Design of Body Structure

- Sub-Systems Selection for BEV
  - Selection criteria
- Sub-System Integration into Body Design
  - Joining methods
  - Body structure assembly

Design of Body Structure

- Sub-Systems Selection for BEV
  - mass reduction in every sub-system is crucial to achieve a lightweight body structure
  - Look into manufacturing feasibility aspect for the respective sub-systems
  - level of difficulty of the manufacturing technology, and the time period during when these technologies would be more practical leading to feasible high volume production
    - 2010-2015 - Conservative approach (C)
    - 2015-2020 - Mid-term approach (M)
    - 2020- Beyond - Aggressive approach (A)
- Possible criteria
  - low cost solution, the light weight solution, the low CO_2e solution, the manufacturing capability of the OEM, etc

FSV Selection Criteria

- Mass
- Cost
  - "technical cost modeling" approach was applied to all the parts to estimate the subsystem manufacturing costs
- Life Cycle Assessment (LCA) for CO_2e
  - an extended Greenhouse Gases (GHG) emissions comparison model was used to conduct a LCA assessment for the FSV using input data from Forschungsgesellschaft Kraftfahrwesen mbH Aachen (fka), University of California, Santa Barbara (UCSB) and EDAG

- New aspect of vehicle design associated with advanced powertrains: mass/cost paradigm shift
- Critical target: reduction of total life cycle emissions while maintaining affordability

Rocker Sub-System (1)

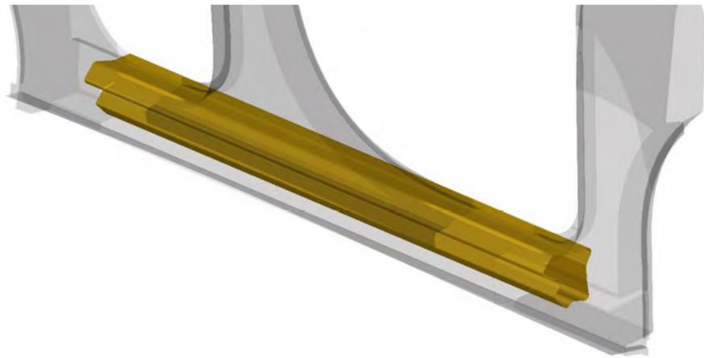
- the lowest mass (hydroformed): complex design
- rollformed single thickness or a rollformed with Tailor

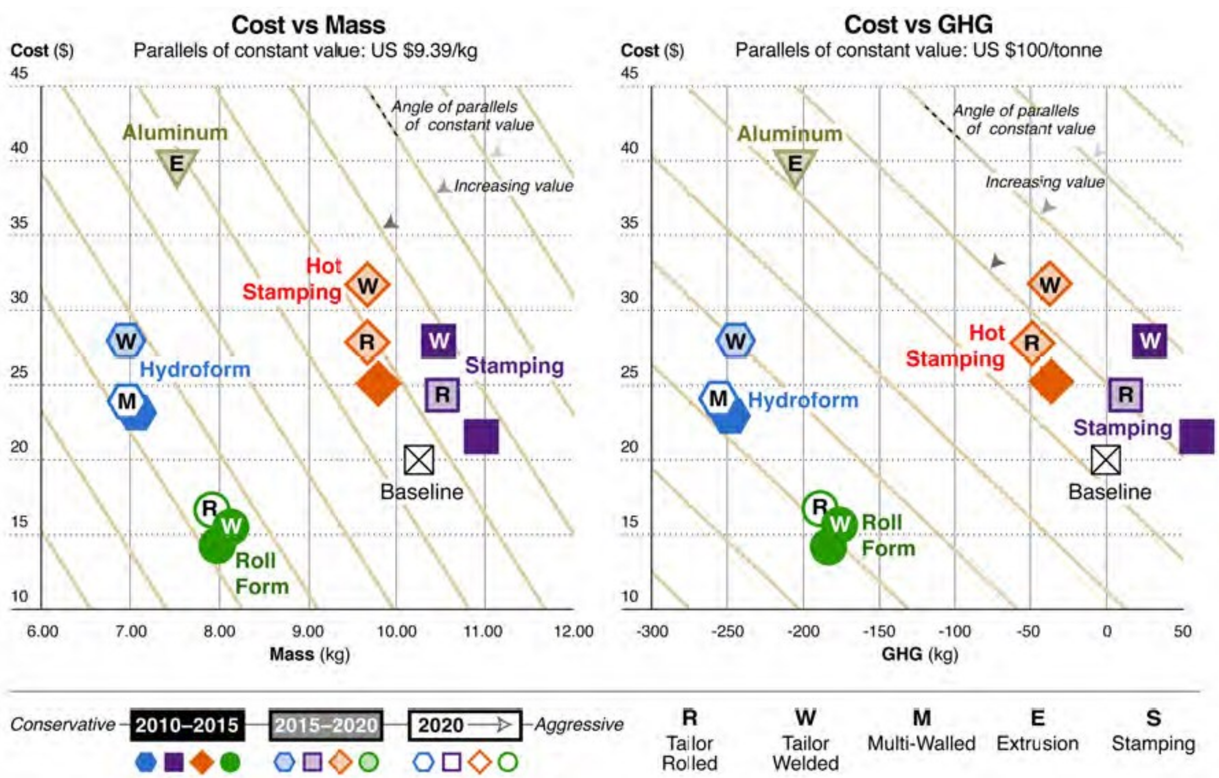
FSV Rocker HF3G Technology Assessment	FSV Rocker HF3G Manufacturing Interpretation		High Volume Manufacturing Feasibility	FSV Rocker Sub-System Mass (kg)	FSV Rocker Manufacturing Cost ($)	FSV Rocker LCA CO_2eq Savings (kg)
Baseline	B ST	Stamping	(C)	10.26	19.99	0
Stamping Solution	ST	Stamping	(C)	10.95	21.50	53
	ST TRB	Stamping TRB	(M)	10.52	24.36	16
	ST LWB	Stamping LWB	(C)	10.47	28.04	30
	HST	Hot Stamp	(C)	9.80	25.16	-37
	HST TRB	Hot Stamp TRB	(M)	9.66	27.86	-47
	HST LWB	Hot Stamp LWB	(M)	9.66	31.78	-37
Roll Form	RF	Roll Form	(C)	7.98	14.27	-183
	RF TRB	Roll Form TR Coil	(A)	7.95	16.56	-189
	RF TWC	Roll Form TW Coil	(C)	8.07	15.74	-177
Hydroform	HF	HydroForm	(C)	7.05	22.88	-248
	HF LWT	Hydroform LWT	(M)	6.96	27.98	-245
	HF MWT	Hydroform MWT	(A)	6.96	24.00	-255
Aluminum	AL	Extrusion	(C)	7.53	39.78	-204

(C) Conservative (M) Mid-term (A) Aggressive

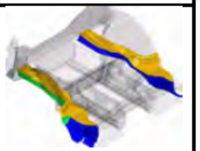
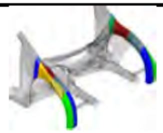
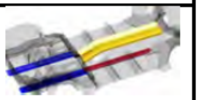
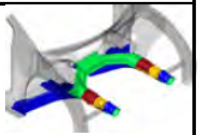
* The mass, costs and LCA CO_2e savings shown above are only for one side of the vehicle

Rocker Sub-System (2)



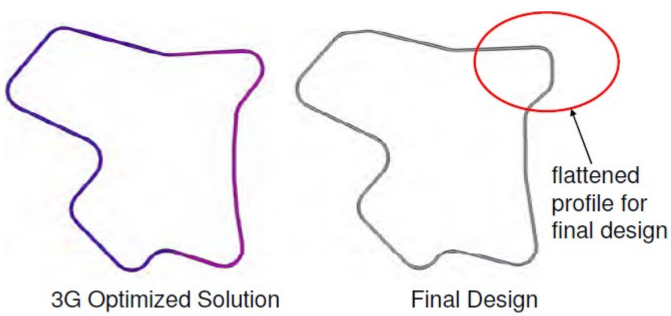


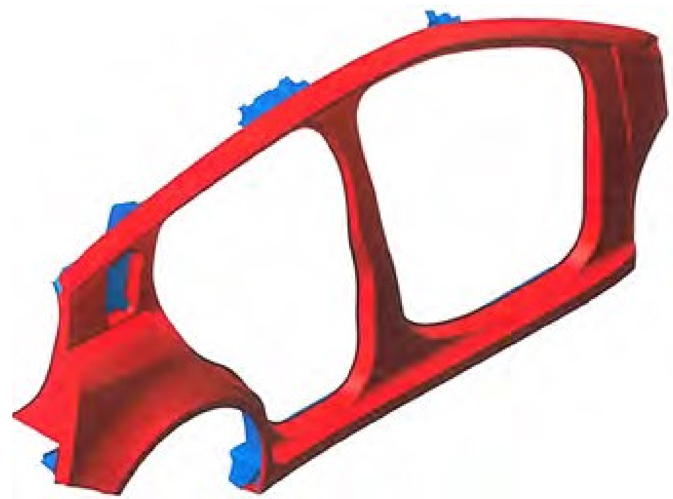
Sub-System Selections Summary

FSV Sub-system	FSV Selection (Mid-Term)	Baseline		FSV Selected Sub-system			
		Weight (kg)	Manufacturing Cost ($ USD)	Weight (kg)	Manufacturing Cost ($ USD)	LCA CO_2e Savings (kg)	Illustration
Rocker	Rollformed single thickness or rollformed TWC (with conventional outer)	10.26	$19.99	7.98 / 8.07	$14.27 / $15.7	-183 / -177	
Rear Rail	Stamping LWB/TRB	6.28	$12.73	4.98 / 5.19	$16.86 / $12.95	-92 / -86	
B-Pillar	Hot stamping LWB with conventional B-pillar outer	8.79	$30.84	5.48	$30.44	-247	
Roof Rail	Hot stamping LWB	12.73	$27.71	9.31	$31.71	-256	
Shotgun	Hot stamping LWB (with tailor quench)	4.2	$14.24	4.98	$22.11	73	
Tunnel	Open rollform	7.72	$20.20	4.29	$11.56	-277	
Front Rail	Stamped LWB	6.24	$28.91	5.72	$20.91	-65	

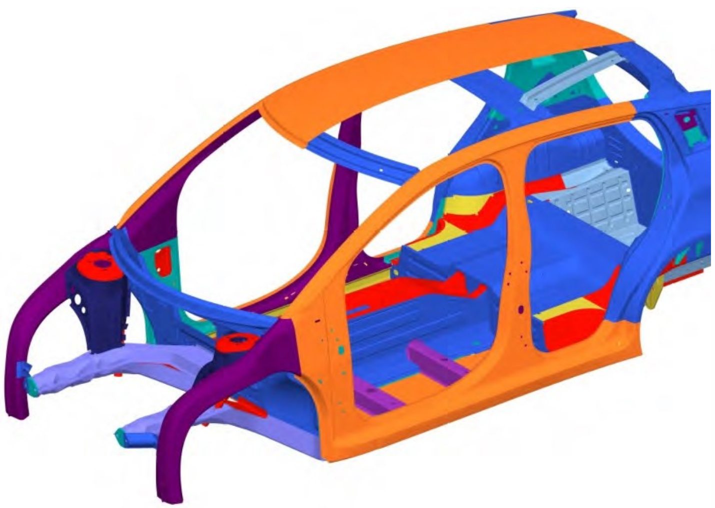
Sub-System Integration into Body Design: Rocker Sub-System

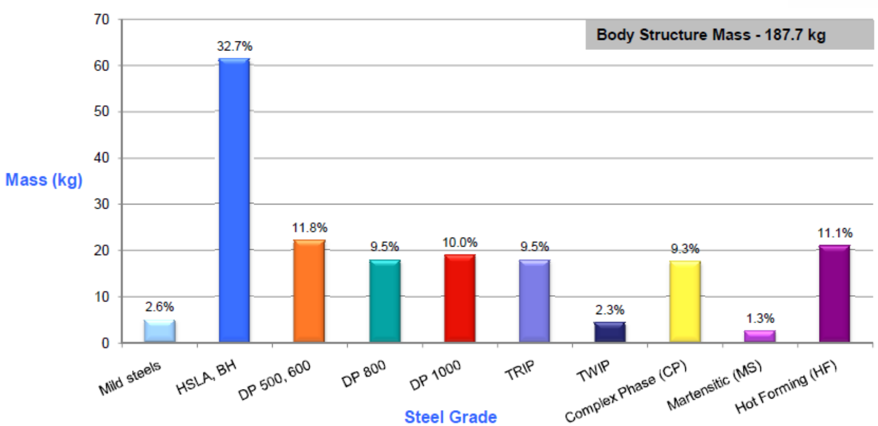
- inner edge of the rocker was flattened (highlighted in the figure) to make it easier for integration with body side inner and seat cross members
- Holes were added to the inner side of the rocker to aid the flow and drainage of electro-coat

