Multi-Material Lightweight Vehicles

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Project ID #
LM072

Acknowledgement

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Overview

Timeline

• Start Date:	2012-Feb
• End Date:	2015-Sep

Budget

Total Project Funding	$20,288,755
• DOE:	$10,000,000
• Vehma/Ford	$10,288,755
Budget Period 1,2 & 3	$18,535,141
Expenditure of Funds (thru BP3)	
• DOE	$ 9,320361
• Vehma	$ 4,605,207
• Ford	$ 4.966,591

Partners

- Vehma International
- Ford Motor Company

Barriers

Mach I – As defined in the 2014 Annual Merit Review, a mass reduction of 364kg was achieved while maintaining size, performance and features. The interior quietness of the Mach-I is challenged by the reduced mass components. Further mass reduction was constrained by 2012 FMVSS regulations, donor vehicle architecture, and project scope and funding.

Mach II – The availability of mature material information required for impact, fatigue and sound quality CAE analysis is limited for the composite materials researched for application development. While keeping the size and cargo space, much of the customer comfort, convenience and quietness attributes must be compromised to achieve the target mass reduction.

Project Objectives / Relevance

Multi-Material Lightweight Vehicle MMLV

Project Objectives

1. Design and build Mach-I prototype vehicles, maintaining donor vehicle architectural space to reduce mass relative to a 2002 baseline vehicle. Mach I design shall a) utilized “commercially available” or “demonstrated” materials and manufacturing processes, b) include an OEM Partner to validate and test the vehicle, c) demonstrate integration of the lightweight material vehicle system into an existing OEM body shop, avoiding niche assembly/coating processes. The Mach-I concept will be prototyped using an existing production donor vehicle with new MMLV components integrated to create full vehicles and subassemblies for testing. The prototype vehicles will be tested by the OEM to validate the design, material, and process used to manufacture the lightweight Mach-I prototypes (Safety, NVH, Durability, and Corrosion)

   Mach I Result: 23.5% Vehicle-level Mass Reduction was reported at 2013 AMR
   Mach I Result: Prototype vehicles produced reported at 2014 AMR
   Mach I Result: Prototype vehicles tested reported today, 2015 AMR

2. Design a Mach I concept vehicle, without architectural constraints, that will obtain a mass reduction of 50%, as compared to the 2002 Taurus baseline vehicle. Mach-II design will incorporate materials and manufacturing process that “show potential” but are not yet proven commercially viable for high volume production. Examples include magnesium wrought body components for both class A surfaces and inner panels and carbon fiber materials in structural and sheet components. The use of these materials pose a large challenge in joining and corrosion. The Mach-II design concept will identify the joint and material combinations that will need further research to mitigate corrosion and joint challenges.

   Mach II Result: Work in progress reported at 2014 AMR
   Mach II Result: Final design reported today, 2015 AMR

The Mach-I vehicle architecture is defined by the donor vehicle to facilitate full-vehicle integration required for vehicle testing and validation by the OEM. The Mach-I design includes a manufacturing component, which includes modular assembly methods which illustrate the feasibility to build the Mach-I vehicle in an existing body shop.* The Mach-II design will be a “new design architecture” without architecture and integration constraint imposed by the donor vehicle and existing body shop and bill-of-process.

Project Relevance

- Reducing weight is an key enabler to reducing fuel consumption.
- Lightweight vehicle architecture design
  - Multi-material body in white and closure architectures do not exist in today’s market for high volume vehicles*.
  - High volume/low cost joining of dissimilar materials for BIW and Closures does not exist in today’s market*.
  - High volume/low costs polycarbonate and chemically toughened glass does not exist in today’s market*.

