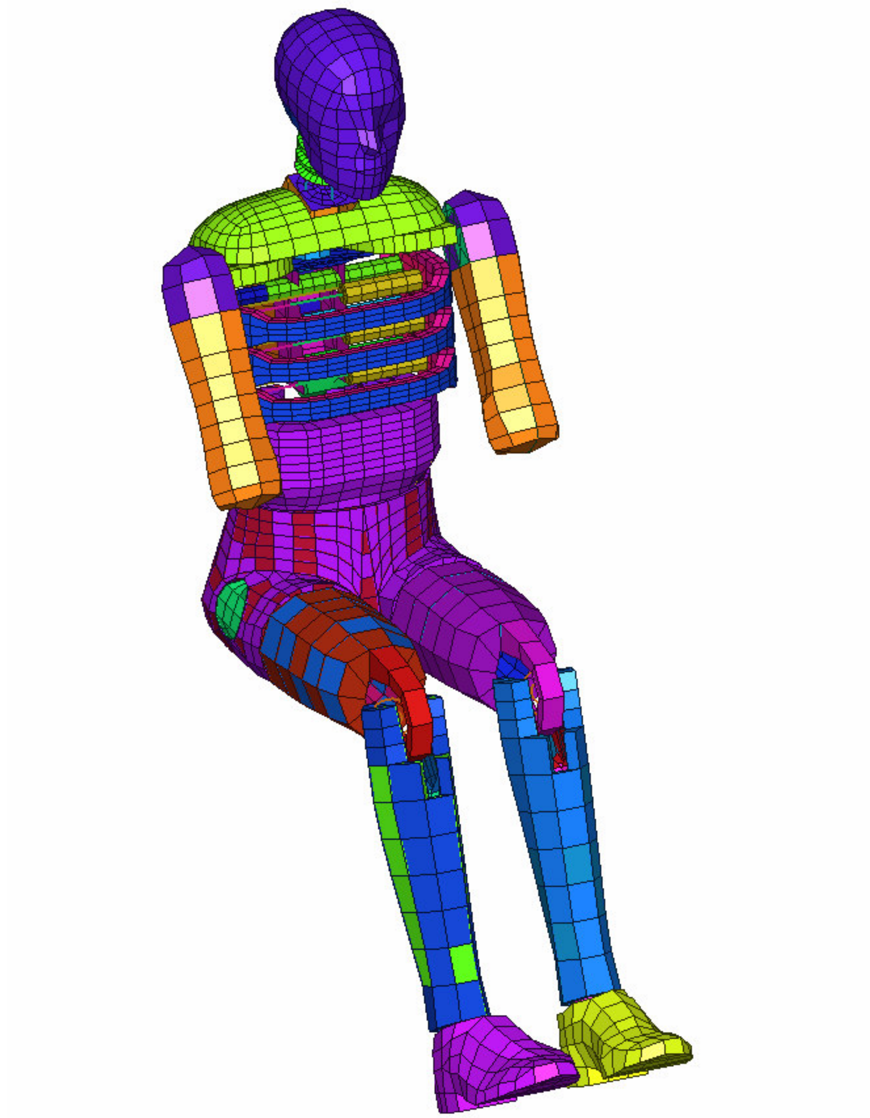

Figure 8.11 : Angular view of Eurosid-II dummy finite element model

9. CRASH TEST AND FINITE ELEMENT MODEL COMPARISON

9.1 Vehicle Deformation Comparison

In the analysis, an initial velocity of 13.89 m/s in negative y direction is applied to all nodes of the barrier. Barrier is constrained in five of six degrees of freedom. Translation in x and z global coordinates, rotation in x, y and z global coordinates are constrained. Only translation in y direction is free. Vehicle bodyside and barrier front plate are positioned so that, at the first milisecond of the analysis, barrier contacts the vehicle bodyside and doors, then crash begins. Analysis runs until vehicle springs back from the barrier (160 miliseconds). Good correlation of real test and finite element model is necessary to make required or desired changes on the vehicle by using finite element model. For correlation purposes of test and finite element model (FEM), displacements and accelerations are checked. Displacements are checked by comparing the displacements from marked points before and after crash. Marked points on test vehicle is shown in Figure 9.1 below.

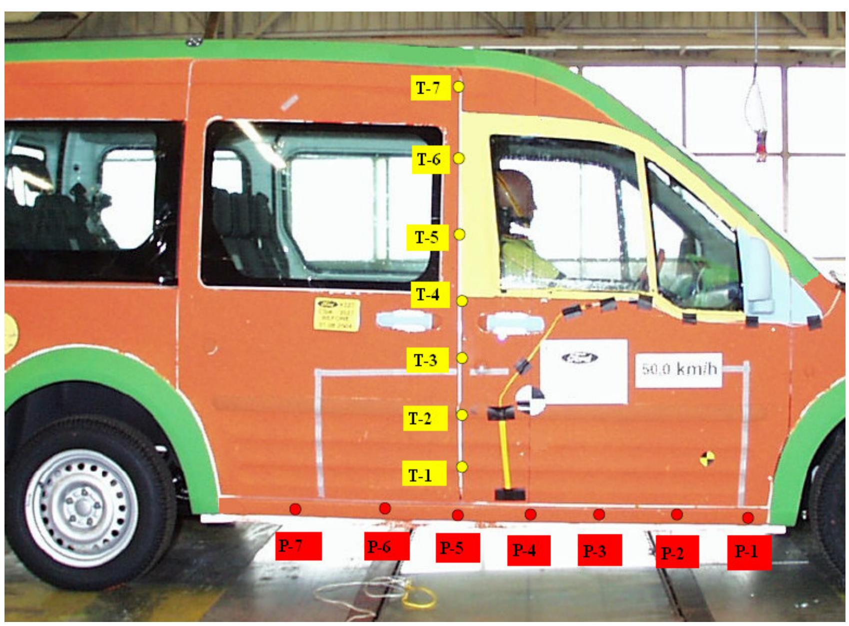

Figure 9.1 : Marked points on the outer surface and inner surface before crash

Accelerations are checked by comparing the pulses measured at the B-Pillar lower ends of the vehicle. Final displacements are calculated from the points on the FEM. FEM displacements are compared to post-crash measurements taken on the real crash test vehicle. Red points on the figure above are bodyside rocker outer points. Yellow points are B-Pillar inner panel points. In Table 9.1, the compared values of total displacement in y direction for real test and analysis are shown.

Table 9.1: Post crash measurements on the vehicle and calculation in FEM

POINT	FEM DISPLACEMENT IN Y DIRECTION [mm]	TEST DISPLACEMENT IN Y DIRECTION [mm]
P-1	47.2	48.0
P-2	88.9	88.9
P-3	162.2	158.8
P-4	191.3	200.7
P-5	141.2	152.3
P-6	107.4	112.5
P-7	60.7	64.9
T-1	148.1	146.8
T-2	138.7	133.4
T-3	125.9	120.3
T-4	109.6	105.9
T-5	92.0	85.7
T-6	53.1	56.6
T-7	28.8	27.2

P and T point's lateral (y direction) displacements are shown as a graph in Figure 9.2 and Figure 9.3 below.