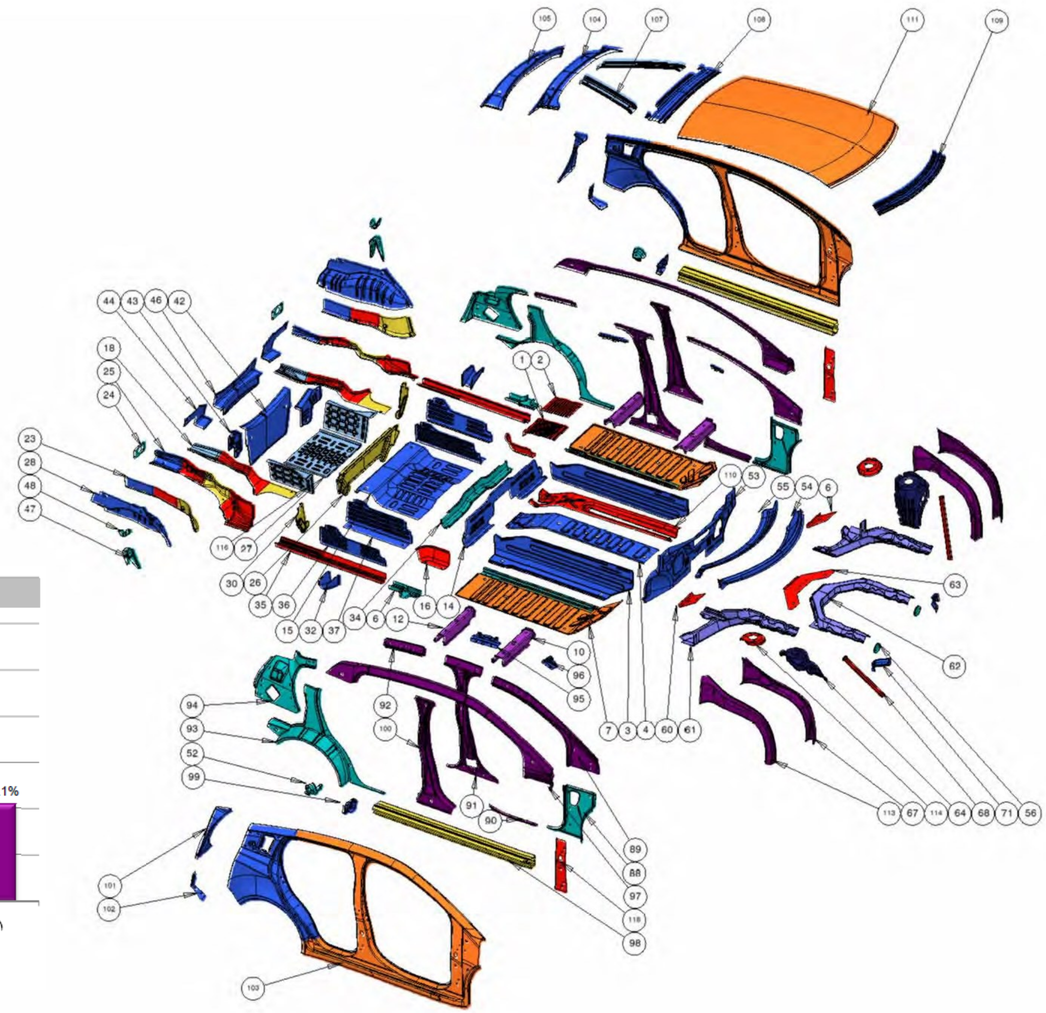




Final BEV Body Structure Design





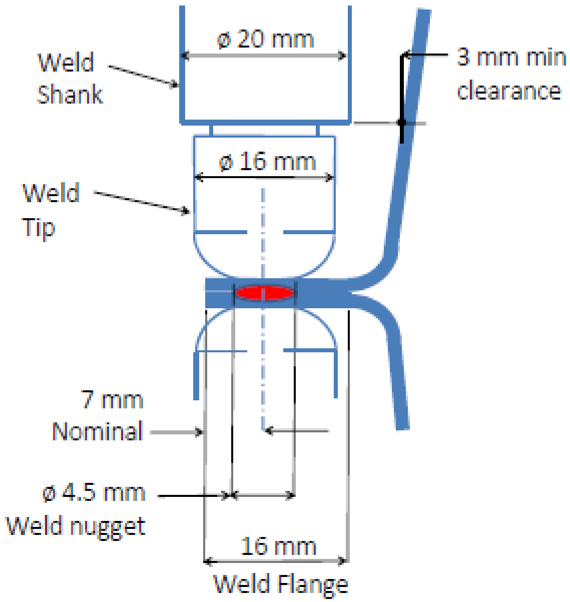


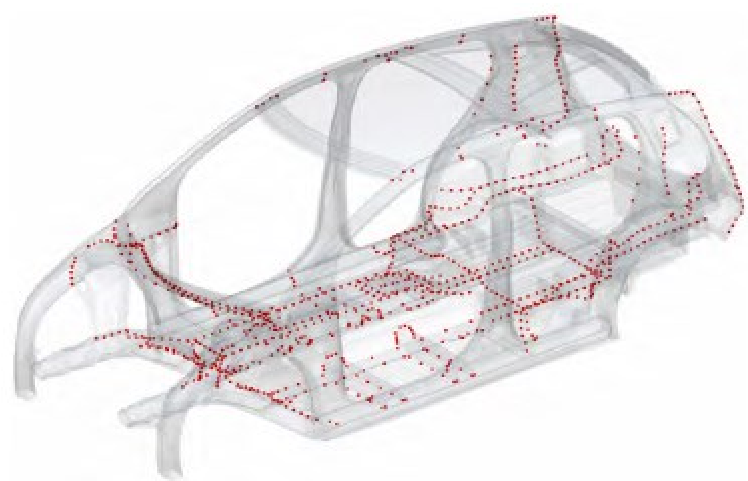
Joining Methods

- Resistance Spot Welding
- Laser Welding
- Laser Brazing
- Roller Hemming
- Adhesive Bonding

Resistance Spot Welding

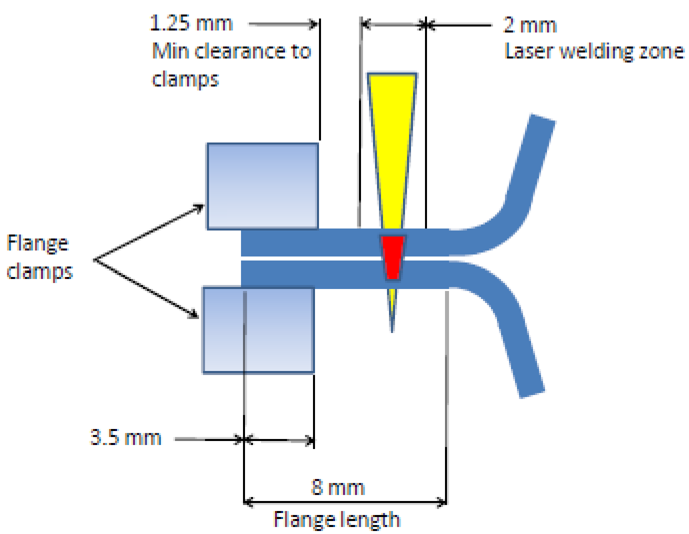
- Weld flange width requirements are generally 16 mm to accommodate the weld tip and clearance from the part to be welded to the weld gun shank
- Distinct cost advantage over laser welding
- spot weld spacing generally ranges from 30 mm to 100 mm

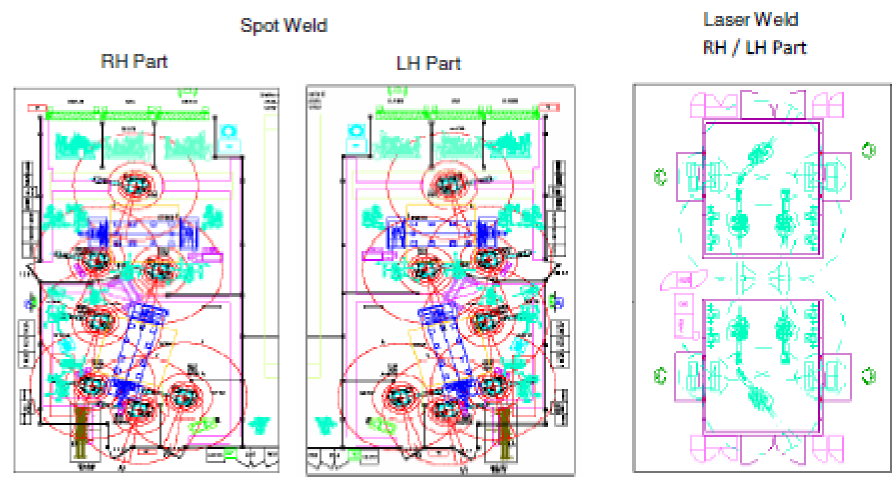




Laser Welding (1)

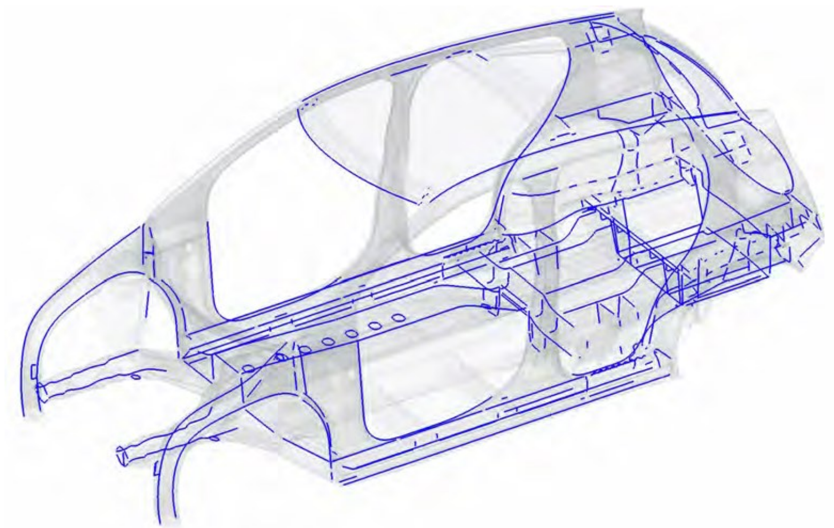
- Higher initial cost, but replace a number of spot welders
- Flange width reduction to 8 mm → weight savings (6 kg for BEV)
  - Using a remote laser set-up with the laser head up to 400 mm above the part
- Floor space savings of up to 50% at the body shop assembly area

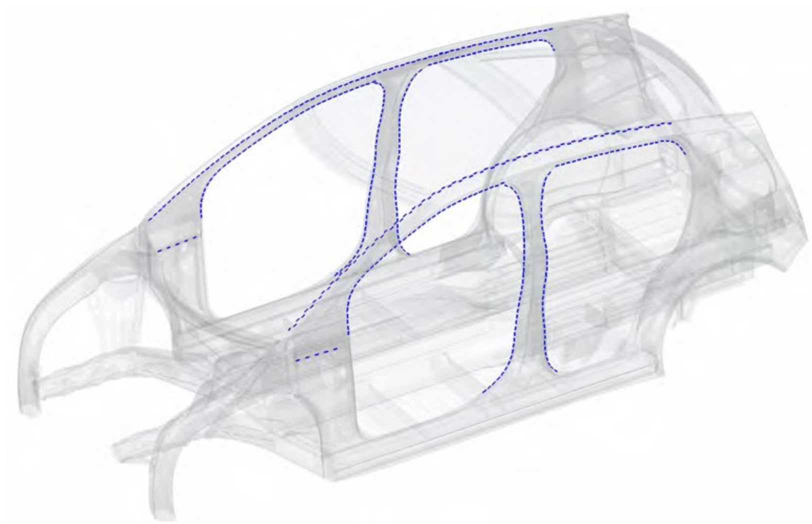




Laser Welding (2)

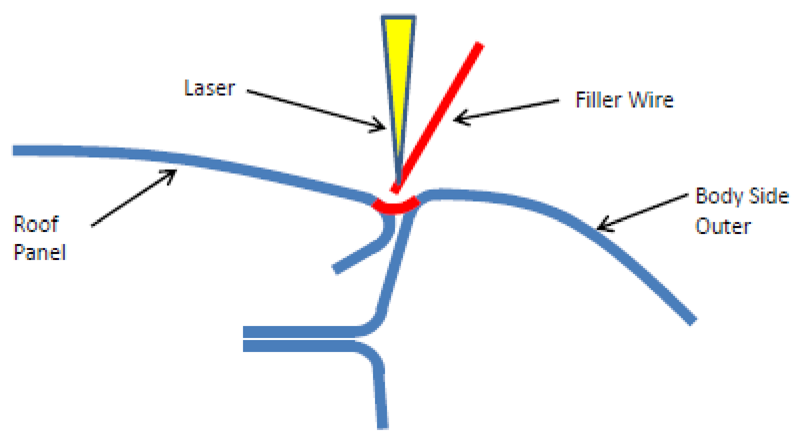
- Greater weld speed
  - Single spot welding: 3.0 sec
  - Laser welding: 80 mm/sec
  - For example, 10 welds with 45 mm weld spacing using a single spot weld robot, continuous laser weld?





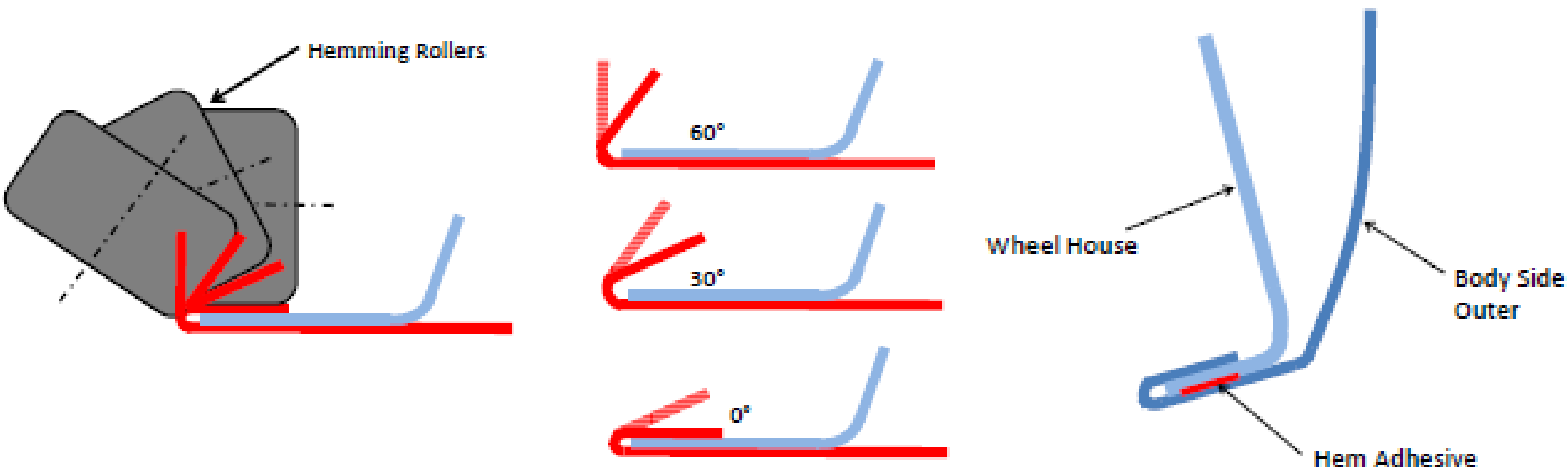
Laser Brazing

- added advantage of eliminating the need for a roof ditch molding
- Laser beam: 2~3 mm diameter
- filler wire (1 mm diameter) can be 'guided' along the joint gap between the roof and body side
    - copper based alloy with a melting point of between 900~1025 °C
- correct positioning of both the laser beam and the filler wire to the joint gap is critical: self-tracking laser head



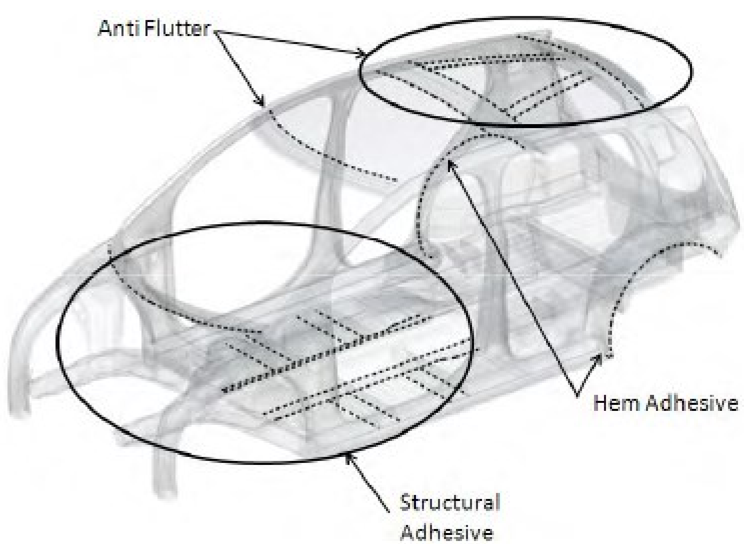
Roller Hemming

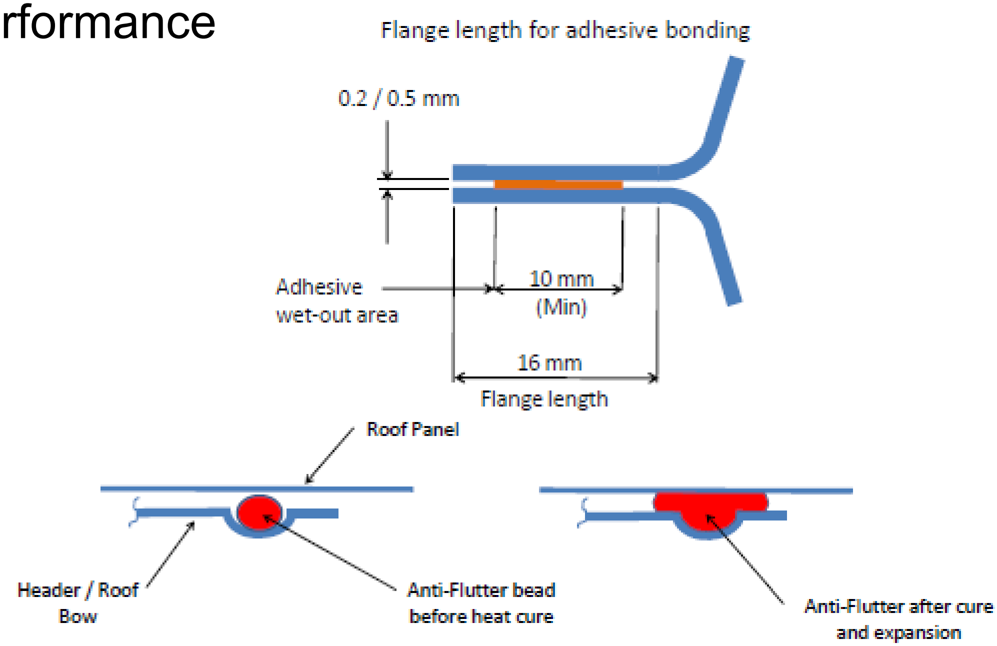
- flange of the outer panel is bent over the inner panel in progressive steps by means of a series of rollers carried on the hemming head
- using a robotic system the hem station floor foot print can be greatly reduced from what would be necessary for a hemming die



