Reducing Vehicle Weight By Developing A Comprehensive Design Philosophy

Global Automotive Lightweight Materials Conference

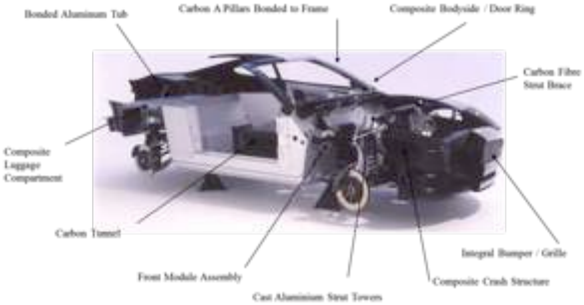
August 20, 2015

Lotus Background

- Lotus has been building lightweight vehicles using innovative construction methods for over fifty years

- Lotus has been constructing riv-bonded chassis for over twenty years

- Lotus designed (under contract) an aluminum/carbon fiber intensive body structure over fifteen years ago



- Current Lotus products use multi-materials and riv-bonding assembly techniques

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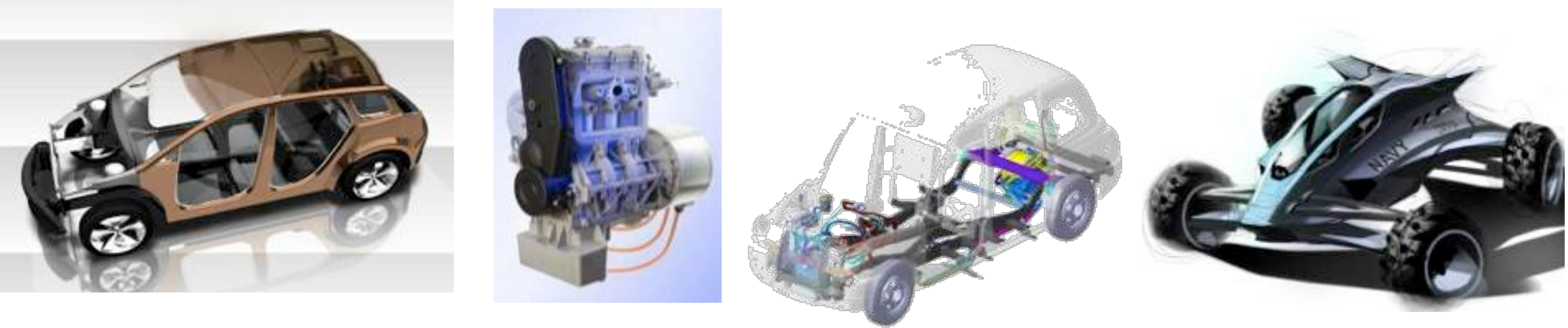
Lotus – Not Just Sports Cars

New Cutting Edge Technology Engineering Solutions



Returning to Motorsports

Variations on Lightweight Engineering

Presentation Topics

1. Creating a Design and Engineering Methodology that Supports Achieving Total Vehicle Objectives

2. Selecting Manufacturing Approaches that Can Contribute to Reduced Tooling and Assembly Costs

3. Assessing Joining Technologies: Opportunities for Reducing Weight and Increasing Strength

4. Creating Robust Assembly Techniques That Support Non-traditional Construction

LOTUS ENGINEERING

1. Creating a Design and Engineering Methodology That Supports Achieving Total Vehicle Objectives

Total Vehicle Objectives

- Improved fuel economy & reduced CO_2 emissions
- Enhanced occupant safety
- Improved dynamic performance
  - Ride
  - Braking
  - Handling
  - Acceleration
  - Towing
  - Aerodynamics

Create compelling, competitive advantages apparent to customers

https://www.youtube.com/watch?v=KXmWOXyjMrM

http://www.lotuscars.com/lotus-exige-s-roadster

Pending Fuel Economy and CO_2 Emissions Regulations

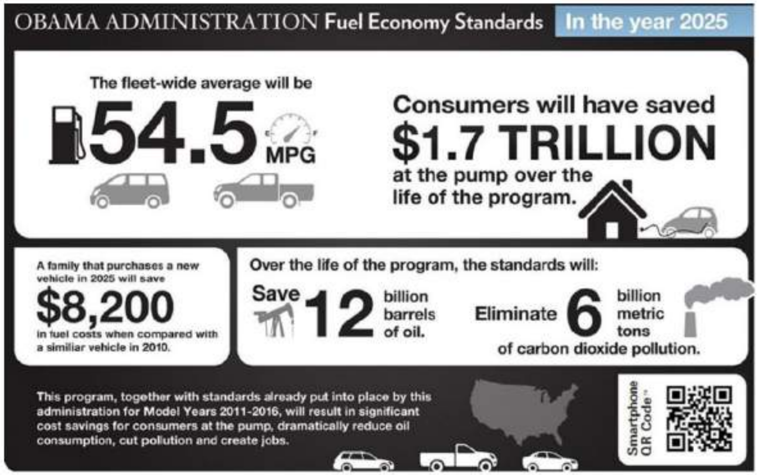
- 54.5 mpg for cars and light-duty trucks by Model Year 2025
- Fleet average equivalent of 54.5 mpg translates to an EPA "window sticker" combined city/highway average of about 39 - 40 mpg
- Projected consumer savings of more than $1.7 trillion at the gas pump
- Estimated reduction in U.S. oil consumption of 12 billion barrels
- Emissions reduced by 6 billion metric tons over the life of the program

CO_2 = Carbon (fuel) Combusted *0.99*(44/12)

CO_2 = CO_2 emissions in lbs.
Fuel = weight of fuel in lbs.
0.99 = oxidation factor (1% un-oxidized)
44 = molecular weight of CO_2
12 = molecular weight of Carbon
16 = molecular weight of Oxygen

1 gallon of gasoline creates approx. 20 lbs CO_2

1 gallon of diesel fuel creates approx. 22 lbs CO_2



OBAMA ADMINISTRATION Fuel Economy Standards In the year 2025

The fleet-wide average will be 54.5 MPG

Consumers will have saved $1.7 TRILLION at the pump over the life of the program.

A family that purchases a new vehicle in 2025 will save $8,200 in fuel costs when compared with a similiar vehicle in 2010.

Over the life of the program, the standards will: Save 12 billion barrels of oil. Eliminate 6 billion metric tons of carbon dioxide pollution.

This program, together with standards already put into place by this administration for Model Years 2011-2016, will result in significant cost savings for consumers at the pump, dramatically reduce oil consumption, cut pollution and create jobs.

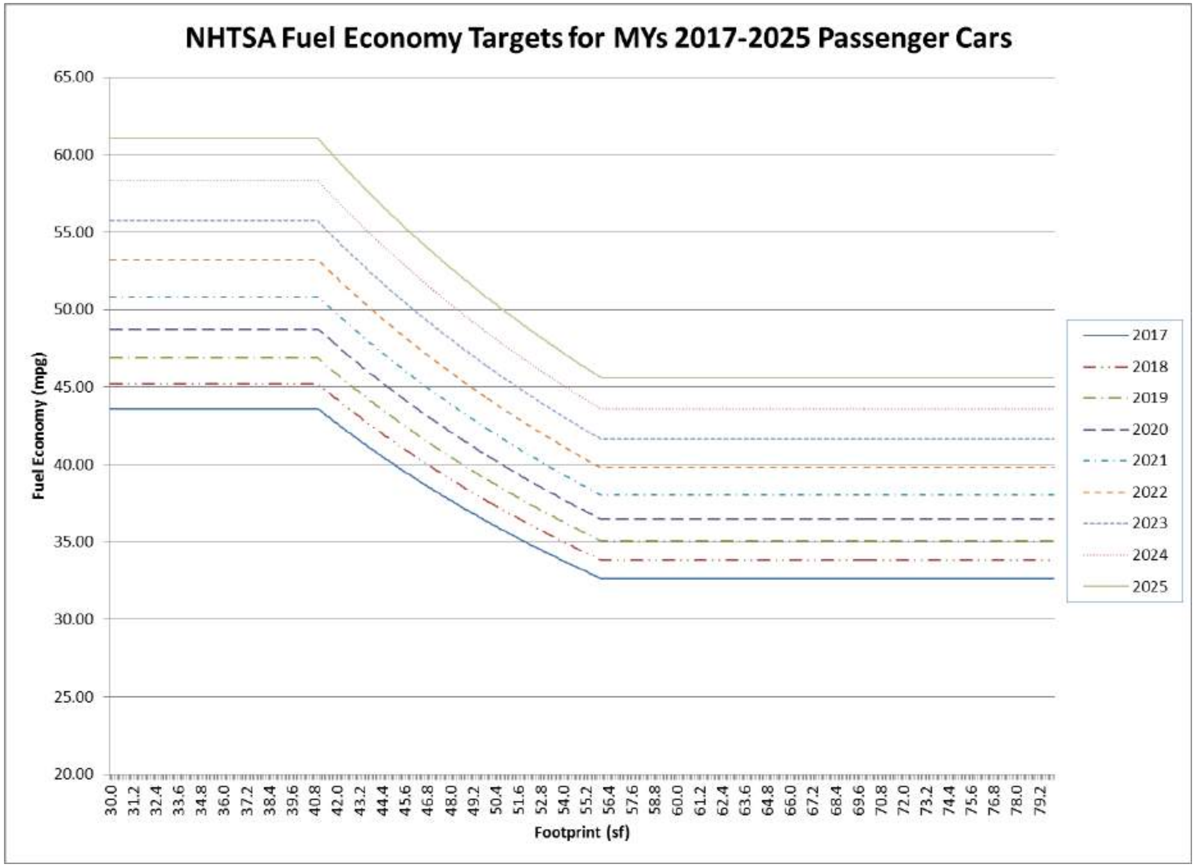
http://www.edmunds.com/fuel-economy/faq-new-corporate-average-fuel-economy-standards.html

http://www.greencarreports.com/image/100357923_54-5-mpg-cafe-standard-for-2025

http://www.whitehouse.gov/the-press-office/2012/08/28/obama-administration-finalizes-historic

http://www.insideline.com/car-news/historic-545-mpg-still-goal-in-final-2025-cafe-rules.html

NHTSA Fuel Economy Requirements: 2017 Through 2025



- > 60% fuel economy improvement typically required for 2025 vs. current models <40 ft^2 footprint)

http://en.wikipedia.org/wiki/
File:CAFE_Fuel_Economy_vs_Model_Year_and_Footprint_with_2017-2022_Proposals.png

Prioritizing Vehicle Objectives – Primary Focus

1. Improved fuel economy & reduced CO_2 emissions
    1. Penalty: $5.50 per 0.1 MPG x total domestic annual production

    Example:

        1. 1.0 MPG below standard
        2. 2,000,000 vehicles sold
        3. Penalty: $110,000,000