* Technology Gap

MMLV Milestone Status

Milestones	Component	Start Date	End Date	% Complete
Mach-I Vehicle design complete, CAE Predictive models complete Vehicle assembly Bill of Materials (BOM) complete	BIW, Closure, Suspension, Component	01/2012	01/15/2013	100%
Component part build complete – stampings, castings, extrusions complete for assembly build. Vehicle components complete for vehicle integration	Vehicle Build	08/2013	3/15/2014	100%
Vehicle Build – completion of BIW modules and final assembly. Integration into full drivable vehicles	BIW, Closures,	010/01/2013	08/06/2014	100%
Mach-II Vehicle design – Completion of Bill of materials and design direction for analysis	Vehicle	03/04/2013	10/31/2014	100%
Mach-II CAE Predictive Models – Completion of Stiffness and Durability models, FMVSS side impact, roof crush, frontal off-set	Vehicle	10/01/2013	12/15/2014	100%
Powertrain prototype components complete	Powertrain	05/01/2013	10/31/2014	100%
Component level testing for vehicle integration components	Chassis, Interior	01/30/2013	05/30/2015	100%
Component level testing for powertrain components	Powertrain	03/01/2014	04/30/2015	100%
Full vehicle durability and corrosion testing	Vehicle	04/30/2014	1/30/2015	100%
Full vehicle safety testing	Vehicle	07/15/2014	1/30/2015	100%

Technical Accomplishments
Mach I Mass Distribution

Mach I Design

The MMLV design demonstrates the lightweighting potential of a five passenger sedan, while maintaining performance, packaging, occupant safety while using commercially available materials and production processes.

The Mach I design achieves a 364 kg (23.3%) full vehicle mass reduction, enabling the application of a 1.0-liter three-cylinder engine resulting in a significant environmental benefit and fuel reduction. The 364 kg weight reduction from the 2013 Fusion results from redesigning and lightweighting five vehicle systems: Body and Closures, Interior, Chassis, Powertrain and Electrical.

Subsystem Description	2002 Taurus	2013 Fusion	MMLV Mach-I DESIGN FINAL
Body Exterior and Closures (kg)	**574**	**594**	**456**
Body-in-White	n.a.	326	250
Closures-in-White	n.a.	98	69
Bumpers	n.a.	37	25
Glazings - Fixed and Movable	n.a.	37	25
Remainder - trim, mechanisms, paint, seals, etc.	n.a.	96	87
Body Interior and Climate Control (kg)	**180**	**206**	**161**
Seating	n.a.	70	42
Instrument Panel	n.a.	22	14
Climate Control	n.a.	27	25
Remainder - trim, restraints, console, etc	n.a.	88	80
Chassis (kg)	**352**	**350**	**252**
Frt & Rr Suspension	n.a.	96	81
Subframes	n.a.	57	30
Wheels & Tires	n.a.	103	64
Brakes	n.a.	61	49
Remainder - steering, jack, etc.	n.a.	33	29
Powertrain (kg)	**350**	**340**	**267**
Engine (dressed)	n.a.	101	71
Transmission and Driveline	n.a.	106	92
Remainder - fuel, cooling, mounts, etc.	n.a.	133	104
Electrical (kg)	**67**	**69**	**59**
Wiring	n.a.	28	25
Battery	n.a.	14	8
Remainder - alternator, starter, speakers, etc.	n.a.	27	26
Total Vehicle (kg)	**1523**	**1559**	**1195**

Weight Save Compared to 2013 Fusion 23.3%
Weight Save Compared to 2002 Taurus 21.5%