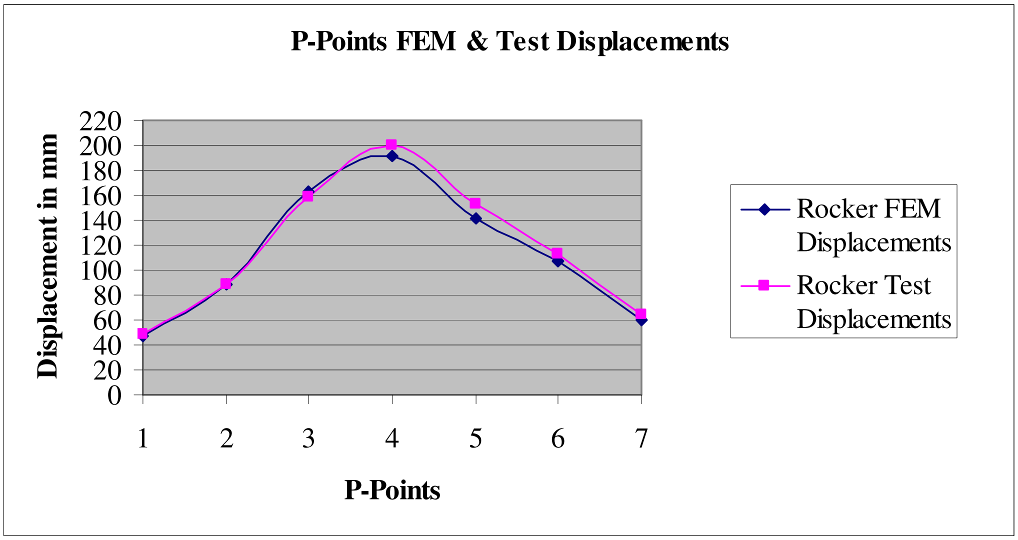

Figure 9.2 : Post crash displacement values of P-Points for FEM and Test

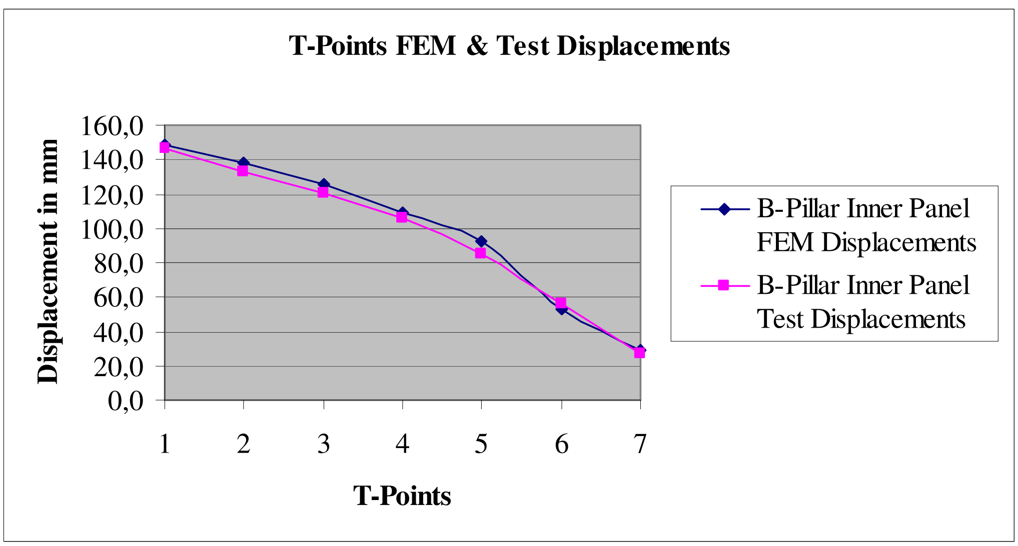

Figure 9.3 : Post crash displacement values of T-Points for FEM and Test

Post crash picture of tested vehicle and underbody view of FEM analysis at the end of simulation are shown in Figure 9.4 and Figure 9.5. Deformation and bending characteristics of the rocker panel are very similar in test and FEM.

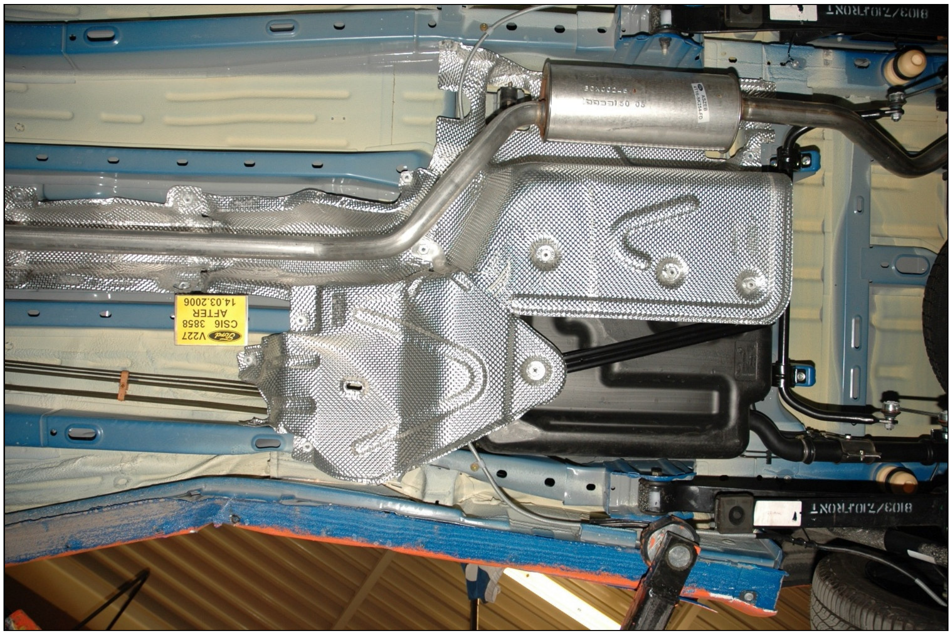

Figure 9.4 : Post crash picture of the test vehicle (Bottom View)

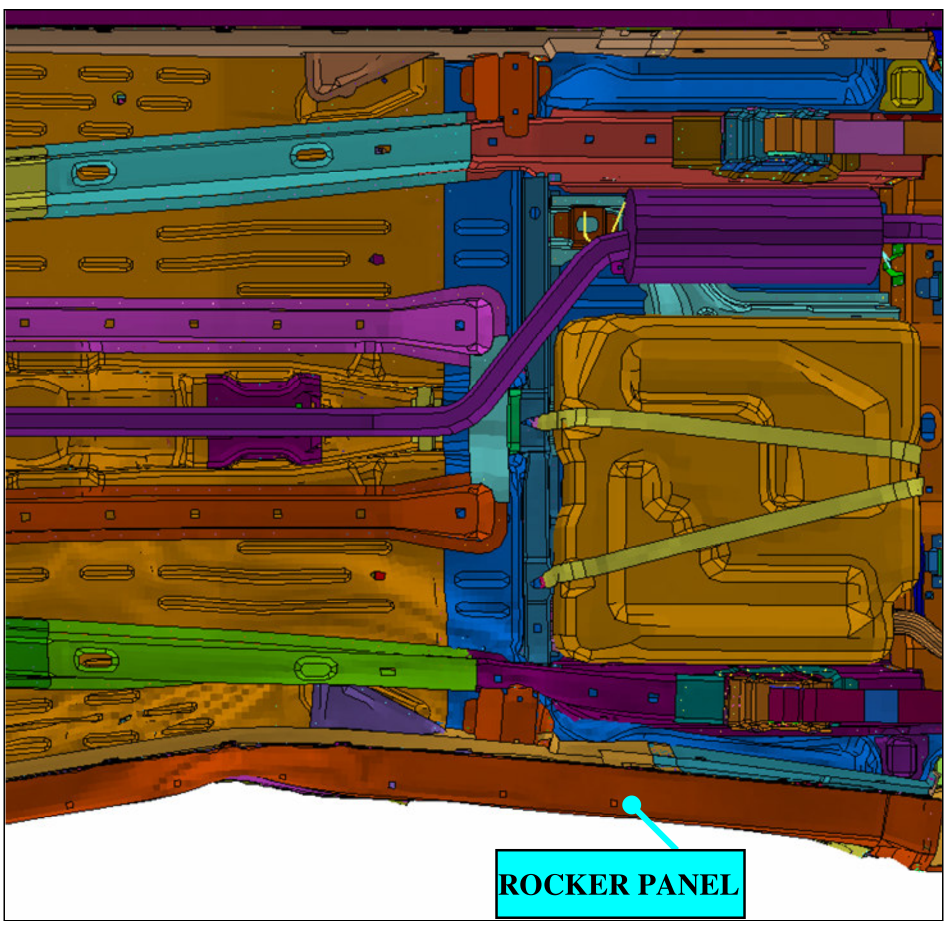

Figure 9.5 : FEM snapshot of the vehicle at the end of analysis (Bottom View)

For comparing the acceleration values of physical test and FEM, various accelerometers are inserted into test vehicle. In side crash analysis, one of the most critical accelerometer location is B-Pillar lower location. For side crash test, in which barrier impacts from right side of the vehicle, the right hand side lower accelerometer is used to measure the deformation of the structure. Left hand side lower accelerometer is located on the non-deformed side and used to measure the movement of the vehicle during test. The accelerometer locations are shown in Figure 9.6 below.