Adhesive

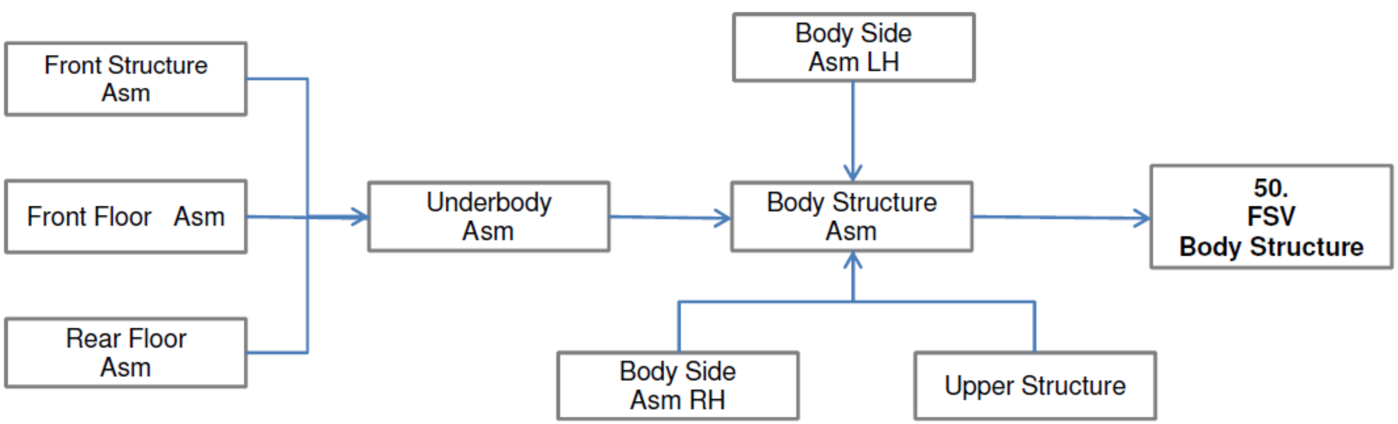
- Structural adhesive (Henkel Terokal 5089 or similar)
  - maximum strength with curing temperatures at 155~190°C
- Hem adhesive: two part epoxy (3M 5026 or similar)
  - low activation temperatures to minimize panel distortion
- Anti-flutter adhesive (Henkel Terostat 06-1273 or similar)
  - between the upper structure and the roof panel to improve stiffness and NVH performance



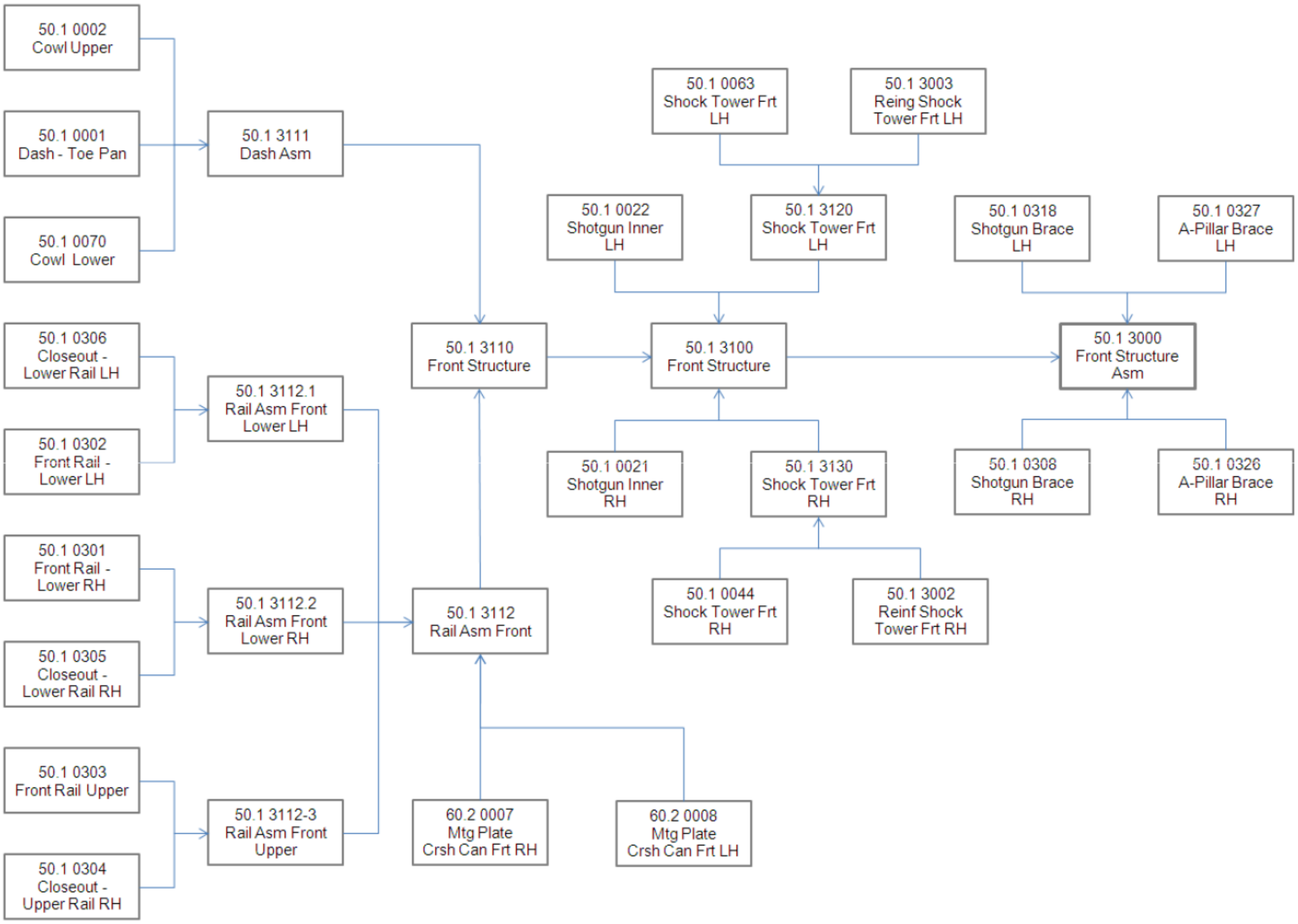


Body Structure Assembly: Body Shop

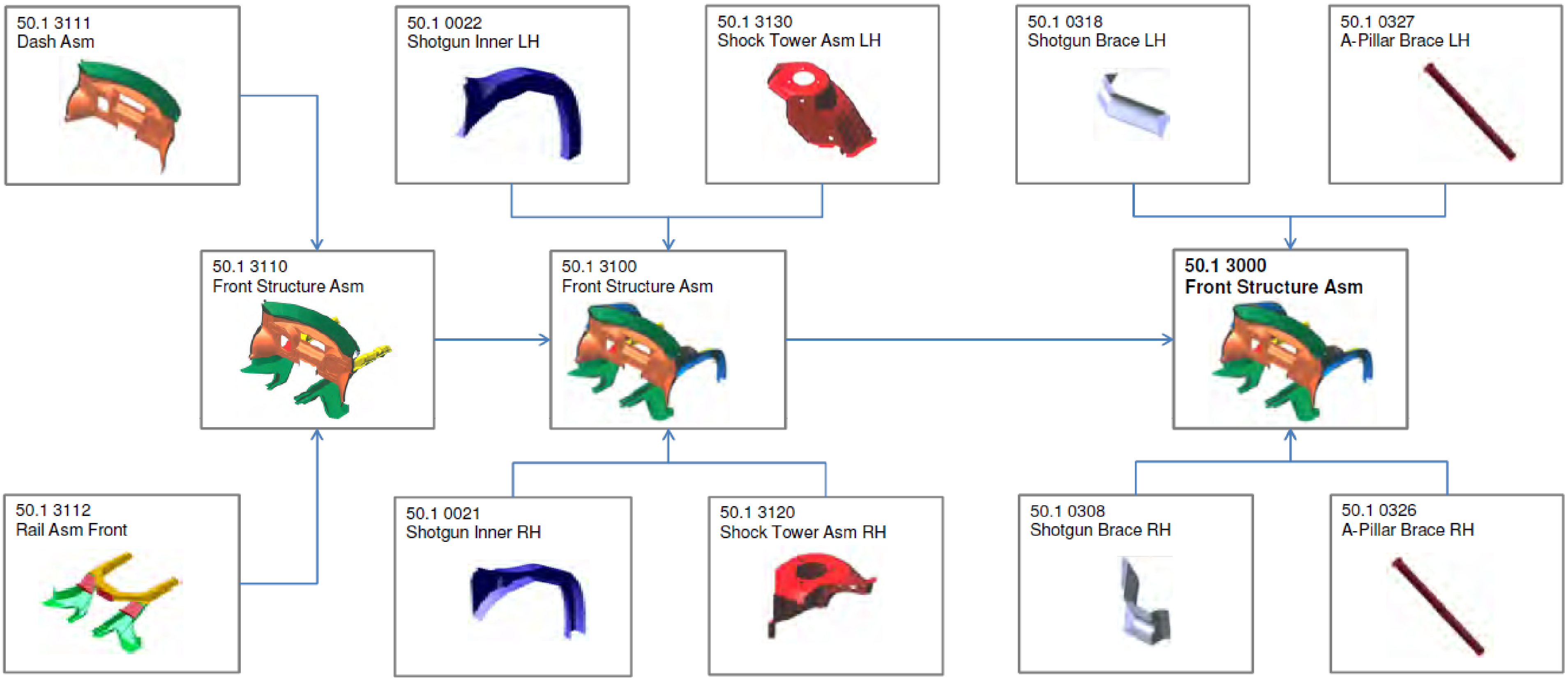
– the most complex manufacturing phase of the entire vehicle manufacturing and assembly process
– major assemblies
  - Front Structure
  - Front Floor
  - Rear Floor
  - Under-Body
  - Body Side LH/RH
  - Upper Structure and Shotgun

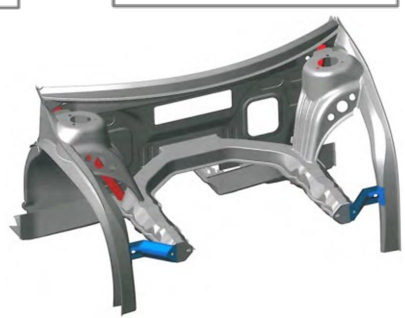


Front Structure Assembly (1)

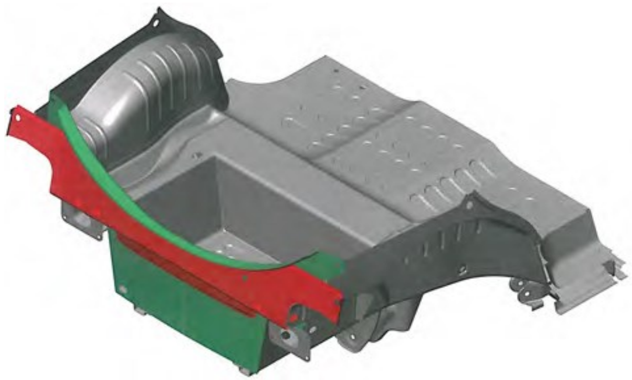


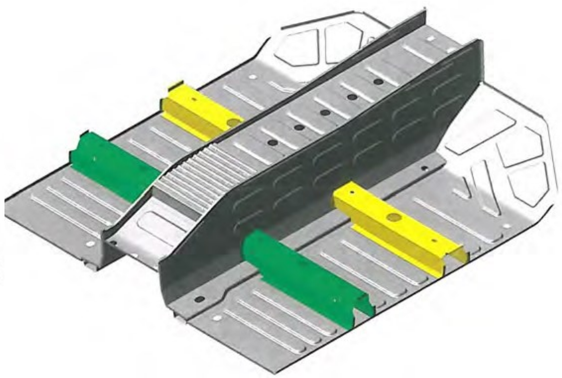
Front Structure Assembly (2)

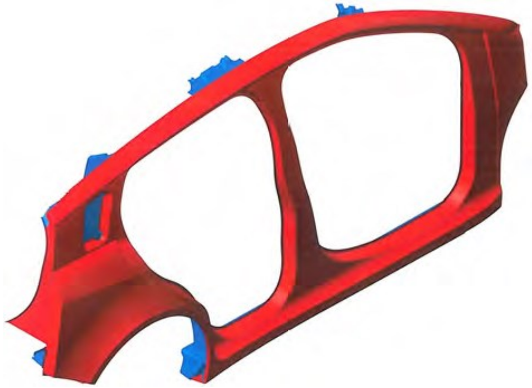


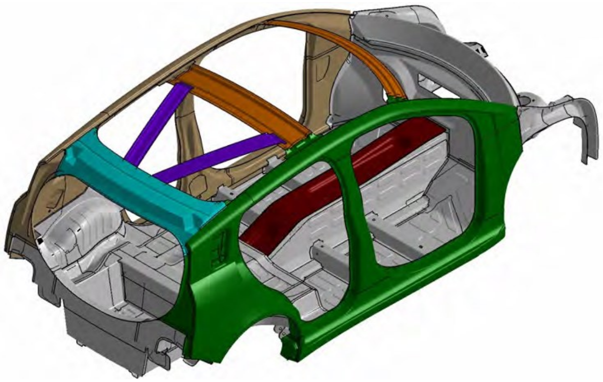


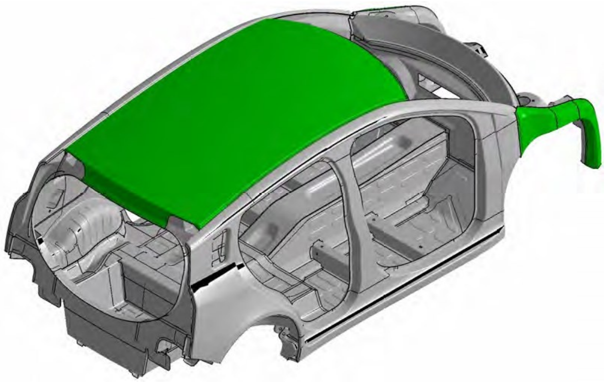
Body Structure











Number of Joining Techniques

- Number of spot welds: 1023
- Length of laser welds: 83,584 mm
- Length of laser braze: 3,348 mm
- Length of hem flange: 2,257 mm
- Length of hem adhesive: 2,257 mm
- Length of structural adhesive: 9,786 mm
- Length of anti-flutter adhesive: 6,542 mm

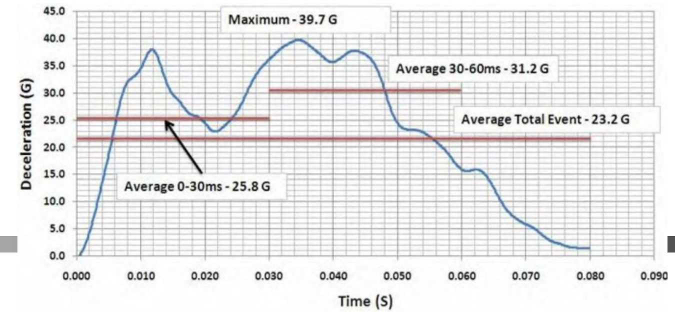
Body Structure Performance CAE Analysis Results