Technical Accomplishments
Mach I Life Cycle Assessment

Multi-Material Lightweight Vehicle MMLV

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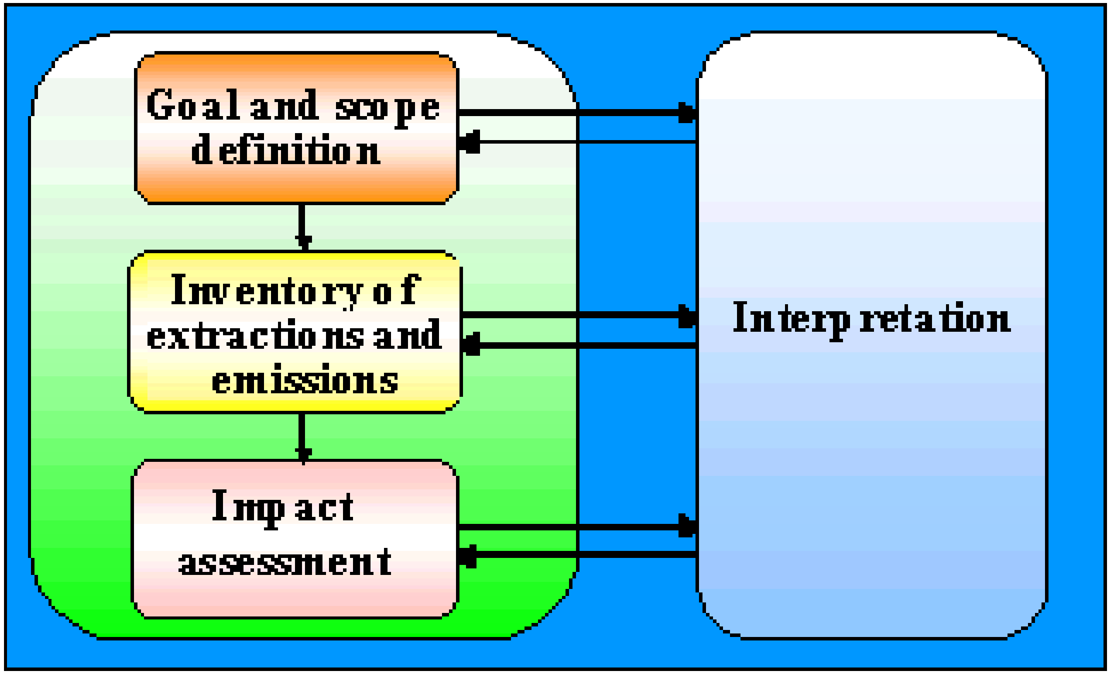
The ISO 14044 Definition of Life Cycle Assessment (LCA)
Phases of an LCA as per ISO 14044:2006

Life Cycle Assessments...

... address the environmental aspects and potential environmental impacts (e.g. resource use and environmental consequences of releases) throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment and disposal (i.e. cradle-to-grave).

[ISO 14040:2006]



Technical Accomplishments
Mach I Life Cycle Assessment

Multi-Material Lightweight Vehicle MMLV

Material Matrix comparing 2013 Fusion to Mach I

Material	2013 Fusion (kg)	Mach I (kg)	Delta (kg)
AHSS	417.5	66.9	(350.6)
Conventional steel	413.7	289.8	(123.9)
Cast iron	50	19.6	(30.4)
Paint, fluid, adhesive	72.1	60.5	(11.6)
Glass, Ceramics	38.3	27.2	(11.1)
Stainless steel	19.1	9.7	(9.4)
Forged iron	16	10	(6.0)
Batteries	14	8	(6.0)
Copper	33.7	29.3	(4.4)
Cold-rolled aluminum	12.8	143.8	131.0
CFRP, GFRP	0	57.6	57.6
Extruded aluminum	15.6	66.9	51.3
Magnesium	2.3	16	13.7
Forged aluminum	0	9.8	9.8
Titanium	0	3.3	3.3
Die-cast aluminum.	146.4	147.7	1.3
Total Vehicle	**1559.4**	**1195.2**	**(364.2)**

Technical Accomplishments
Mach I Life Cycle Assessment

Multi-Material Lightweight Vehicle MMLV

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MMLV Mach I Design Life Cycle Assessment

- LCA conducted as per ISO 14044 Standards & CSA Group 2014 LCA Guidance Document for Auto parts;
- Conducted by *third party LCA consultant*: Lindita Bushi, Ph.D. in LCA, ON, Canada;
- *Third party critical review* of LCA Report completed as per ISO 14044.

Conclusions

- The MMLV Mach I design is superior to the 2013 Ford Fusion, both built and driven for 250,000 km (~155,000 miles) in North America, in terms of total Global Warming Potential and Total Primary Energy.
- The cradle-to-grave total net savings of the MMLV Mach I (in percentage basis), relative to the cradle-to-grave LCA of the 2013 Ford Fusion, resulted in significant environmental benefits of:
  - **Global Warming Potential (kg CO_2 eq) : 16% reduction vs 2013 Fusion**
  - **Total Primary Energy (MJ) : 16% reduction vs 2013 Fusion**

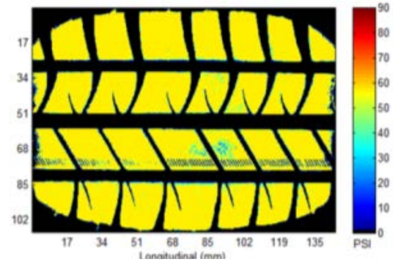
Note:

2013 Fusion at 28 mpg CFE at 1559 kg curb
(www.fueleconomy.gov)

Mach I Design at 34 mpg CFE at 1195 kg curb
(estimated in LCA study)

Technical Accomplishments
Mach I Component Testing


Door Deflection



Tire Contact Patch

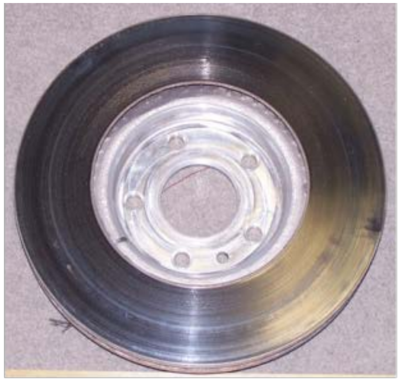

Composite Spring Fatigue

Hollow Stabilizer Bar Fatigue



Carbon Fiber Wheel Scratch + Weathering


(a) Coated Rotor Prior to Test


(b) Coated Rotor After Test

Technical Accomplishments
Mach I Vehicle Definitions & Testing

Multi-Material Lightweight Vehicle MMLV

U.S. Department of Energy · Ford · Magna

1. Test Buck: Body-in-White + Closures + Bumpers + Glazing + Front Subframe
- Body-in-Prime NVH modes, global stiffness, attachment stiffness, selected Durability

2. Durability A: DRIVABLE, full MMLV content with Fusion powertrain
- MPG Structural Durability, Square Edge Chuckhole Test for Wheels and Tires

3. Corrosion A: DRIVABLE, with <u>*alternative surface treatment*</u> and paint process
- MPG Corrosion R-343

4. Corrosion B: DRIVABLE, with <u>*traditional surface treatment*</u> and paint process
- MPG Corrosion R-343

5. Safety A: NON-Drivable, most MMLV content, without carbon fiber instrument panel
- Low Speed Damageability test (front) Right Hand (passenger) side
- IIHS Front ODB 40% Offset 40 mph, Left Hand (driver) side
- Side Pole Test on Right Hand (passenger) side (FMVSS 214)

6. Safety B: NON-Drivable, most MMLV content, without carbon fiber instrument panel
- NCAP Frontal 35 mph rigid wall, then 70% Offset Rear Impact (FMVSS 301)

7. NVH + Drives: DRIVABLE, full MMLV content with downsized and boosted powertrain, 1.0-liter I3 EcoBoost, gasoline turbocharged direct injection engine plus six-speed manual transmission
- Wind Tunnel, Rough Road Interior Noise, Engine & Tire Noise, Ride & Handling

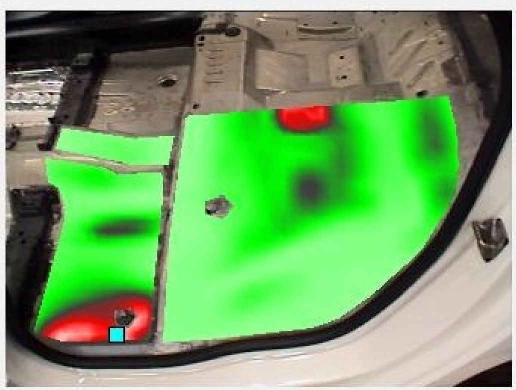
Body Structure Results: Noise, Vibration and Harshness Testing

Table 1 – Table of modal frequency results.

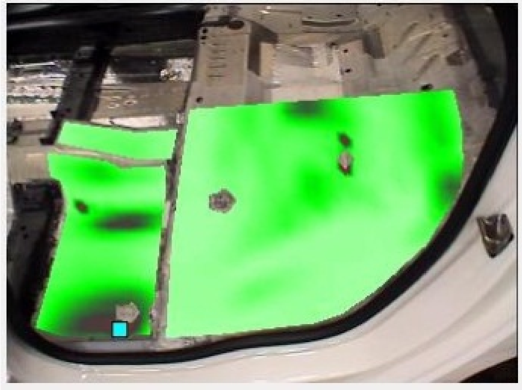
Mode Description	Test (Hz)	CAE (Hz)
Global Torsion	44.17	44.78
Rear-End Bending	46.09	40.89
Vertical Bending	48.53	48.07
Rear Match-Boxing	49.25	48.73
Lateral Bending	54.40	54.71

Table 2 – Table of global stiffness results

	Test	CAE	Target
Global Bending (N/mm)	12,695	12,148	11,458
Global Torsion (kNm/rad)	1,079	1,207	1,100



Without Damping



With Damping

Rear floor laser scan results showing RMS average over each scan point.
The red colors are areas of higher vibration.

