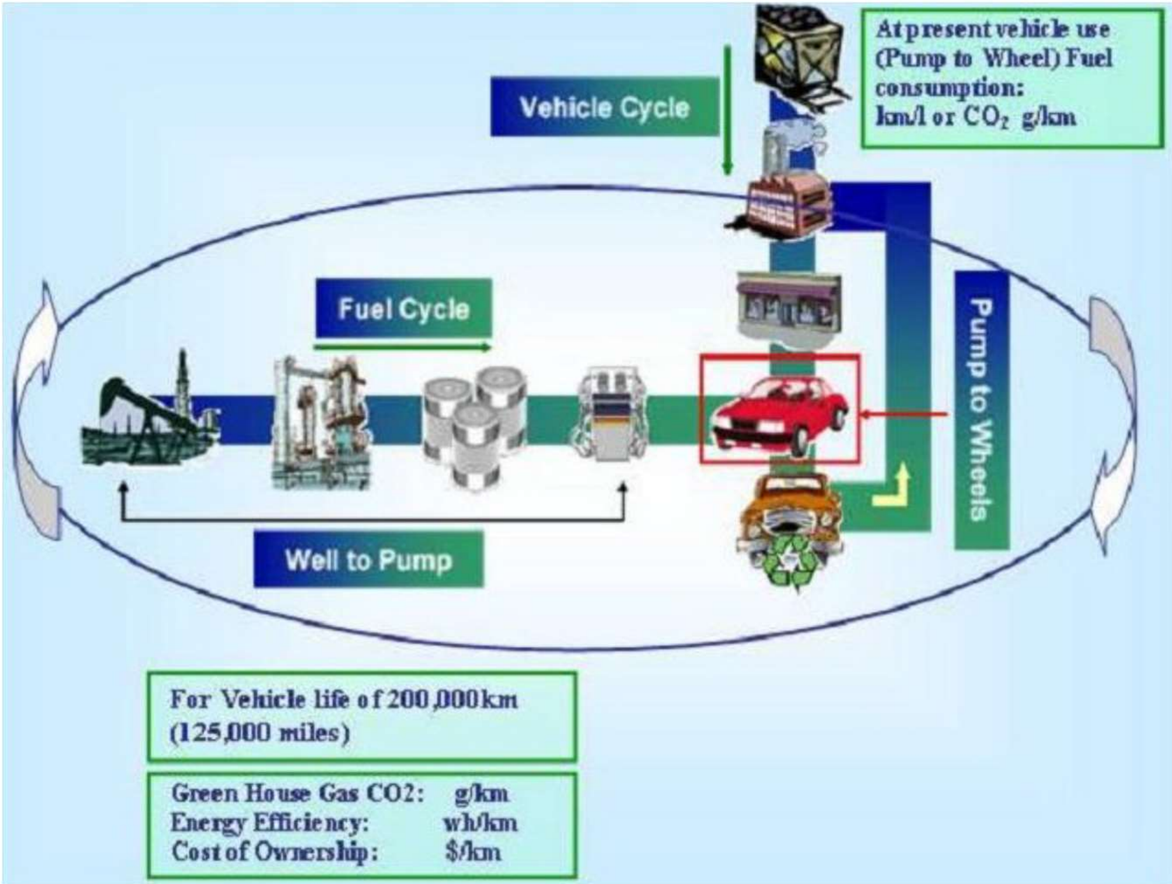
Environmental Impact

- Overview
  - Fuel Efficiency and CO2 Relevance
  - Air Pollution
  - Noise Pollution
- Well-to-Wheel Efficiencies
- FSV Environmental Assessment
- Well-to-Wheel Energy Usage

Total Life Cycle Assessment

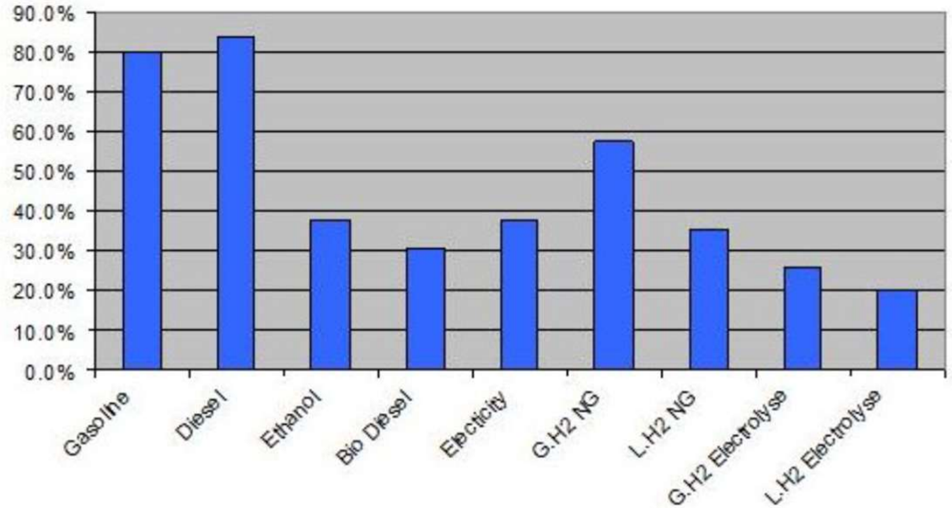
- "Pump-to-Wheel" fuel consumption and corresponding CO_2 emissions
- Fuel production cycle also known as "Well-to-Pump"
- Vehicle manufacturing cycle

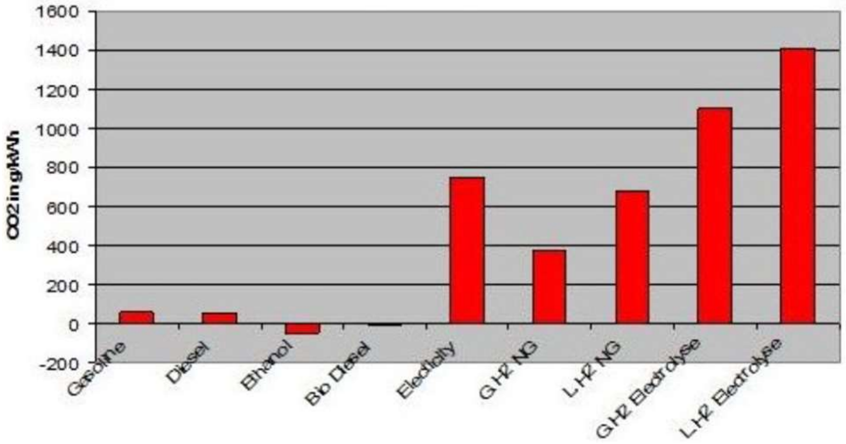


Well-to-Pump Assessment: Fuel Cycle

- Electricity (US mix, Europe, China, Japan, India, 100% coal and 100% renewable)
- Gasoline and diesel from petroleum
- Bio-fuels, ethanol and bio-diesel
- Hydrogen gas and liquid made using electrolysis process and from natural gas

Feedstocks [%]	USA	Europe	China	Japan	India	Coal	USA Green Mix
Coal	50.7	29.5	79	28.1	68.7	100	0
Natural Gas	18.9	9.9	0	21	8.9	0	0
Oil	2.7	4.5	2.4	13.2	4.5	0	0
Nuclear	18.7	31	2.1	27.7	2.5	0	20
Biomass	1.3	2.1	0	0	0	0	0
Others	7.7	13	16.5	10	15.4	0	80
	100	100	100	100	100	0	100
Electricity Pathway:							
Efficiency [%]	37.9	44.2	35	41.6	35.1	30.7	91.5
CO2 [g/kWh]	750.6	520.3	973	596.7	923.5	1201.3	0
VOC [g/kWh]	0.07	0.05	0.08	0.06	0.08	0.09	0
Nox [g/kWh]	0.82	0.61	1.05	0.76	1.01	1.26	0
Sox [g/kWh]	1.8	1.25	2.64	1.74	2.46	3.15	0



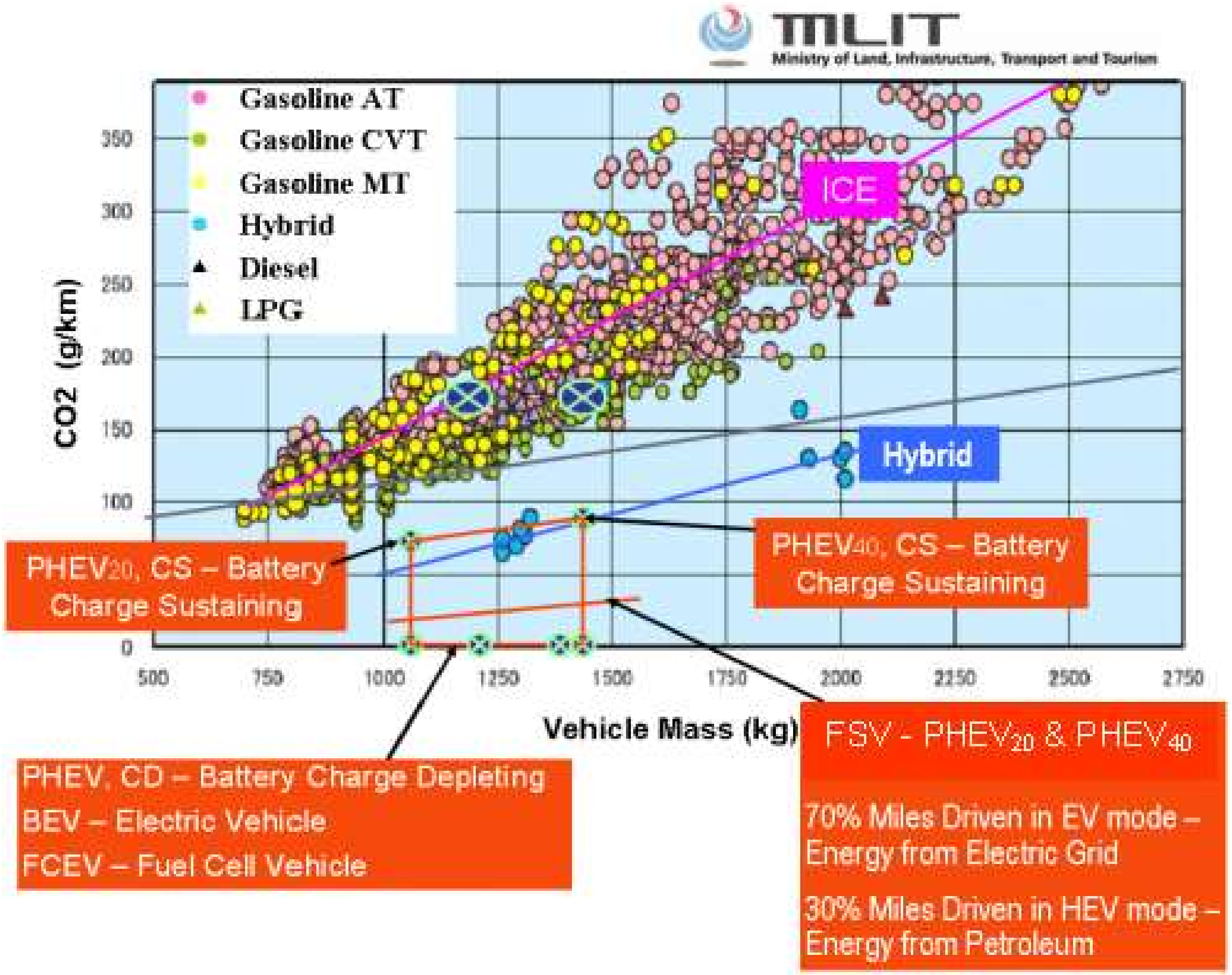


Pump-to-Wheel Assessment: FSV

European Union (EU): 95 g(CO_2)/km (passenger car fleet average), by year 2020
Zero Emissions Vehicles (ZEV) by the California Air Resources Board (CARB)

	FSV1 BEV	FSV1 $PHEV_{20}$	FSV2 FCEV	FSV2 $PHEV_{40}$	Reg. Limit ALL
European Drive Cycle (NEDC)					
CO2 Emissions g/km	0	23	0	27	95
Fossil Fuel l/100km	0	0.99	0	1.14	4.1
Electricity Usage $\frac{Wh}{km}$	89	65	0	75	N/A
Total Energy Usage ** $\frac{Wh}{km}$	89	152	211	175	361
2008 US EPA Drive Cycle					
CO2 Emissions (combined) g/km	0	31	0	35	156
Combined MPG	∞	177	∞	157	35
Combined Electricity Usage $\frac{Wh}{km}$	109	80	0	92	N/A
Combined Energy Usage ** $\frac{Wh}{km}$	109	196	295	224	590
City MPG	∞	177	∞	157	N/A
City Electricity Usage $\frac{Wh}{km}$	103	75	0	86	N/A
City Energy Usage ** $\frac{Wh}{km}$	103	192	304	218	N/A
Highway MPG	∞	177	∞	157	N/A
Highway Electricity Usage $\frac{Wh}{km}$	117	85	0	99	N/A
Highway Energy Usage ** $\frac{Wh}{km}$	117	202	295	231	N/A

Fuel Economy and CO_2 Emissions



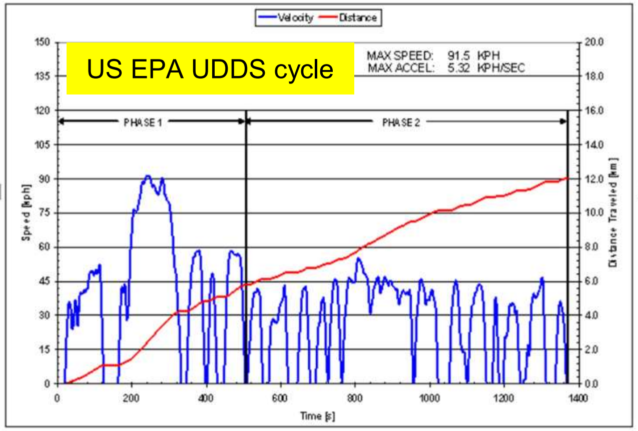
Japan - Ministry of Land, Infrastructure, Transport and Tourism

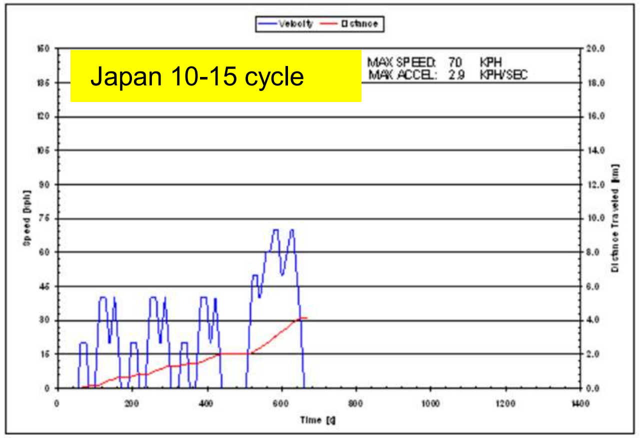
FSV Environmental Assessment

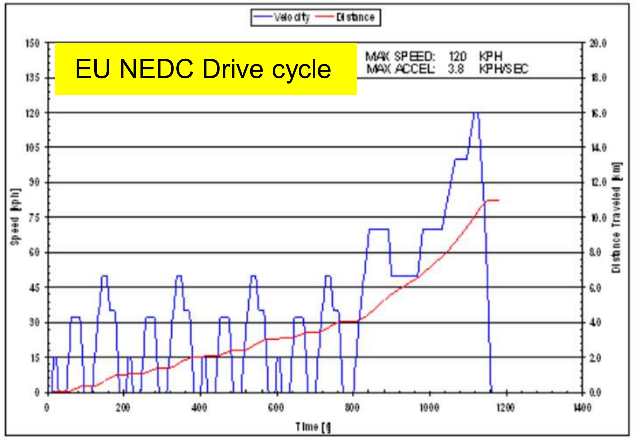
- Pump-to-Wheel fuel economy
  - Powertrain System Analysis Toolkit (PSAT)
  - standard drive cycles from North America, Japan, and Europe