- Crash Worthiness
- Static Stiffness Study
- Dynamic Stiffness Study
- Full Vehicle Dynamic Analysis
- Durability Study
- FSV NVH Assessment

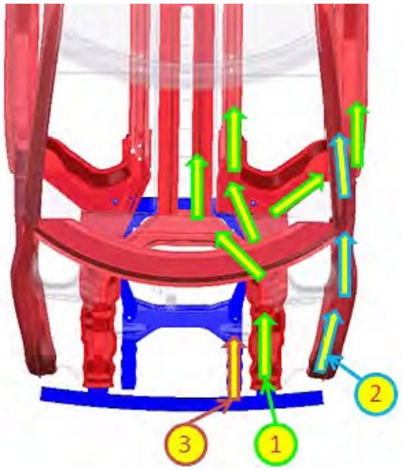
Crash Worthiness

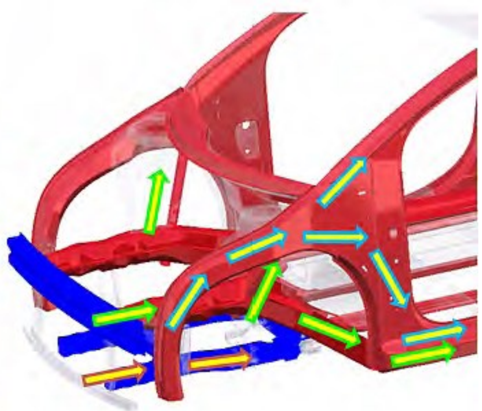
- FSV-1 BEV Body Structure Load Paths
  - Front End, Side, Rear Structure
- Frontal Impact
  - US NCAP Front, Euro NCAP/IIHS Front Crash Analysis
- Side Impact
  - IIHS Side Impact, US SINCAP Crash Analysis
- Rear Impact
  - FMVSS 301 Rear, ECE R32- 55 km/h 0° Deformable Barrier
- Side Pole Impact
  - FMVSS 214 Pole, EURO NCAP - 29 km/h 0° Impact
- Roof Crush
  - FMVSS 216-a and IIHS Roof Crush Analysis
- Low Speed Regulations
  - RCAR/IIHS (10 km/h 0° Rigid Barrier)

Front End Structure



- smaller package space required for the electric drive motor
- straighter fully optimized front rails with larger sections
- manage frontal crash events with minimal intrusions into the passenger compartment
  - front rails load path 1: rocker section → base/top of tunnel, behind shock tower → base of A-pillar
  - curved shotguns load path 2
  - motor cradle load path 3: support motor assembly and front suspension



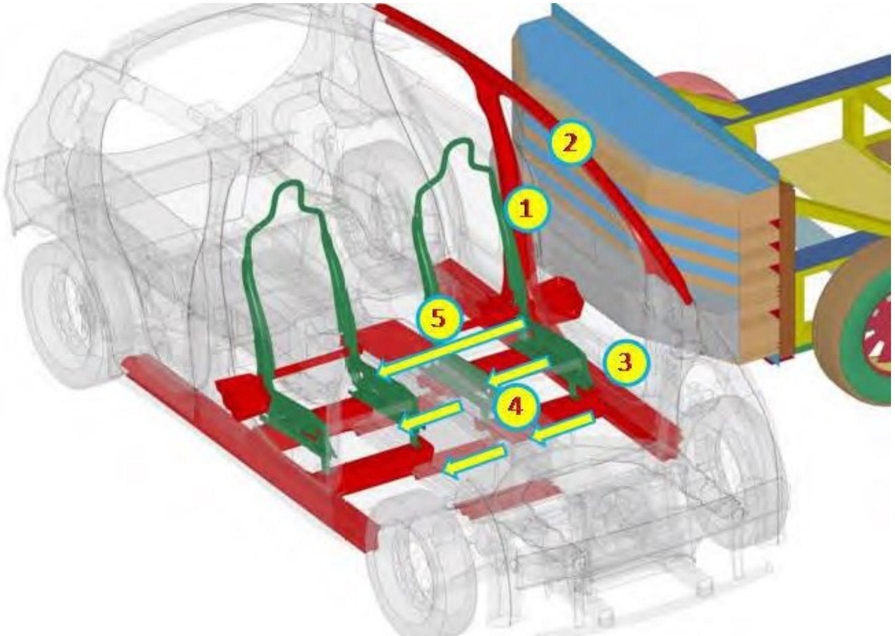


* three manufacturing options and materials:

- Hot Stamping with tailor quenching - HF 1050/1500 grade of steel
- TWIP 500/980 grade of steel
- TRIP 600/980 grade of steel

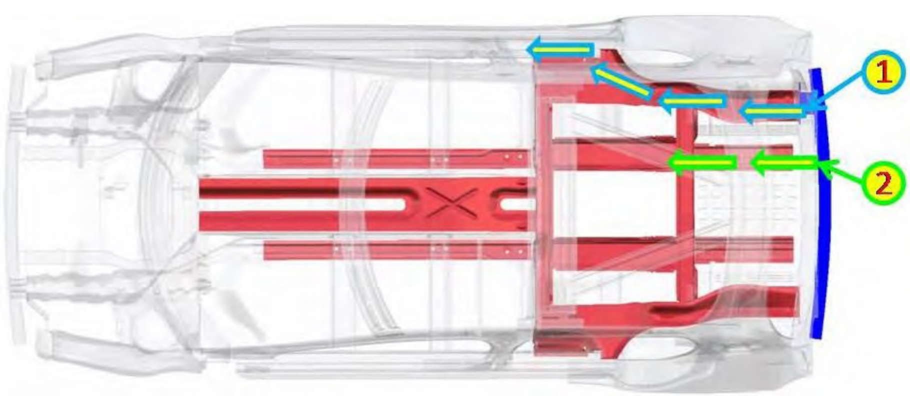
Side Structure

- Load path 1: B-pillar, Hot-Stamped (HF1050/1500)
- Load path 2: Roof Rail, Hot-Stamped (1500 to 1600 MPa)
- Load path 3: Rocker, major role in side impact (pole)
- Load path 4: front seat mounting cross members, MS950/1200
- Load path 5: seat back cross tubes



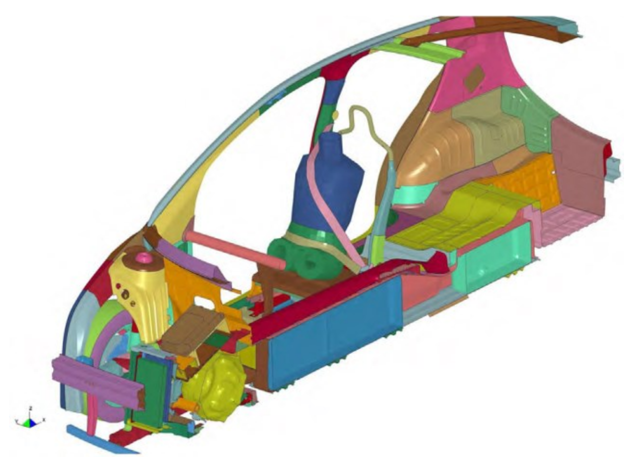
Rear Structure

– Load path 1: rear rail section, three LWB stampings
– Load path 2: roll formed sections, from the bottom of the tunnel towards the rear of the vehicle under the rear floor
– + rear cross-member: form a very rigid cage around the battery pack



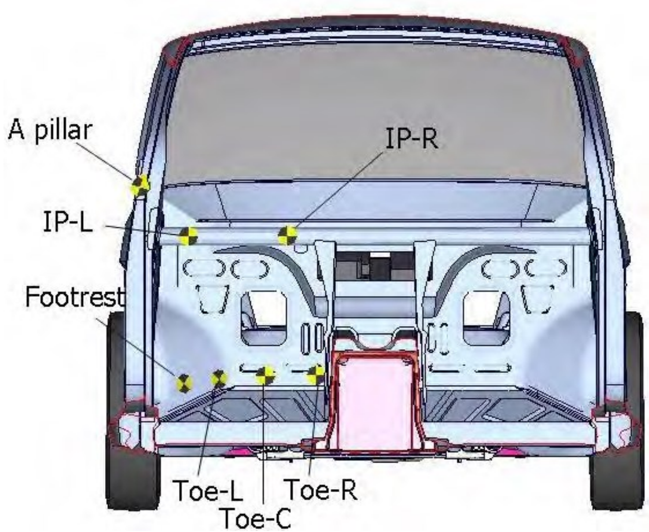
Frontal Impact: US NCAP Front (1)

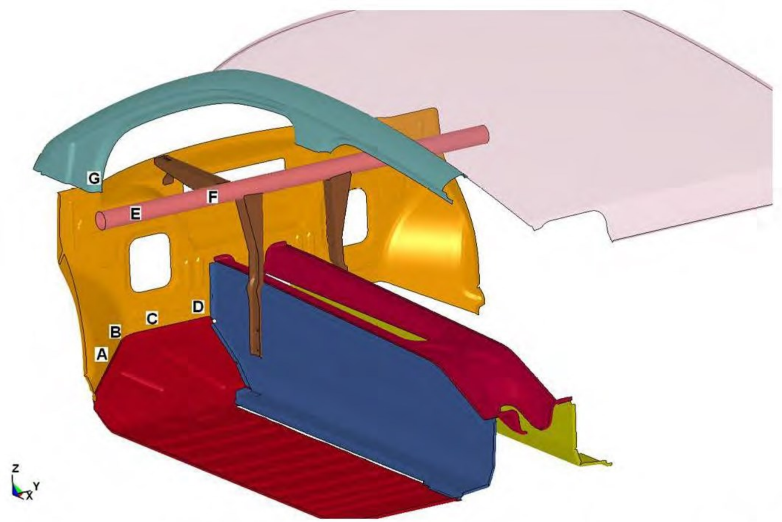
- New Car Assessment Program(NCAP), undertaken by the National Highway Traffic Safety Association (NHTSA)
- full frontal barrier test at a vehicle speed of 56 km/h (35 mph)
- FSV model 1078 kg including a body structure 187.7 kg
- Hybrid III 50% driver of 75 kg, Hybrid III 5% passenger of 45 kg
- general simple seatbelt system
  - Seatbelt shoulder anchorage and retractor location: at the B-pillar
  - outboard lap belt anchorage location: at the rocker inner panel
  - inboard lap belt anchorage: on the seat



Frontal Impact: US NCAP Front (2)

- Intrusion measurements on cabin structure
- reference points in the luggage area of the FSV body structure, locations follow IIHS standards
- Instrument Panel (IP) movements: two reference points from the cowl cross member

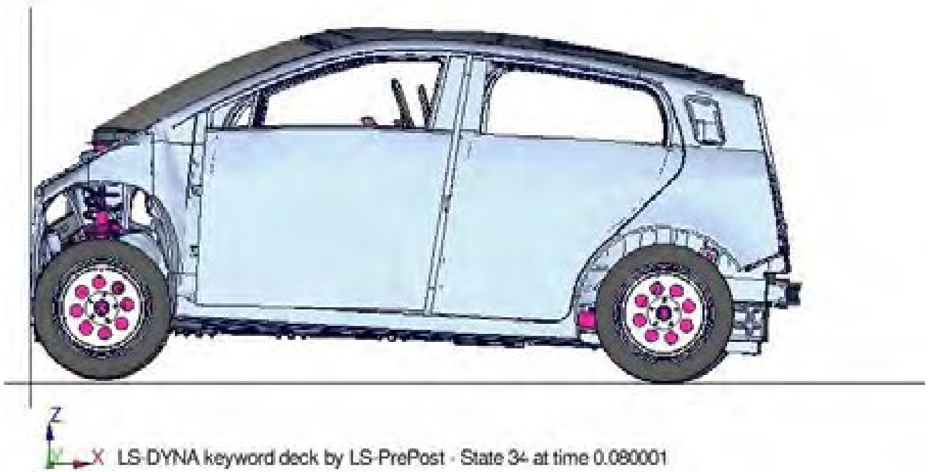


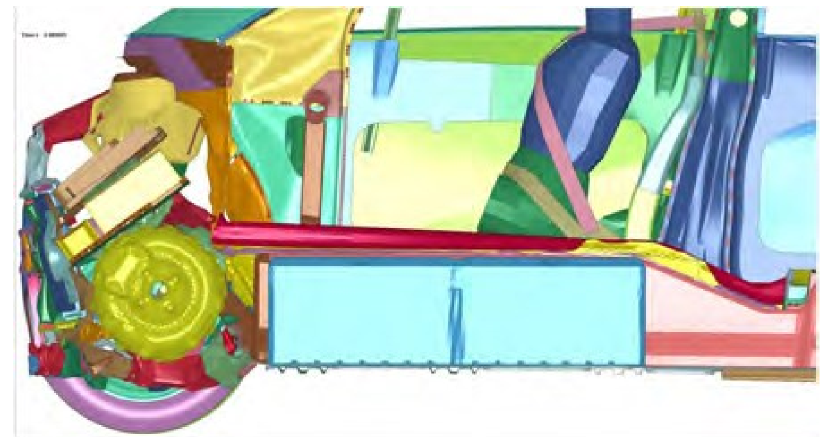


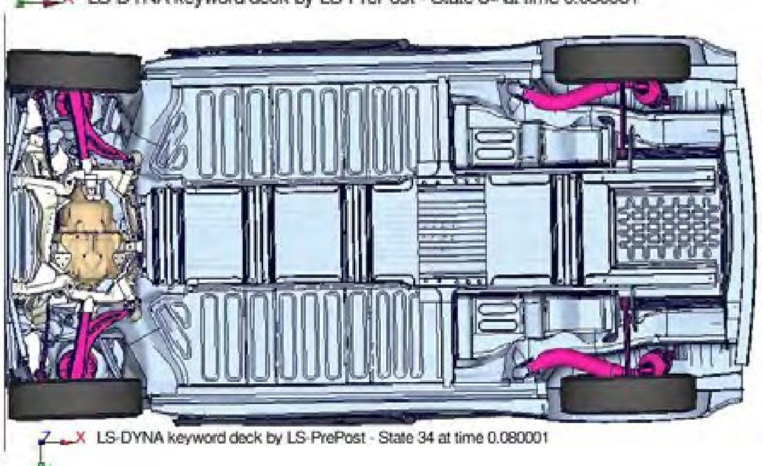
A – Footrest, B – Toe-left, C – Toe-center, D – Toe-right, E – IP-left, F – IP-right, G – A-pillar

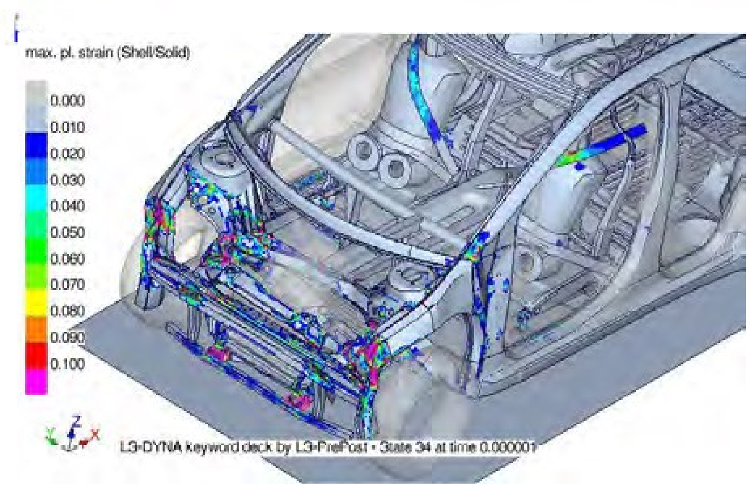
Frontal Impact: US NCAP Front (3)