Technical Accomplishments
Mach I Durability Testing

Multi-Material Lightweight Vehicle MMLV

The Durability vehicle completed rough road durability testing representing 150,000 miles of severe customer with only these seven issues.

NO Body structure or Chassis structure durability issues!

PT mounting bracket

Shock tower

Inner hinge pillar

Rear shelf area

Front subframe & Control arm

Issues List:

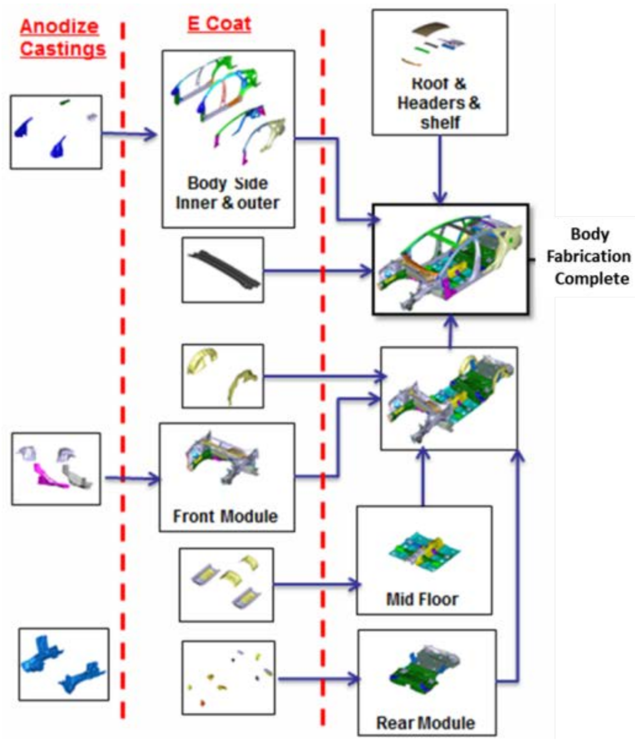
1. Rear stabilizer bar bracket bolt cracked at 85%.
   (this production part had been repeatedly removed and re-attached during the build)
2. Rear hollow steel stabilizer bar cracked at ~90%.
   (this was expected since the chosen bar size was under capacity)
3. Front aluminum thermally sprayed brake rotor had coating degrade at ~90%.
4. Left front door chemically toughened laminated glass cracked at ~95%.
5. Left rear door chemically toughened laminated glass cracked at ~95%.
6. Left front lower ball joint softened ~95%.
   (this production part saw higher loads due to the thin wheels)
7. Left rear door chemically toughened laminated glass cracked at 100%.

Technical Accomplishments
Mach I Corrosion Testing

Multi-Material Lightweight Vehicle MMLV

Two Mach I prototypes were constructed with different surface treatment corrosion mitigation strategies.

Corrosion A - Alternative Corrosion Strategy



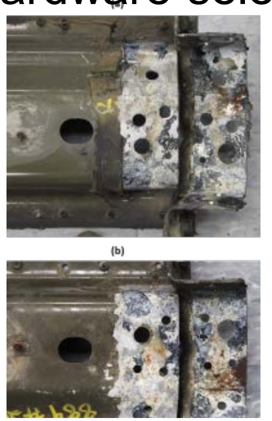
Corrosion B –Traditional Corrosion Strategy

Technical Accomplishments
Mach I Corrosion Testing

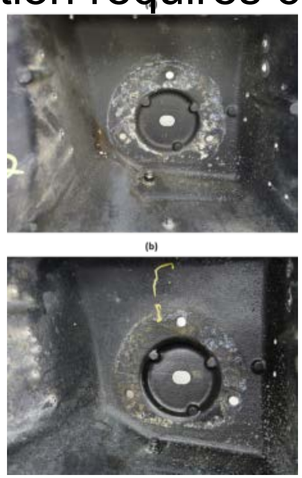
Results: Both the *alternative* and *traditional* corrosion mitigation strategies produced acceptable results in full vehicle accelerated corrosion testing at Ford's Michigan Proving Grounds.