2. Gas guzzler tax for passenger cars < 22.5 MPG (EPA combined)

http://www.epa.gov/fueleconomy/regulations.htm

http://www2.epa.gov/enforcement

Prioritizing Vehicle Objectives – Non Fuel Economy & Emissions Areas

1. Enhanced occupant safety
2. Improved dynamic performance
    1. Ride
    2. Braking
    3. Handling
    4. Acceleration
    5. Towing
    6. Aerodynamics

http://search.tb.ask.com/search/AJimage.jhtml?searchfor=10+airbag+deployment&p2=%5EY6%5Exdm003%5EYYA%5Eus&n=780cbf3d&ss=sub&st=bar&ptb=37C591F3-A913-43AB-A9A5-92A61AD8A5A2&si=CM-s14ramMECFcRAMgodZ2wABw&tpr=sbt#./&imgs=1p&filter=on&imgDetail=true?&_suid=143958542649706360933476036092

http://www.lotuscars.com/lotus-exige-s-roadster

Holistic Approach to Vehicle Design

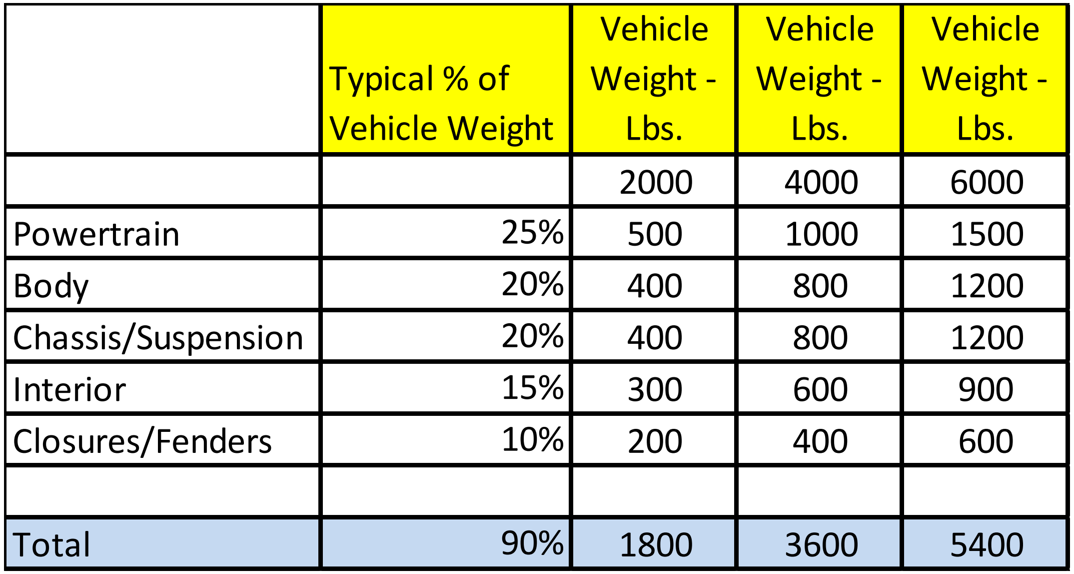
- Focus on total vehicle objectives
- Assign equal mass reduction to all vehicle systems
- Use the Pareto principle (80/20 rule) to prioritize engineering resources
- Consider all materials at design kick-off
- Consider all manufacturing processes at design kick-off
- Consider all joining processes at design kick-off
- Iterate to a total vehicle solution as opposed to idealized system solutions

http://www.motortrend.com/features/consumer/1206_temple_of_tesla_touring_elons_factory/photo_09.html

http://info.tolomatic.com/linear-actuator-blog/?Tag=Actuators+in+Robotic+Spot

Maximizing Weight Reduction With Finite Engineering Resources

- Prioritize systems based on % of vehicle weight:
    - Powertrain, Body, Chassis/Suspension, Interior, Closures/Fenders
- Define systems that are directly proportional to vehicle weight:
    - Powertrain, Chassis/Suspension
- Focus on systems that contribute most to mass de-compounding:
    - Body, Interior, Closures/Fenders



	Typical % of Vehicle Weight	Vehicle Weight - Lbs.	Vehicle Weight - Lbs.	Vehicle Weight - Lbs.
		2000	4000	6000
Powertrain	25%	500	1000	1500
Body	20%	400	800	1200
Chassis/Suspension	20%	400	800	1200
Interior	15%	300	600	900
Closures/Fenders	10%	200	400	600
Total	90%	1800	3600	5400

Projected Powertrain Effect on Fuel Economy Through 2025

Powertrain Evolution – Three Phases of Change Required to Meet CAFE

Short-term: 2012-17

- Downsizing & boosting:
  - Turbocharging
  - Supercharging
- Low-speed torque enhancements
- Stop-start & low-cost micro-hybrid technology
- Friction reduction
- Advanced thermal control
- Niche HEV, PHEVs, EVs
- More transmission gears (2013 ZF 9-spd shown)
- Return of the CVT

+2 to +3% FE increase

Mid-term: 2017-25

High-efficiency advanced combustion ICEs:

- Lean stratified SI
- Low temperature combustion

- Combined turbo/ supercharging systems (VW 1.4L Twincharger shown)
- Low-carbon fuels
- PHEVs in premium & performance products
- EVs for city vehicles
- Electric transmissions

+5% to +12% FE increase

Post-2025

PHEVs and HEVs dominate:

- Purpose-built, high-specific power ICEs

- Range of application-specific low-carbon fuels
- Exhaust & coolant energy recovery
- Advanced thermodynamic cycles
  - Split cycle engines-?
  - Heat pumps-?
- Practical EV charging infrastructure emerges

> +12% FE increase through 2025

Holistic Design Approach Example – Lightweighting Impact on Powertrain

- Target a specific mass reduction requirement for the total vehicle: 25%
- Maintain weight/HP ratio of baseline vehicle: 15.6 Lbs./HP
- Calculate HP based on reduced weight vehicle target: 270 HP (4200 lbs./15.6 lbs./HP)
- Utilize 2015 specific I4 engine output to calculate engine displacement: 135 HP/L
- Calculate engine displacement: 2.0L (270 HP/135 HP/L)

	Power	Weight		Lbs./HP	Specific Output	Engine Displacement	Length	Interior Volume
	(HP)	(Lbs.)			(HP/L)	(L)	(inches)	(Ft^3)
Generic 2015 SUV - Non Turbo	360	5600		15.6	70	5.1	220	150
Generic 2015 SUV - Turbo	360	5600		15.6	100	3.6	220	150
25% Mass Reduced SUV	270	4200		15.6	135	2.0	220	150

A pressurized four cylinder engine has the potential to replace six and eight cylinder engines in a 25% mass reduced large SUV

There is longer term potential for a 1.5L three cylinder engine to provide adequate power for a large SUV (180 HP/L)

Powertrain Weight Reduction Opportunities (25% Lighter Vehicle)

- Engine cylinder count reduced by 33% to 50% depending on baseline engine
- Engine weight reduced substantially - estimated range: 20% to 40%
- Transmission size/weight reduced to match lower HP & torque levels
- Rear axle size reduced to match lower HP & torque levels

A 25% vehicle mass reduction can contribute to powertrain mass reductions of similar magnitude or greater

Lightweight Body Design

Traditional Body Design

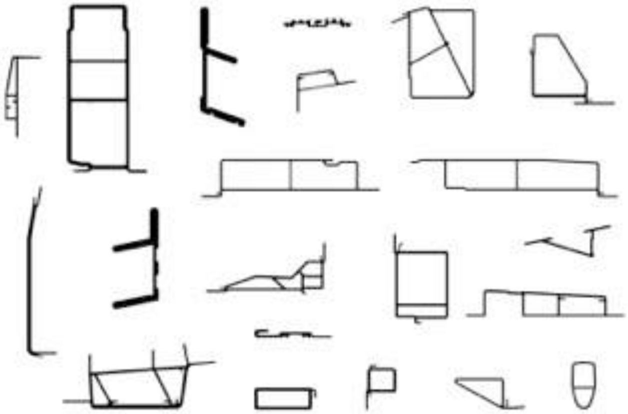
- 100% stamped steel body panels
  - Typically creates significant scrap
  - Low level of component integration (vs. casting) for deep draw parts
- Welded construction
  - RSW requires a significant amount of energy relative to other options
  - Weld head size drives flange width
  - RSW degrades parent material strength
- Discontinuous flange joints

http://www.motortrend.com/features/consumer/1206_temple_of_tesla_touring_elons_factory/photo_09.html

http://info.tolomatic.com/linear-actuator-blog/?Tag=Actuators+in+Robotic+Spot

Non-Traditional Body Design

- Multi-material construction
- Extensive use of extrusions and castings
- Flat sheet aluminum panels (no stampings)
- Structural adhesive bonding
- 100% continuous flange joints
- Rivets used to stabilize bonded joints and for “peel”
- Minimized flange width
- No parent material degradation



Images prepared by Richard Rackham and David Marler, Lotus

Material Options

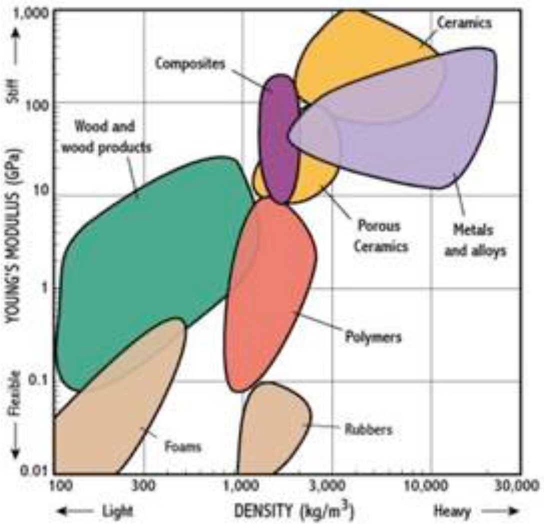
- A multi-material approach provides flexibility to select materials which best support the total vehicle mass, cost, performance and infrastructure constraints

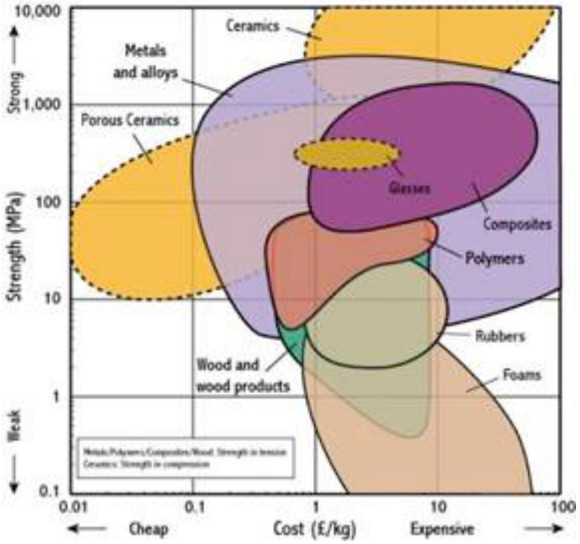
- Choose materials based on performance, cost and mass for each specific area

- Incorporate recycled materials into design

- Utilize proven software

- Consider all materials
  - Steel
  - Aluminum
  - Magnesium
  - Plastics
  - Wood
  - Carbon fiber
  - Titanium
  - Ductile cast iron
  - Etc.