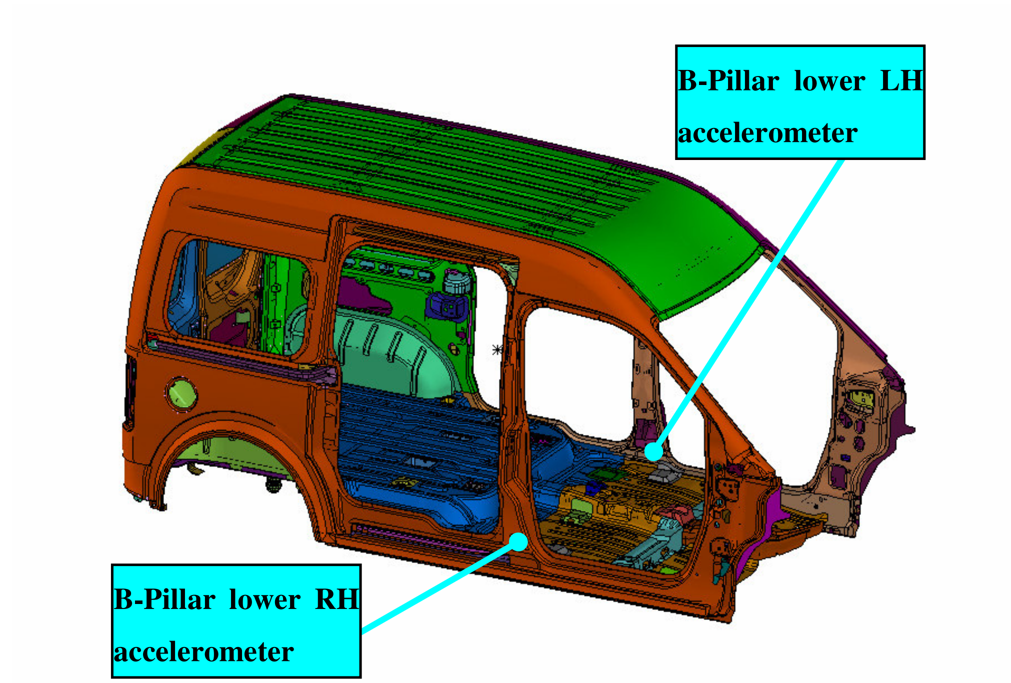

Figure 9.6 : Accelerometer locations at B-Pillar lower left and right hand side

B-Pillar lower left hand side acceleration data for physical test and calculated acceleration data for FEM is shown in Figure 9.7. B-Pillar lower right hand side acceleration data for physical test and calculated accelertion data for FEM is shown in Figure 9.8 below.

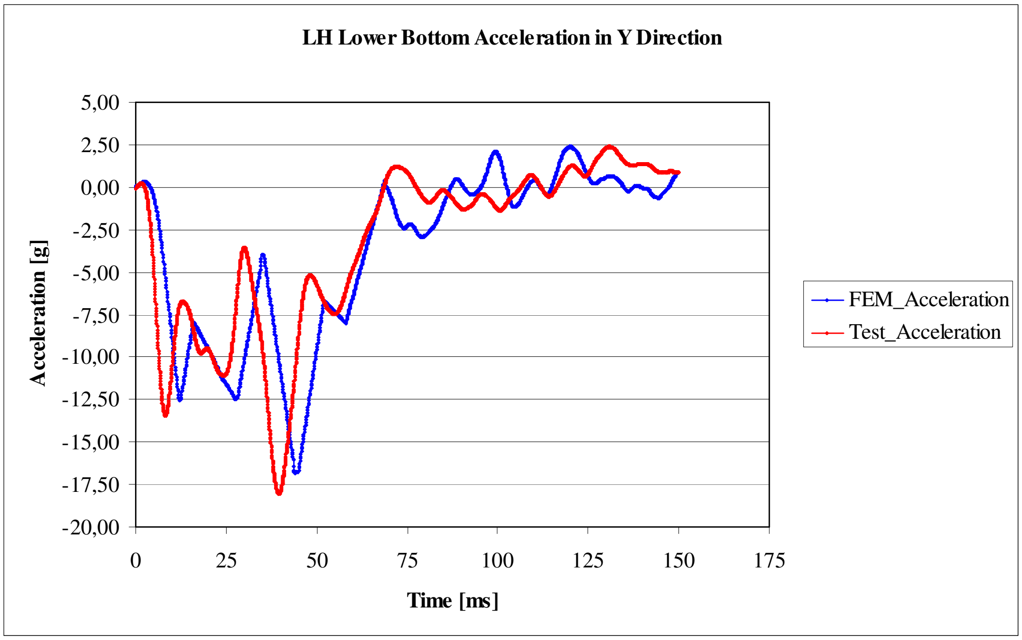

Figure 9.7 : B-Pillar lower left hand side acceleration values for physical test and Finite Element Model

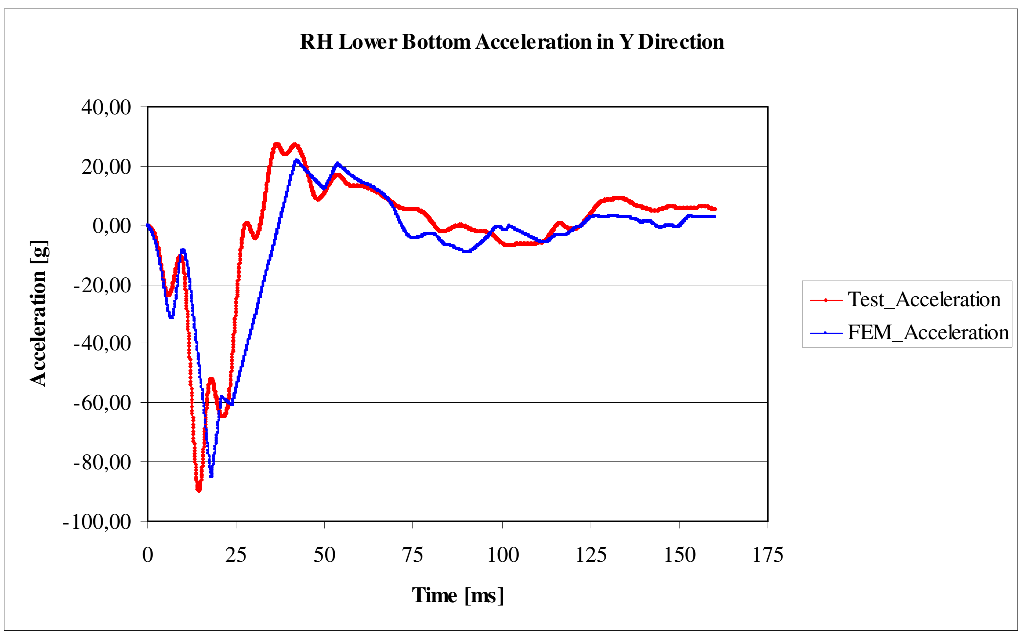

Figure 9.8 : B-Pillar lower right hand side acceleration values for physical test and Finite Element Model

9.2 Seat Envelope And Dummy Seating Position

Vehicle manufacturers define a seat envelope for driver and passengers in the beginning of each vehicle project according to ergonomy requirements. Driver visibility, distance to shifter knob, distance between H-point and heel point, distance to steering wheel and H-point distance to depressed clutch pedal actutation point are the most important items for creating the seat envelope. Border of the envelope is defined according to H point (Hip joint point) of 95th percentile male dummy. 95th percentile male dummy's seat envelope also covers and valid for 50th percentile male and 5th percentile female dummies. In the vehicle tested, seat envelope allows driver to travel 228 mm in x direction (longitudinally forward and rearward of the vehicle) and 31 mm in z direction (vertically upwards and downwards of the vehicle). Seat envelope is shown by red coloured rectangular frame in Figure 9.9 below.