Lessons Learned:

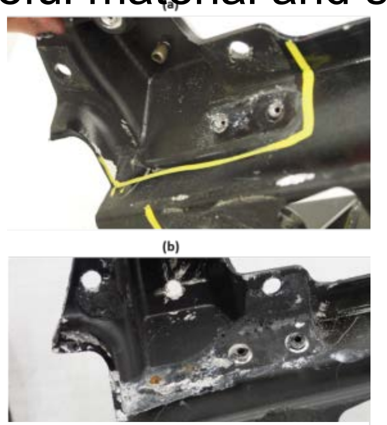
- Additional seam sealer applied to bi-metallic joints improves corrosion protection.
- Aluminum castings showed little evidence of corrosion products, however, anodizing the castings before assembly further reduces chances of corrosion.
- Magnesium castings need both surface treatment, such as a ceramic coating, AND must be protected from water ingress.
- Hardware selection requires careful material and surface specification.



Seam sealer improves performance



Al castings



Mg castings, same surface, different sealer

Hardware selection

Technical Accomplishments
Mach I IIHS Front ODB 40% Offset 40mph

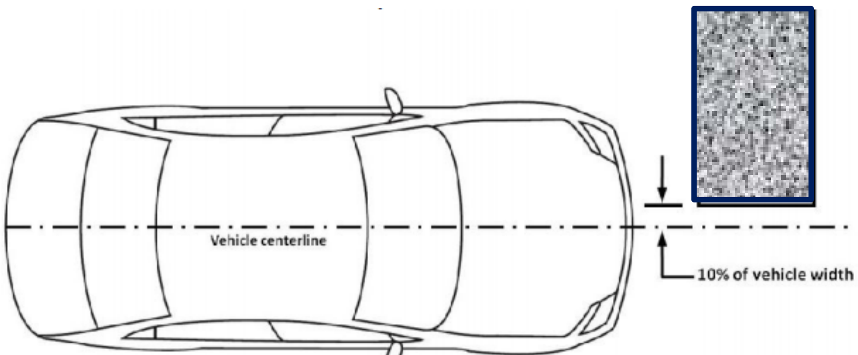
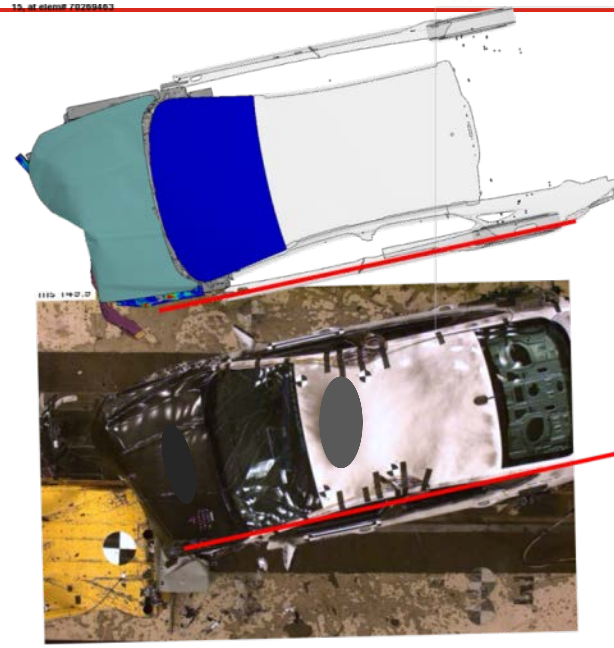