- Deformation @ 80 msec
- Energy absorption: plastic strain contours

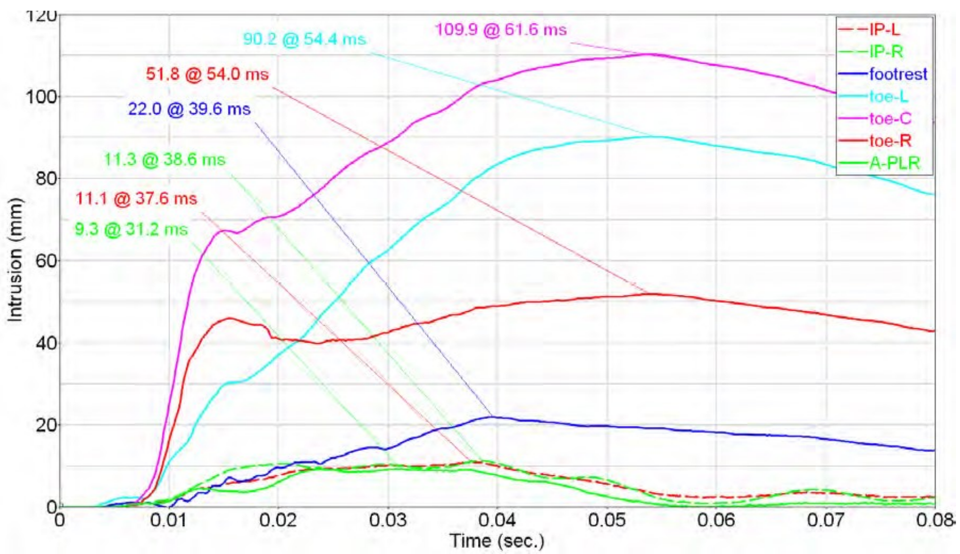


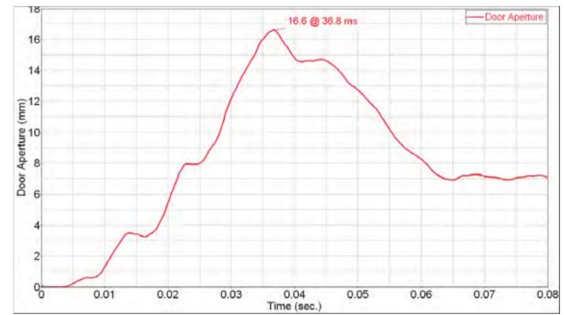


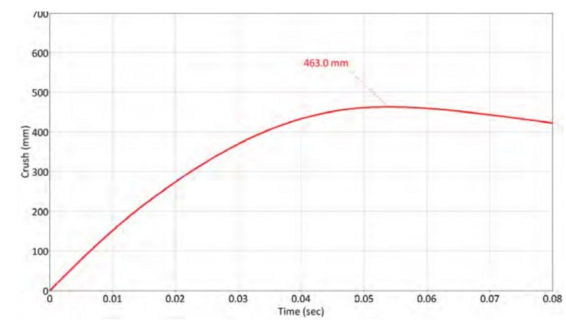


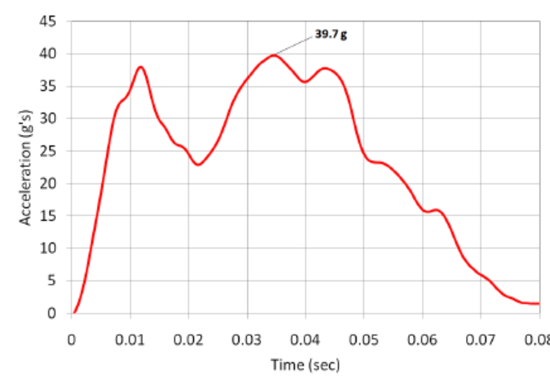


Frontal Impact: US NCAP Front (4)





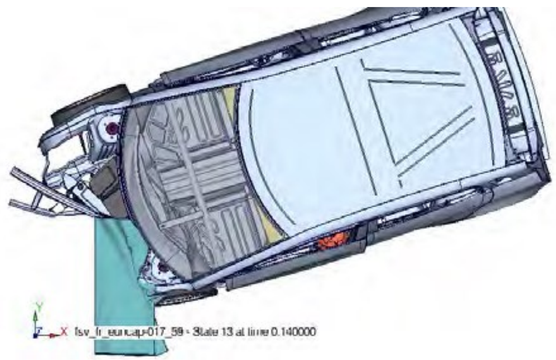




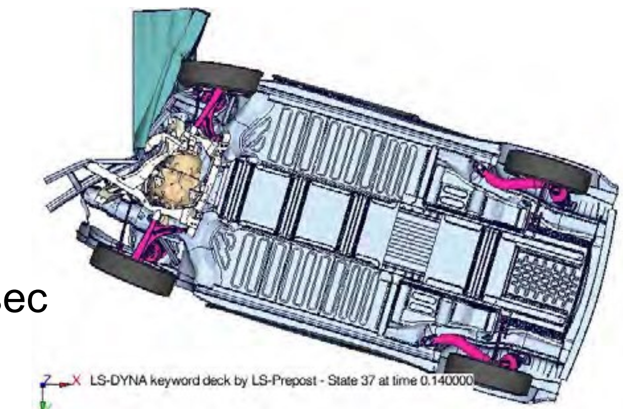
FSV Cabin Structure Measuring Point	Intrusion (mm)	Intrusion Target for Good Rating (mm)
Footrest	22.0	< 100
Toe-L	90.2	< 100
Toe-C	109.9	< 100
Toe-R	51.8	< 100
IP-L	11.7	< 100
IP-R	11.3	< 100
A-pillar	9.3	< 100

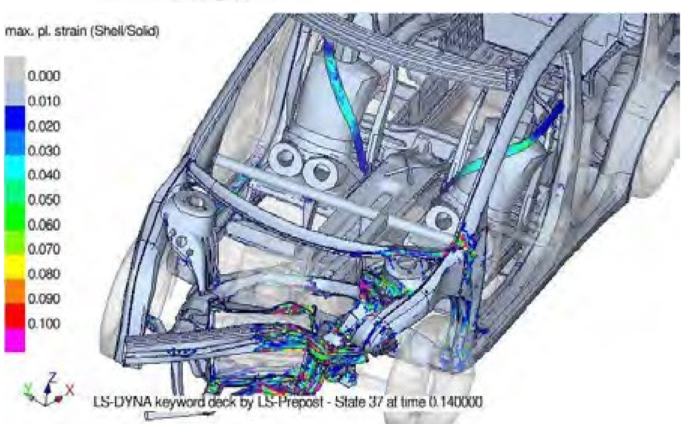
Frontal Impact: Euro NCAP/IIHS Front (1)

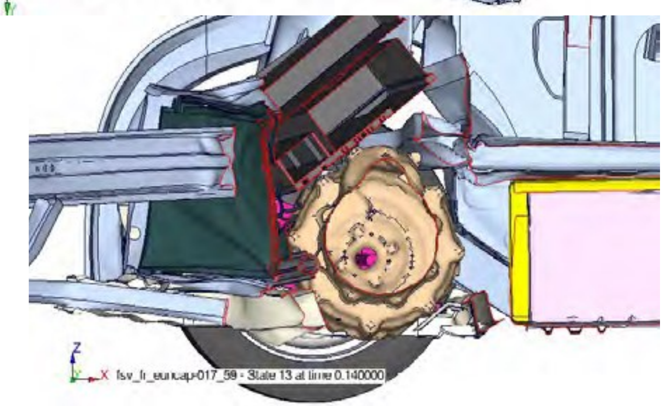
- offset frontal impact of 64 km/h into a deformable barrier with a vehicle overlap of 40%
- deformable barrier: ECE R.94 “Frontal Collision Protection”
- two Hybrid III 50 % dummies (driver, front seat occupant)



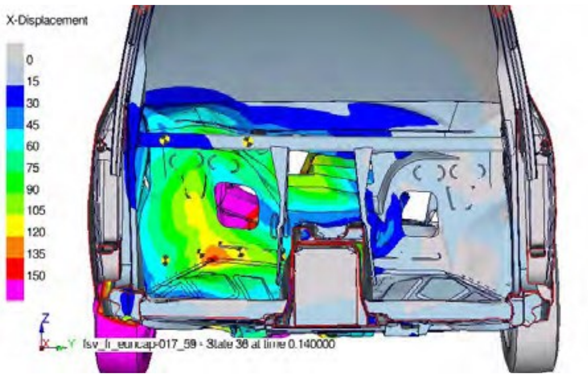
@140 msec

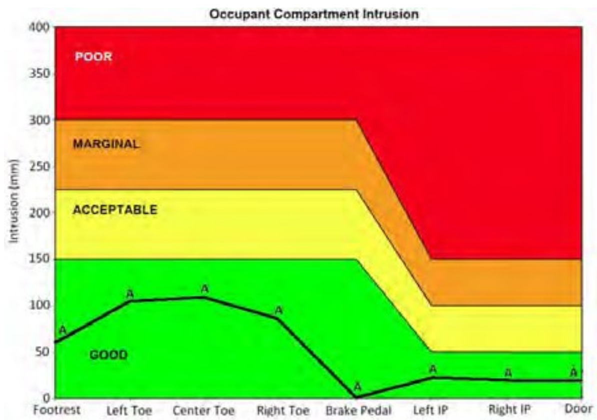




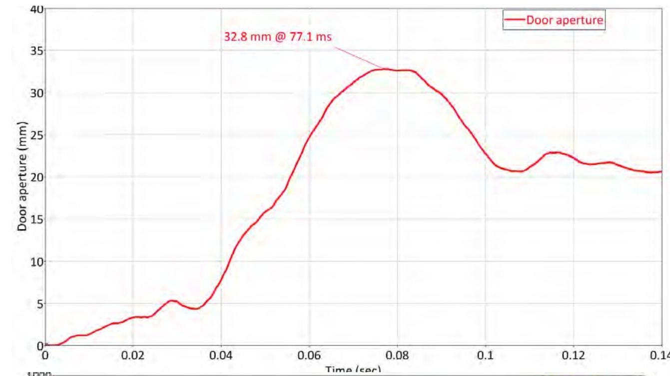


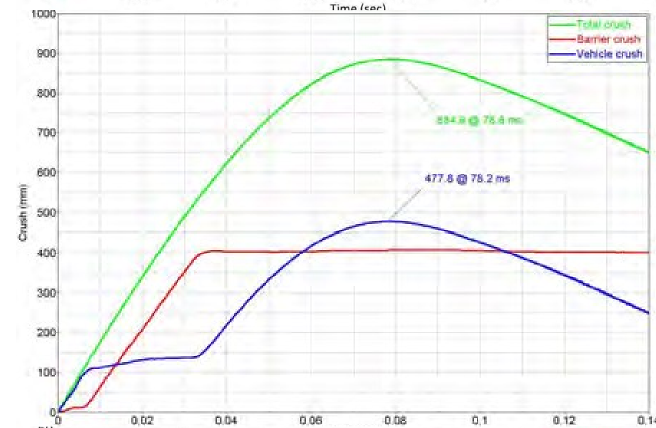
Frontal Impact: Euro NCAP/IIHS Front (2)

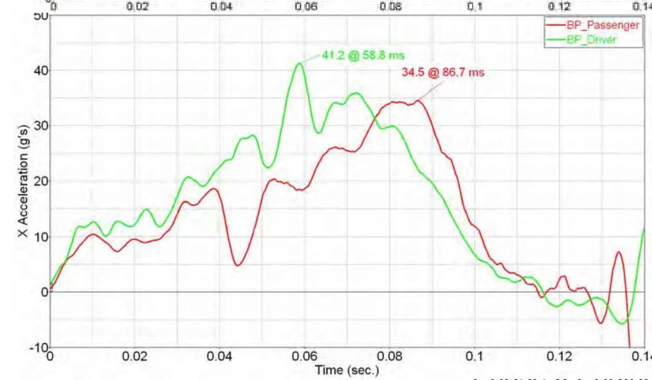




FSV Cabin Structure Measuring Point	Intrusion (mm)	Intrusion Target for Good Rating (mm)
Footrest	56.0	< 150
Toe-L	106.0	< 150
Toe-C	119.0	< 150
Toe-R	80.0	< 150
IP-L	21.2	< 50
IP-R	17.9	< 50
A-pillar	18.0	< 50

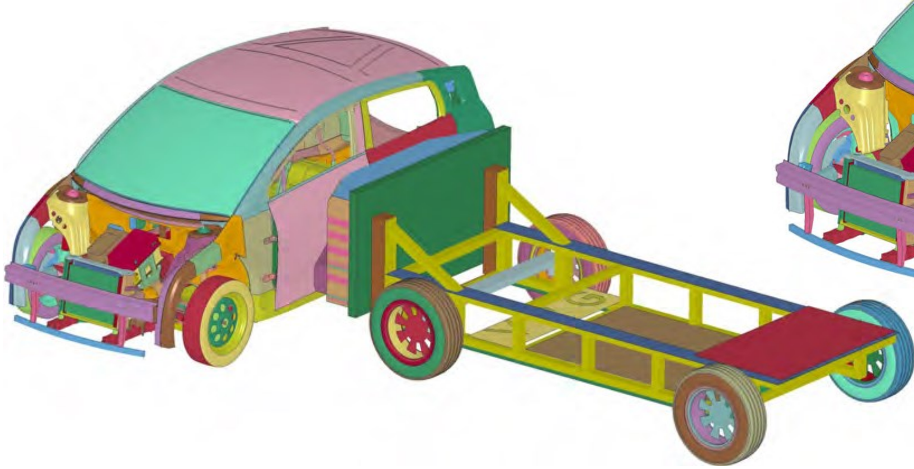


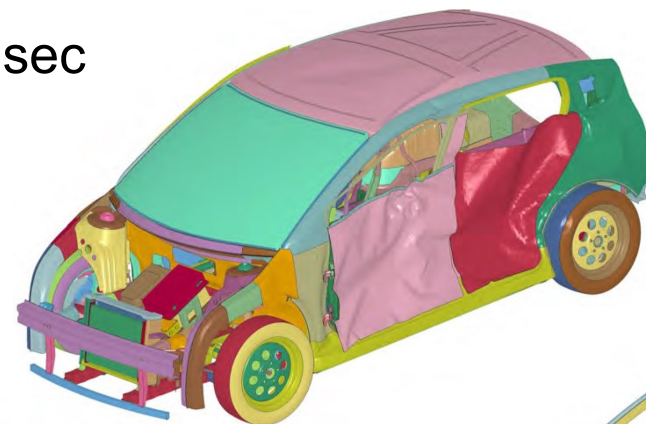




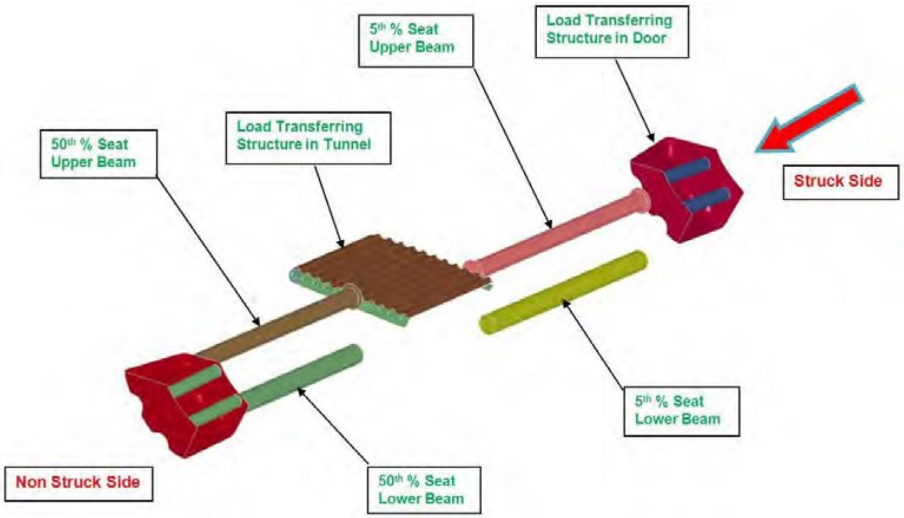
Side Impact: IIHS Side Impact (1)