		UDDS	Japan 10-15	NEDC
PHEV$_{40}$ Series Mid-size: 1300kg Vehicle + 75kg driver				
Charge Depleting	[Wh / km]	107	110	111
	[L / 100km]	0	0	0
	[g CO_2 / km]	0	0	0
Charge Sustaining	[Wh / km]	0	0	0
	[L / 100km]	3.8	3.79	3.79
	[g CO_2 / km]	88.4	88	88
PHEV$_{20}$ Series Small-size: 1000kg Vehicle + 75kg driver				
Charge Depleting	[Wh / km]	92.5	94.9	96.9
	[L / 100km]	0	0	0
	[g CO_2 / km]	0	0	0
Charge Sustaining	[Wh / km]	0	0	0
	[L / 100km]	3.3	3.27	3.43
	[g CO_2 / km]	76.7	76	79.8
EV Series Small-size: 1100kg Vehicle + 75kg driver				
	[Wh / km]	88.9	92.8	96.4
	[g CO_2 / km]	0	0	0
FCEV Series Mid-size: 1300kg Vehicle + 75kg driver				
	[kg / 100km]	0.632	0.669	0.653
	[g CO_2 / km]	0	0	0

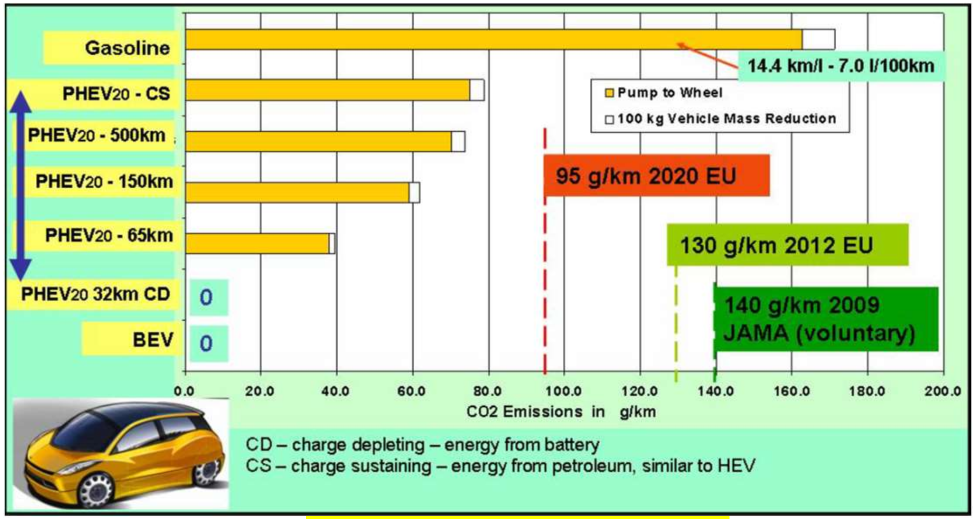
Table 8.4: *Pump-to-Wheel GHG CO_2 emissions*

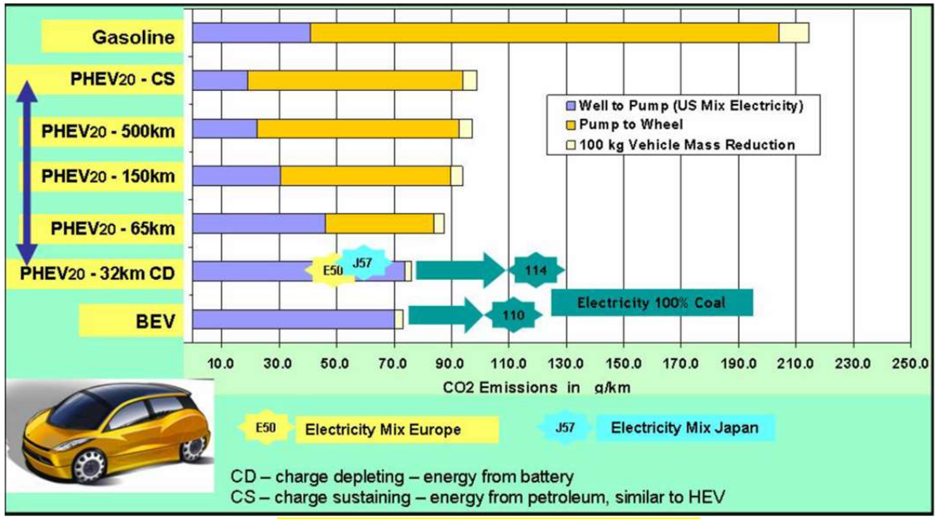






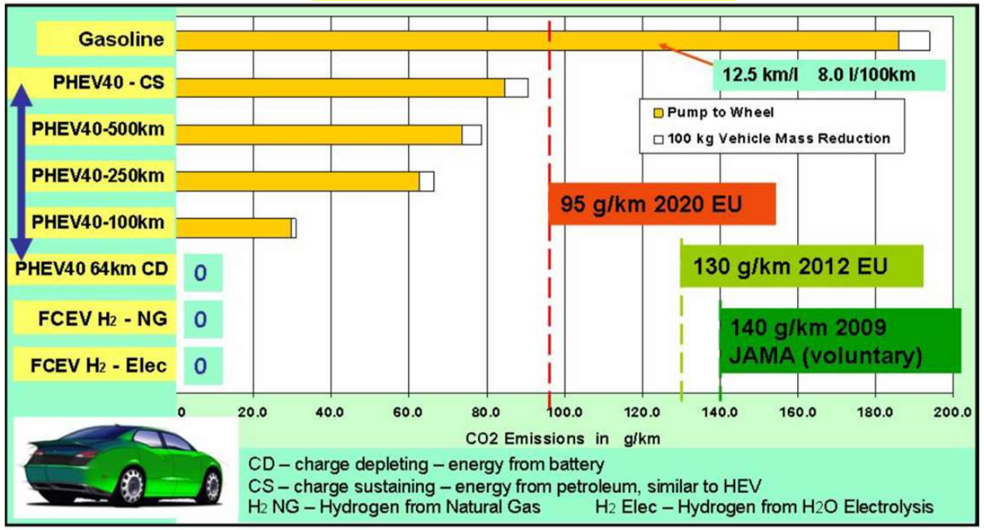
Assessment: FSV-1, FSV-2

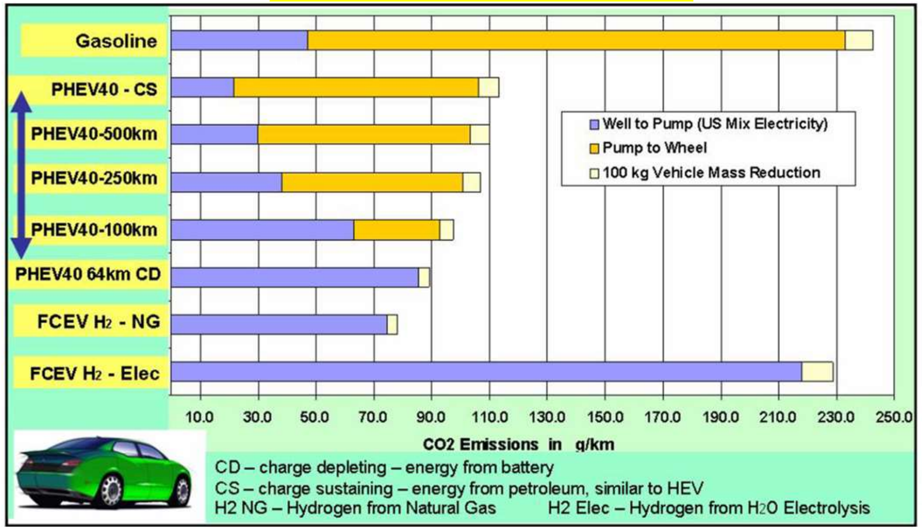




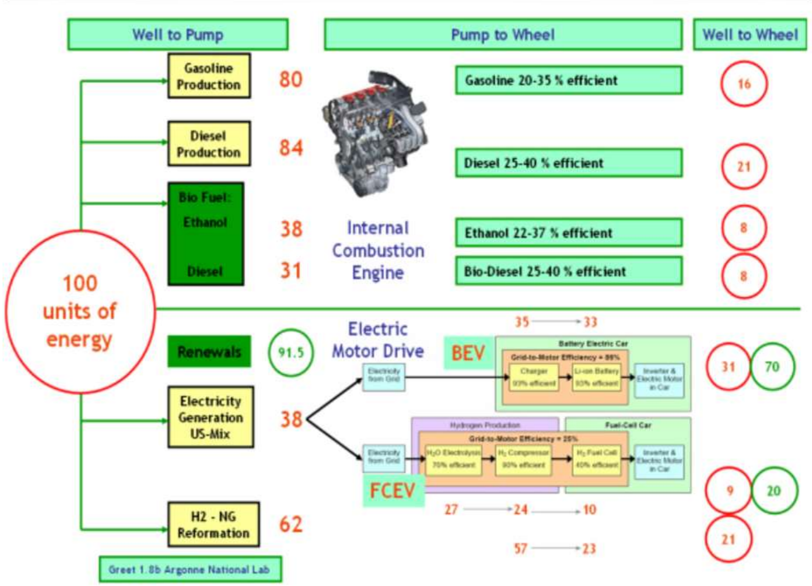
Pump-to-Wheel CO_2 Emissions

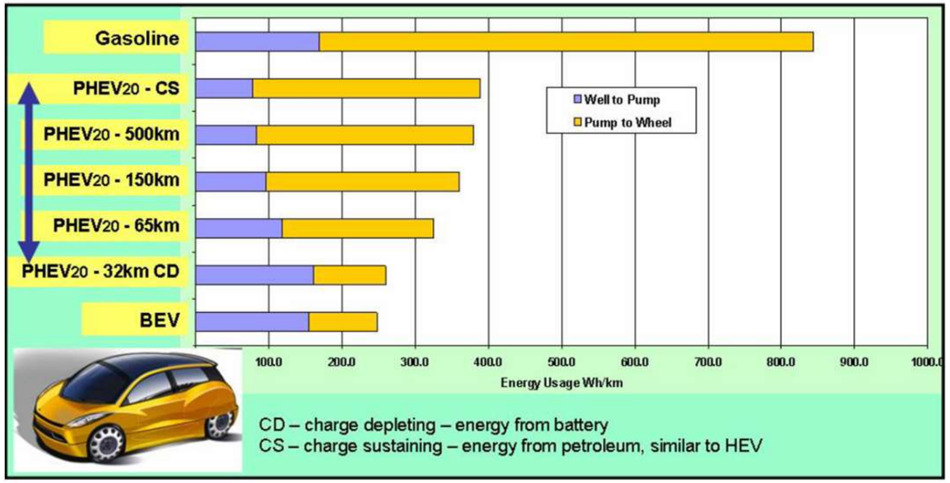
Well-to-Wheel CO_2 Emissions

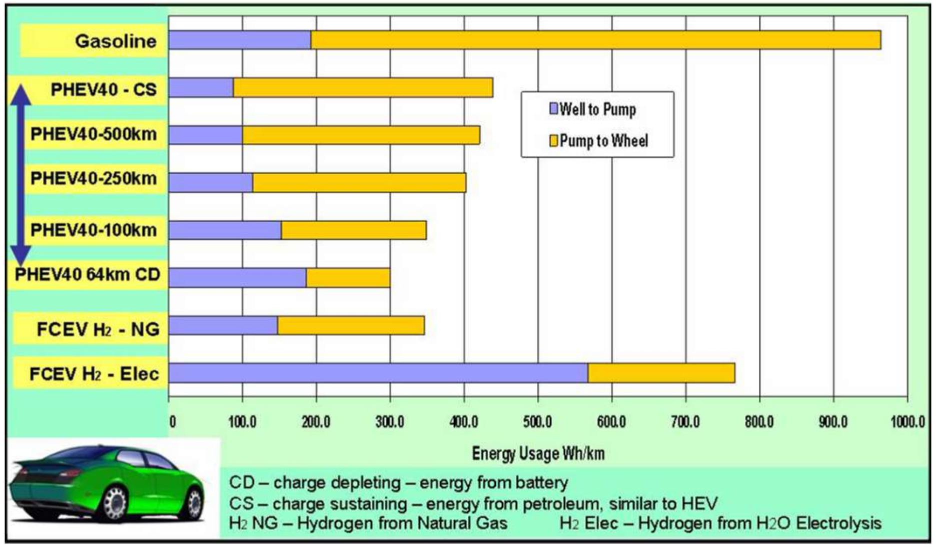




Well-to-Wheel Energy Usage





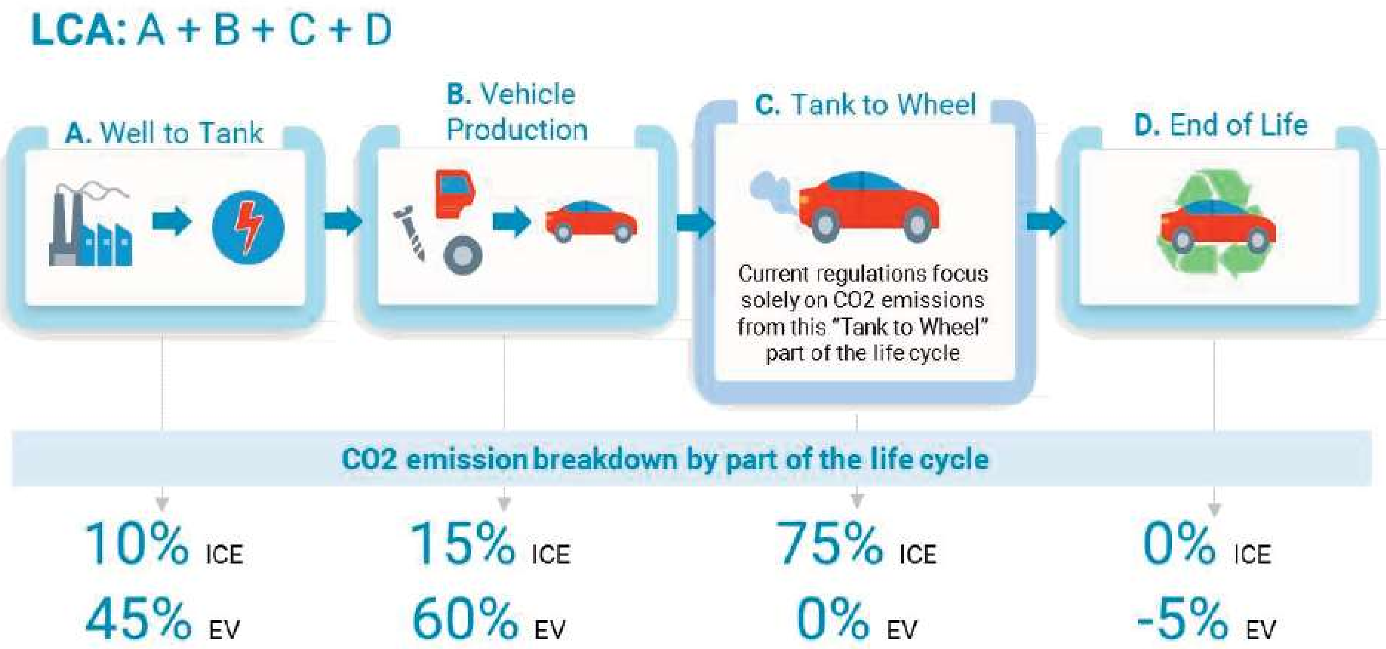


New era in CO_2 regulation: EVs to be tested across life cycle, not only on running performance (Goldman Sachs, 2019)