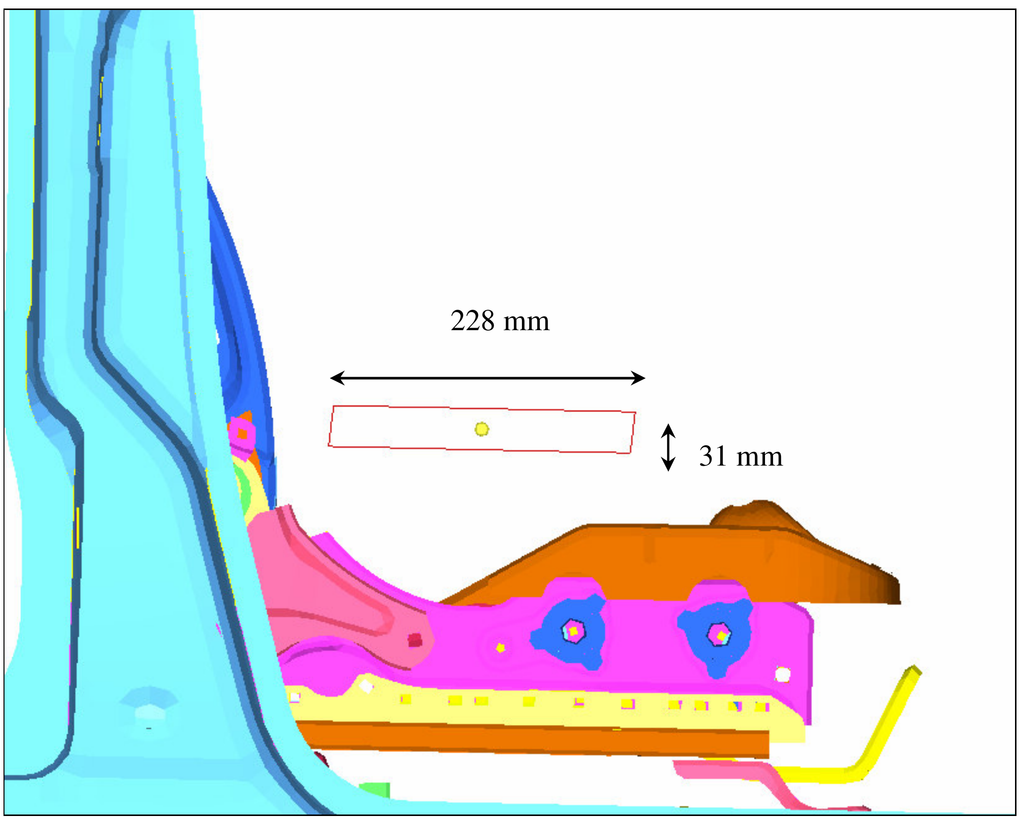

Figure 9.9 : Seat envelope of commercial vehicle (Side View)

In side crash test and analyses according to ECE-R95, 50th percentile dummy's H-point must be in mid-mid position of seat envelope. Mid-mid means middle point of longitudional line and middle point of horizontal line of the seat envelope which is also the geometrical centre of seat envelope. H-point of dummy is shown by yellow spot in seat envelope in Figure 9.10 below. To see the seat envelope clearly seat foam and cushion is removed from display screen.

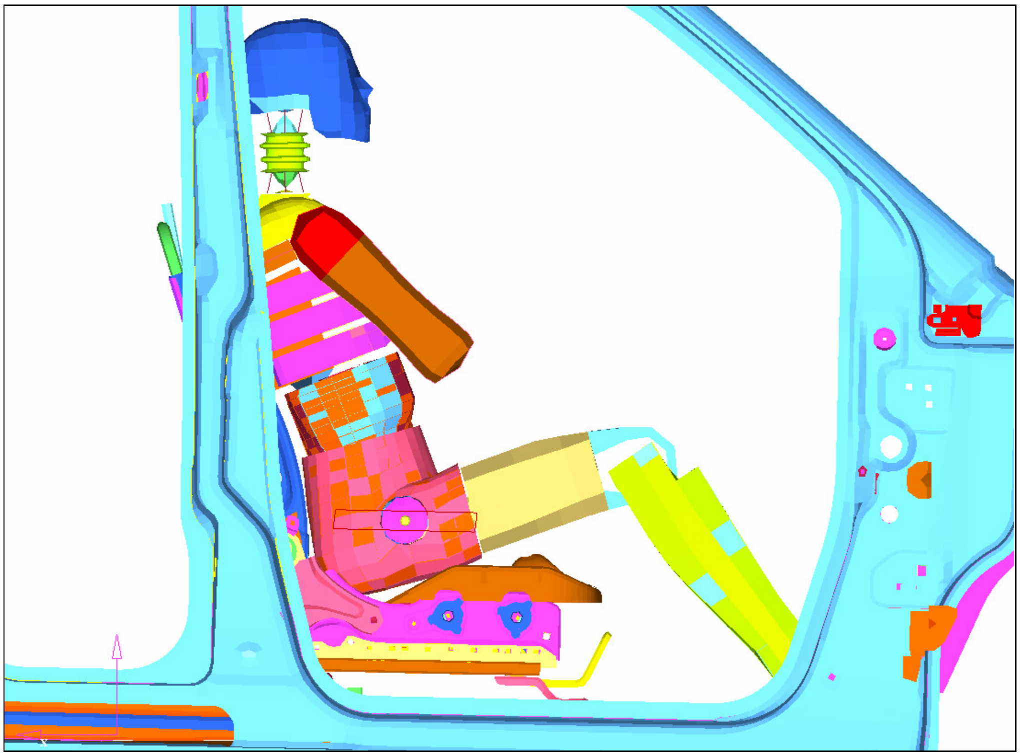

Figure 9.10 : Seating position of 50th percentile dummy in mid-mid position (Side View)

9.3 Test And FEM Dummy Injury Criteria Comparison

Acceleration, displacement and load cell data collected from physical test dummy are used to calculate the injury criteria according to ECE 95 regulation. Head Injury Criteria (HIC), rib deflection, viscous criterion, abdomen load and pubic load criteria of test dummy and calculated FEM dummy results are compared and shown in Table 9.2 below.

Table 9.2: Injury criteria values of test dummy and FEM dummy

Injury Criteria	Test	Finite Element Model	ECE-95 Max. Values
HIC	96,94	105,6	1000
Rib deflection upper	19,21 mm	20,69 mm	42 mm
Rib deflection middle	20,54 mm	21,42 mm	42 mm
Rib deflection lower	21,87 mm	22,11 mm	42 mm
Viscous criterion upper rib	0,236 m/s	0,264 m/s	1 m/s
Viscous criterion middle rib	0,194 m/s	0,208 m/s	1 m/s
Viscous criterion lower rib	0,293 m/s	0,304 m/s	1 m/s
Abdomen load	0,797 kN	0,848 kN	6 kN
Pubic load	1,23 kN	1,14 kN	6 kN

Injury criteria values measured during test and calculated in the analysis are close and good correlation is achieved between the test and analysis. Looking at the results, HIC value is very low compared to ECE 95 regulation target. This is because, no impact was observed between head and side door glass both in test and analysis. Head was moving naturally according to body movement during impact. If there had been a contact between head and window or head and B-pillar trim, HIC value would have been higher. Rib deflection and rib viscous criterion values are below regulation limits. Abdomen load and pubic load are also lower than the maximum acceptable regulation limits.

10. DUMMY PERFORMANCE AT VARIOUS LOCATIONS

10.1 Various Positions Of Seat Envelope

After obtaining a correlation between test and finite element analysis, dummy injury criteria performance for various locations of seat envelope were calculated by rerunning the model with seat and dummy repositioned in the vehicle. Eight locations were chosen on the edges of seat envelope. Physical test correlation model was in mid-mid position. Total nine locations for dummy H-point are shown with yellow spots on the edges of seat envelope, which is shown by green coloured rectangular, in Figure 10.1 below.

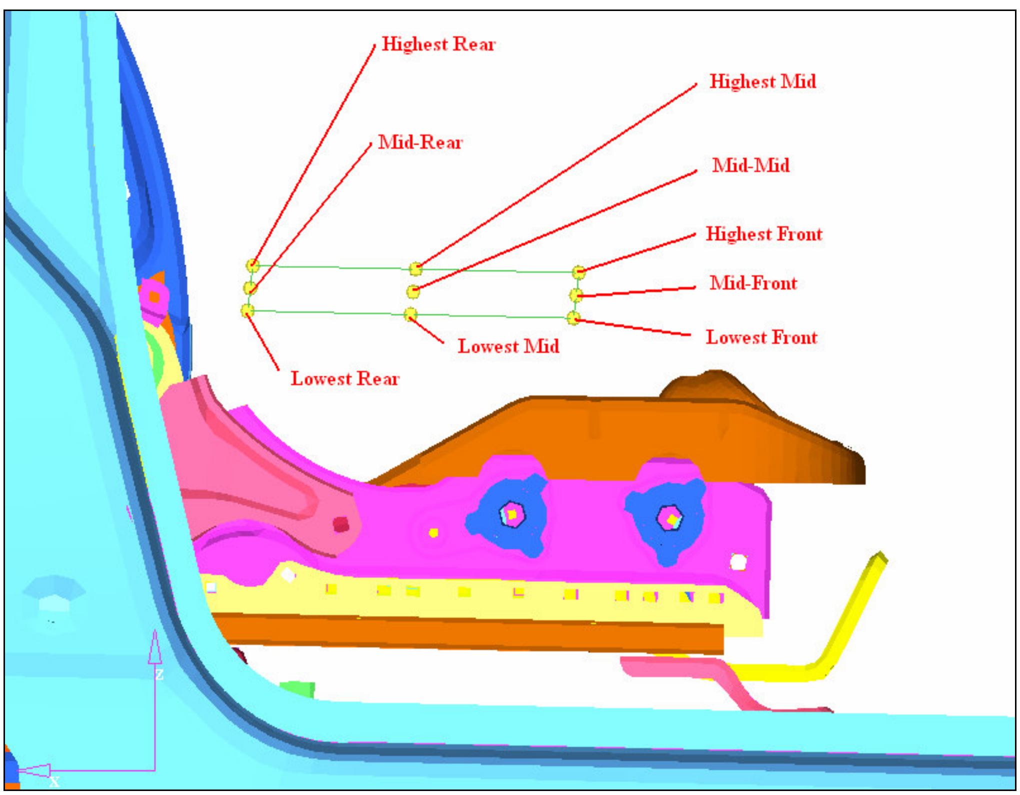

Figure 10.1 : Chosen eight locations and mid-mid location for H-point

Coordinates and name of the locations are listed below. These are;