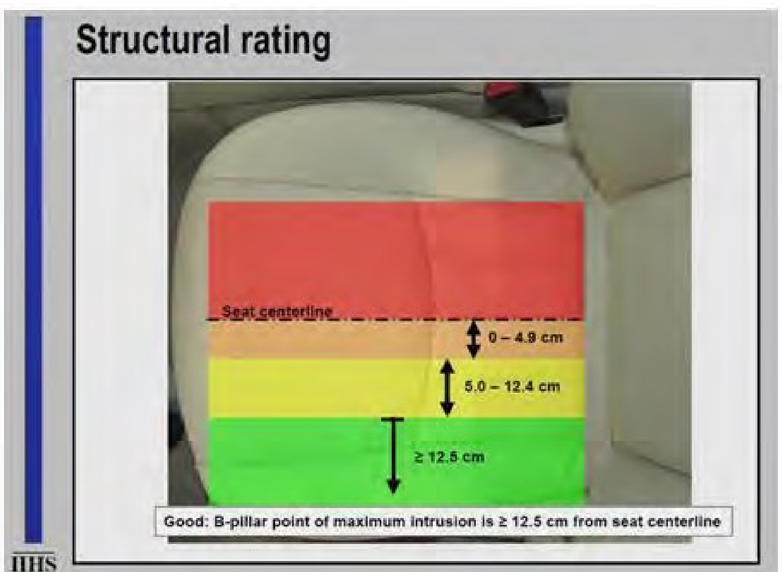
- Insurance Institute for Highway Safety(IIHS), test protocol
- front end of the Moveable Deformable Barrier (MDB): SUV
  - test weight of 1500 kg with a velocity of 50 km/h
- FSV weight 958 kg, two 5th percentile test dummies (45 kg each)
- Instrumentation: 32 kg in the cargo area, 59 kg on the non-struck front and rear side doors
- Deformation @ 100 msec

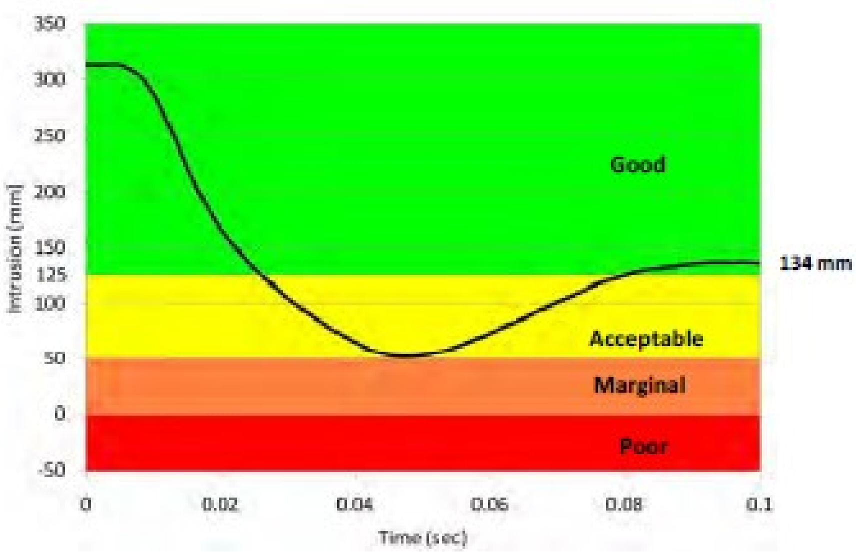




Side Impact: IIHS Side Impact (2)

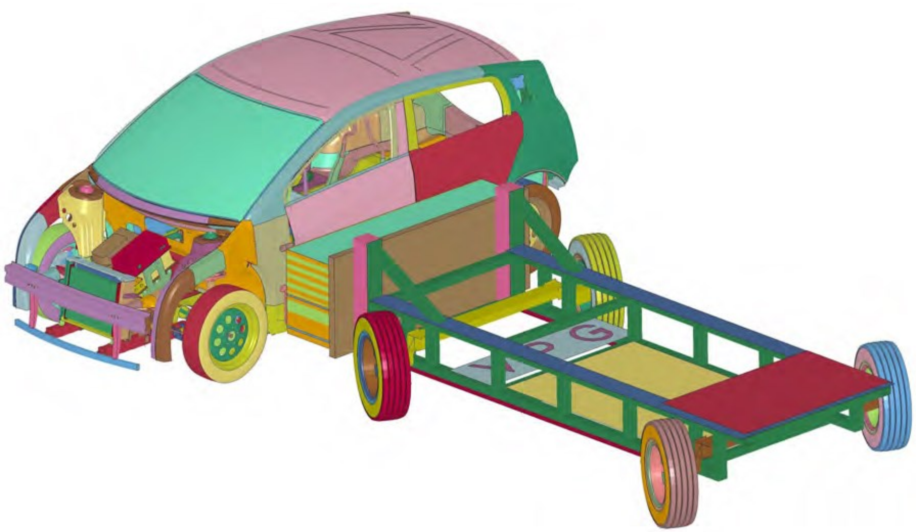


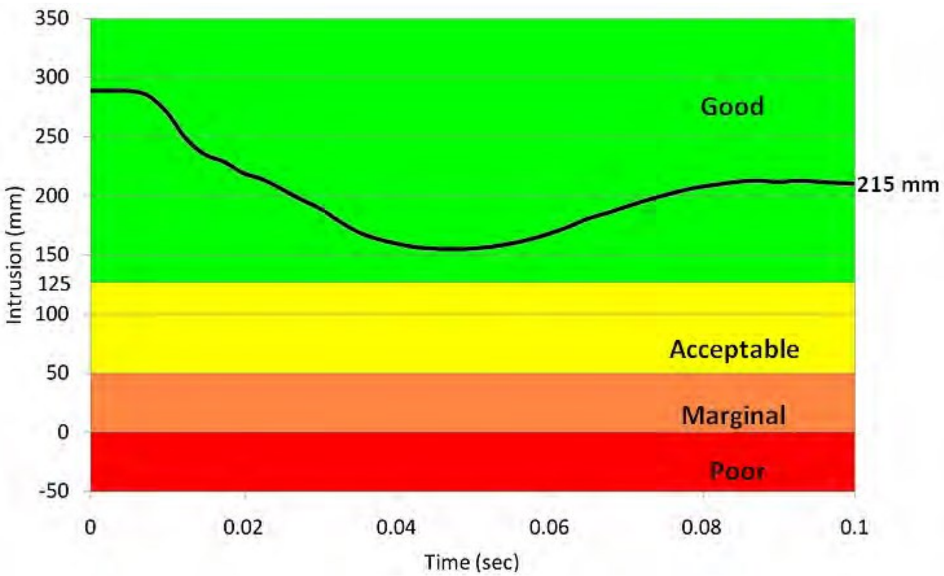




Side Impact: US SINCAP Impact

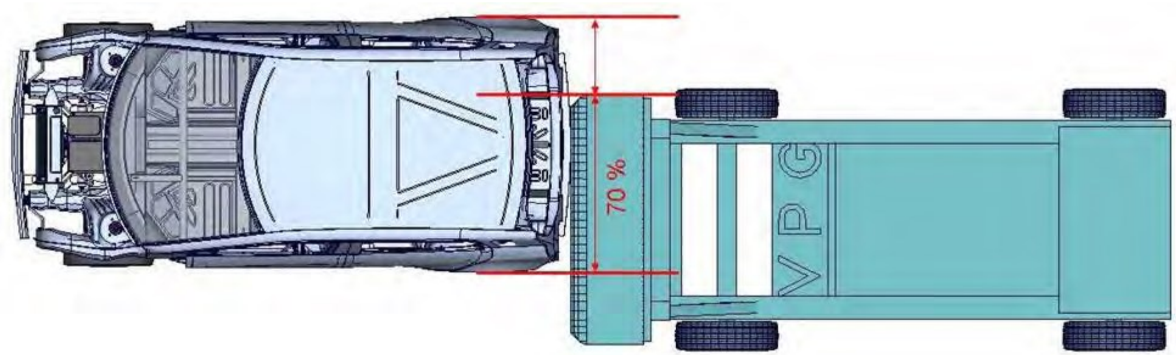
– Moveable Deformable Barrier (MDB), with a mass of 1370 kg impacts the FSV on the driver's side with velocity of 61 km/h
– B-pillar intrusion

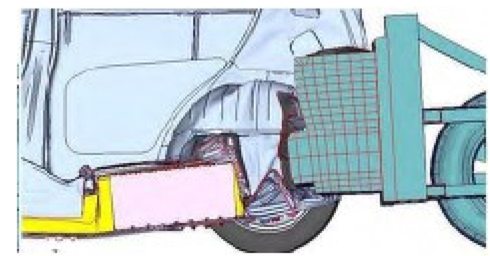


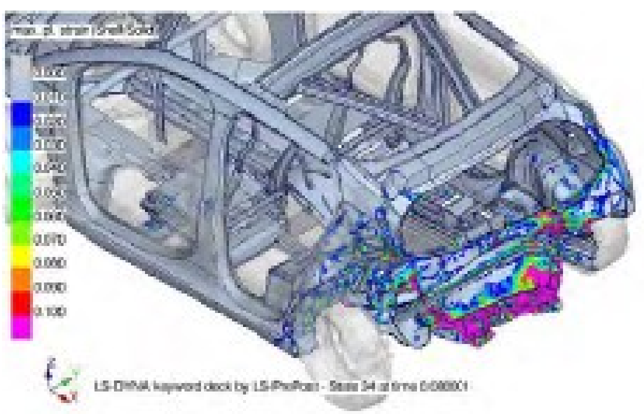


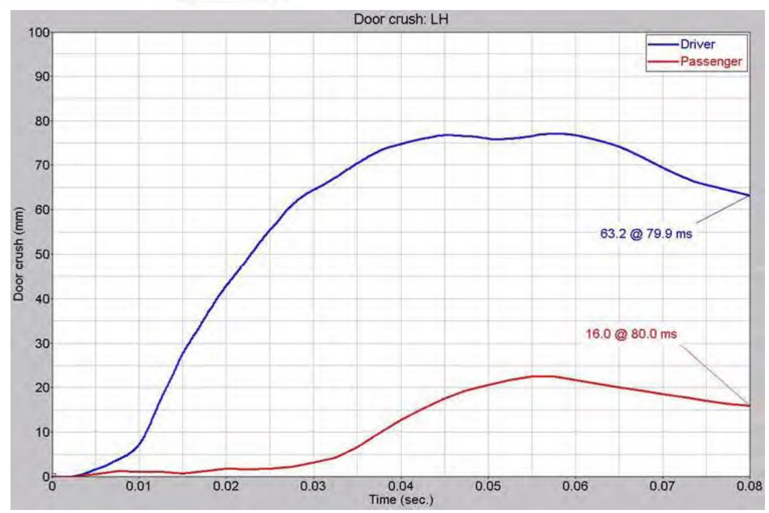
Rear Impact: FMVSS 301 Rear Impact

- moveable deformable barrier (MDB) 1380 kg, impact at 80 km/h into a stationary vehicle with an overlap of 70%
- Deformation @ 50 msec



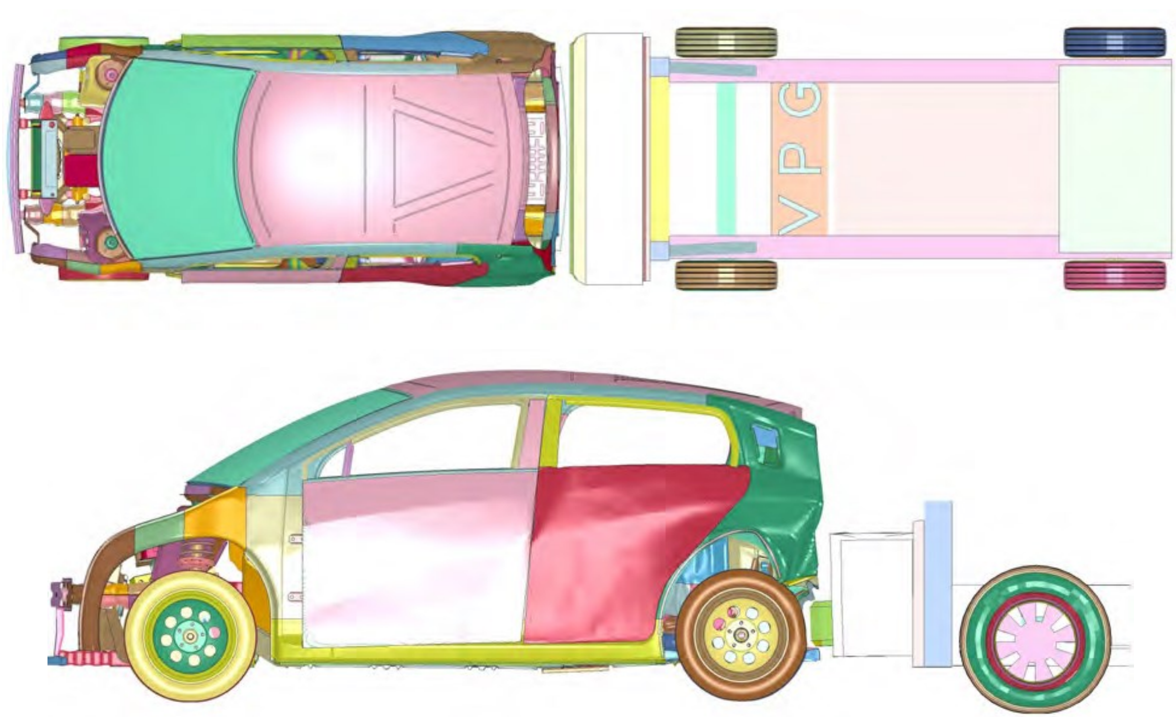






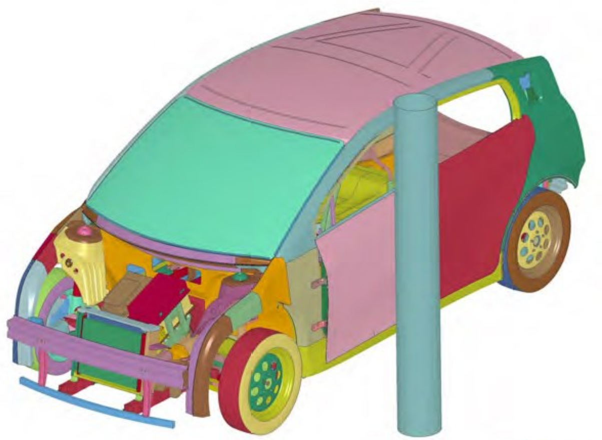
Rear Impact: ECE R32

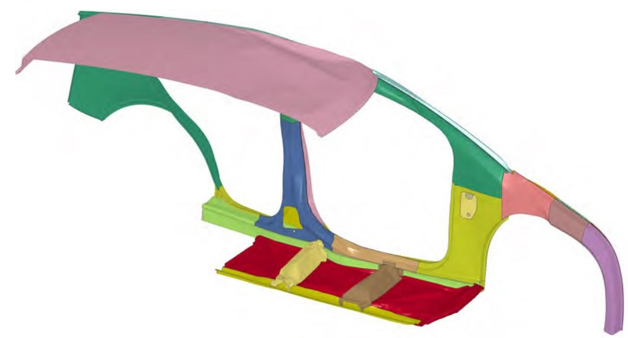
– deformable barrier impact at 55 km/h into a stationary vehicle with an overlap of 100%
– battery package space: no physical contact with other parts
    • very small amount of strain in the battery structure outer cover
    • very localized strain far away from the main battery modules