http://www-materials.eng.cam.ac.uk/mpsite/physics/introduction/default.html

Key Material Selection Criteria

- Maximize material capability for specific vehicle areas
    - Steel B pillar contributes to both side impact and roof crush performance
        - Steel can be the lightest weight solution
    - Aluminum extrusions are tunable for absorbing impact energy
    - Magnesium castings can provide a structural base for energy absorbing components
    - Composites can be used for structural and non-sructural panels

Evora FMVSS 208

- Utilize section properties to optimize structure
    - $I = bh^3/\text{Shape Factor}$

Viper frame with magnesium dash and cowl, super-formed aluminum cross-brace (SRT image at allpar.com)

2013 SRT Viper

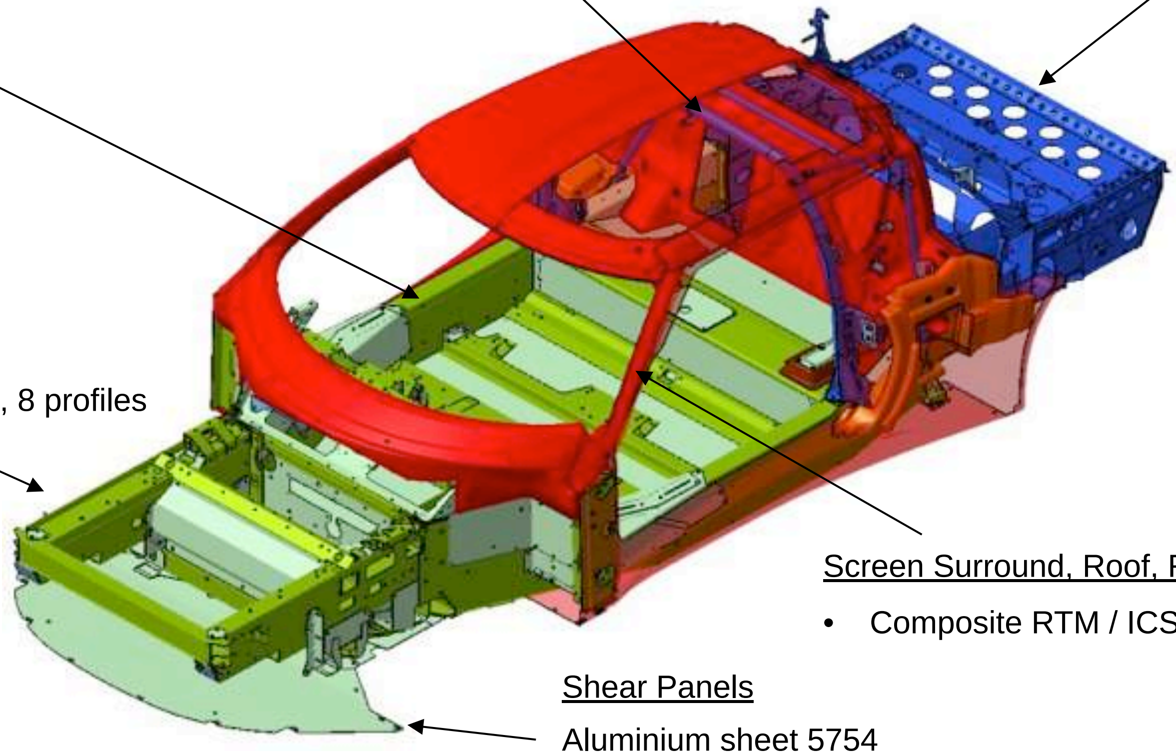
- Select component manufacturing processes that optimize sectional properties
    - Aluminum castings
        - Suspension mounting structure
    - Aluminum Extrusions

2014 Corvette chassis

Lotus VVA structure

Non-Lotus images from OEM sites

Non-Traditional Multi-Material Design: Lotus Evora



Seat Belt Anchorage Frame

E355 steel

MIG welded

Powder coat

Chassis Tub

Aluminium sheet 5754

Aluminium extrusions

6060-35, 20 profiles

Bonded and riveted

Rear Subframe

Tenform 300 HSLA steel

Spot /MIG welded

Galvanised

Front Subframe

Aluminium sheet 5754

Aluminium extrusions 6060-35, 8 profiles

Bonded and riveted

Screen Surround, Roof, Rear Bulkhead and Body-Side

- Composite RTM / ICS

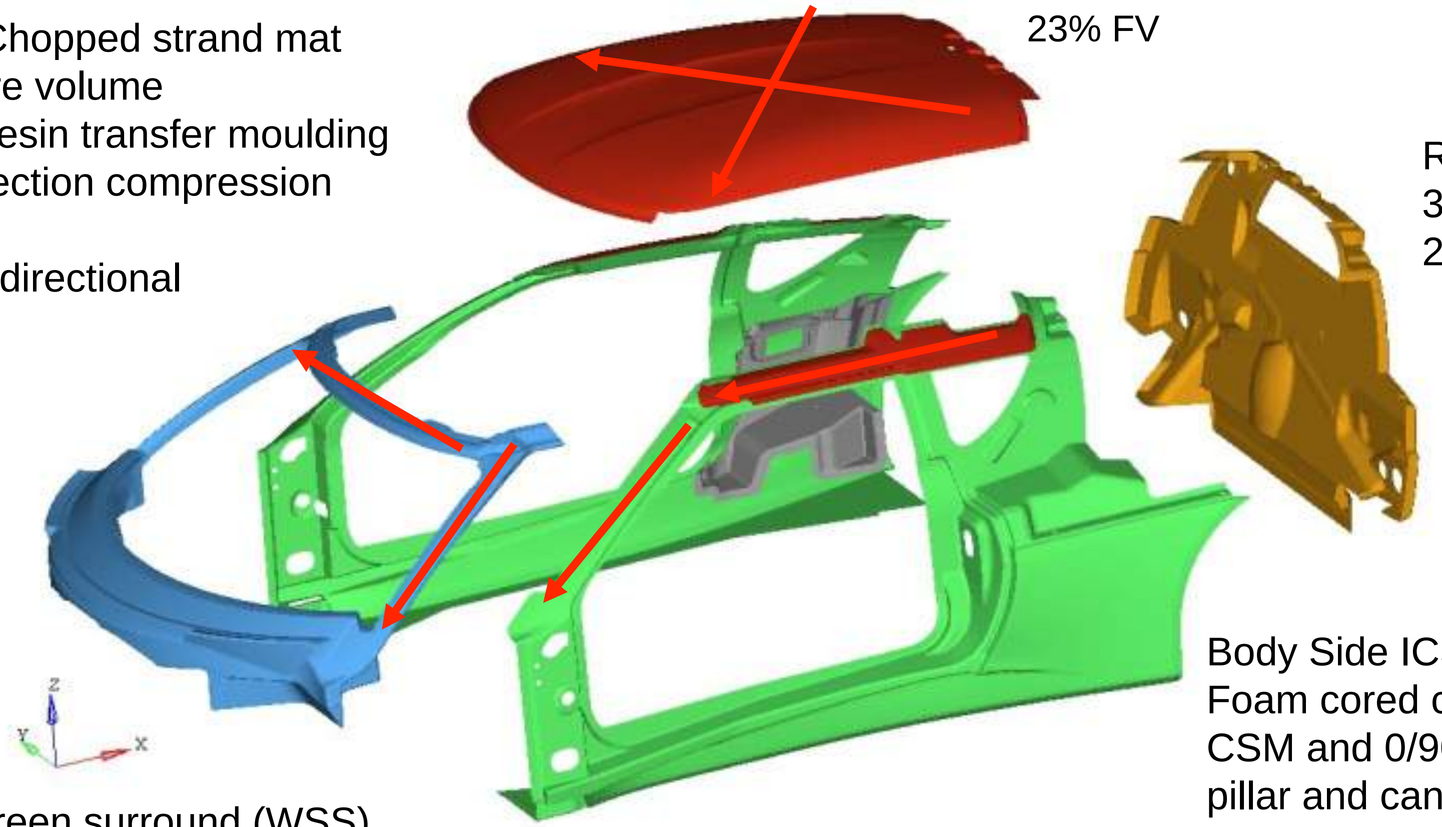
Shear Panels

Aluminium sheet 5754

Front, rear

Structural Composite Panels

Key
CSM – Chopped strand mat
FV - Fibre volume
RTM - Resin transfer moulding
ICS - injection compression system
UD - Unidirectional



Roof panel ICS/RTM
2.5mm CSM and +/-45 UD Stitch Mat.
23% FV

Rear Bulkhead RTM
3.5mm CSM
23% FV

Body Side ICS/RTM 2.5mm-5mm.
Foam cored cant rail
CSM and 0/90 UD Stitch mat in A pillar and cantrail. 22% FV

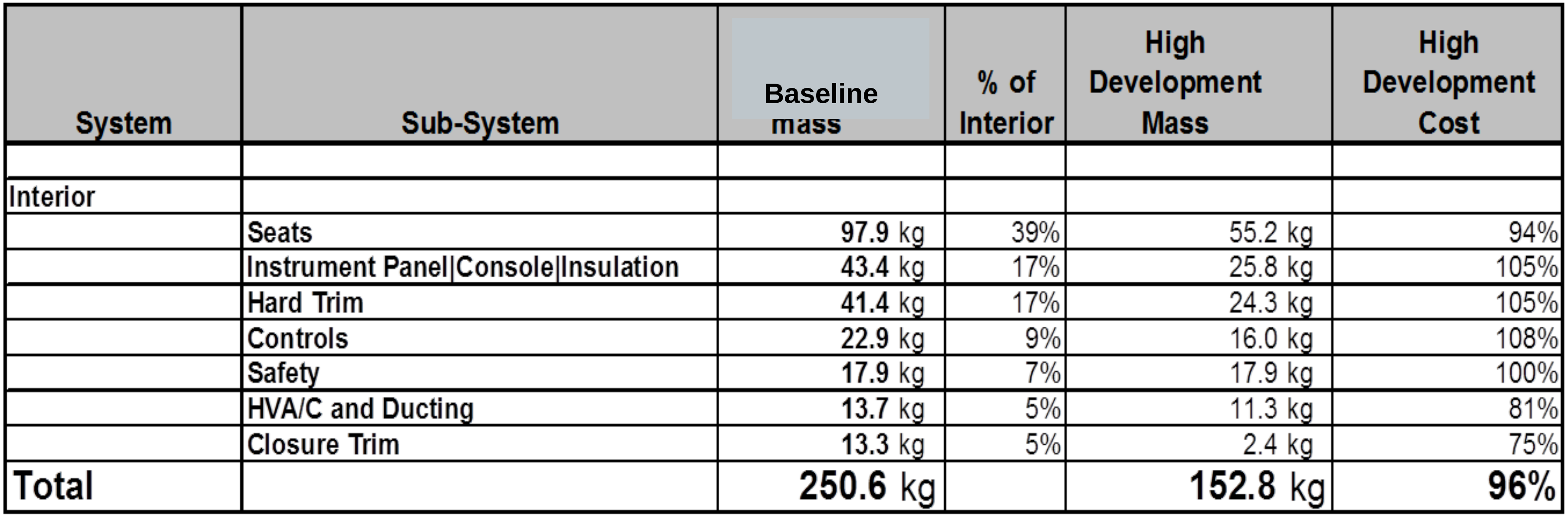
Windscreen surround (WSS) ICS/RTM 3mm-5mm Foam cored
CSM and 0/90 UD Stitch mat in A pillar and header. 23% FV

- Bonded composite body panels are structural unlike Elise
- Bonded to tub with Betamate 2800 series and large bond areas

Lightweight Interior Design

Applying Lotus Lightweight Design Principles to Interiors

- Interior mass reduced by 60% in peer reviewed ICCT study
- Seats, IP and Hard Trim represent approximately 75% of interior mass



System	Sub-System	Baseline mass	% of Interior	High Development Mass	High Development Cost
Interior					
	Seats	97.9 kg	39%	55.2 kg	94%
	Instrument Panel|Console|Insulation	43.4 kg	17%	25.8 kg	105%
	Hard Trim	41.4 kg	17%	24.3 kg	105%
	Controls	22.9 kg	9%	16.0 kg	108%
	Safety	17.9 kg	7%	17.9 kg	100%
	HVA/C and Ducting	13.7 kg	5%	11.3 kg	81%
	Closure Trim	13.3 kg	5%	2.4 kg	75%
Total		**250.6 kg**		**152.8 kg**	**96%**

2010 ICCT Study

Applying Lotus Lightweight Design Principles to Individual Seats

Lotus Seat Design

Weight: 24.2 lbs.