Life Cycle Assessment

- measures the environmental burden across the whole life cycle of a car, from production to driving and ultimately recycling parts of the vehicle
- CO_2 emissions on a tank-to-wheel basis vs. LCA approach

Exhibit 1: LCA takes a holistic view of CO2 emissions
CO2 life cycle for automobiles (image of mid-size sedan)



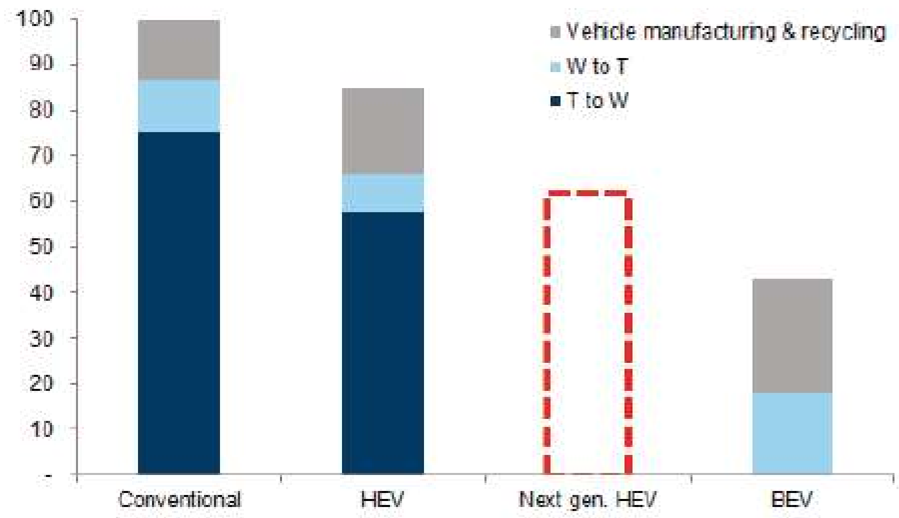
Source: Goldman Sachs Global Investment Research

CO2 (g/km)	Well-to-Tank	Tank-to Wheel
ICE	50~60	120
EV	100~120	0

– total driving distance(km): 180k(EU), 110k(Japan)

Exhibit 2: EVs come out on top in Europe

CO2 emissions measured on an LCA basis in Europe (assuming emissions of 100 for ICE vehicles)

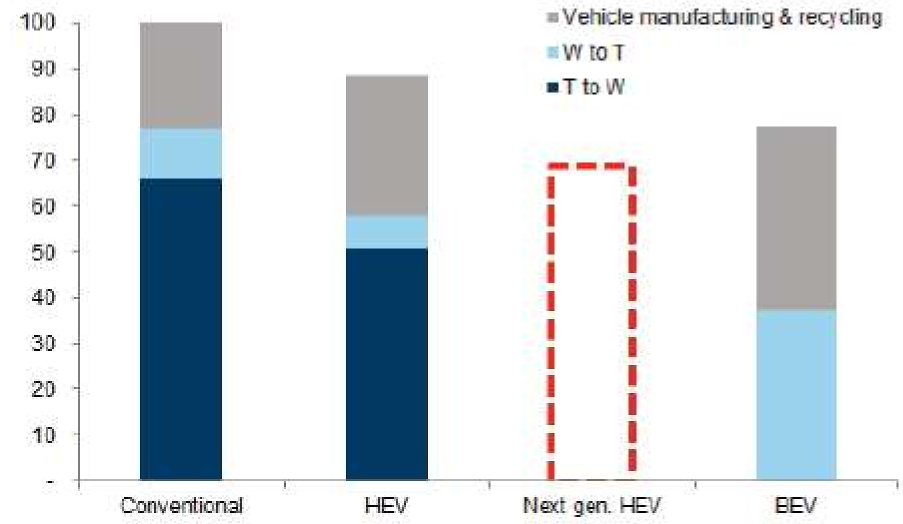


Based on Europe's projected energy mix in 2030, CO2 intensity includes power transmission loss

Source: Toyota Motor presentation at the 2019 Vienna Motor Symposium

Exhibit 3: Next-generation hybrid vehicles may provide a solution

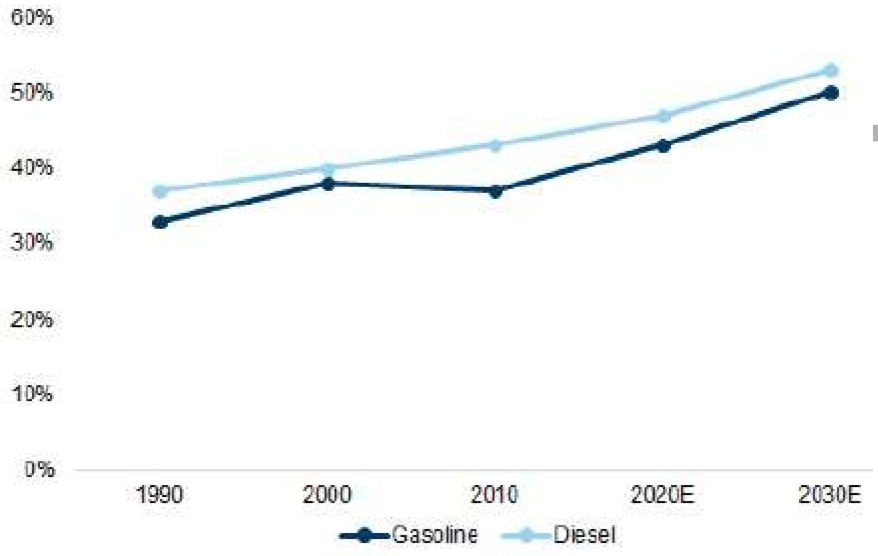
CO2 emissions measured on an LCA basis in Japan (assuming emissions of 100 for ICE vehicles)



Based on Japan's projected energy mix in 2030, CO2 intensity includes power transmission loss

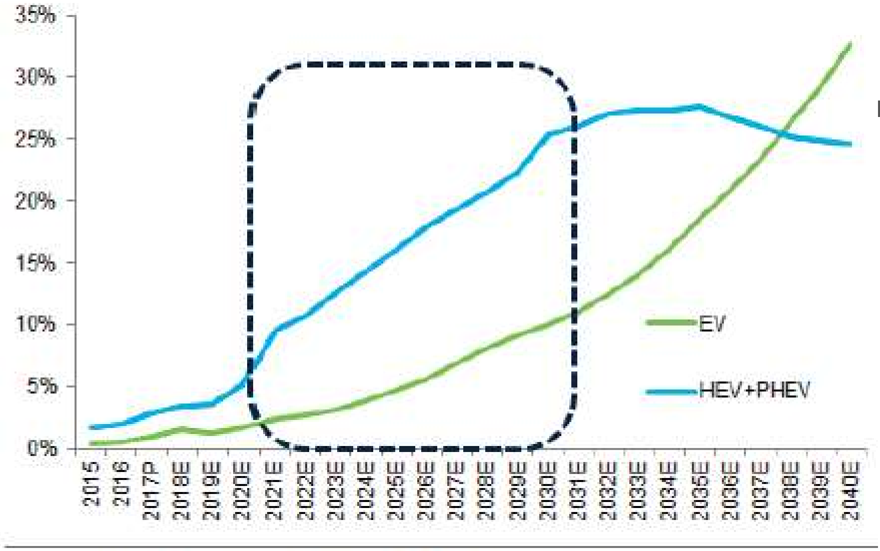
Source: Toyota Motor presentation at the 2019 Vienna Motor Symposium

Exhibit 4: Good prospects for increased engine efficiency
Engine thermal efficiency



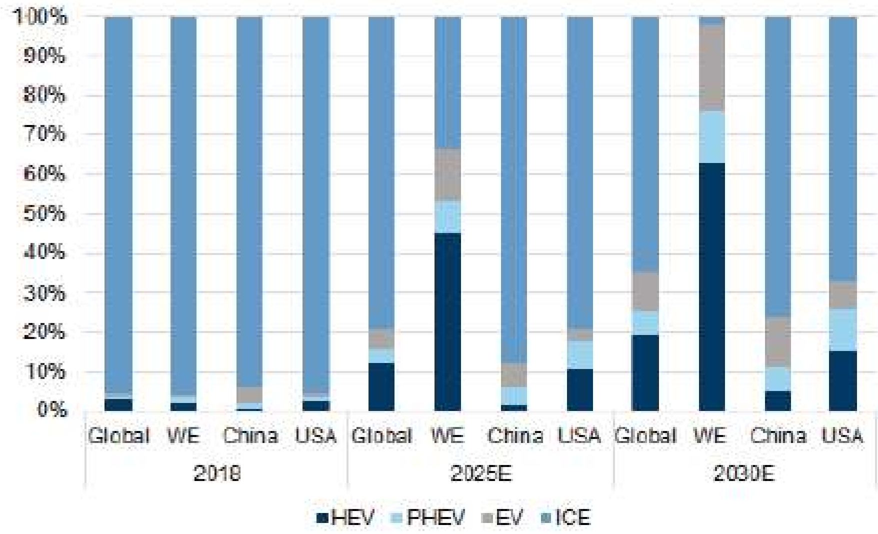
Source: Goldman Sachs Global Investment Research

Exhibit 6: EVs and HEVs likely to trade places in 2037
Electrification forecasts through 2040



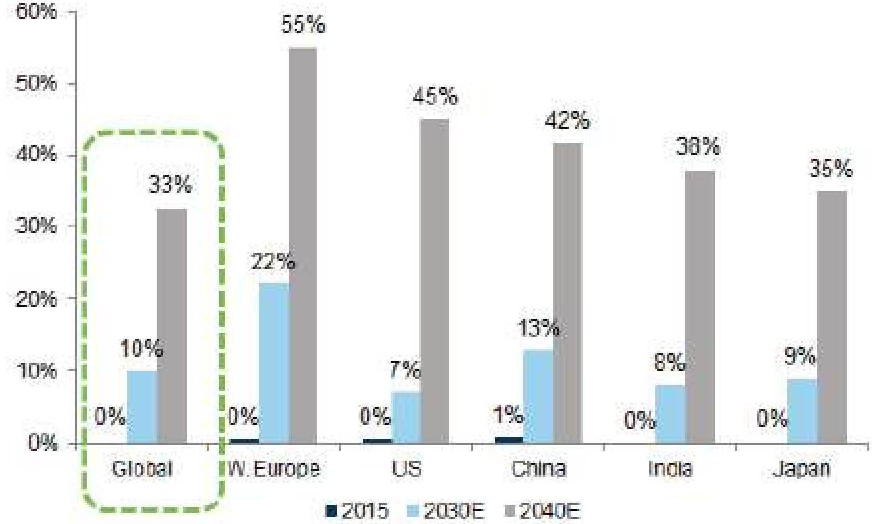
Source: IHS Global Insight, Goldman Sachs Global Investment Research

Exhibit 7: Europe set to take the lead in the shift to EVs
Powertrain forecasts by region



Source: Goldman Sachs Global Investment Research

Exhibit 8: Other countries likely to catch up with Europe by 2040
EV sales weighting



Source: Global Insight, Goldman Sachs Global Investment Research

Paris Agreement

– international treaty on climate change control that was concluded by numerous countries at the 2015 United National Climate Change Conference (COP21) in Paris

Exhibit 9: Waiting for 2050 target announcements

Countries' CO2 emission reduction targets and weightings in global auto demand

Each Country's Target	
Developed Countries	
USA	Cutting more than 80% CO_2 by 2050 vs. 2005 (Obama Administration). President Trump announced to quit the agreement on Nov. 2020
Japan	Cutting 80% CO_2 by 2050 vs. 2013.
EU	Cutting 80-95%/75%/more than 80% CO_2 in Germany/France/UK by 2050 vs. 1990.
Developing Countries	
China	Cutting 60-65% CO_2 per GDP by 2030 vs. 2005.
India	Cutting 33-35% CO_2 per GDP by 2030 vs. 2005.
Indonesia	Cutting 29% CO_2 by 2030 vs. BAU (business as usual). Cutting at most 41% CO_2 based on the international support.

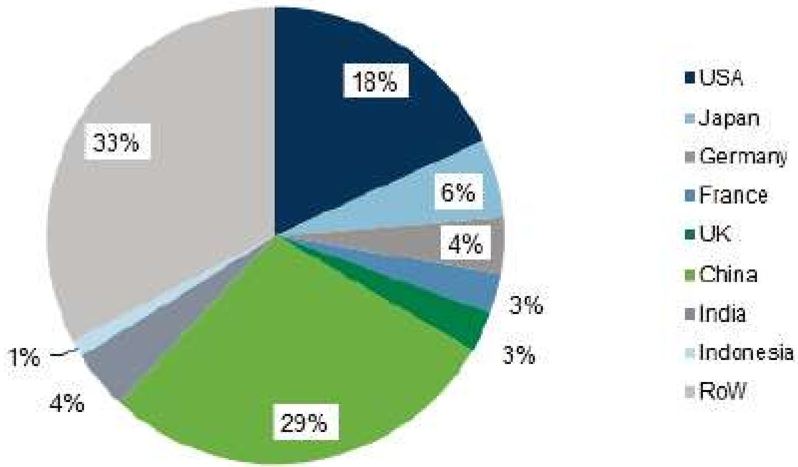
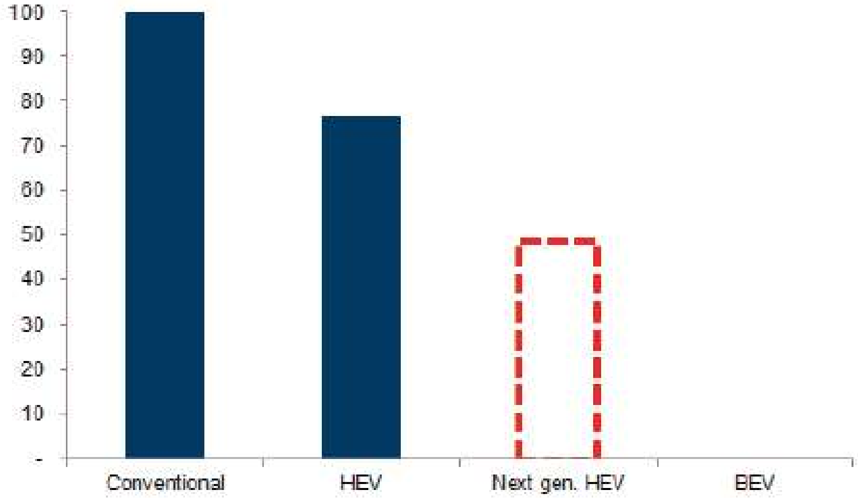