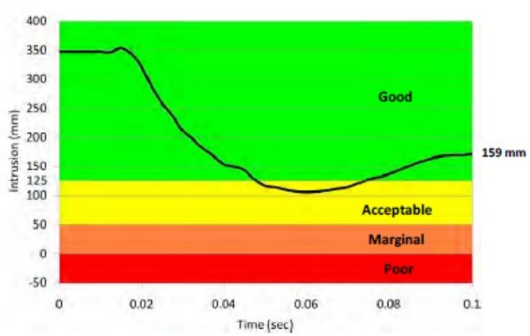


Side Pole Impact: FMVSS 214 Pole

- Impact the rigid pole (metal structure with a diameter of 254 mm) laterally at a speed of 31 km/h in such a way that its line of forward motion forms an angle of 75 degrees with the vehicle’s longitudinal center line
- lateral floor pan bead pattern: continuous vs. discontinuous

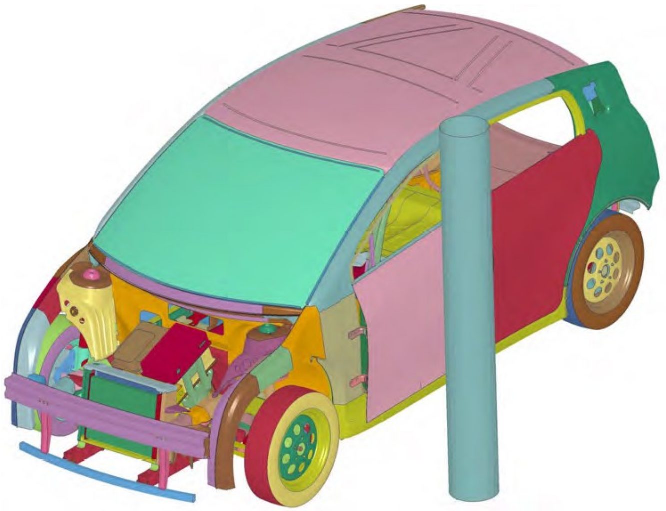


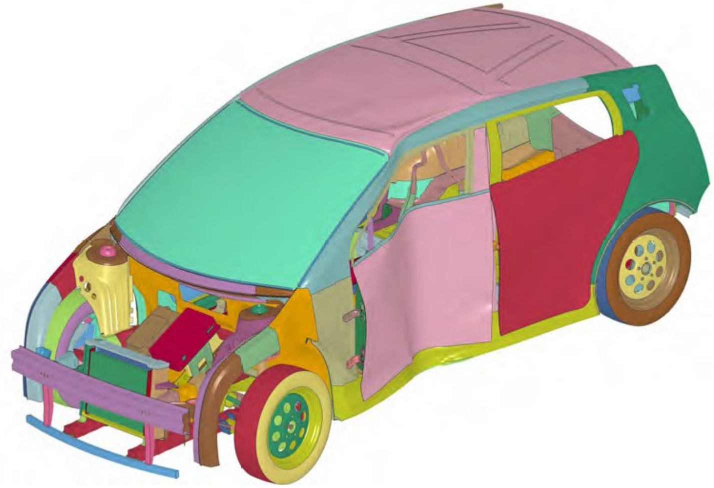


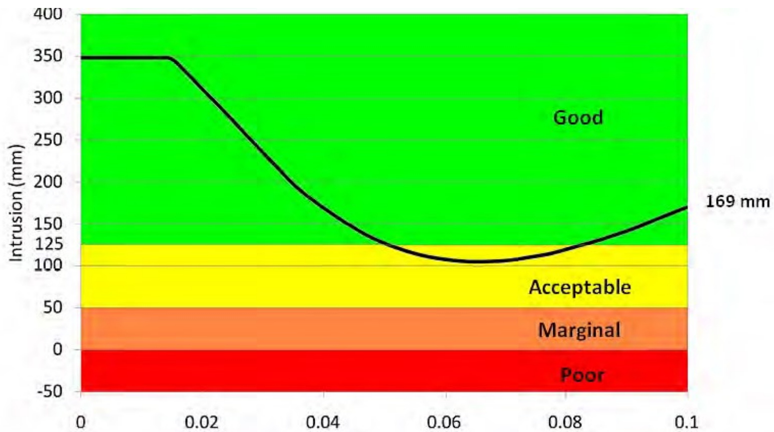


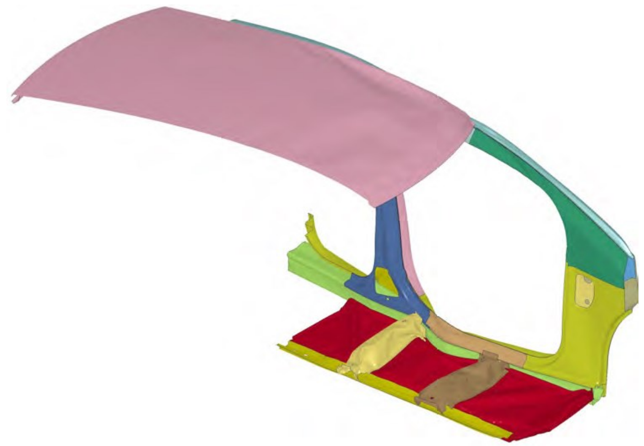
Side Pole Impact: Euro NCAP

– impact the rigid pole perpendicular to the direction of the movement of the vehicle at a speed of 29 km/h



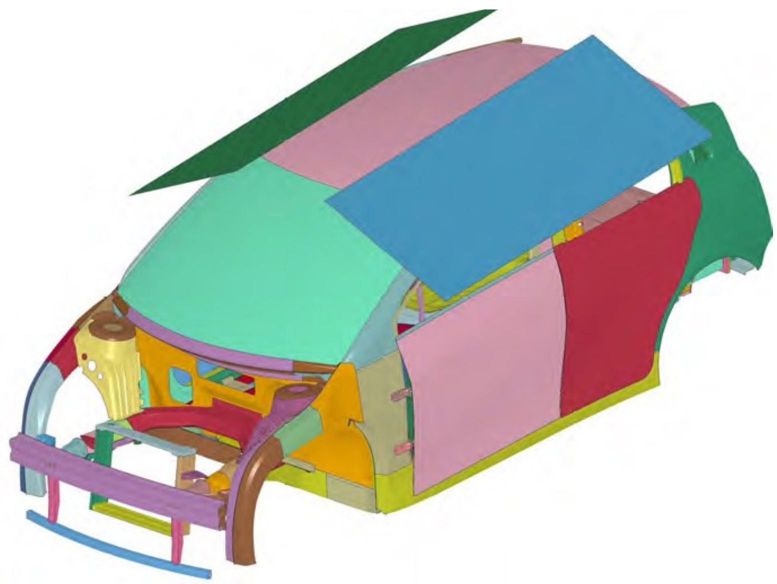


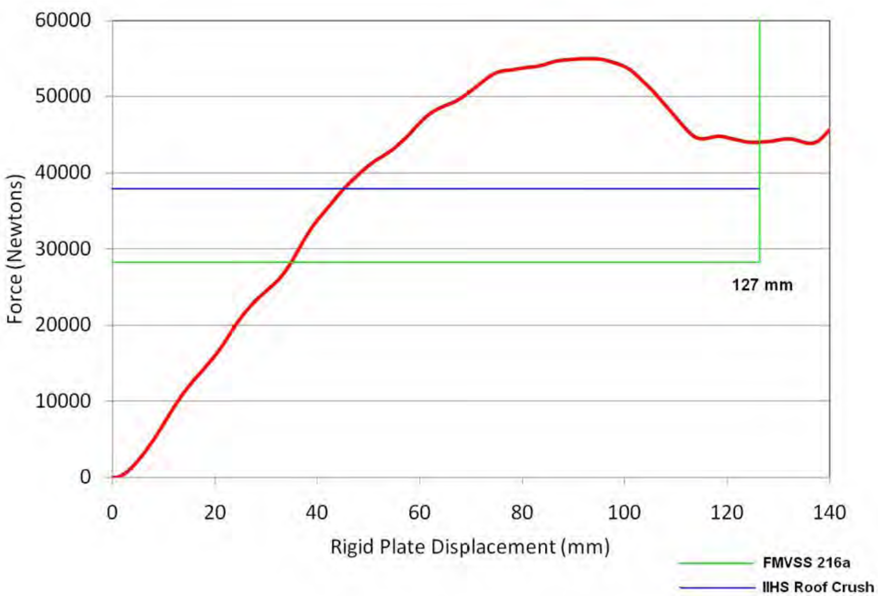




Roof Crush: FMVSS 216-a and IIHS

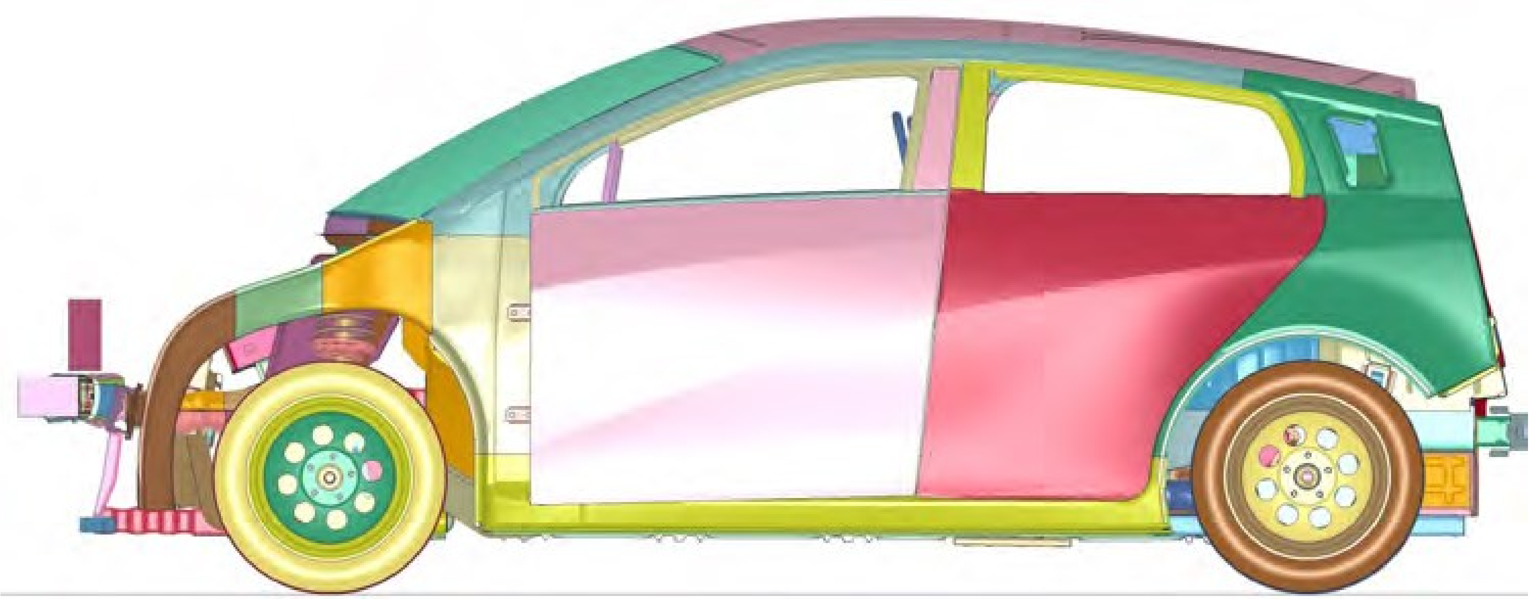
- crashworthiness of the vehicle in a roll over
- resist a maximum applied force equal to 3.0/4.0 times the curb weight of the vehicle in kilograms (958) and multiplied by 9.8 m/sec^2, for vehicles weighing less than 2,722 kg, prior to the lower surface of the rigid plate moving more than 127 millimeters





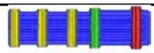
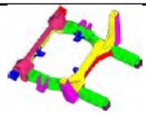
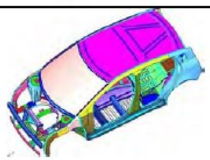
Low Speed Regulations: RCAR/IIHS

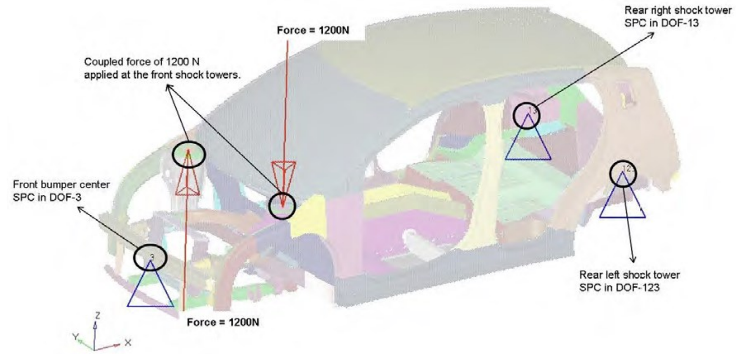
- when a vehicle hits another vehicle with a low speed
  - front bumper and crash box are allowed to deform, as those are bolt on parts and can be replaced easily
  - front rails will not deform
- rigid bumper barrier with an energy absorber (height 455 mm) hitting it at a speed of 10 km/h

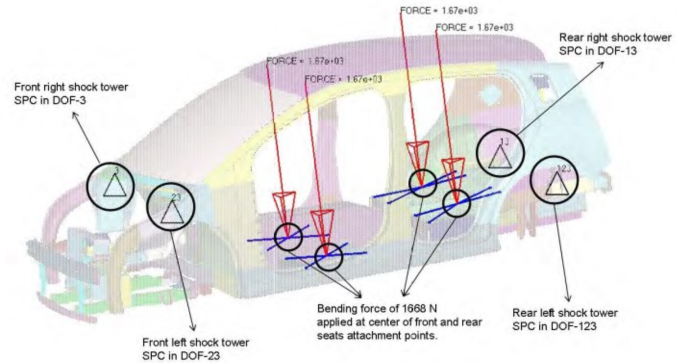


Static Stiffness Study

– static stiffness target: approximately 20kN-m/deg
  - competitive C-class vehicles (15~20 KN-m/deg)

S.No.	Assemblies	Total mass of the assembly (kg)	Illustration
1	Body Structure	187.7	
2	Battery Tray	12.0	
3	Engine Cradle	13.9	
4	Rear Bumper	3.2	
5	Front Bumper	5.9	
6	Radiator Support	1.8	
7	Windshield	15.0	
	BIP	239.5	