Typical Seat Design

Weight: 49.5 lbs.

Lotus design is 51% lighter

Applying Lotus Lightweight Design Principles to Bench Seats

Lotus Rear Seat Design

Weight: 56.0 lbs.

Typical Rear Seat Design

Weight: 87.8 lbs.

Lotus design is 36% lighter

Aerospace Case Study - ICON A5 Interior Design & Development

Develop lightweight, integrated cockpit system solution

- •Low mass system solution - seats, IP, consoles, trim panels and flooring weigh <45 lbs.
- •Class A surfaces are the structure – no added reinforcements
- •Carbon fiber composite interior and seat system
- •Reduced assembly complexity and cost achieved by system integration;
- •High level of component Integration, e.g. structural air duct

Styling and CAD by ICON Aircraft

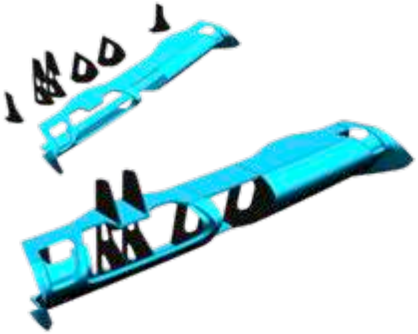
Applying Lightweight Design Principles to Interiors

- Lightweight, ergonomically correct seats - Lotus Elise/Exige seats rated comparable to Rolls Royce seats for comfort by London Times reviewer

- Lotus engineered seven pound seats for the Icon A5 LSA

- Structural IP enhances appearance and reduces weight (< 2.4 lbs.)

- Structural air distribution duct helps reduce instrument panel weight



Styling and CAD by ICON Aircraft

Structural Carbon Fiber Instrument Panel Concept

- Typical automotive IP cross sections are similar in area to automotive rocker panels, one of the strongest elements of a vehicle body
- A carbon fiber IP has the potential to eliminate the cross car beam and the IP internal reinforcements
- The estimated weight of a properly designed carbon fiber structural IP is less than 4 lbs. for most passenger cars
- Incorporating a structural carbon fiber instrument panel in a high performance vehicle could reduce weight and improve perceived value (non-structural carbon fiber IP trim panels typically cost > $1,000)
- A properly styled carbon fiber IP could be included as part of an up level interior package

Styling and CAD by ICON Aircraft

Lightweight Chassis Design

Chassis/Suspension System

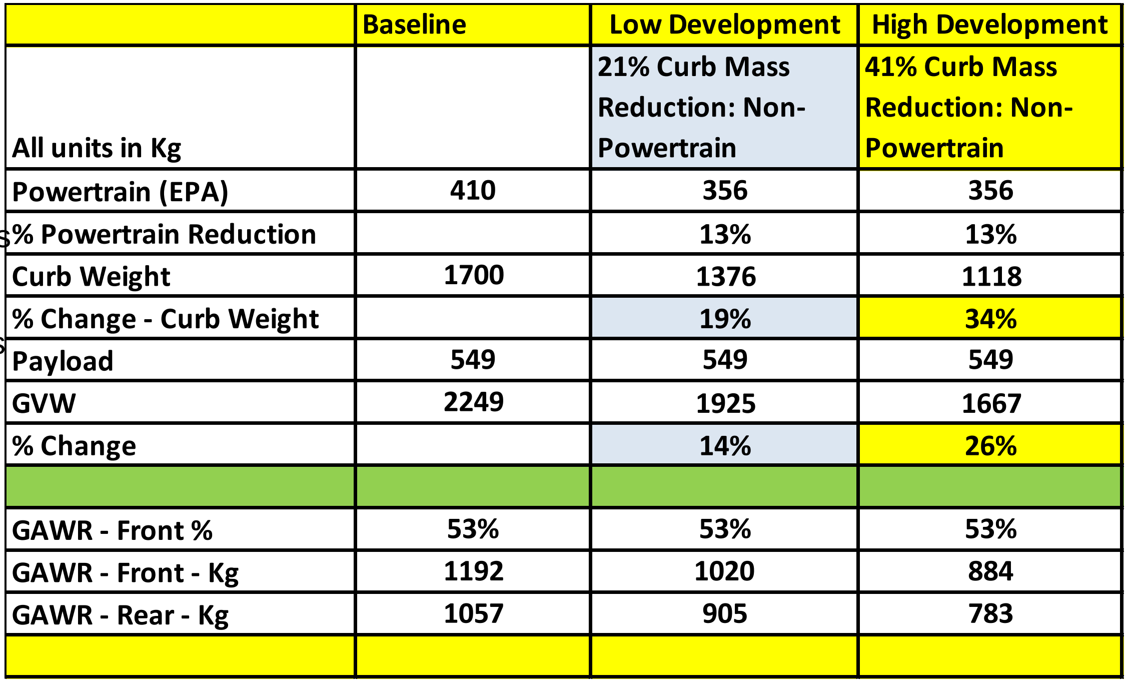
- The chassis and suspension system is composed of:
  - suspension support cradles
  - control links
  - springs
  - shock absorbers
  - bushings
  - stabilizer bars & links
  - steering knuckles
  - brakes
  - steering gearbox
  - bearings
  - hydraulic systems
  - wheels
  - tires
  - jack
  - spare tire (deleted)
  - steering column

Chassis/Suspension GAWR (Gross Axle Weight Rating) Calculation

- Powertrain weights are typically not reduced at the same percentage as the rest of the vehicle
- Baseline payloads are typically maintained for an equivalent lightweight vehicle

Methodology

1. Calculate curb weight and add payload to determine gross vehicle weight
2. Use gross vehicle weight to calculate front and rear Gross Axle Weight Ratings (GAWR's)
3. Use GAWR's to determine wheel load capacity requirements



	Baseline	Low Development	High Development
All units in Kg		**21% Curb Mass Reduction: Non-Powertrain**	**41% Curb Mass Reduction: Non-Powertrain**
Powertrain (EPA)	**410**	**356**	**356**
% Powertrain Reduction		**13%**	**13%**
Curb Weight	**1700**	**1376**	**1118**
% Change - Curb Weight		**19%**	**34%**
Payload	**549**	**549**	**549**
GVW	**2249**	**1925**	**1667**
% Change		**14%**	**26%**
GAWR - Front %	**53%**	**53%**	**53%**
GAWR - Front - Kg	**1192**	**1020**	**884**
GAWR - Rear - Kg	**1057**	**905**	**783**

Data From 2010 ICCT Study

Chassis/Suspension Mass and Cost Analysis

- Based on the projected gross vehicle weight, including baseline cargo capacity, the chassis and suspension components were reduced in mass by 43%.
- The projected cost savings was 5%.

	Mass (kg)		**Cost(% of baseline)**	
	Baseline	**High Dev**	**Baseline**	**High Dev**
Front Chassis Total	101.3	57.3	100%	101%
Rear Chassis Total	67.8	39.5	100%	92%
Tires&Wheels	144.5	76.0	100%	81%
Brakes	65.2	44.3	100%	117%
Total Chassis	378.9	217.0	100%	95%
% Reduction		43%		5%

Cost Analysis

Lightweight Material Cost Analysis – Infrastructure Constrained

- Material Cost = 4x base material
- Body weight = ½ weight of the base structure
- Carryover manufacturing process = $0 savings
- Carryover parts count = $0 savings
- Carryover joining process = $0 savings
- Carryover assembly process = $0 savings

Total lightweight body cost = 2x base cost

Affect of 25% Vehicle Weight Reduction on Engineering Budget

25% weight reduction translates to a 33% budget increase

	Baseline Vehicle	Lightweight Vehicle
Cost - MSRP - $	30,000	30,000
Curb Weight - lbs.	4,000	3,000
Cost/lb.	7.5	10
Relative Cost/lb. vs. Baseline	100%	133%
Added Budget per lb. - %		**33%**
Assumes lighweight vehicle is identical dimensionally and volumetrically to baseline		

- Making a vehicle lighter can allow a higher $/lb cost for materials without impacting the MSRP
- A lighter weight vehicle can have a higher $/lb cost and still be competitive

Affect of 25% Vehicle Weight Reduction on EPA Fuel Economy

- 25% weight reduction translates to a 3 to 4 MPG advantage in fuel economy
- Based on typical industry weight reduction/MPG ratio*

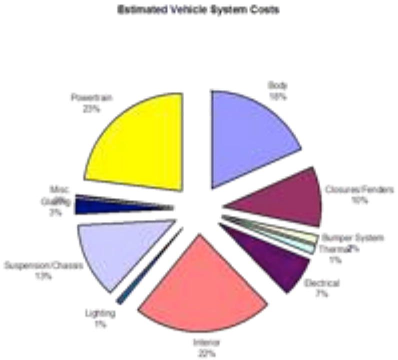
Vehicle Weight - Lb.	Vehcle Fuel Economy - MPG		
	City	Highway	Combined
4,000	17	25	20
3,000	20	29	23
MPG Improvement	3	4	3

* Assumption: 10% weight reduction = 6% FE improvement with adjusted powertrain

Weighted Vehicle Cost Analysis for a 40% More Expensive Body (25% Lighter Vehicle)

With New Body Plant Amortization	Cost Factor	Cost Weighting Factor	Weighted Cost Factor
Complete Body	140%	18%	25.2%
Non-Body	100%	82%	82.0%
Totals		100%	107.2%
Cost Differential			7.2%