- Lowest Front (X: 2878.4 , Z: 806.5)
- Lowest Mid (X: 2992.4 , Z: 809)
- Lowest Rear (X: 3106.4 , Z: 811.5)
- Mid-Front (X: 2876.5 , Z: 822)
- Mid-Mid (X: 2990.5 , Z: 824.5)
- Mid-Rear (X: 3104.5 , Z: 827)
- Highest Front (X: 2874.7 , Z: 837.5)
- Highest Mid (X: 2988.7 , Z: 840)
- Highest Rear (X: 3102.6 , Z: 842.5)

Dummy sitting position at lowest front (LF), lowest mid (LM) and lowest rear (LR) locations are shown in Figure 10.2, 10.3 and 10.4.

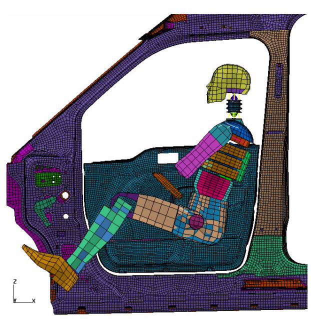

Figure 10.2 : Lowest Front

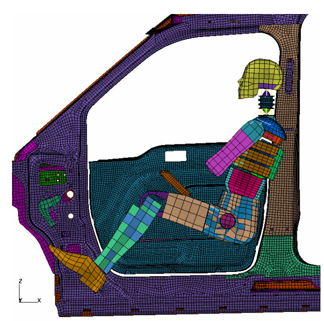

Figure 10.3 : Lowest Mid

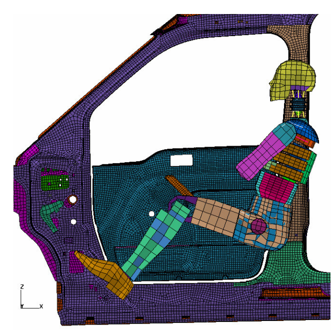

Figure 10.4 : Lowest Rear

Mid front (MF), mid-mid (MM) and mid-rear (MR) locations are shown in Figure 10.5, 10.6 and 10.7. Highest front (HF), highest mid (HM) and highest rear (HR) locations are shown in Figure 10.8, 10.9 and 10.10 below.

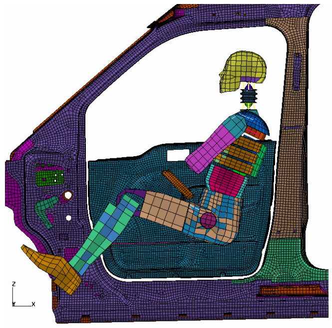

Figure 10.5 : Mid-Front

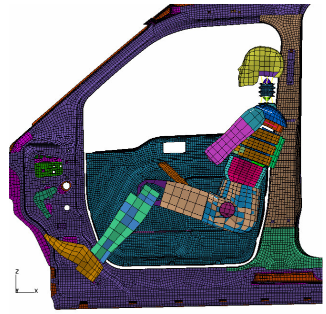

Figure 10.6 : Mid-Mid

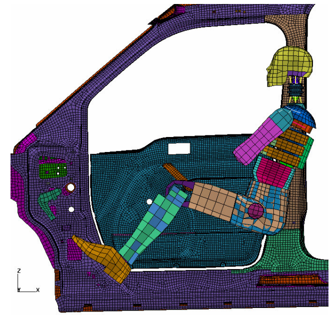

Figure 10.7 : Mid-Rear

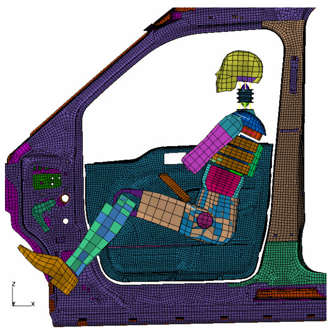

Figure 10.8 : Highest Front

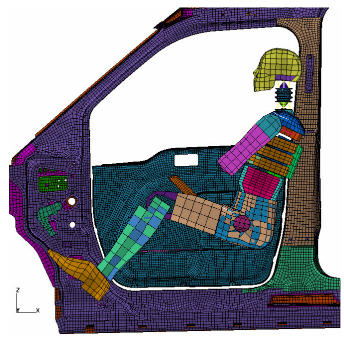

Figure 10.9 : Highest Mid

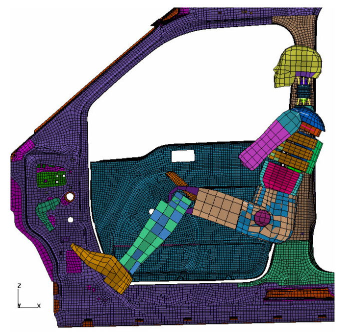

Figure 10.10 : Highest Rear

10.2 Dummy Injury Criteria Comparison For Various Locations

10.2.1 Head injury criterion results

In finite element iteration models, highest HIC values are obtained in the most rear position of seat envelope. This can be the result of impact point on dummy. When dummy (driver) is sitting at the seat rearmost position, dummy's body is in B-pillar zone. B-pillar structure is more robust than front door structure. Crush performance of B-pillar structure is lower than crush performance of the door structure. When the barrier hits to vehicle, B-pillar stands robustly, showing less deformation. Accelerations on non-crushable structures are higher than crushable structures. B-pillar trim impact acceleration is higher than door trim impact acceleration. When there is no head contact to interior components head acceleration is governed by dummy body and as a result head acceleration is slightly higher for the rearmost position of seat envelope.

Head injury criteria results for highest front (HF), highest mid (HM), highest rear (HR), mid-front (MF), mid-mid (MM), mid-rear (MR), lowest front (LF), lowest mid (LM) and lowest rear (LR) are shown in Table 10.1 below.

Table 10.1: HIC values for defined seat envelope locations

	HF	**HM**	**HR**	**MF**	**MM**	**MR**	**LF**	**LM**	**LR**
HIC	153	156	164.4	130.8	105.6	158.2	155	140.1	172.2

HIC value graph for all these locations is shown in Figure 10.11 below.

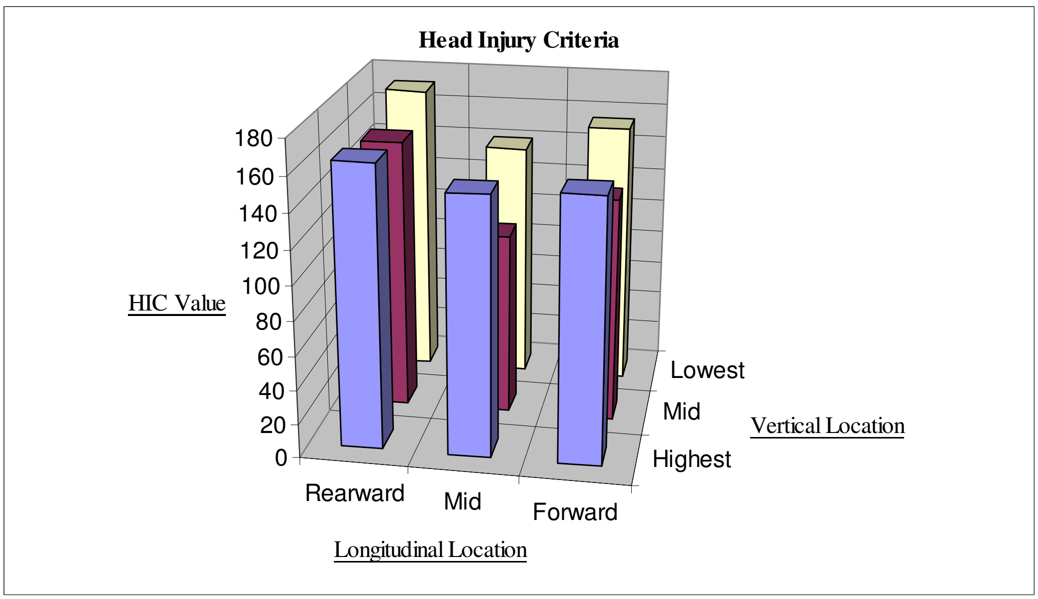

Figure 10.11 : Head Injury Criteria graph for nine locations of H-point

10.2.2 Rib deflection and viscous criterion results

Rib deflection values are high in the middle region of seat envelope compared to front and rear seating positions of driver in the vehicle. Dummy positions during impact for mid-front, mid-mid and mid rear location from side view are shown in Figure 10.12 below.