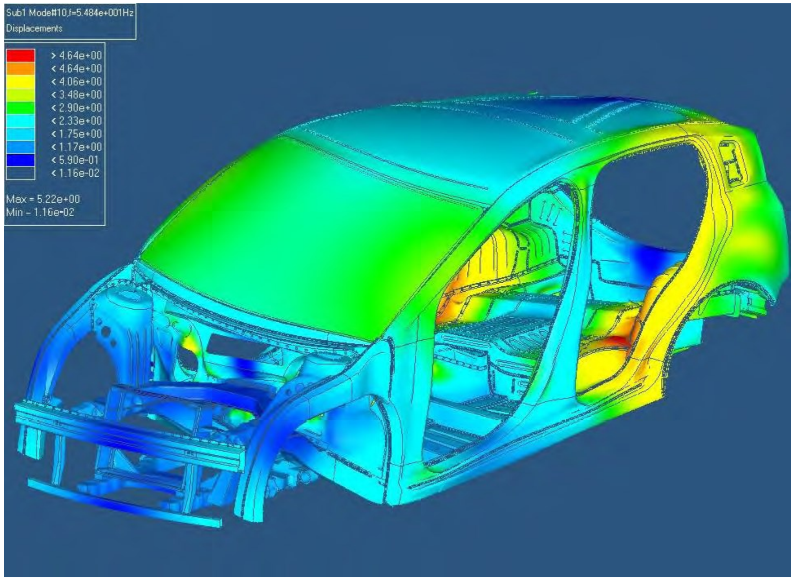


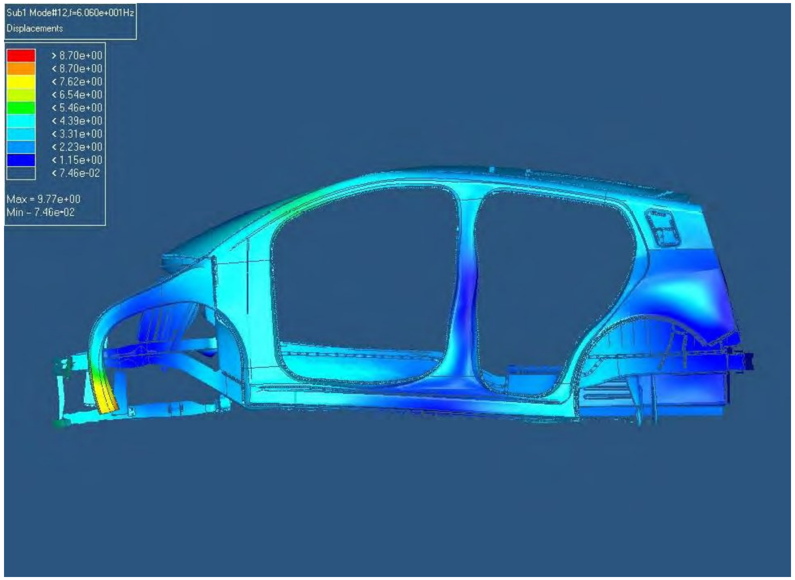


Analysis Type	Target	FSV Model Results
Torsion stiffness (KN-m/deg)	20.0	19.604
Bending stiffness (N/mm)	12.0	15.552

Dynamic Stiffness Study

– For a vehicle to be dynamically stiff, it is important to have high natural frequencies for the global modes

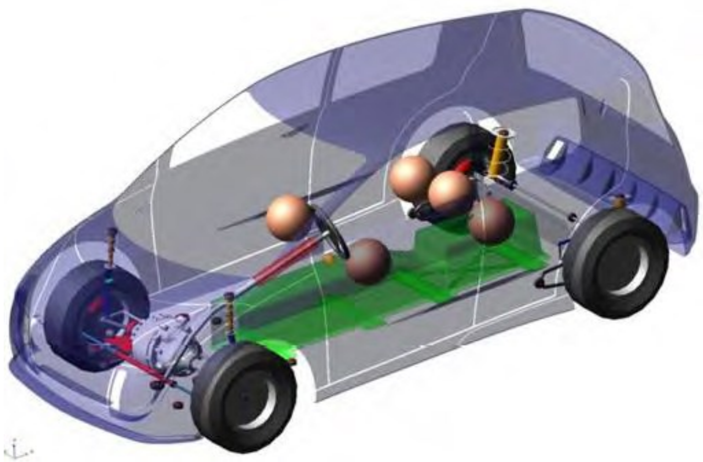


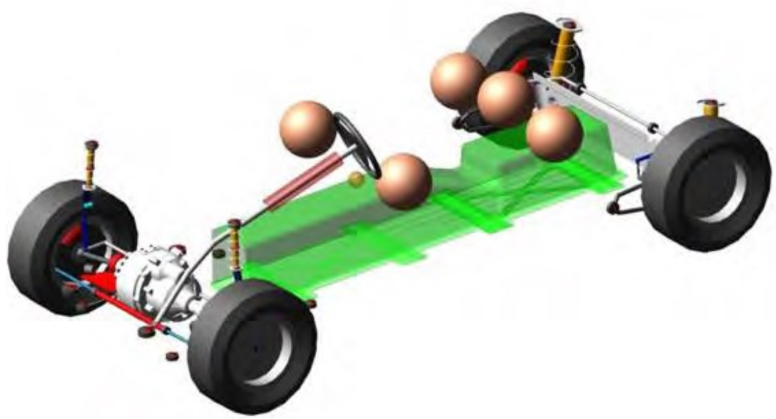


Global Mode Type	Frequency (Hz)	Target
Torsion	54.84	Both the modes should be >40 Hz and also have a difference of atleast 3 Hz
Vertical Bending	60.6	

Full Vehicle Dynamic Analysis

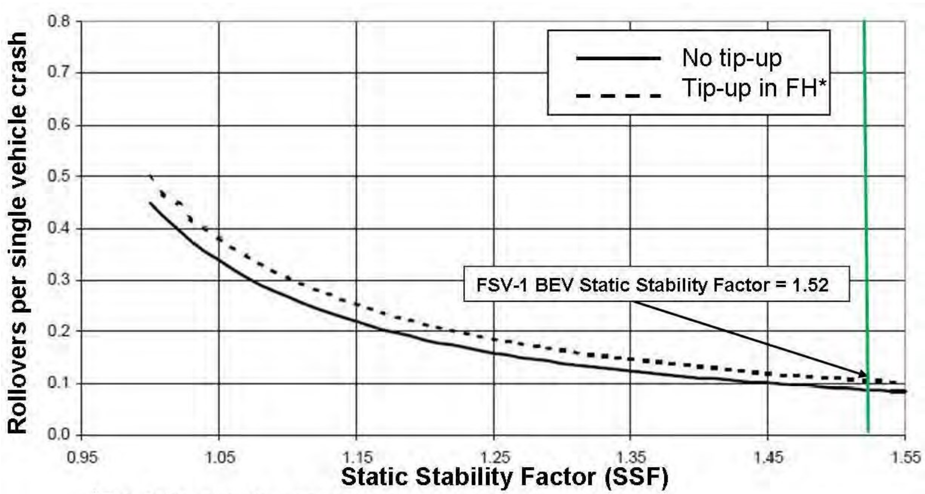
– MSC/ADAMS (Macneal-Schwendler Corporation/Automatic Dynamic Analysis of Mechanical Systems)
– Five vehicle ride and handling conditions
  • NHTSA: Fish-hook test
  • Industry standard maneuvers: Double lane change maneuver (ISO 3888-1), 3 g pothole test, 0.7 g constant radius turn test, 0.8 g forward braking test





Fishhook Test

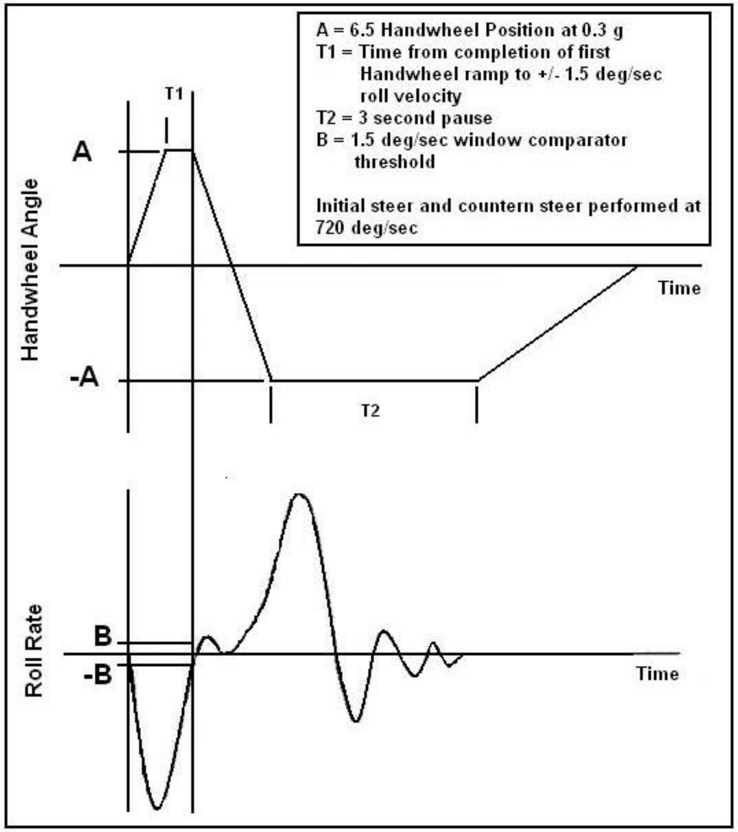
– National Highway Traffic Safety Administration (NHTSA)
– Static Stability Factor (SSF) to rate the propensity for vehicle rollover
  - ratio of half of a vehicle's track width to its center of gravity height
  - FSV-1: 1.52 (track width=1450, center of gravity height= 476)
– NHTSA statistical model to determine the vehicle's rollover rate per single vehicle crash percentage
  - Rollover rate: 5 star (≤10%)



*FH- fishhook with a heavy load

Fishhook Test Procedure

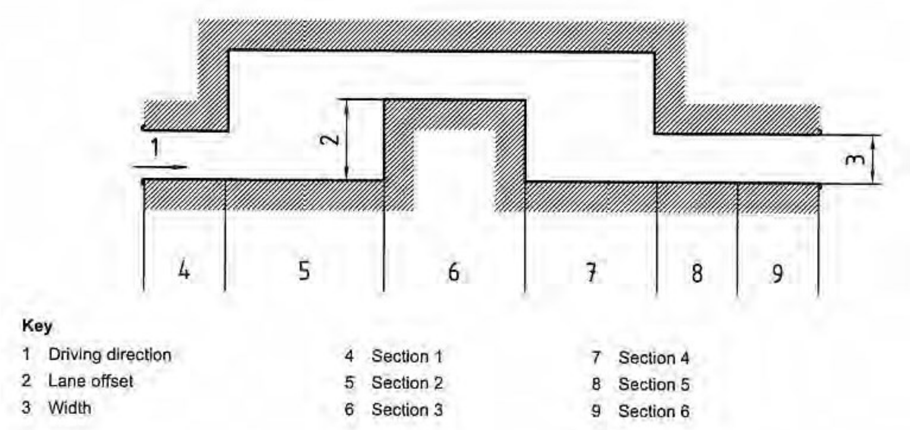
- Conducted with a five passenger load
- Vehicle is driven at 80.5 km/h with a steering input from 0 to 270° at 13.5 ° /s, and held at 270° for two seconds
- Amplitude of the resulting steering angle that produces 0.3 g is then multiplied by 6.5
- run at 56.3 km/h, 64.3 km/h, 72.4km/h, 76.4 km/h and 80.5 km/h making a left to right turn and then repeated making a right to left turn



Vehicle Speed (km/hr)	Two Wheel Tip-Up (Yes/No)
56.3	No
64.3	No
72.4	No
76.4	No
80.5	No

Double Lane Change Maneuver Test

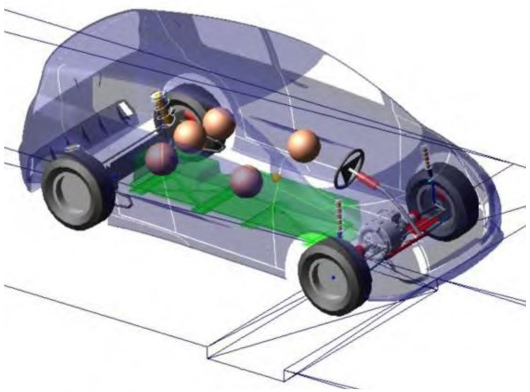
- subjective dynamic maneuver
  - first test: initial speed 80 +/- 3 km/h, the throttle position is held steady and the driver maneuvers through the test track
  - second test: the driver maneuvers through the test track at the maximum speed of which the vehicle is capable
  - manipulate the track without exceeding lane boundaries

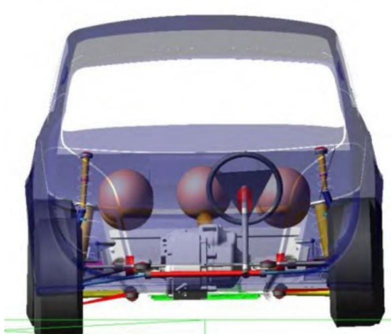


Section	Length (m)	Lane Offset (m)	Width (m)
1	15	-	1.1 * vehicle width +0.25
2	30	-	-
3	25	3.5	1.2 * vehicle width +0.25
4	25	-	-
5	15	-	1.3 * vehicle width +0.25
6	15	-	1.3 * vehicle width +0.25

3 g Pothole Test

- driving a vehicle over a pothole on the left or right side of the vehicle (101.6 mm deep pothole at 3.5 m/s)
- un-sprung vehicle weight measured at the impacting wheel of the vehicle multiplied by three
- Total weight of the test vehicle was 1371 kg





Bushing Description	Bushing Loads		
	fx (N)	fy (N)	fz (N)
FRONT SUSPENSION			
Body mount left	190.69	1232.36	3770.61
Body mount right	430.94	-896.35	5491.90
LCA to subframe frt left	-359.85	-2072.00	-29.53
LCA to subframe frt right	-33.06	527.18	203.65
lca to subframe rr left	4.77	-72.00	-25.28
LCA to subframe rr right	45.64	-397.60	207.11
REAR SUSPENSION			
Trailing arm to body left	-414.27	64.12	591.79
Trailing arm to body right	-848.34	54.62	1529.10
Upper Control Arm (UCA) to subframe left	-26.38	1956.89	-102.06
UCA to subframe right	-133.30	-2603.23	-281.70
Lower Control Arm (LCA) to subframe left	69.54	-2610.23	-62.86
LCA to subframe right	381.11	2350.41	74.43
Rear body mount left	391.03	350.56	1914.16
Rear body mount right	646.29	-345.14	3283.18

- 0.7 g Constant Radius Turn
  - around a 95 m diameter circle
  - Vehicle lateral g's were ramped up from 0.4 to 0.7 g
- 0.8 g Forward Braking
  - driving in a straight line at 7.0 m/s
  - longitudinal deceleration of 0.8 g

Bushing Description	Bushing Loads		
	fx (N)	fy (N)	fz (N)
FRONT SUSPENSION			
Body mount left	-657.92	680.47	3249.60
Body mount right	-656.43	-680.55	3244.79
Lower Control Arm (LCA) to subframe frt left	-159.30	-4280.74	1900.37
LCA to subframe frt right	-157.78	4276.93	1903.96
LCA to subframe Rear left	128.61	3750.29	1899.17
LCA to subframe Rear right	127.70	-3757.02	1902.16
REAR SUSPENSION			
Trailing arm to body left	1051.51	-470.90	-133.88
Trailing arm to body right	1054.74	470.19	-139.00
Upper Control Arm (UCA) to subframe left	-84.02	1663.86	-117.27
UCA to subframe right	-83.45	-1659.53	-116.49
LCA to subframe left	209.69	-1596.07	-6.38
LCA to subframe right	208.11	1596.29	-6.95
Rear body mount left	492.39	326.35	2287.34
Rear body mount right	491.18	-326.50	2281.55

Durability Study

- long term performance of a vehicle under repetitive loading due to driving and other operating conditions
- repetitive loads cause fatigue damage, and the accumulation of damage ultimately results in the initiation of cracks, crack propagation, and system or part failure
- two types of fatigue analyses in use for structural durability
  - stress based or s-N analysis for low stress and high cycle fatigue (engine, transmission, and auxiliaries)
  - strain based or e-N analysis for high stress, low cycle fatigue as from road loads and other transient loads: FSV vehicle
- main road load cases that affect body life
  - 3 g Pothole
  - 0.7 g Cornering
  - 0.8 g Forward braking cases

Process and Tools used for Durability Study

– time series loads extracted at different body mounting locations such as F/R shocks, LCA to F/R subframe (ADAMS) → stresses (NASTRAN with inertia relief) → "n-code Design Life" tool

Loading Type	FSV Predicted Life Cycles	Target Life Cycles
3G Pot Hole	927,000	200,000
0.7G Cornering	1,680,000	100,000
0.8G Forward Braking	275,000 (Engine cradle) 17,300,000 (Body Life)	100,000

right rear gusset

rear cargo box

engine cradle rear rail-upper