Assumptions:
1. New body plant
2. Cost parity for all non-body systems



Cost Chart from 2010 ICCT Study

Body Plant Amortized	Cost Factor	Cost Weighting Factor	Weighted Cost Factor
Complete Body	130%	18%	23.4%
Non-Body	100%	82%	82.0%
Totals		100%	105.4%
Cost Differential			5.4%

Assumptions:
1. New body plant amortized
2. Cost parity for all non-body systems

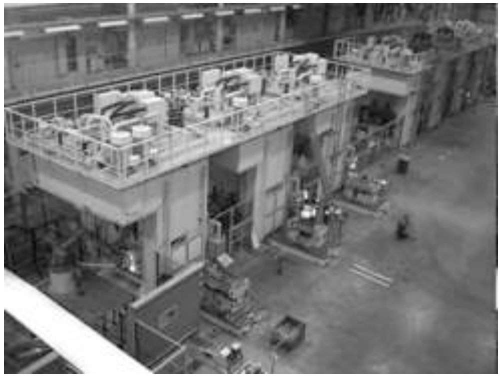
Assumptions:
1. New body plant amortized
2. 2% cost savings for all non-body systems

Body Plant Amortized & 3% Non-Body Savings	Cost Factor	Cost Weighting Factor	Weighted Cost Factor
Complete Body	130%	18%	23.4%
Non-Body	98%	82%	80.4%
Totals		100%	103.8%
Cost Differential			3.8%

2. Selecting Manufacturing Approaches That Can Contribute To Reduced Tooling and Assembly Costs

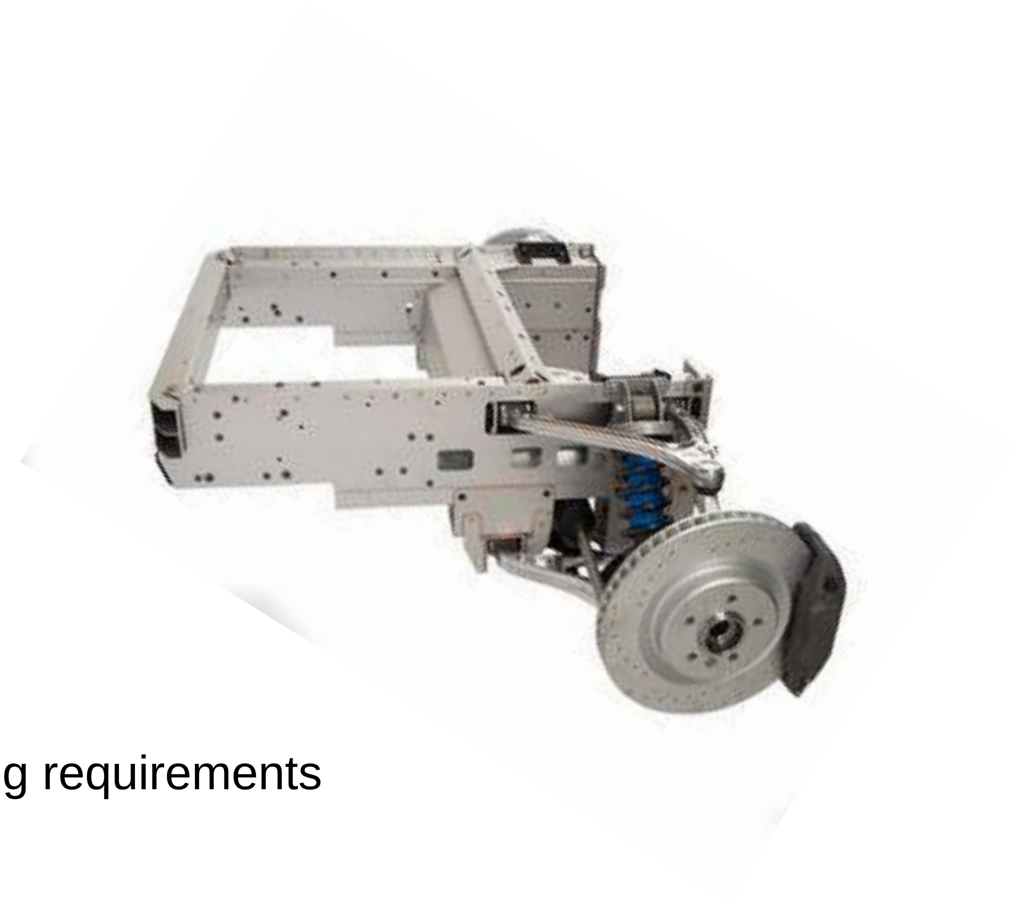
Available Manufacturing Processes

- Manufacturing processes typically chosen based on cycle time, running costs, utilization factor, and investment
- Current processes:
  - Stamping
  - Casting
    - Low pressure
      - Die cast
      - Investment cast
      - Ablation cast
    - High pressure
      - Thixomolding
  - Extrusion
    - Impact
      - Cold forming
  - High pressure forming
  - Molding
  - Ultra high speed forming
    - EMP
  - Additive Manufacturing
  - Other



Manufacturing Process Selection Criteria

- Prioritize processes based on:
  - Part consolidation
  - Parts count reduction
  - Part cost
  - Part quality
  - Cycle time
  - Tool cost
  - Tool count reduction
  - Part tuning ease
  - Tool tuning economics
  - Scrap percentage per part
  - Minimizing/eliminating post processing requirements
    - Fixturing
    - Assembling
    - Joining

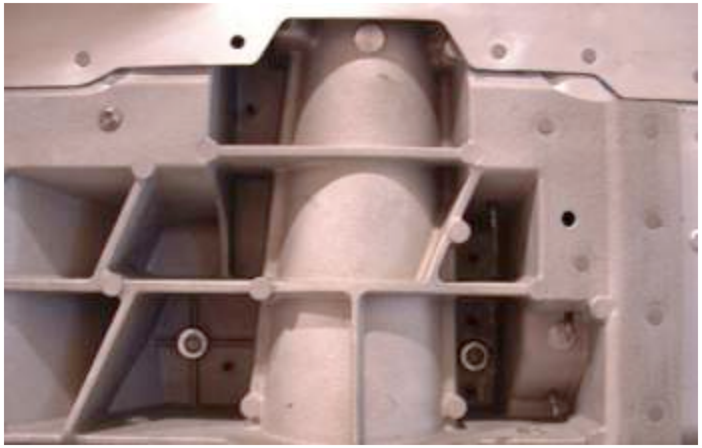


Preferred Manufacturing Processes

- Extrusions
  - Inexpensive relative to other processes
  - Allow part consolidation
  - Easily tunable
  - Flexibility
  - Post processing permits plan view shape
  - Minimal scrap

- Castings
  - Provide high level of component integration
  - Typically eliminate 60% - 80% of tool count
  - Eliminate need for post process fixturing
  - Eliminate need for post process joining
  - Optimize part thickness
  - High level of part stability
  - Eliminate need for post process joining
  - Minimal scrap

- Laser Cutting - Flat Sheets
  - No tooling
  - Excellent dimensional control

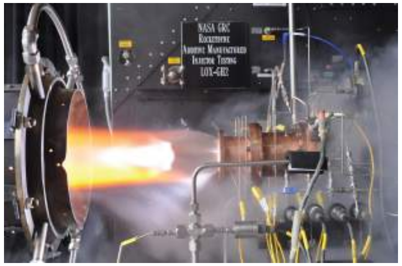


Additive Manufacturing

- AM, e.g., fused deposition modeling (FDM), stereolithography (SLA) and direct metal laser sintering (DMLS) are processes being used in production today to make aerospace and medical parts

- Increasing number of materials available as technology matures
- AM production has helped aerospace manufacturers reduce part counts and the weight of components, e.g., GE Aviation’s AM fuel nozzle for the LEAP jet engine reduced parts count from 18 to 1

- Jet engine manufacturer Pratt & Whitney, East Hartford, Conn., recently announced that AM parts are in use on the PurePower turbine engines that power some of the new C series jets built by Bombardier Inc.
- Aerojet Rocketdyne makes a rocket engine fuel injector nozzle via AM, and verified its capabilities through a series of tests at NASA’s Glenn Research Center.

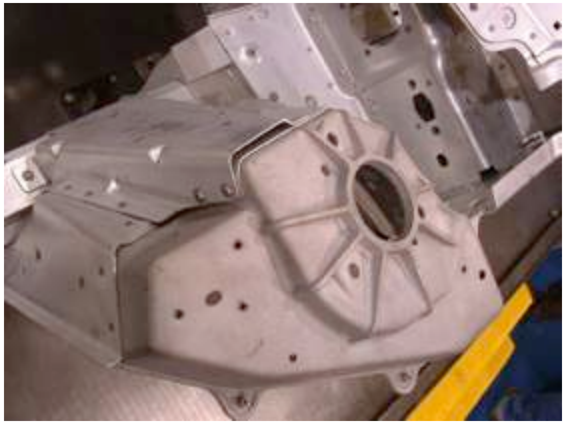


Above information from SEPTEMBER/OCTOBER 2013 | MICROmanufacturing (article courtesy of NASA)

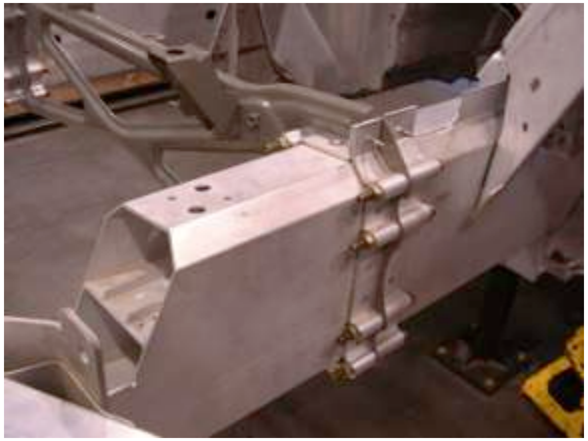
3. Assessing Joining Technologies: Opportunities for Reducing Weight and Increasing Strength

Opportunities for Improved Joining for A Lightweight Structure

- Utilize castings and extrusions
- Minimize number of joints
- Reduce energy consumption
- Minimize flange width
- Maintain parent material strength
- 100% flange interface



Lotus VVA Body



http://www.motortrend.com/features/consumer/1206_temple_of_tesla_touring_elons_factory/photo_09.html

http://info.tolomatic.com/linear-actuator-blog/?Tag=Actuators+in+Robotic+Spot

Joining Process Selection – Key Criteria

- Process chosen based on strength, fatigue/durability, cost and mass for each specific attachment

- Process selected to contribute to overall system performance, cost & mass targets
  - 100% continuous joint contributes to an increase in body stiffness
  - Increase in body stiffness allows reduction in material thickness which contributes to mass and cost savings
  - Minimize parent material property degradation (HAZ)
  - Minimize flange width - contributes to mass and cost reduction
    - Typically driven by weld head size
    - Scalloped flanges can reduce mass