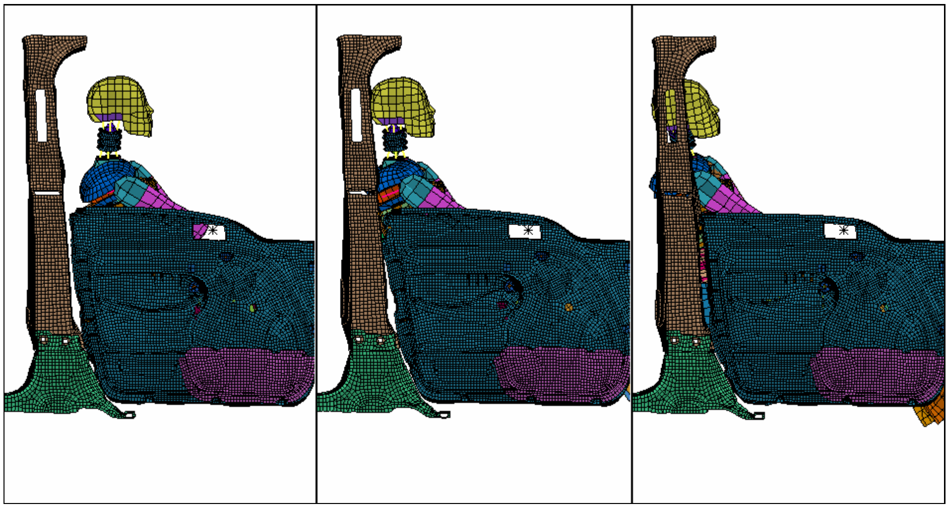

Figure 10.12 : Mid-front, mid-mid, mid rear sitting location of dummy (Side View)

In Figure 10.12 for dummy mid-mid position, rib deflection values are higher than other mid positions of dummy. In mid-mid position, plastic door trim upper corner directly hits to ribs and compress them. In foremost or rearmost seating positions dummy ribs are either faced by the b-pillar trim or door trim and there is a smoother contact between the ribs and the hitting parts. Even at the mid-mid position which has the highest rib deflection values, the calculated values are within the acceptance interval according to ECE 95 rib deflection criterion. Dummy positions during impact for mid-front, mid-mid and mid rear locations from front view are shown in Figure 10.13 below.

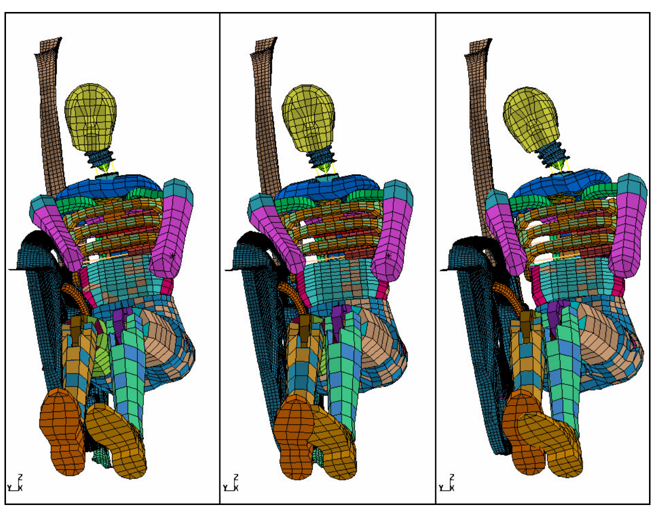

Figure 10.13 : Mid-front, mid-mid, mid rear sitting location of dummy (Front View)

Rib deflection and viscous criterion results for nine defined locations are shown in Table 10.2 below.

Table 10.2: Rib deflection values in mm and Viscous criterion values in m/s for defined seat envelope locations

	HF	HM	HR	MF	MM	MR	LF	LM	LR
Upper Rib Def.	4.2	14.1	9.1	4.4	20.7	9.7	3.7	22.0	7.6
Middle Rib Def.	4.7	22.0	6.9	5.3	21.4	7.0	6.1	21.0	5.0
Lower Rib Def.	9.8	21.9	11.3	8.7	22.1	9.8	6.9	22.0	11.3
Upper Rib VC	0.012	0.151	0.052	0.015	0.264	0.055	0.009	0.25	0.044
Middle Rib VC	0.025	0.233	0.026	0.029	0.208	0.031	0.035	0.173	0.022
Lower Rib VC	0.073	0.257	0.073	0.054	0.304	0.046	0.041	0.255	0.091

Rib deflection values of upper rib are shown in Figure 10.14. Rib deflection values of middle rib are shown in Figure 10.15. Rib deflection values of lower rib are shown in Figure 10.16 below.