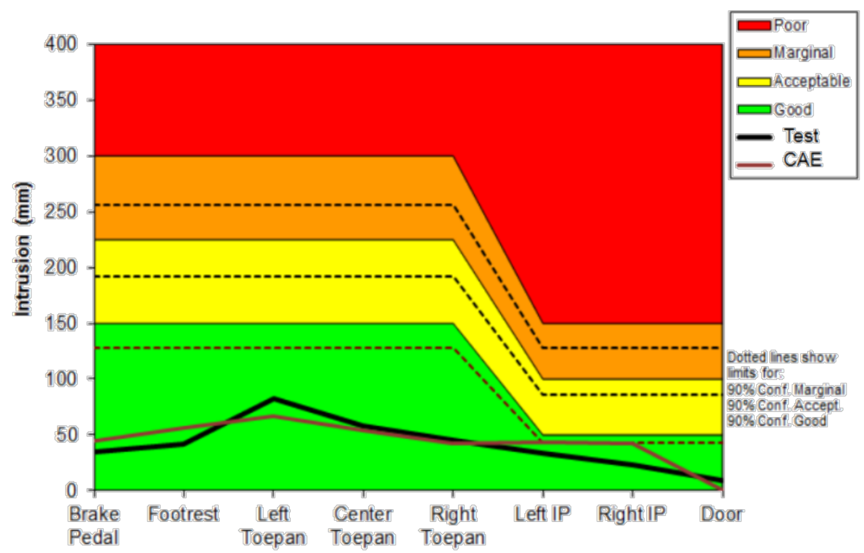
Image from IIHS Moderate Overlap Frontal Crashworthiness:
Crash Test Protocol (Version XV), May 2014



Occupant Space Intrusion

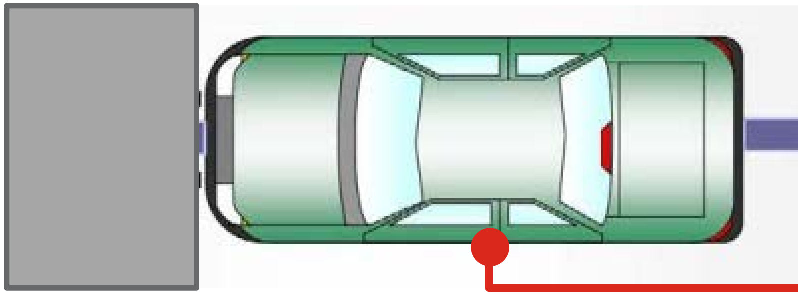
- Offset Deformable Barrier
- 40 mph
- Dimensional Analysis of several cabin points
  - Floor Pan
  - Instrument Panel
  - A-Pillar

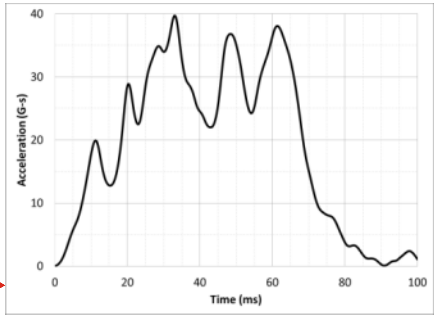
“Good" IIHS Structure Rating



Technical Accomplishments
Mach I NCAP Full Frontal 35 mph

- Rigid Barrier
- 35 mph





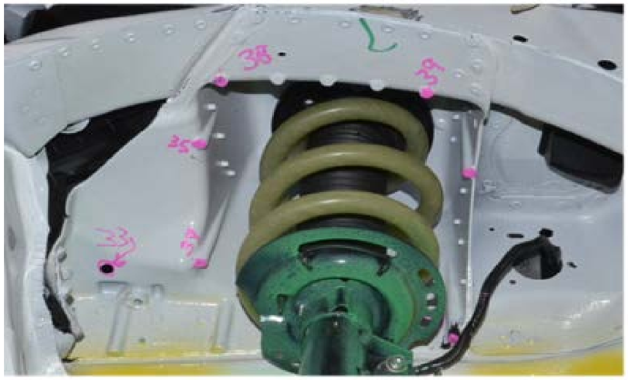
Extruded Aluminum Front Bumper and Crush Can