- Process chosen to meet cycle time requirements

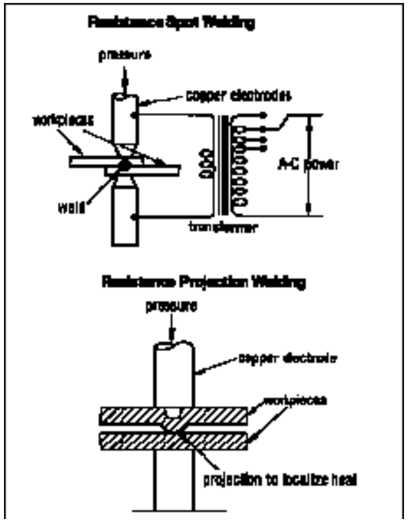
- Software modeling for the selected process has high level of fidelity

ENGINEERING

http://www.autosteel.org/~/media/Files/Autosteel/Great%20Designs%20in%20Steel/GDIS%202012/Advanced%20High-Strength%20Steel%20Technologies%20in%20the%202013%20Cadillac%20ATS.pdf

Joining Process Selection – Key Processes Available

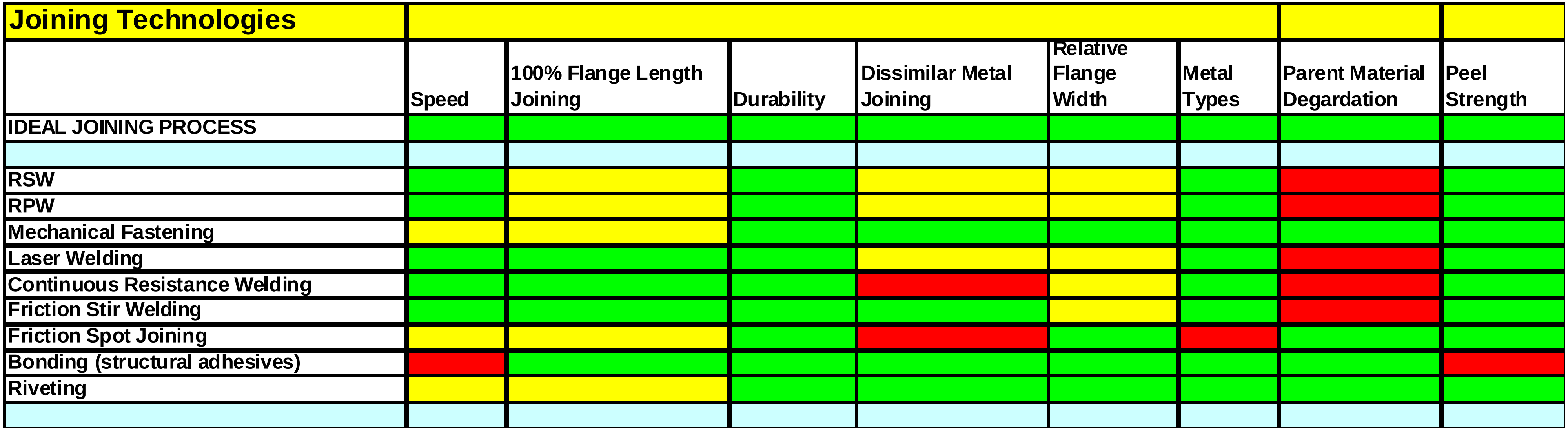
- RSW
- RPW
- Clinching
- Mechanical fastening
- Laser welding
- Continuous resistance welding
- Friction stir welding
- Friction spot joining
- Bonding (structural adhesives)
- Riveting
- EMP joining
- Other



http://www.makeitmetal.com/resources/ch13_spweld.htm

Ideal Technology For Joining Multi-Material Structures

- No single joining methodology meets every possible design criteria
- There are a wide variety of joining options available to automotive engineers
- The joining processes shown below are all proven technologies used with confidence by international OEMs
- Combining the strengths of several processes to create a hybrid joint can generate cost and structural advantages



Joining Technologies								
	Speed	100% Flange Length Joining	Durability	Dissimilar Metal Joining	Relative Flange Width	Metal Types	Parent Material Degardation	Peel Strength
IDEAL JOINING PROCESS	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
RSW	🟩	🟨	🟩	🟨	🟨	🟩	🟥	🟩
RPW	🟩	🟨	🟩	🟨	🟨	🟩	🟥	🟩
Mechanical Fastening	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟩
Laser Welding	🟩	🟩	🟩	🟨	🟨	🟩	🟥	🟩
Continuous Resistance Welding	🟩	🟩	🟩	🟥	🟨	🟩	🟥	🟩
Friction Stir Welding	🟩	🟩	🟩	🟩	🟨	🟩	🟥	🟩
Friction Spot Joining	🟨	🟨	🟩	🟥	🟩	🟥	🟩	🟩
Bonding (structural adhesives)	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟥
Riveting	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟩

Joining Process Selection – Galvanic/Corrosion Considerations

- Minimize galvanic/corrosion interactions by material selection
    - General guideline: Limit each joint to a maximum of two dissimilar materials

- Choose material coatings to meet long term durability requirements

- Coatings selected must be compatible with joined materials and joining processes
    - General guideline: choose a single supplier for coatings/joining materials

- Compare total joining costs

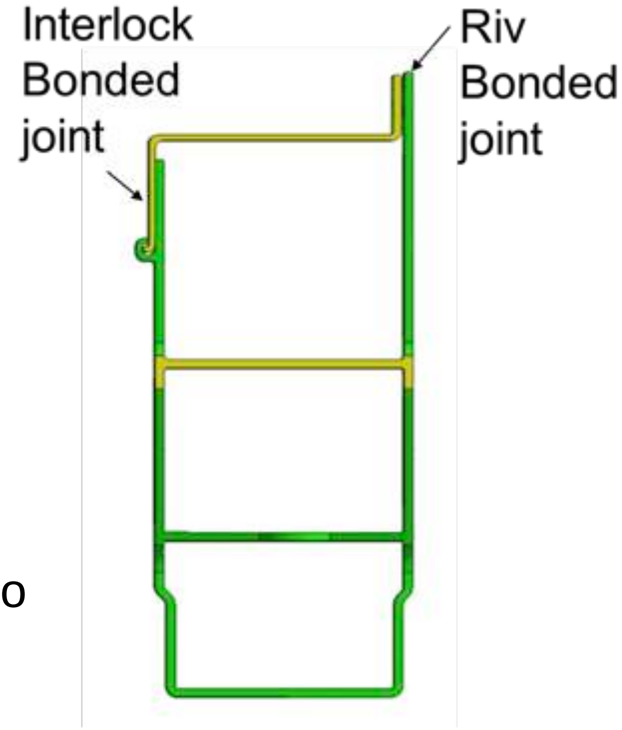
http://www.butchthecat.com/past/s10/rocker.htm

http://www.jeepforum.com/forum/f9/body-mount-rust-issues-1526730/

Joining Considerations Affecting Cost

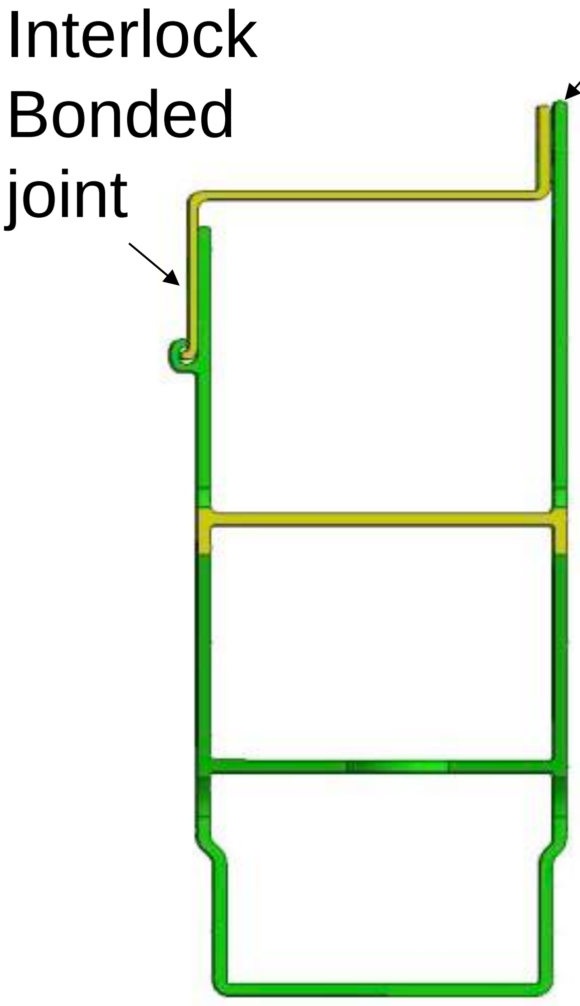
Reduce joining costs by:

- Minimizing the number of welds/ rivets
- Eliminating fasteners
- Reducing energy consumption
- Reducing the weight of the attachments, e.g., rivets
- Creating hybrid joining solutions to maximize strength and minimize costs



Pictures provided by Richard Rackham and David Marler, Lotus UK

Structural Design – Crash Rail Design

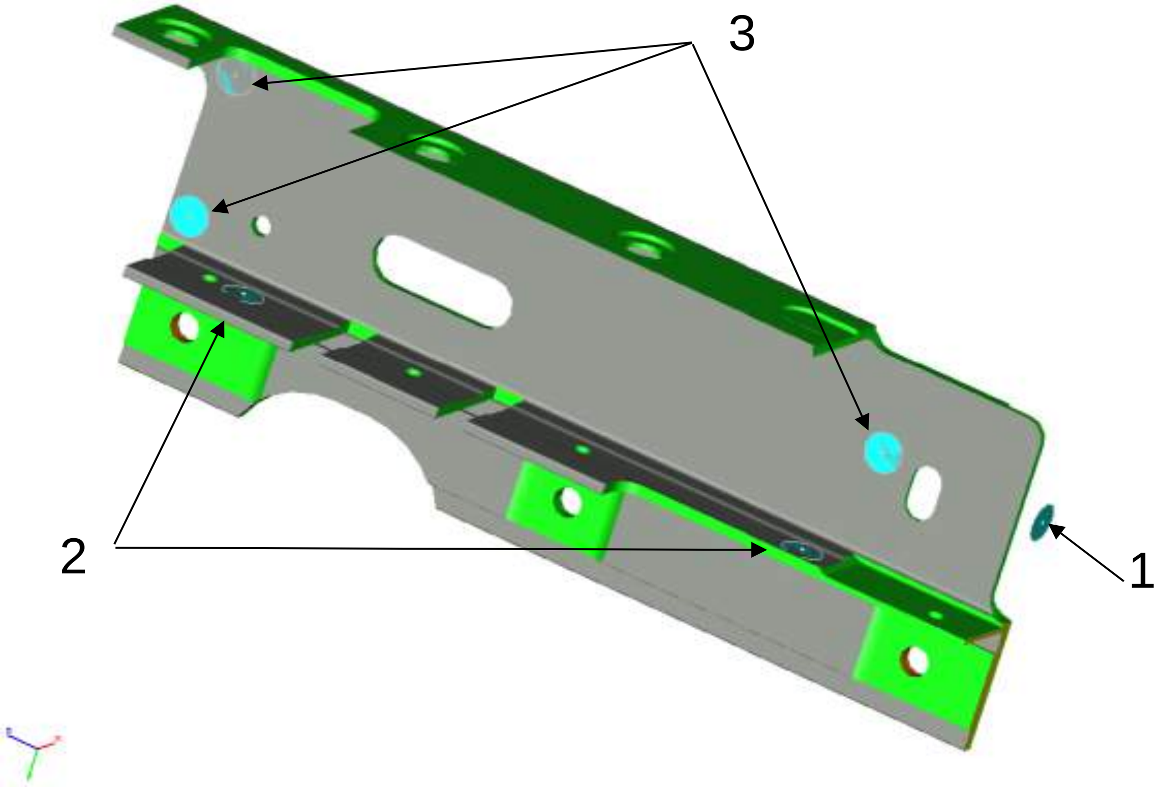


First Lotus application of a bonded assembly crash rail. Initial one piece section was too large to extrude. Therefore upper section riv-bonded to lower section