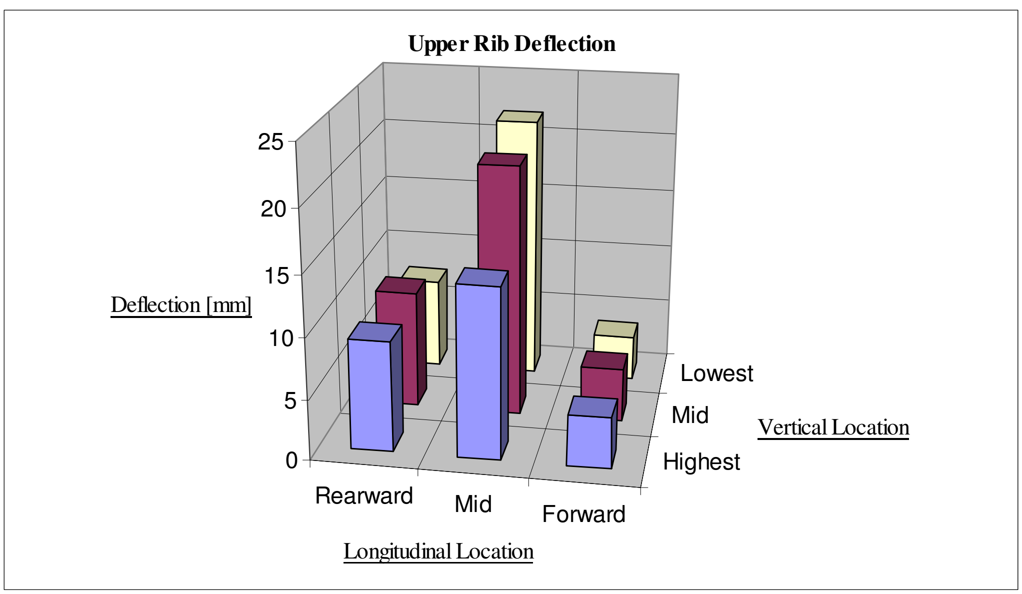

Figure 10.14 : Upper rib deflection graph for nine locations of H-point

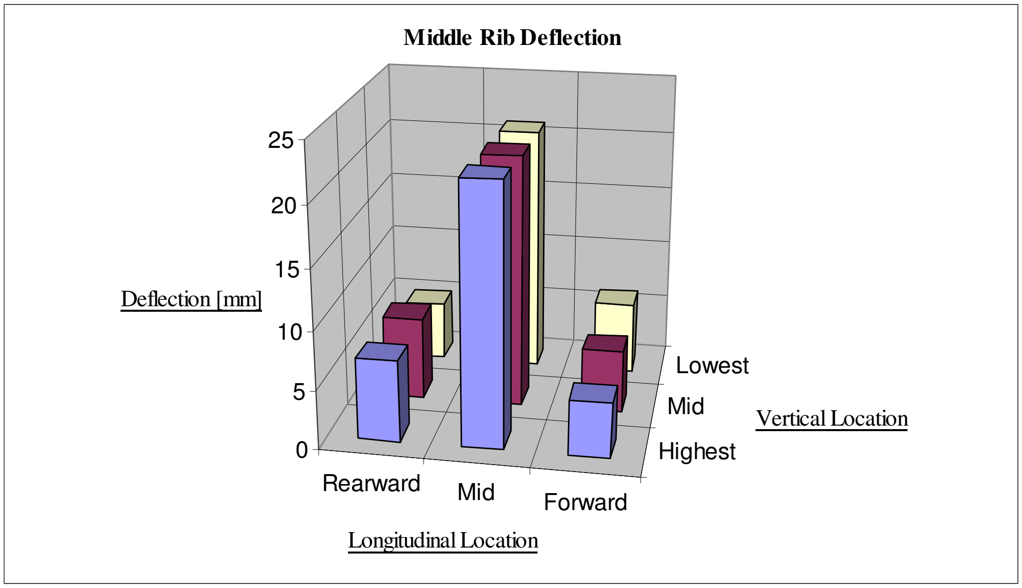

Figure 10.15 : Middle rib deflection graph for nine locations of H-point

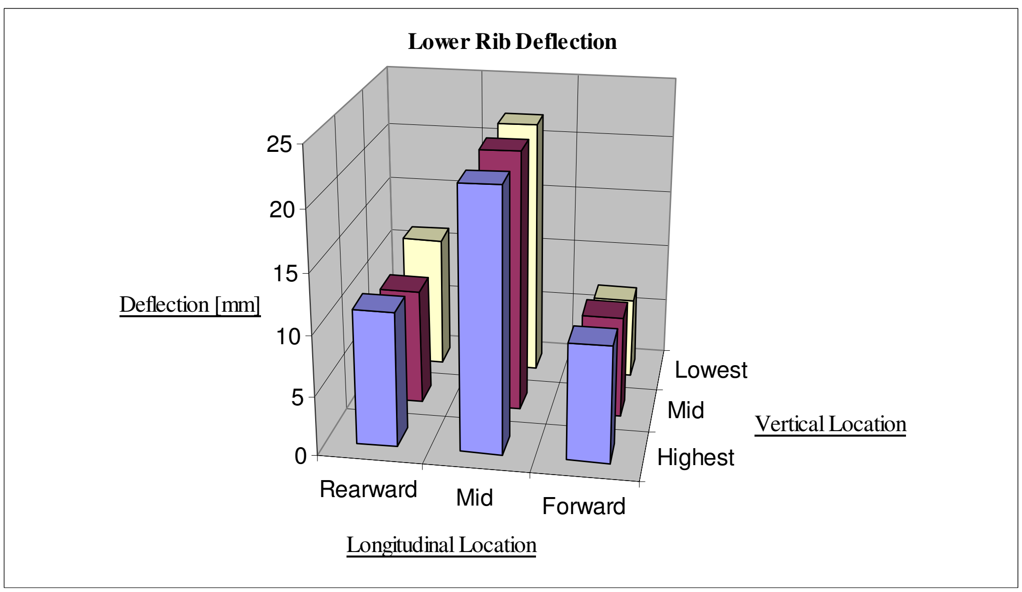

Figure 10.16 : Lower rib deflection graph for nine locations of H-point

Viscous criterion values of upper, lower and middle ribs are shown in Figure 10.17, Figure 10.18 and Figure 10.19 below.