Exhibit 10: EVs are the most logical choice under current rules

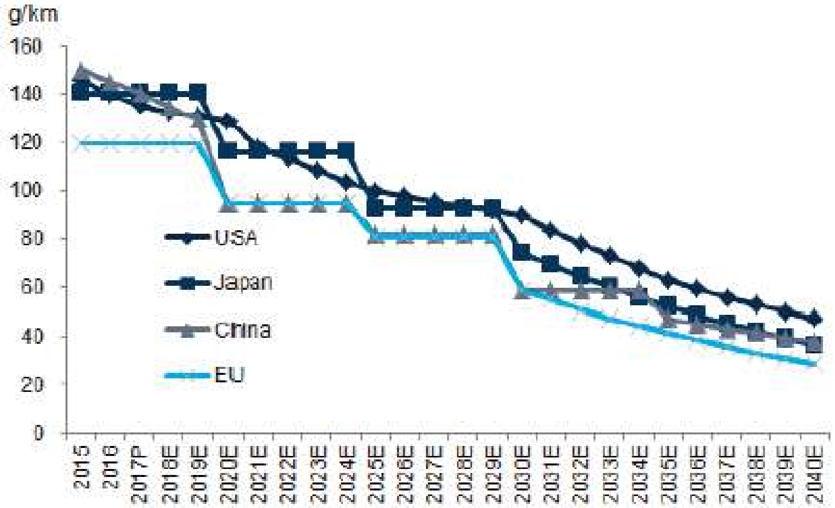
Tank-to-wheel CO2 emissions (LCA emissions of existing vehicles = 100)



Source: Toyota Motor presentation at the 2019 Vienna Motor Symposium, Data compiled by Goldman Sachs Global Investment Research

Exhibit 11: European rules are the strictest

CO2 emission regulations for certain countries/regions



Source: US Department of Transportation, European Commission, Ministry of Industry and Information Technology, Ministry of Land, Infrastructure, Transport and Tourism, Goldman Sachs Global Investment Research

Exhibit 12: Electricity generation produces more CO2 than gasoline in the production/transportation process

Well-to-tank CO2 emissions (LCA emissions of existing vehicles = 100)

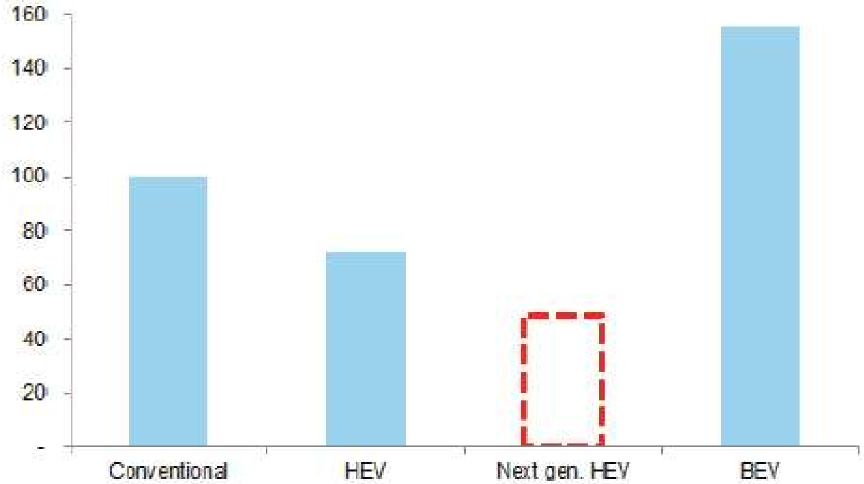


Exhibit 14: Environmental load varies by region

CO2 emissions during power generation per kWh by region

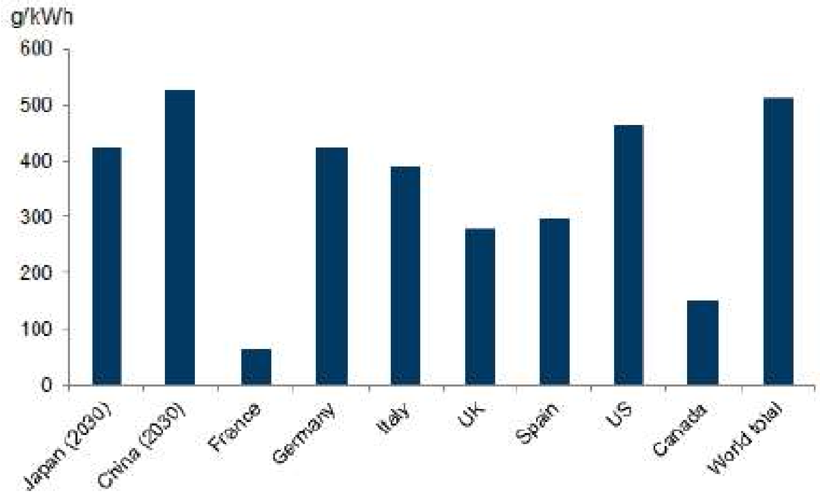
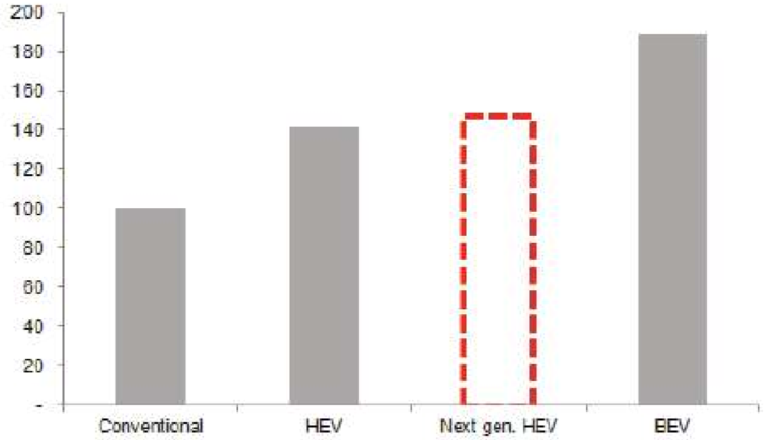
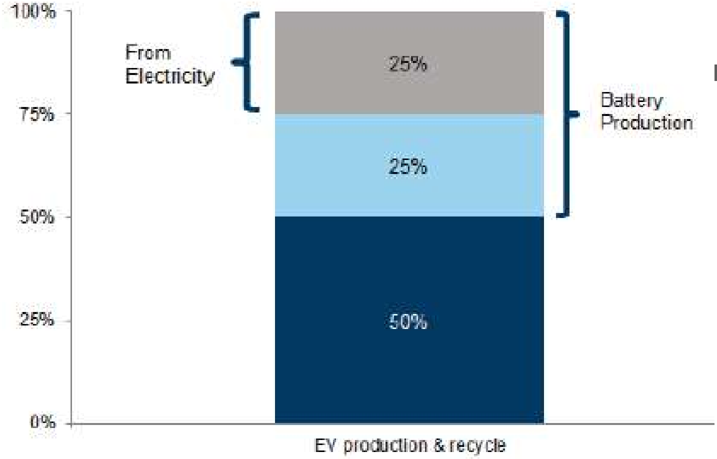


Exhibit 17: Battery production process has high environmental load in EV production
CO_2 emissions from vehicle production/recycling (LCA emissions of conventional vehicle=100)



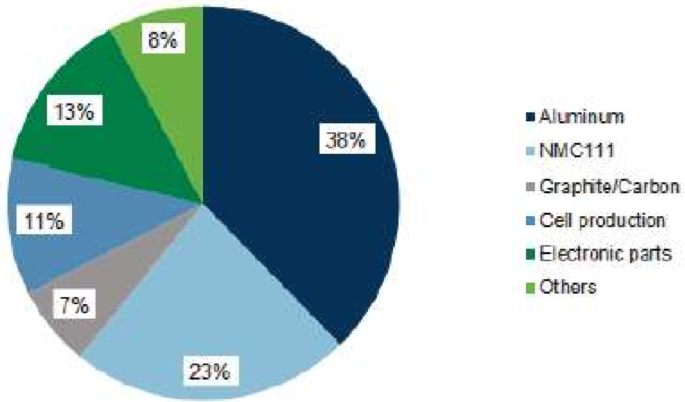
Source: Toyota Motor presentation at the 2019 Vienna Motor Symposium, Data compiled by Goldman Sachs Global Investment Research

Exhibit 18: CO2 emissions from battery production account for roughly half of emissions from EV production
Breakdown of CO_2 emissions from EV production



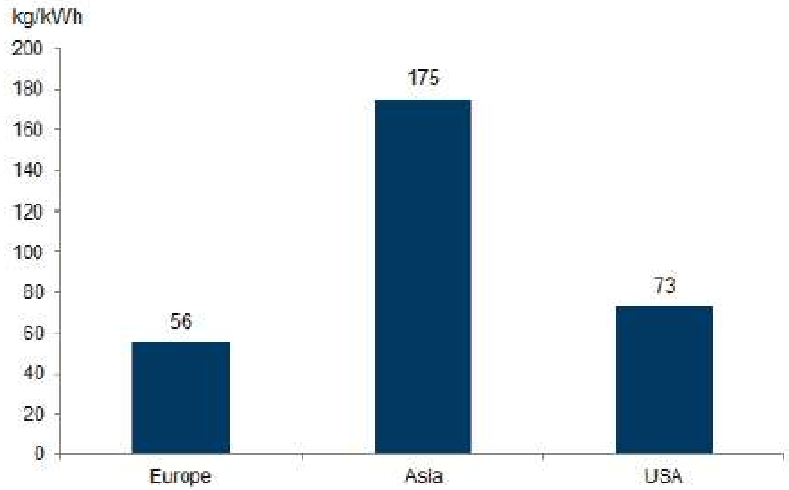
Source: compiled by Goldman Sachs Global Investment Research

Exhibit 19: Aluminum and cathodes account for most of electricity consumption in battery production
Breakdown of electricity consumption in NMC111 battery production



Source: Qiang et al. 2019, "Life Cycle Analysis of Lithium-Ion Batteries for Automotive Applications"

Exhibit 20: Batteries made in Asia have high CO2 load
CO_2 emissions from battery production per kWh by region



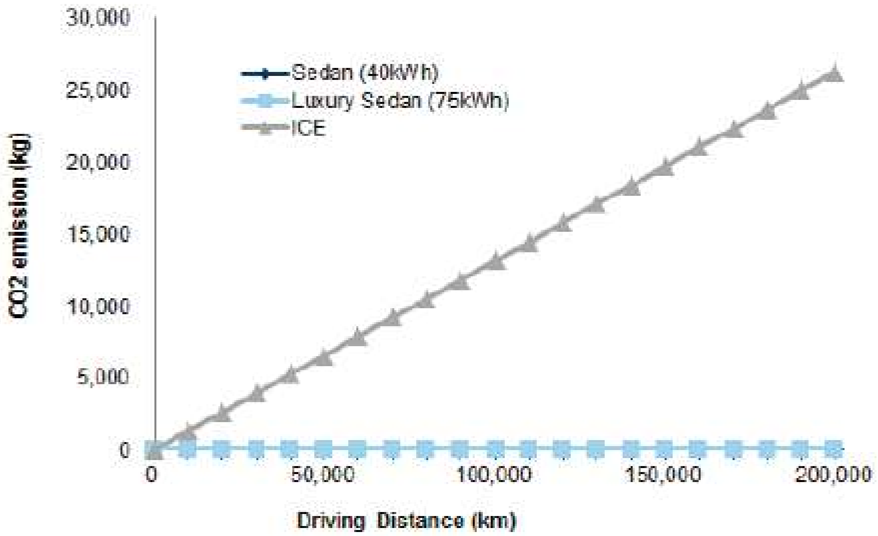
Source: ICCT

Exhibit 21: Honda/Mazda batteries only 36 kWh
Comparison of EV models

	Price	Battery Size (kWh)	WLTP Range (km)
VW ID.3 Standard Range	30,000 €	45.0	330
VW ID.3 Mid Range	< 40,000 €	58.0	420
VW ID.3 Long Range	> 40,000 €	77.0	550
Honda e	29,660 €	35.5	220
Honda e Advance	32,160 €	35.5	220
Mazda MX-30	33,990 €	35.5	200
Tesla Model 3	60,390 €	75.0	530
Nissan Leaf	36,800 €	40.0	270

Source: Company data, Goldman Sachs Global Investment Research

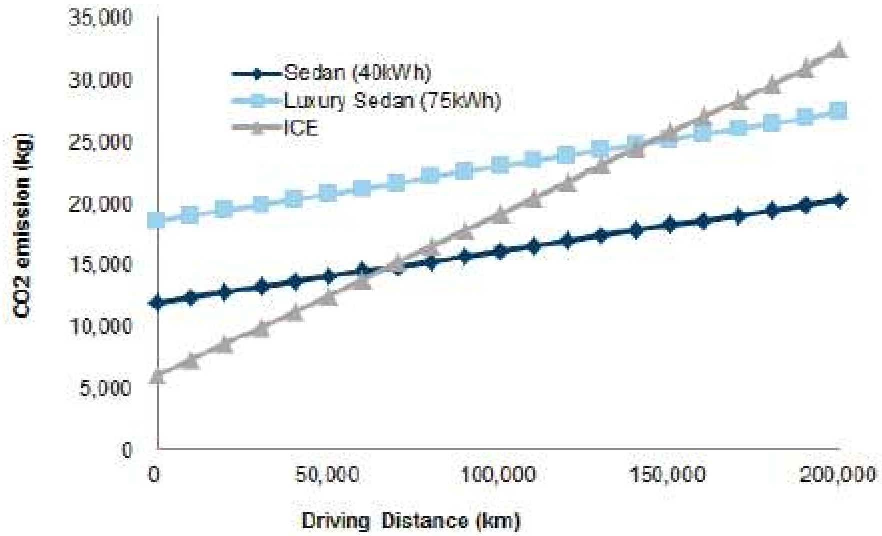
Exhibit 22: EVs clear winner under current assessment criteria, but...
Tank to wheel: Relationship between distance travelled and CO2 emissions