Rail also incorporates weakening holes and variable rivet pitch to tune behaviour both for axial crush and off axis bending

4. Creating Robust Assembly Techniques That Support Non-Traditional Construction

Tolerance Control

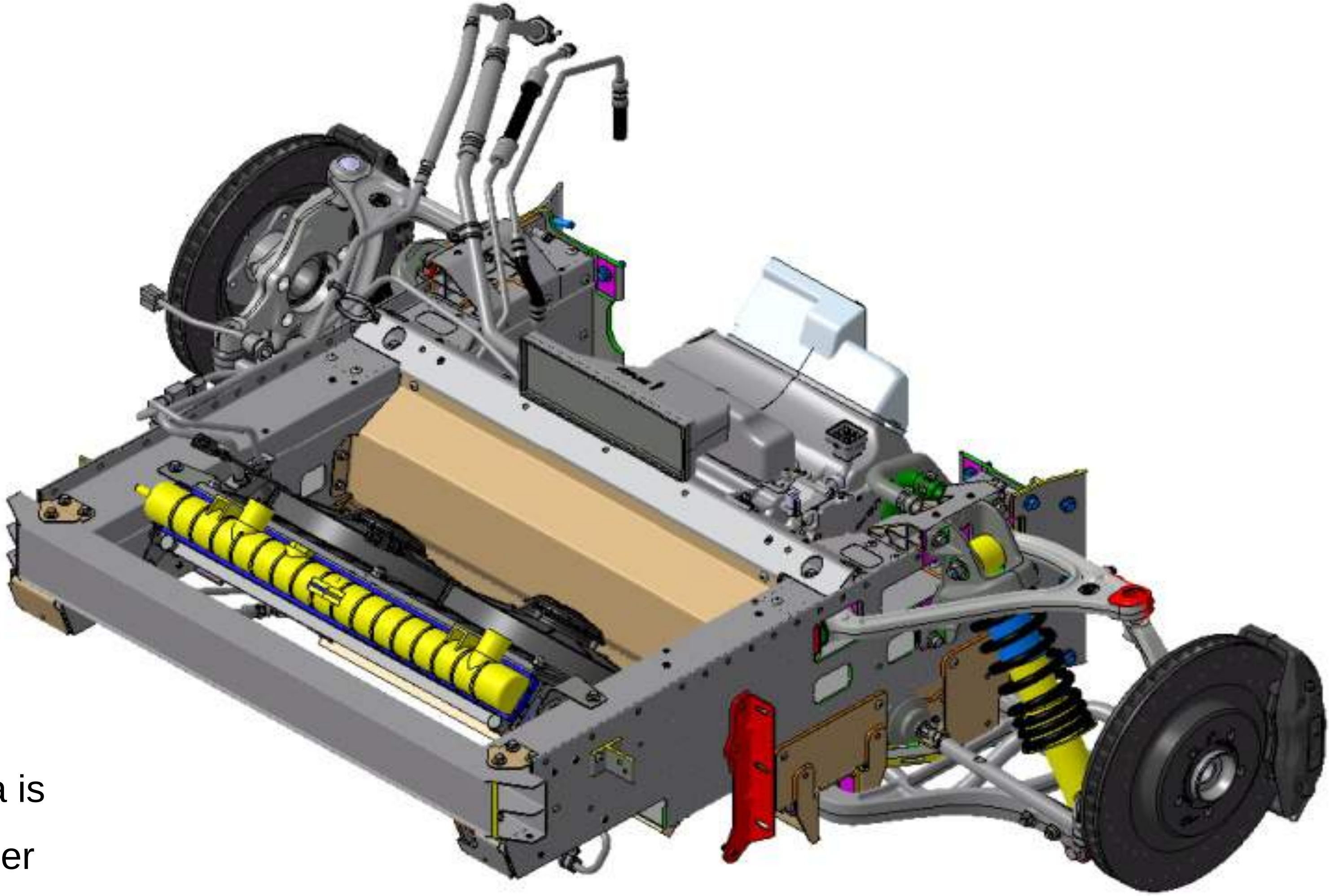


- 321 fixturing strategy used to locate extrusions if machined
- Four master datum locations on underside of main structure
- All other components datumed from these locations
- Tolerance management of machined extrusions ensures hardpoint accuracy of +/- 0.5mm

321 fixturing allows control of 9 degrees of freedom

Chassis Assembly – Front Module

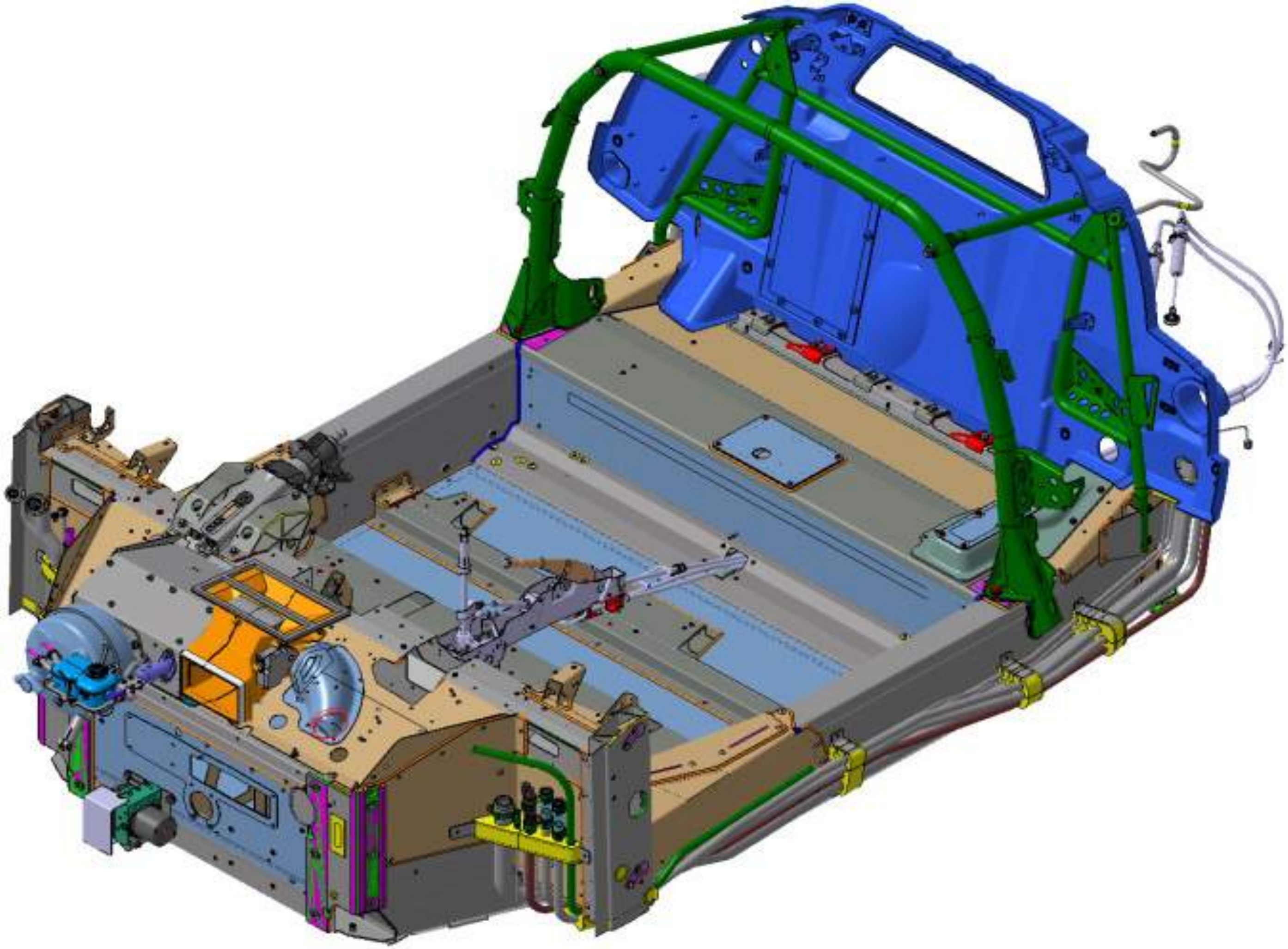
- Subframe
- Cooling pack
- Steering rack
- HVAC
- Suspension
- Brakes