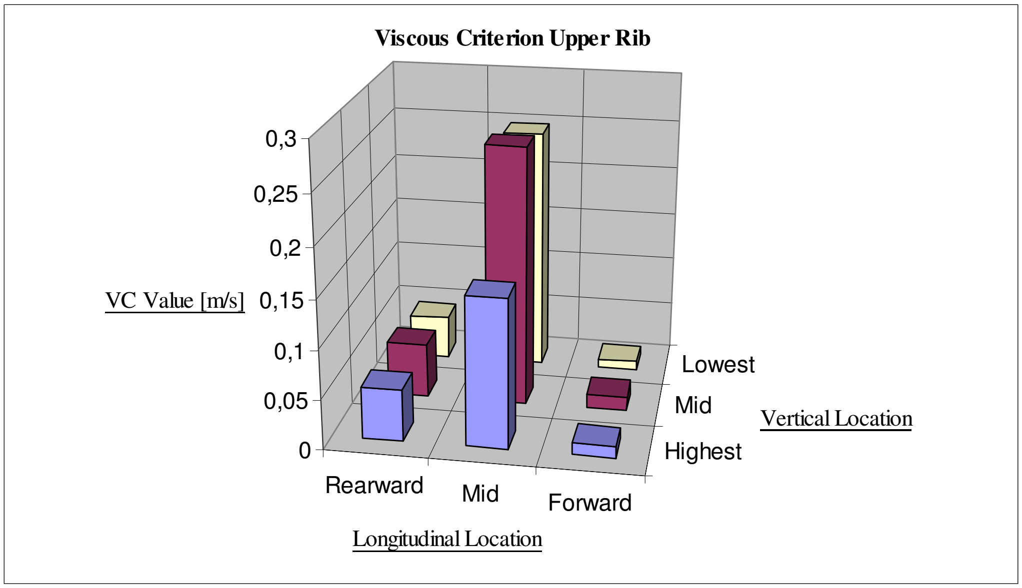

Figure 10.17 : Upper rib VC graph for nine locations of H-point

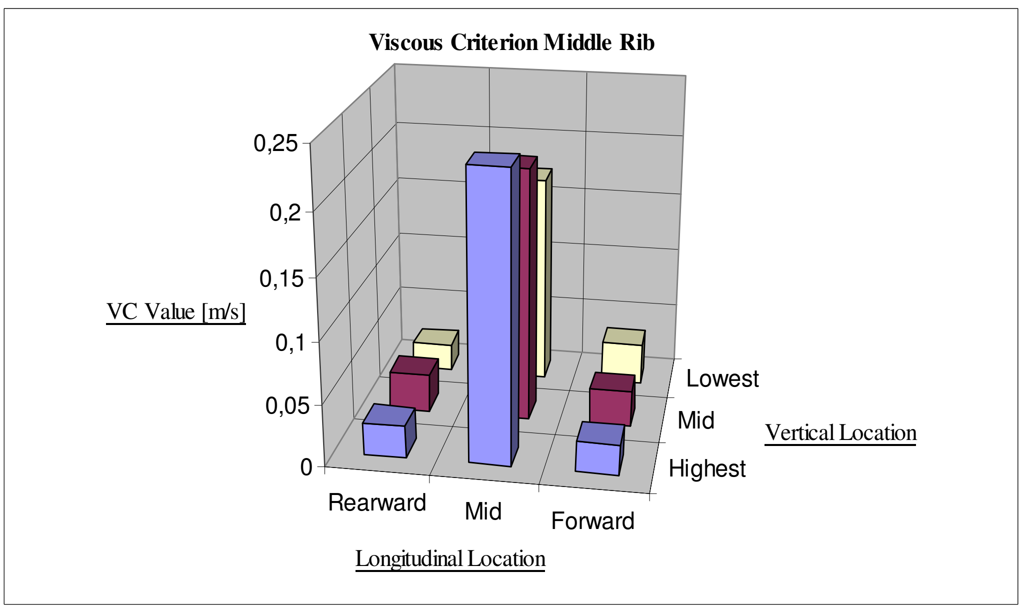

Figure 10.18 : Middle rib VC graph for nine locations of H-point

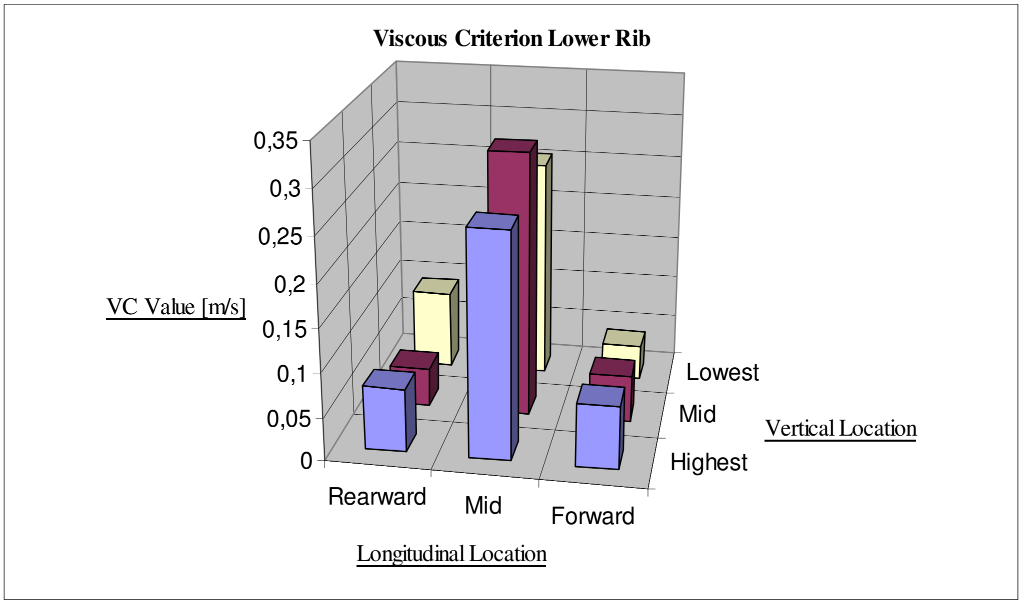

Figure 10.19 : Lower rib VC graph for nine locations of H-point

10.2.3 Abdominal peak force criterion results

Abdominal forces are higher in foremost sitting positions among all positions evaluated. Abdominal forces result due to door trim package hitting the abdomen. During impact, door structure crushes and penetrates inside the vehicle. For foremost seating positions abdomen is subjected to direct door trim impact. In mid or rearmost seating positions a certain portion of abdomen is prevented from impact due to the existence of b-pillar trim. Even at the foremost seating position, abdominal forces are within the regulation limits. Abdominal peak force results for nine defined locations are shown in Table 10.3 below.

Table 10.3: Abdominal peak force values for defined seat envelope locations

	HF	**HM**	**HR**	**MF**	**MM**	**MR**	**LF**	**LM**	**LR**
APF [N]	912	898	540	891	848	508	833	814	680

Abdominal peak values of dummy for defined nine locations are shown in Figure10.20 below.

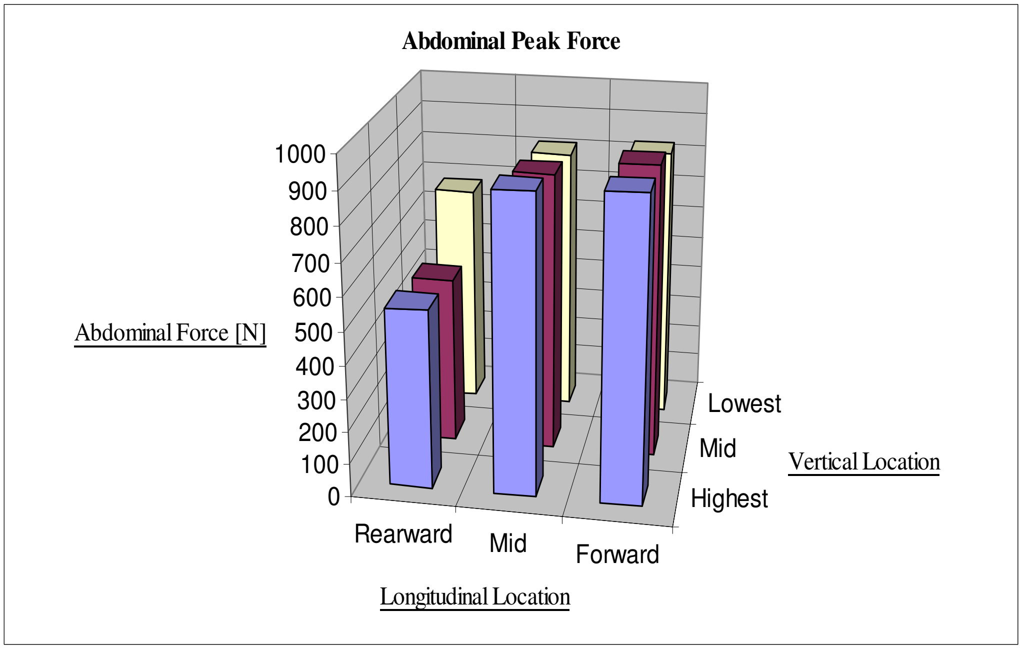

Figure 10.20 : Abdominal peak force graph for nine locations of H-point

10.2.4 Pubic peak force criterion results

Pubic forces are higher in front sitting position among all iteration models similar to the abdominal forces. Door structure crushes and penetrates inside the vehicle and impacts to dummy. For front positions of H point more penetration observed and it results with higher pubic forces within the regulation limits. Pubic peak force results for nine defined locations are shown in Table 10.4 below.

Table 10.4: Pubic peak force values for defined seat envelope locations

	HF	**HM**	**HR**	**MF**	**MM**	**MR**	**LF**	**LM**	**LR**
PPF [N]	1110	817	823	1400	1140	765	1490	970	880

Pubic peak values of dummy for defined nine locations are shown in Figure10.21 below.

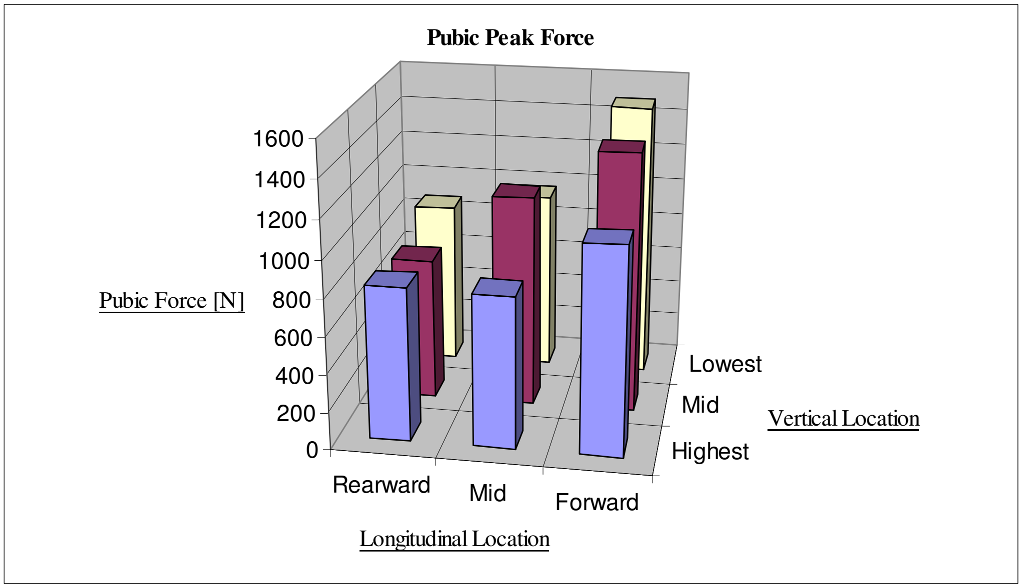

Figure 10.21 : Pubic peak force graph for nine locations of H-point

11. CONCLUSION

Correlation achieved between data measured in physical test and calculated in the finite element analysis is satisfactory. Both the dummy injury criteria measured in test, and calculated in analysis, added with the seating positions that were not tested but calculated in the analyses are all below the ECE 95 side crash regulation limits.

Analyses results for different seating positions show that dummy performance is directly affected by vehicle deformation. If there had been an unrealistic vehicle deformation in analysis compared to vehicle deformation in test, such good correlation could not be achieved between test results and analyses results on dummy. With an uncorrelated model, all design sensitivity analyses evaluated would not have a meaning. Therefore it is essential to achieve a good correlation between vehicle deformation in test and in analysis.

Design sensitivity analyses provided useful data for a safe vehicle compartment design. The analyses clearly show the root causes of higher forces or accelerations measured in test and also provide important data to improve results even more. Without finite element tools in hand, gathering that valuable data would require much effort. At least eight more tests for various locations of dummy seating positions need to be performed which mean money and time. Apart from these, finite element analysis provide frame by frame data during crash from all views helping to understand what is happening inside the vehicle during crash. This opportunity is limited to five or six camera views with components of vehicle blocking to see what is happening inside in test condition.

Once it is decided to improve the dummy performance, the consequences of the above process is also much easier with a finite element model in hand. With a proven and correlated model, any design change proposed can be incorporated into design and be evaluated for all cases without the necessity of new tests allowing a large number of choices for the designer.

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İlker YILDIZÇELİK was born in Ankara in 1980. He received his primary degree from Ulugazi Primary School (1986-1991); and high school degree from Kocaeli Anatolian High School (1991-1998). He started his B.Sc. education at the Mechanical Engineering Department of the Istanbul Technical University in 1998. After receiving his B.Sc. degree in 2003; he has started his M.Sc. education at the Automotive Engineering Programme of the Mechanical Engineering Department in Istanbul Technical University. Since 2004, Yıldızçelik has also been working in Ford OTOSAN A.S. Product Development Department as a Safety Engineer.