Sedan is totally overlapping with Luxury Sedan

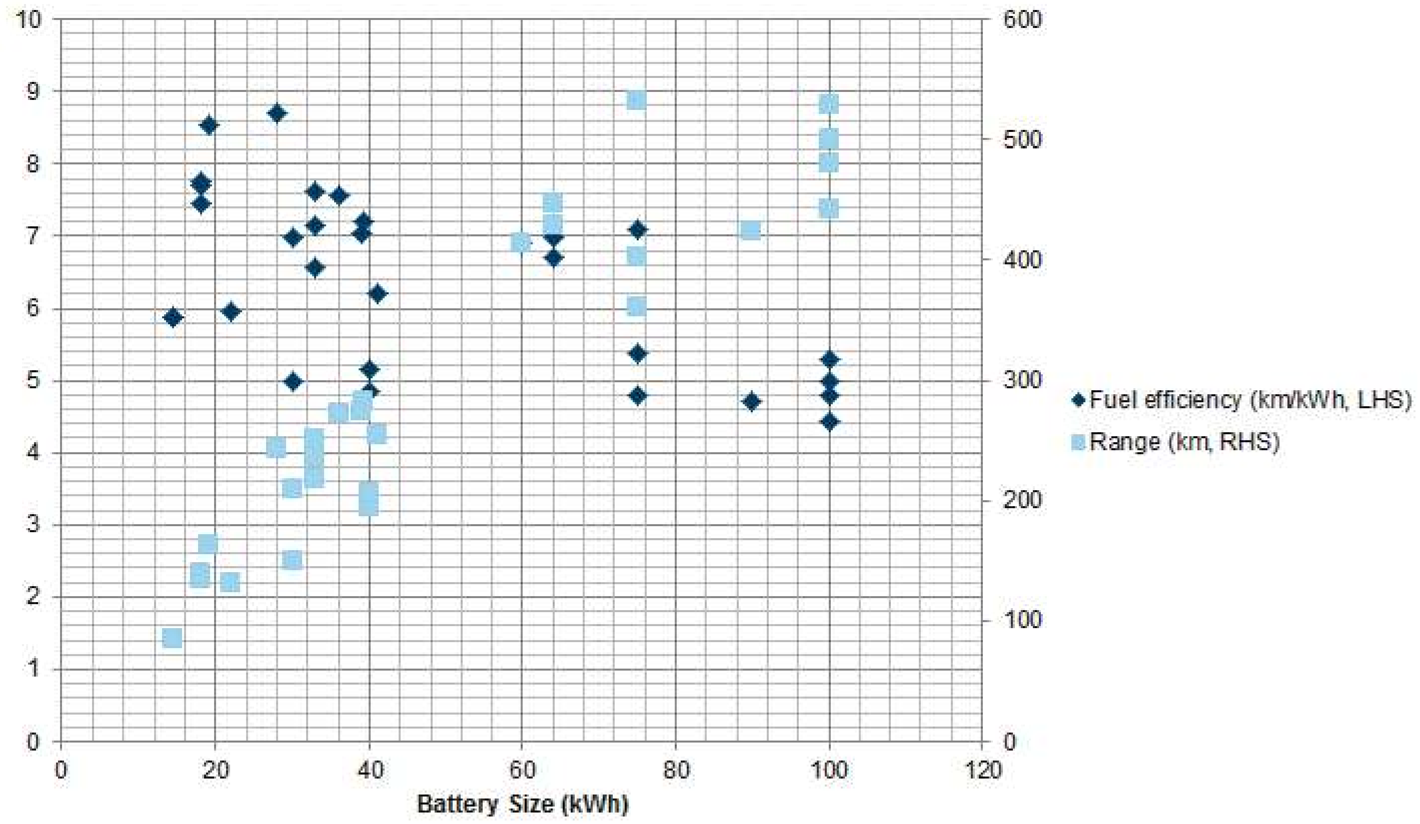
Source: Auto Catalog, Data compiled by Goldman Sachs Global Investment Research

Exhibit 23: LCA: The larger the battery, the worse the emissions
LCA: Relationship between distance travelled and CO2 emissions



Source: Company data, BP, Auto Catalog, Data compiled by Goldman Sachs Global Investment Research

Exhibit 33: Range increases with greater battery capacity, but energy efficiency decreases
Relationship between battery capacity and energy efficiency/range



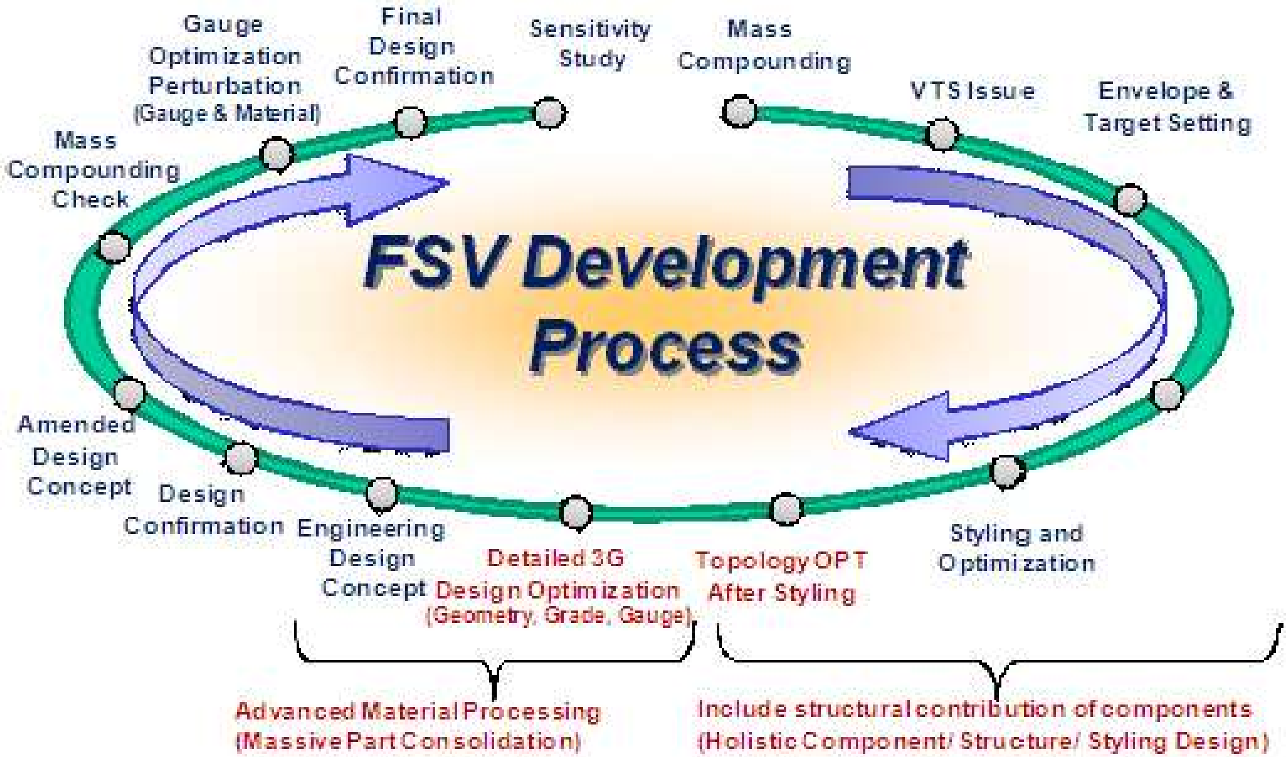
Source: Auto Catalog, Goldman Sachs Global Investment Research

Structure Design Methodology

- Overview
- Baseline model
- Topology optimization
- 3G optimization
- Final design and validation

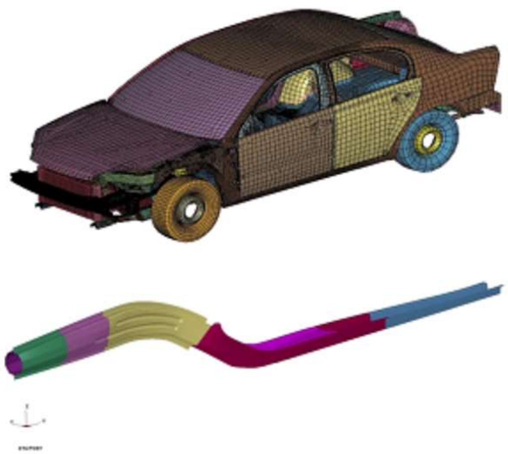
FSV Development Process

– 3G Optimization: Geometry, Grade, Gauge
  - Auto/Steel Partnership (A/SP) projects
  - Future Generation Passenger Compartment(FGPC) Phases 1 & 2
– Topology Optimization
  - define the optimum load path of a clean sheet design

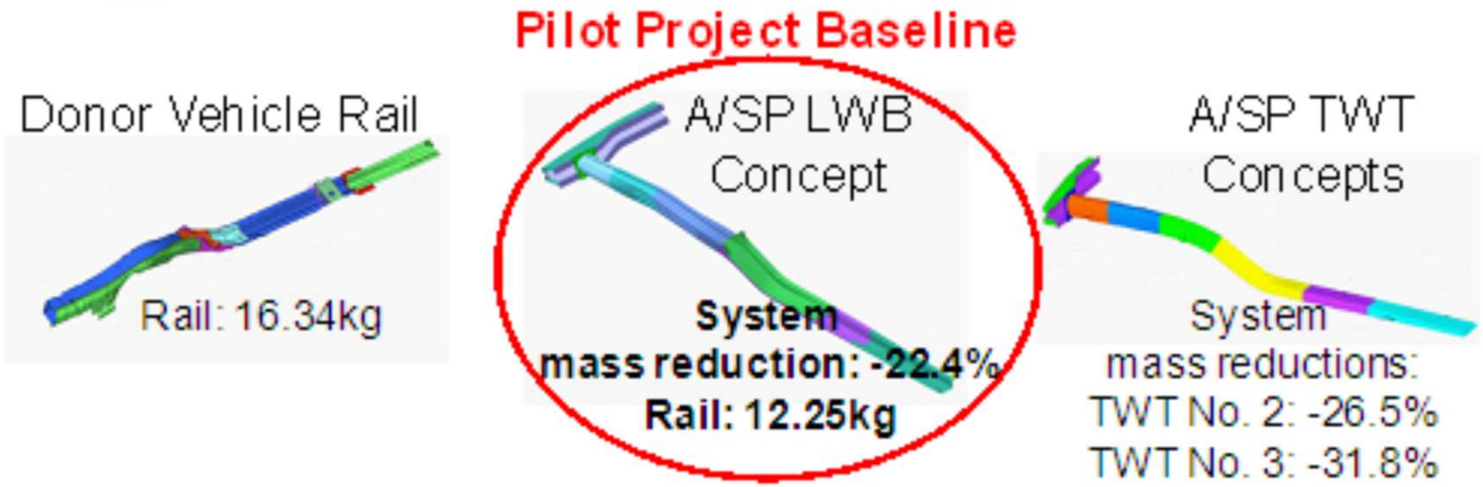


FSV Pilot Project

- A/SP Lightweight Front End (LWFE) front rail to establish any additional mass savings



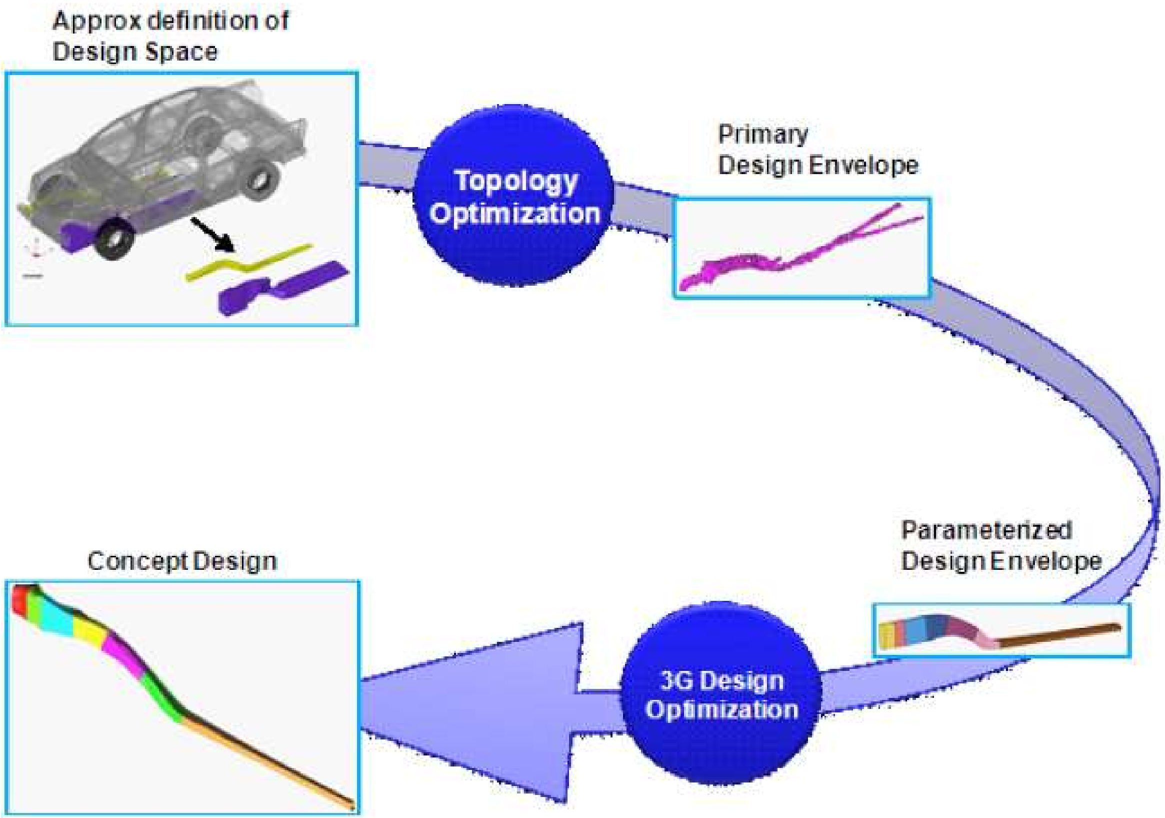
- US-NCAP zero degree front crash
- IIHS front crash 40% ODB
- Torsion
- Bending



https://www.nhtsa.gov/crash-simulation-vehicle-models

Optimization Methodology

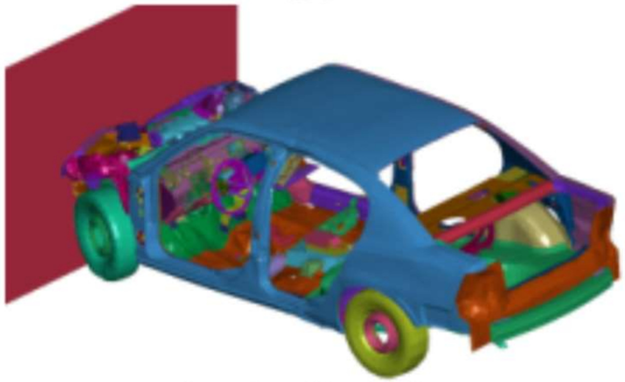
– Block out design envelope
– Topology Optimization
– Parameterize Geometry
– Detailed 3G Optimization: Geometry (Shape), Grade (material) & Gauge



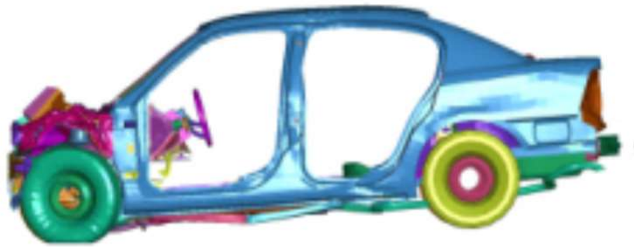
US-NCAP Zero Degree Front Crash

- impact barrier: fixed rigid wall positioned so that it almost contacts the front tip of the front bumper at the start of the simulation
- Ground: rigid wall positioned at the very lowest points of the tires
- vehicle is impacted into a rigid wall at an initial velocity of 35 mph