The only aluminium casting unique to Evora is the spring /damper upper mount

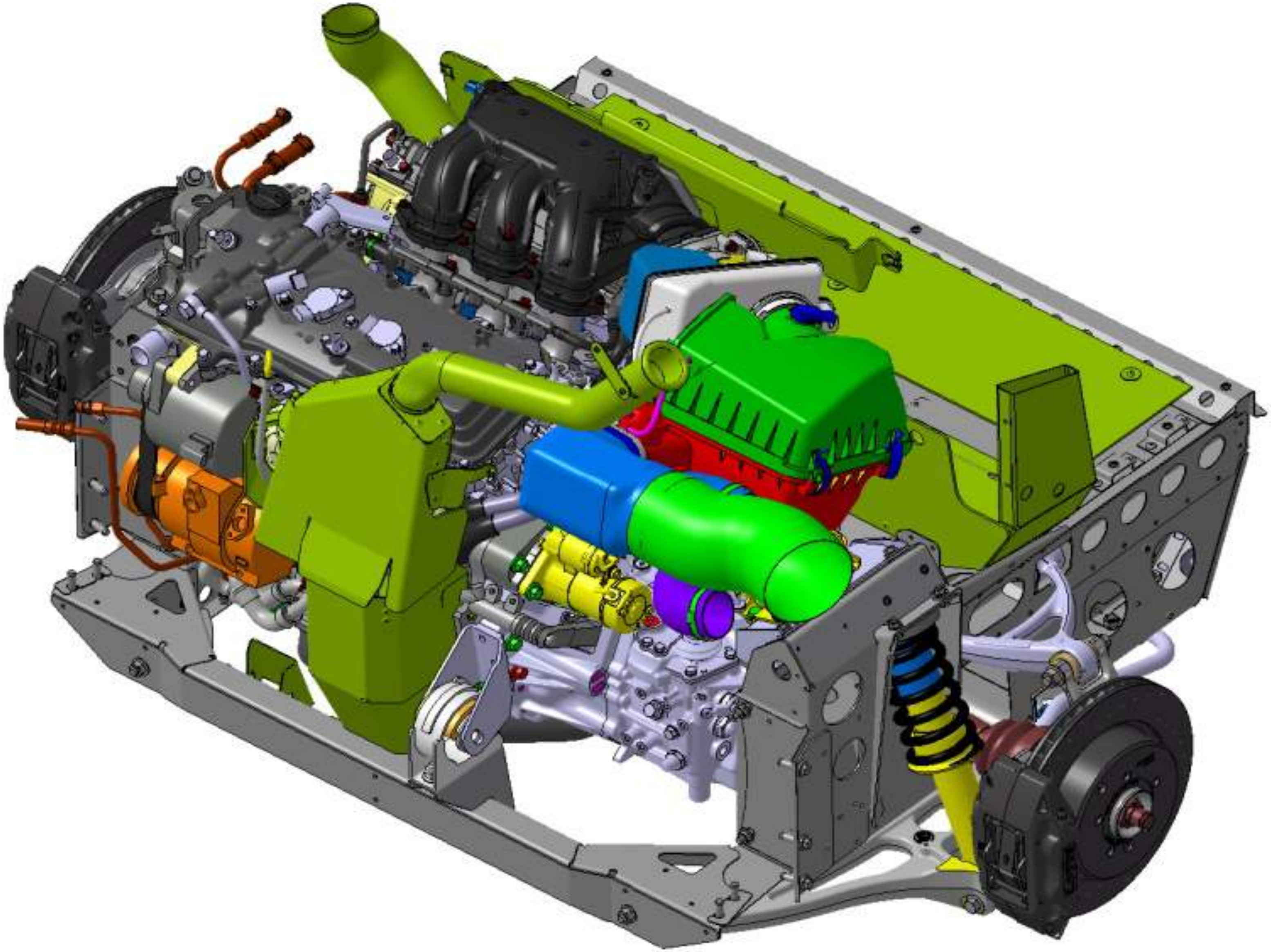
Chassis Assembly – Centre Module

- Tub
- Steering column
- Pedal box
- HVAC distribution
- Gearshift / Handbrake
- Fuel tank
- Seat belt anchor frame
- Rear Bulkhead
- Pipework
- The tub is handed by the steering column, pedalbox and HVAC recirculation duct



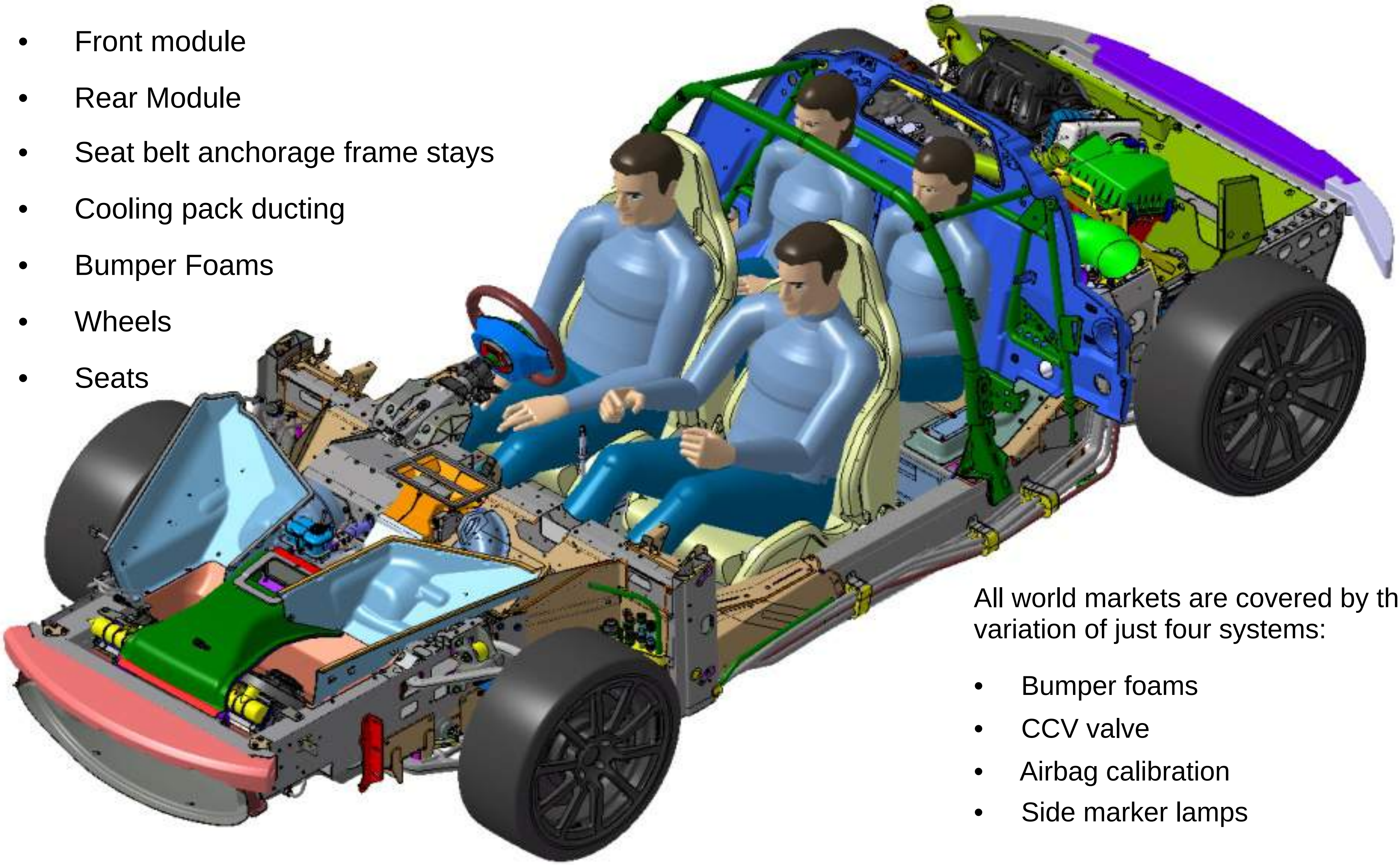
Chassis Assembly – Rear Module

- Subframe
- PAS Pipes
- Powertrain
- Heatshields
- Airbox
- Suspension
- Brakes
- Exhaust
- Ducting



Vehicle Assembly – Evora less body work and trim

- Front module
- Rear Module
- Seat belt anchorage frame stays
- Cooling pack ducting
- Bumper Foams
- Wheels
- Seats

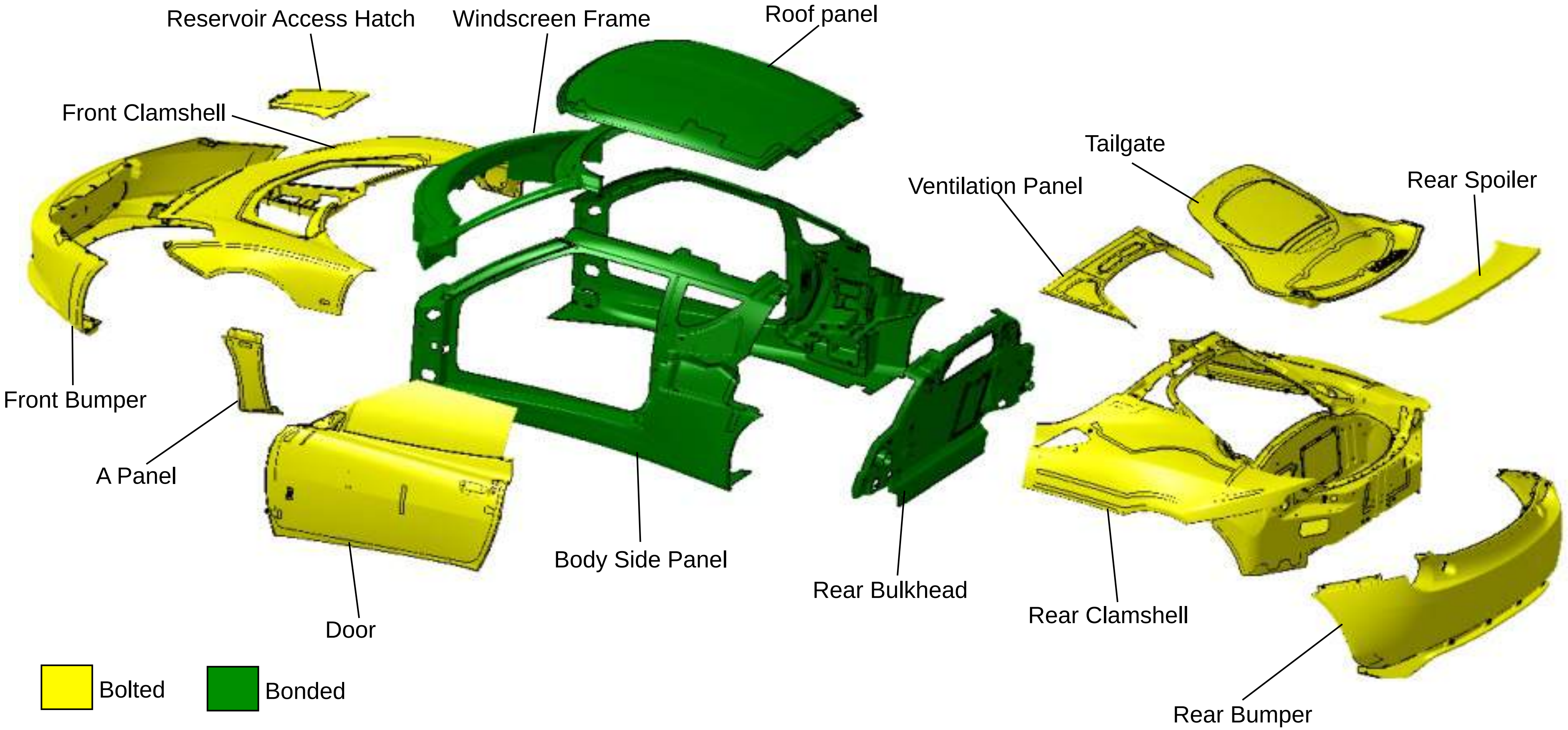


All world markets are covered by the variation of just four systems:

- Bumper foams
- CCV valve
- Airbag calibration
- Side marker lamps

Evora Body Panels

- 17 separate sub assemblies
- Bonded panels are replaceable using windscreen technology



Material prepared by Richard Rackham and David Marler, Lotus Cars Limited

Summary Remarks

Summary Remarks

1. Reducing weight efficiently requires a total vehicle, holistic approach
2. Manufacturing, joining and assembly processes can play a key role in offsetting the cost of more expensive lightweight materials
3. Emerging technologies have the potential to substantially change how parts are made and how body structures are joined in future designs

Thank You

ENGINEERING

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