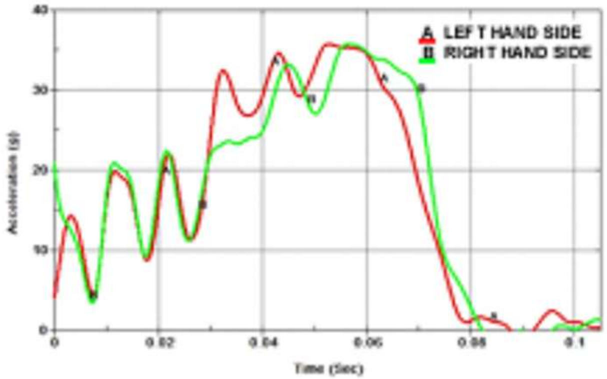
ISO



Side



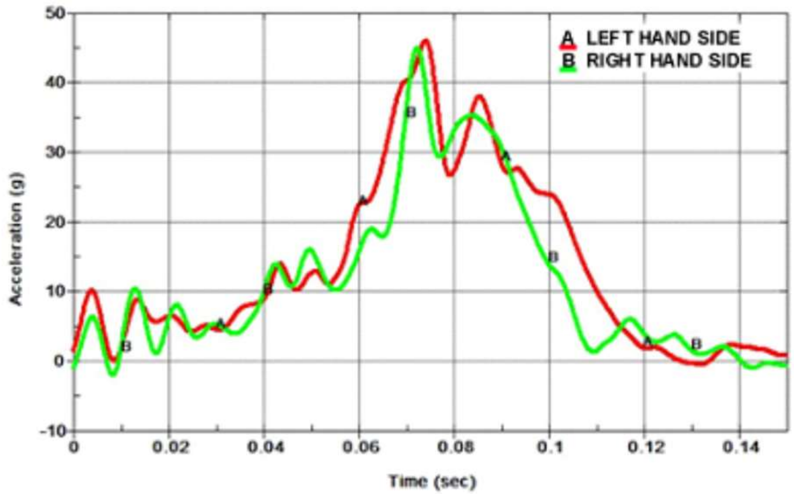
Acceleration Pulse

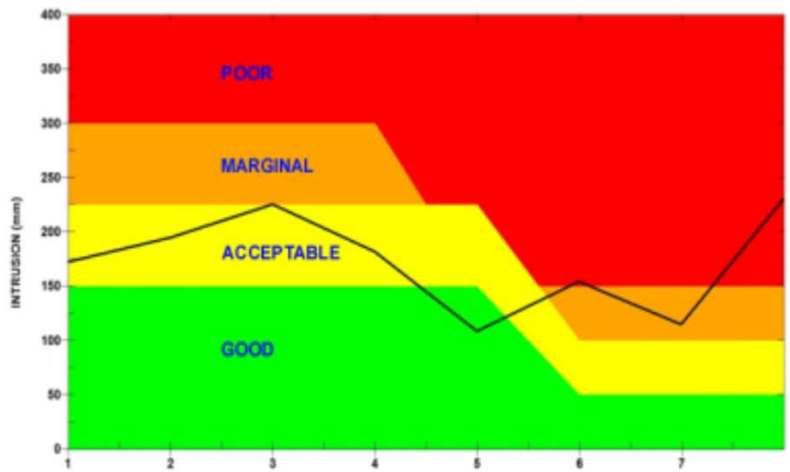


ISO (Front Rails)

IIHS Front Crash 40% ODB

- vehicle impacts a deformable barrier, offset 10% from centerline (40% overlap), at 40 mph

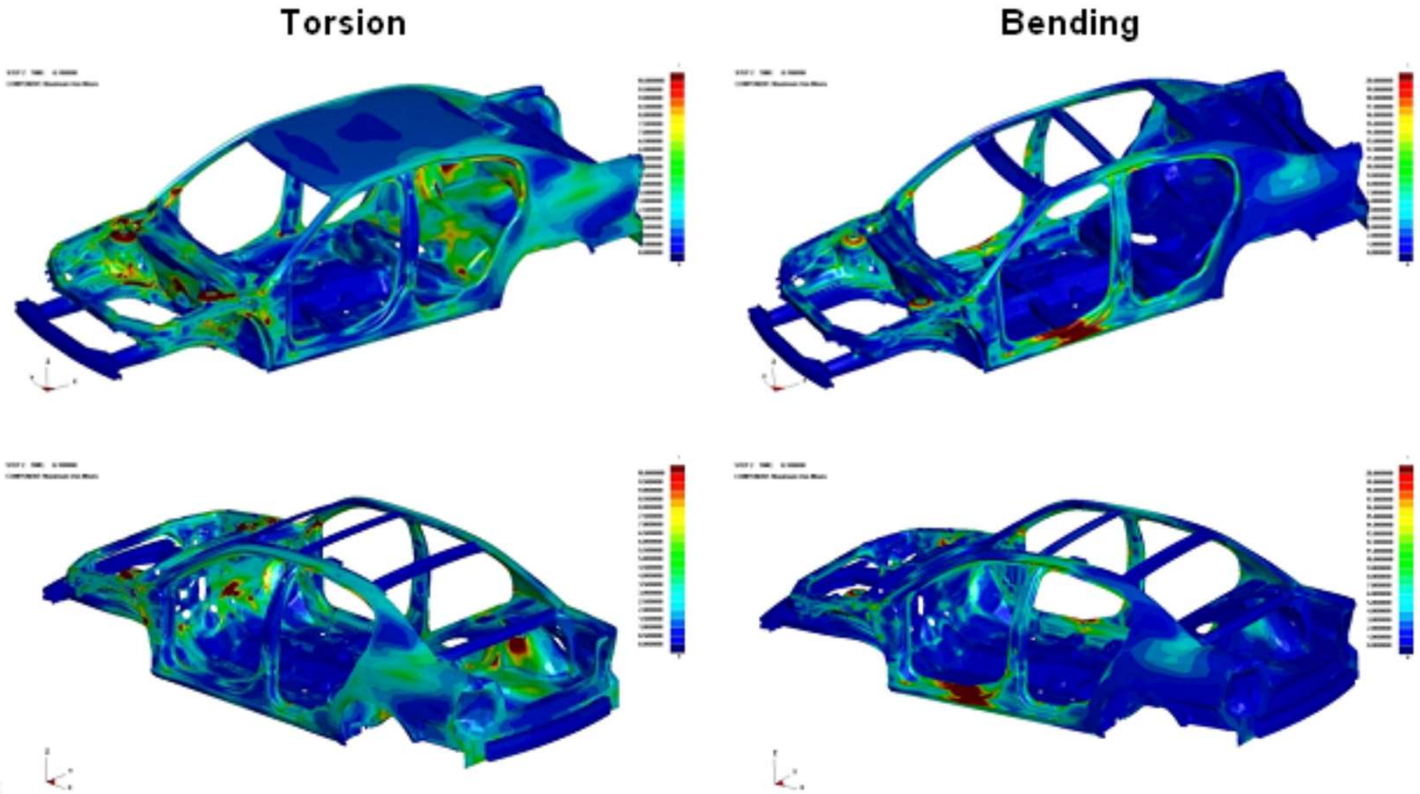




1: Footwell, 2:Left Toe, 3:Center Toe, 4:Right Toe, 5:Brake Pedal, 6:Left IP, 7:Right IP, 8:Door

Static Stiffness

- Torsion: Vehicle is held at the rear stock towers and front bumper. A couple is applied to the front shock towers.
- Bending: Vehicle is supported at all four shock towers, a load is applied in the vertical (negative z-direction) to the rocker at the front door opening



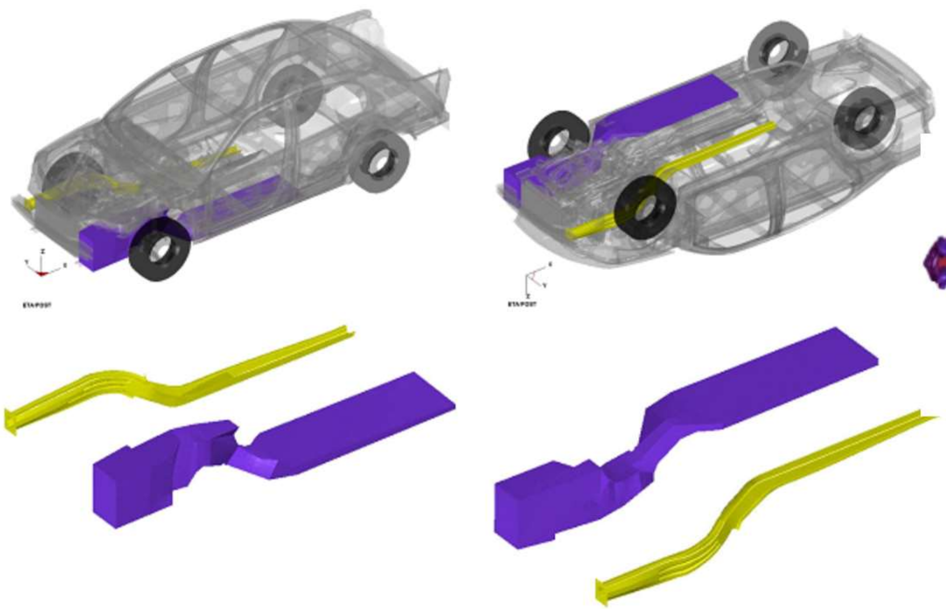
Performance Summary

LOADCASE	PERFORMANCE	
NCAP Front Impact	**Max B-Pillar Pulse**	
	Left Hand Side	36g
	Right Hand Side	36g
IIHS Front Impact 40% ODB	**IIHS Peak Intrusion**	
	Left Toepan	15 cm
	Center Toepan	20 cm
	Right Toepan	24 cm
	A-B Pillar Closure	19 cm
Static Stiffness	Torsion	17,788 Nm/deg
	Bending	12,122 N/mm

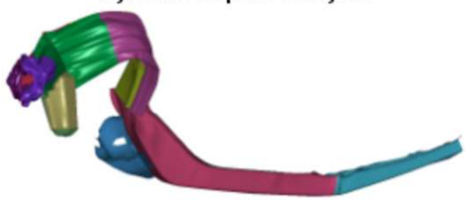
Topology Optimization

Top View   Bottom View

Comparison:
Existing Front Rail Geometry (shown in yellow)
Design Space (shown in purple)



Full Vehicle Model
Dynamic impact analysis



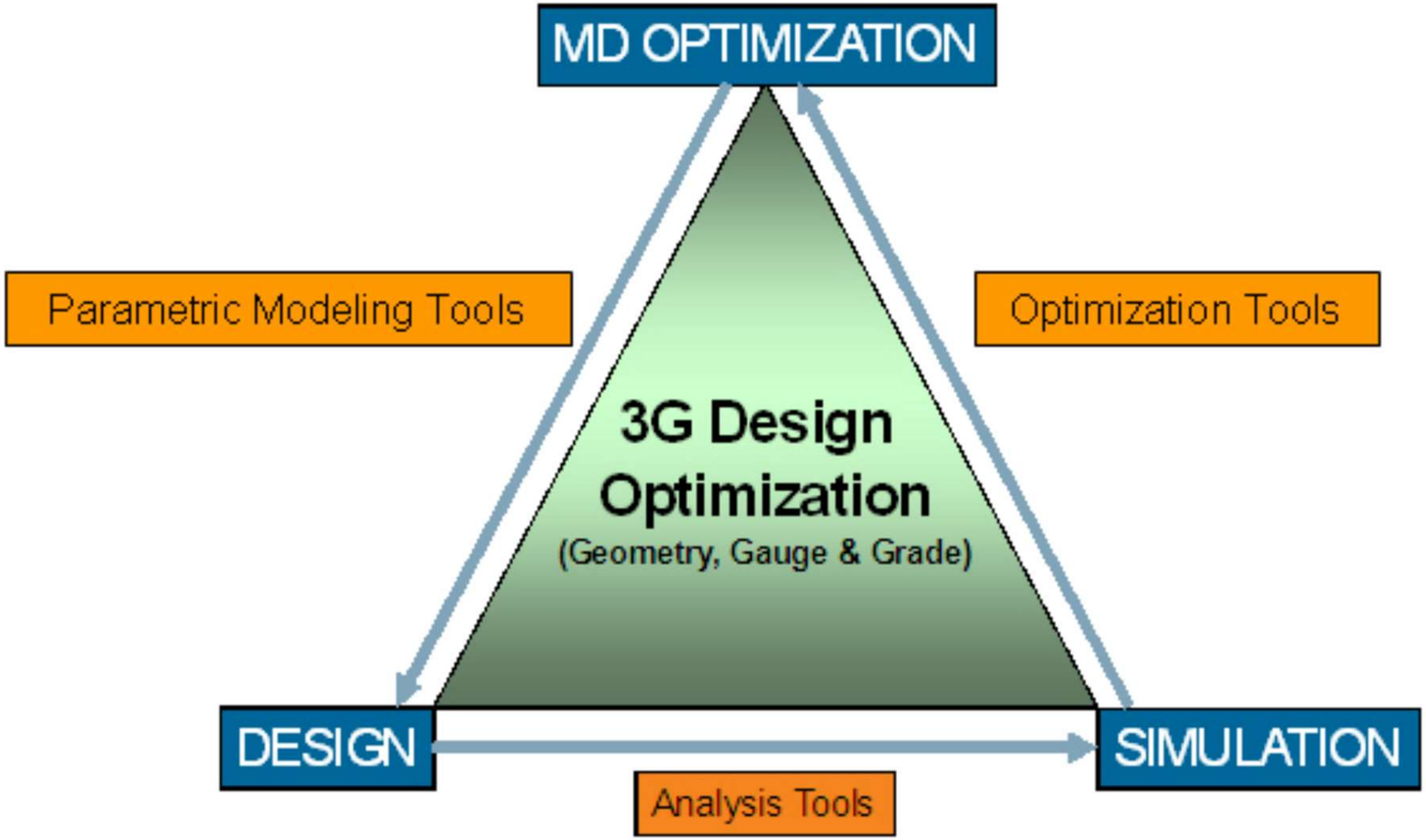
De-Coupled Sub-Model
Static analysis

Design Space & Topology Optimization   Original Rail & Topology Optimization

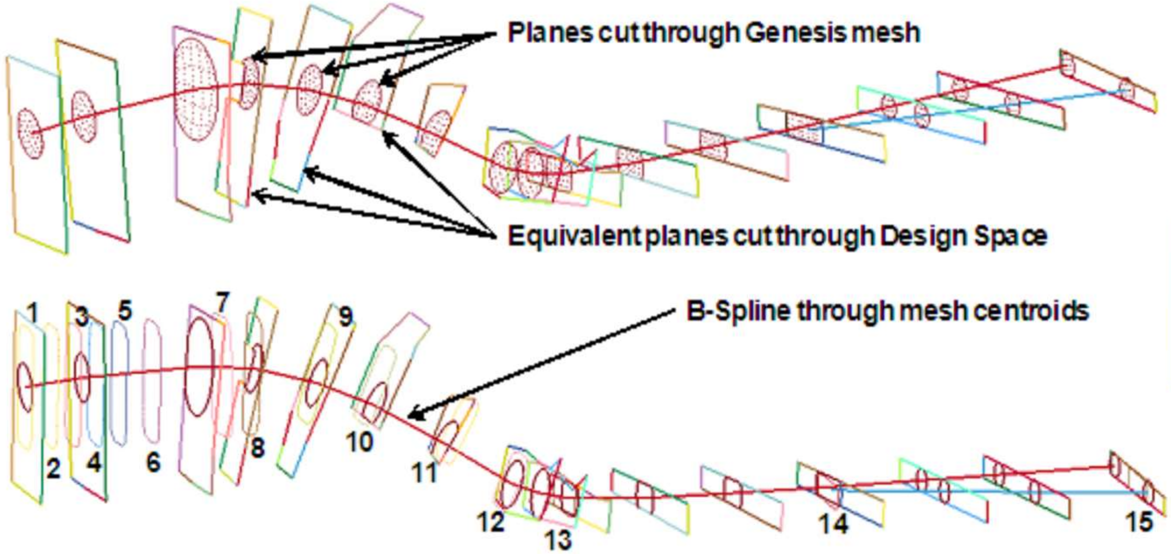
Side View

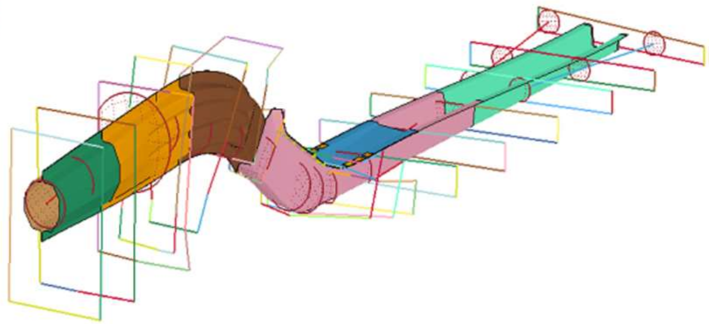
Top View

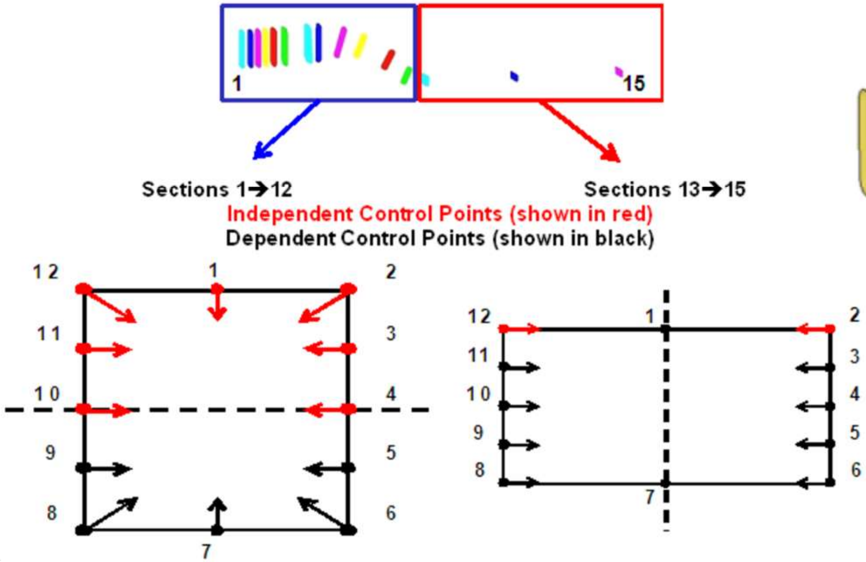
3G Optimization

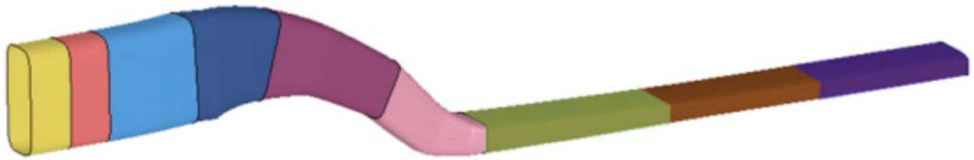


Load Path Parameterization





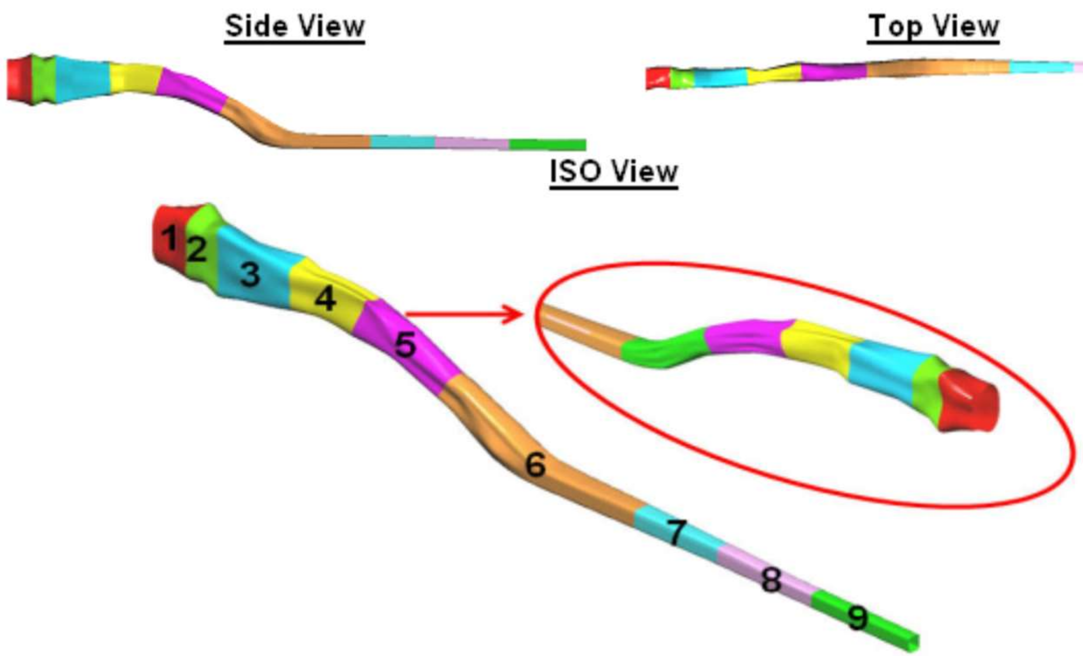




MATERIAL	GAUGE RANGE
DP350/600	0.6 →2.3mm
DP500/800	0.6 →2.3mm
DP700/1000	0.6 →2.3mm

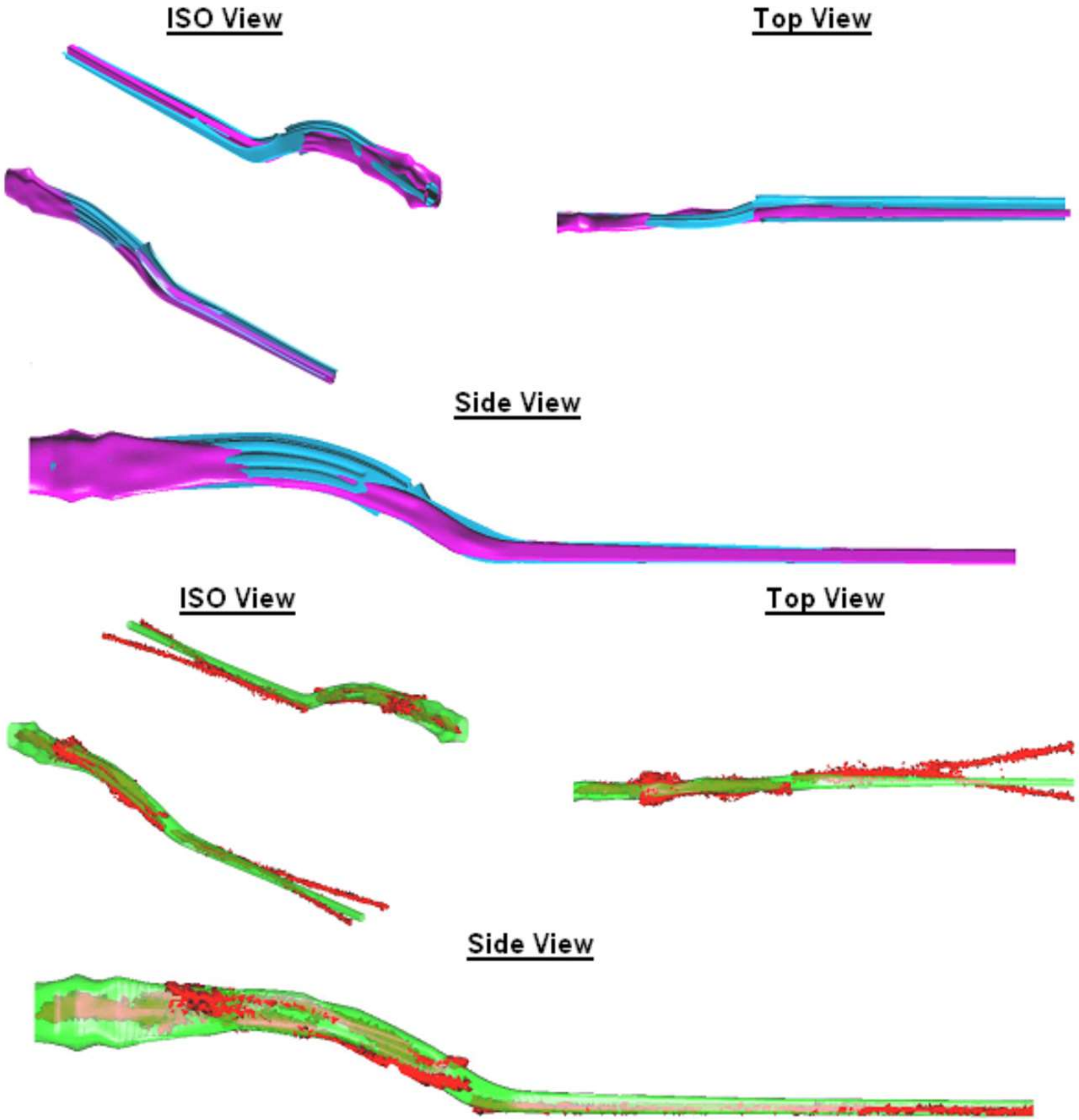
Optimization Problem

Maximize:	Mass Reduction
Subject to:	Section Force <= 35kN
By Varying:	Cross-sectional Shape (106 variables)
Material:	DP350/600, DP500/800, DP700/1000 (9 variables)
Gauge:	0.6 → 2.3 mm (9 variables)



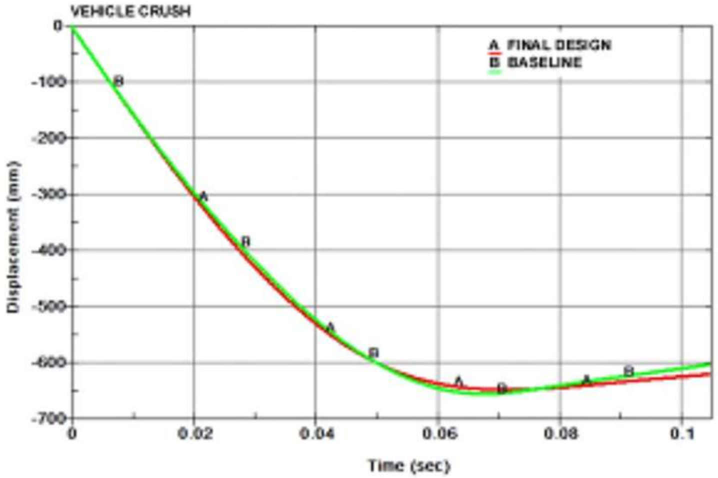
CROSS-SECTION	MATERIAL	GAUGE [mm]	MASS [kg]
1	DP350/600	1	0.48
2	DP500/800	1	0.46
3	DP700/1000	0.7	0.64
4	DP500/800	1.5	0.99
5	DP700/1000	2	1.58
6	DP700/1000	2.3	3.53
7	DP700/1000	1.5	0.69
8	DP700/1000	0.8	0.37
9	DP700/1000	0.6	0.26
		TOTAL	8.98

Optimization Results

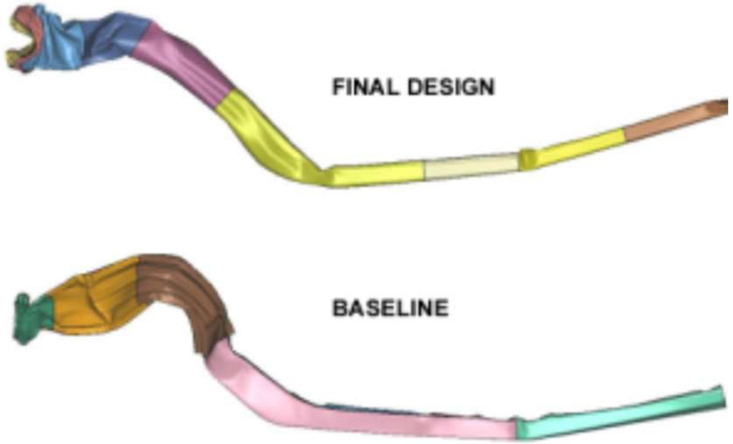


US-NCAP Zero Degree Front Crash

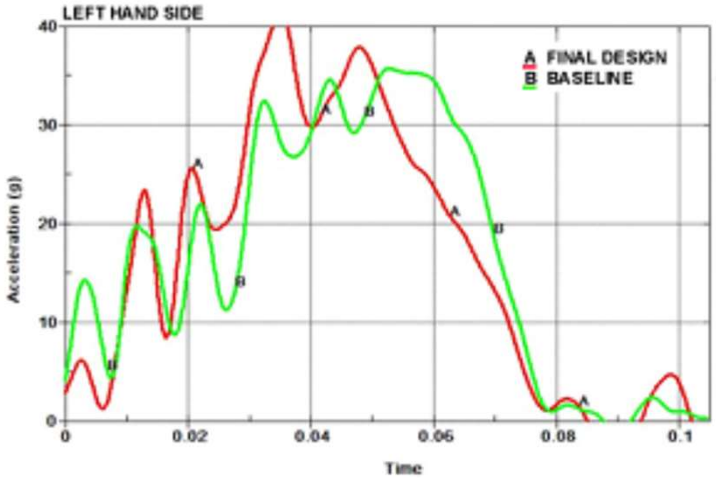
Vehicle Crush



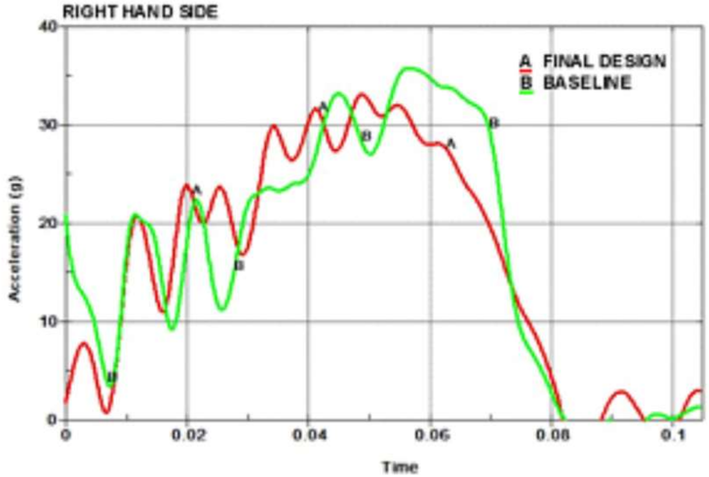
Deformed Shapes



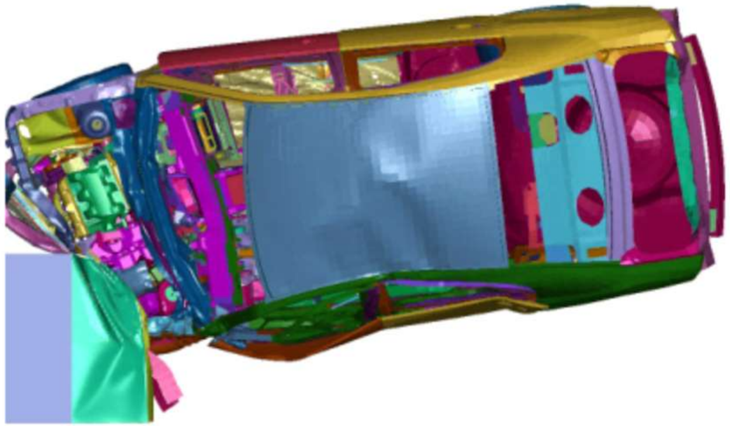
Left Hand Side Acceleration Pulse

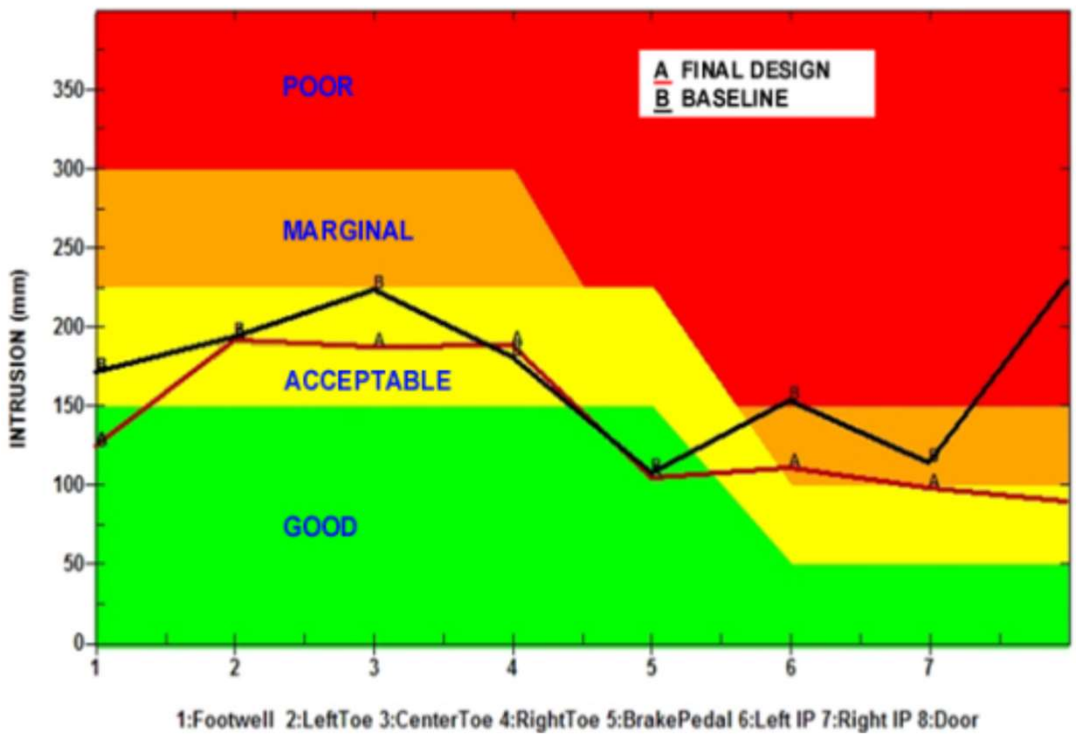


Right Hand Side Acceleration Pulse



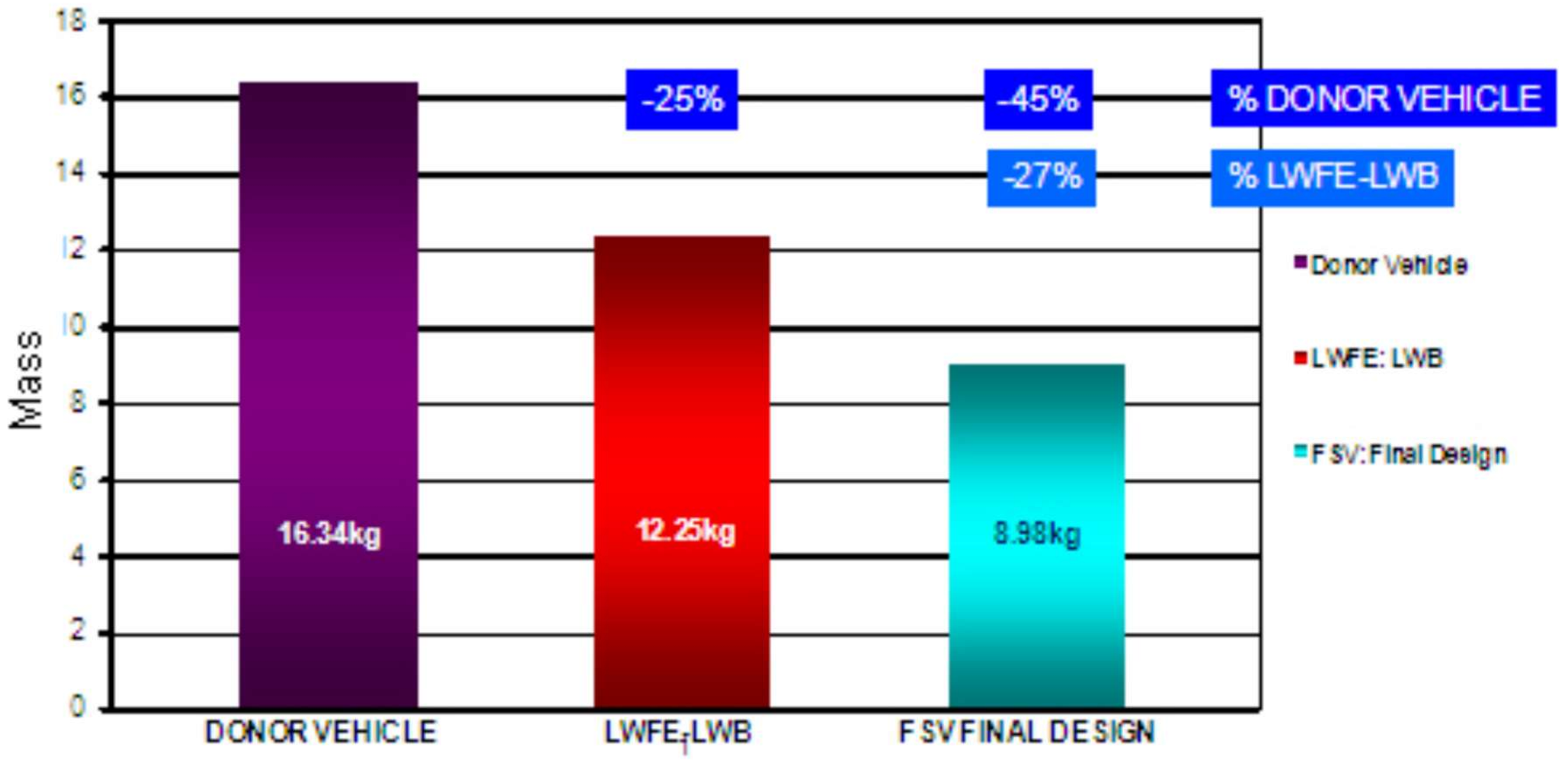
IIHS Front Crash 40% ODB





Comparison

- Static Stiffness
  - Torsion(Nm/deg): 17,094 ← 17,788
  - Bending(N/mm): 11,870 ←12,122

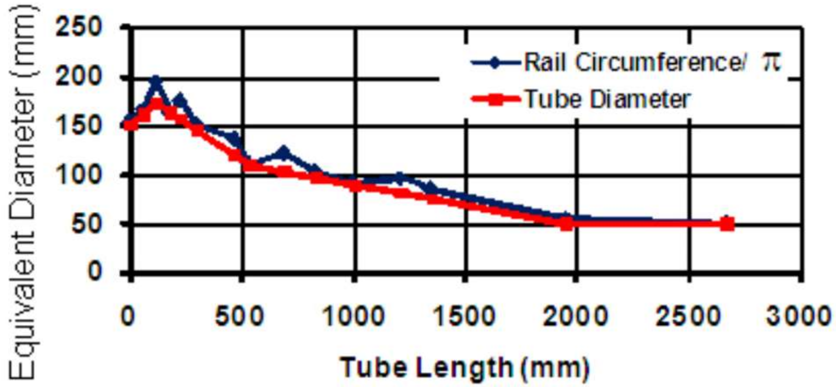


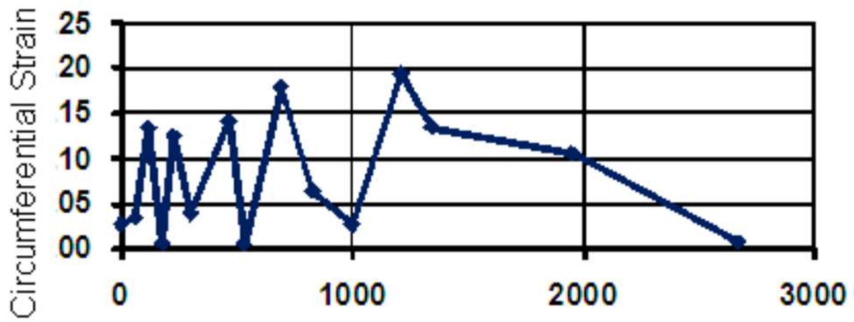
Manufacturability

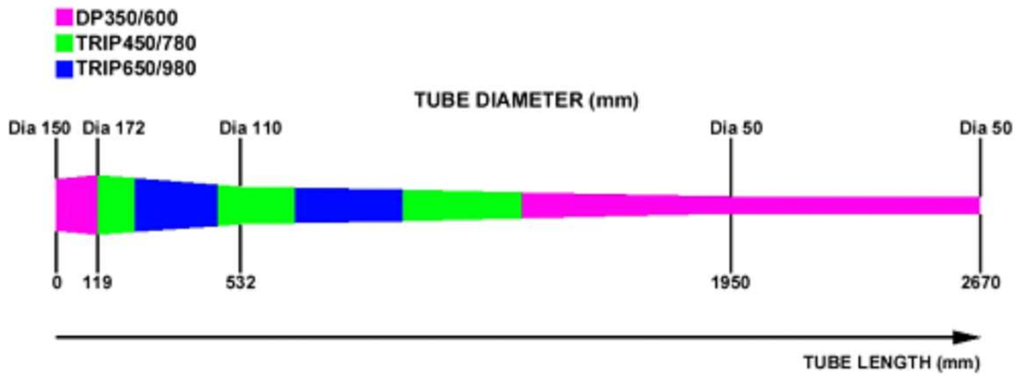
– hydro-formed tube concept
  - DP500/800→TRIP450/780
  - DP700/1000→TRIP650/980

CROSS-SECTION	PERIMETER [mm]	PERIMETER [% Change]	SECTION-DISTANCE [mm]
1	483.5	-	
2	522.5	8%	61
3	612.3	17%	58
4	514.7	-16%	60
5	550.8	7%	47
6	471.2	-14%	76
7	429.2	-9%	165
8	347.1	-19%	65
9	382.4	10%	159
10	325.4	-15%	138
11	290.4	-11%	172
12	304.5	5%	212
13	269.1	-12%	134
14	173.6	-35%	603
15	158	-9%	720

* % change in perimeter from previous cross-section
* * Distance between section centroids





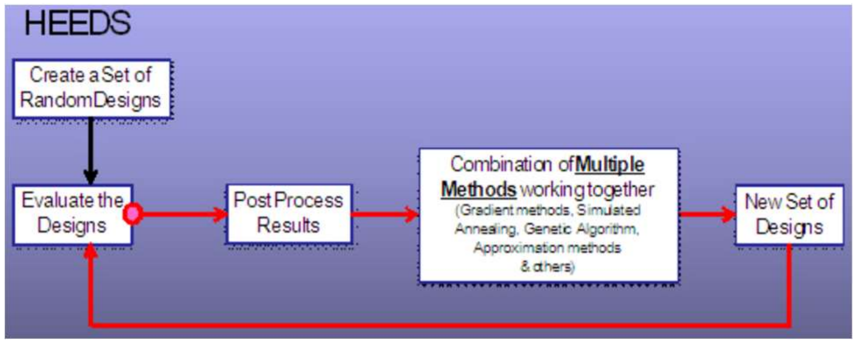


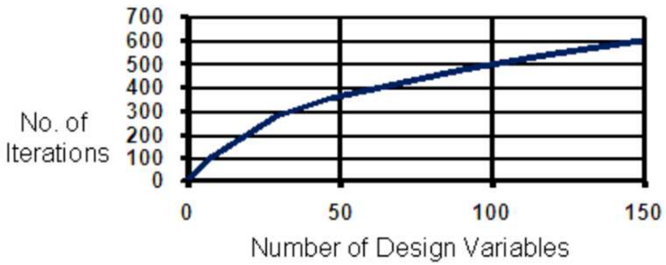
HEEDS Search Algorithm

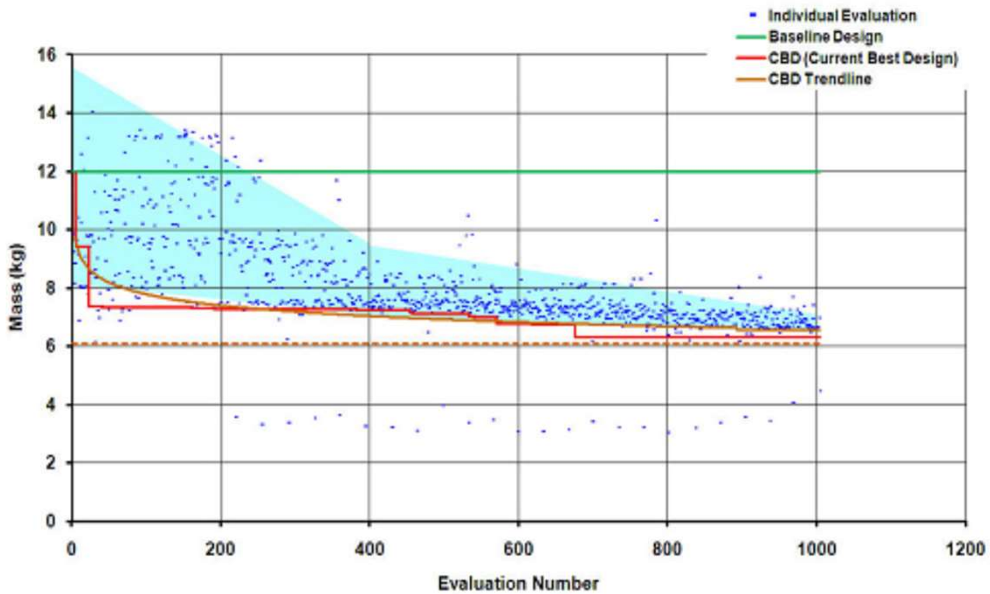
- Hybrid
  - Blend of 'methods' used simultaneously, not sequentially
  - Multiple optimization methodologies used; evolutionary methods, simulated annealing, response surface methods, gradient methods & more
  - Takes advantage of best attributes of each approach
  - Global & local search performed together
- Adaptive
  - Each 'method' adapts itself to the design space
  - Master controller determines the contribution of each 'method' to the search process
  - Efficiently learns about design space & effectively searches even very complicated spaces
- Both single and multi-objective capabilities

Optimization Process

- reduce the number of design evaluations required
  - Depend on the efficiency of the search methodology
- execute multiple design evaluations simultaneously
  - in parallel
- reduce the runtime of each individual analysis
  - simplifying the model, running the analysis in parallel on multiple CPUs, running the analysis for the shortest possible duration







Feasible Designs

- Total 2079 individual design → 968 feasible → 143 feasible designs within 10% mass of the optimal