Laminated Chemically Toughened Windshield

Composite wheel

Subframe – Extrude Aluminum Portion

A-pillar



Composite Coil Spring

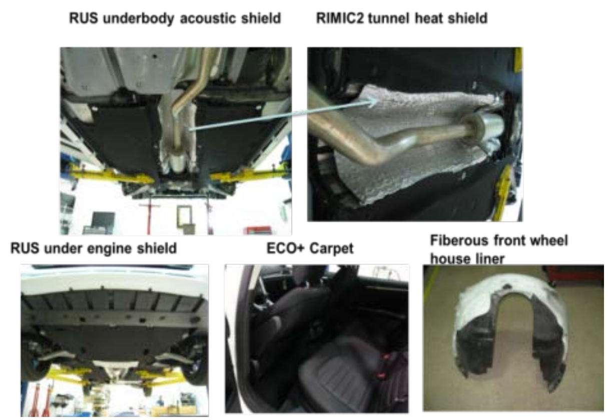
Technical Accomplishments
Mach I NVH Testing

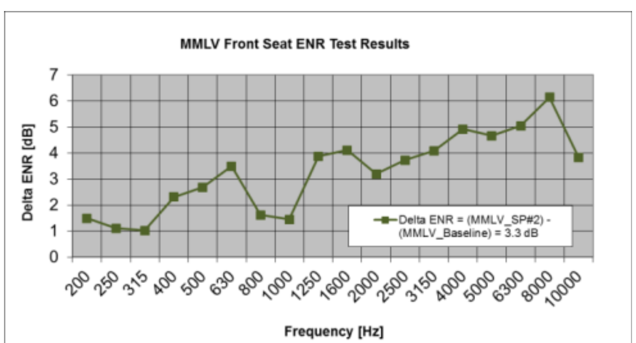
Multi-Material Lightweight Vehicle MMLV

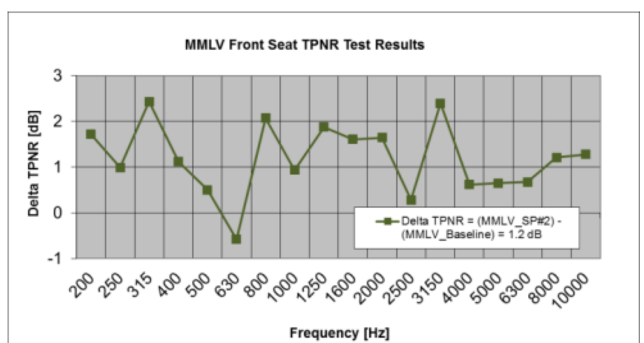
Vehicle NVH Test Results:

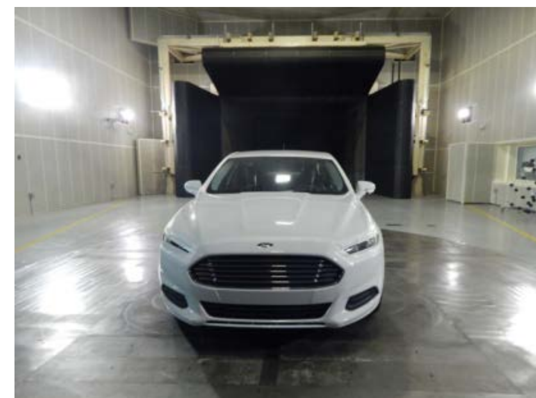
- Engine Noise Reduction (ENR) improved by 3.3 dB
- Tire Patch Noise Reduction (TPNR) improved by 1.2 dB
- Asphalt Road Noise at 50 mph degraded by 1.7 dB
- Wind Noise at 80 mph degraded by 0.9 Sones

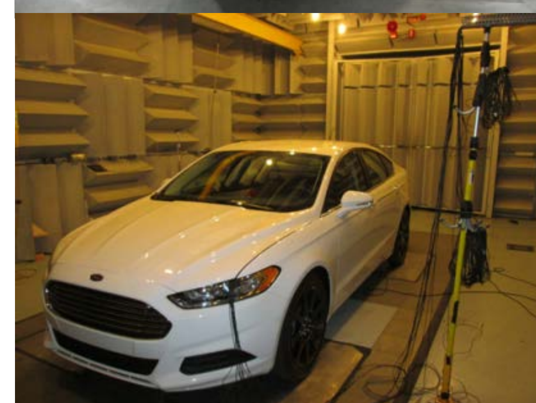
Overall, approximately equivalent to Fusion











Technical Accomplishments
Mach II Design Complete

Multi-Material Lightweight Vehicle MMLV

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Mach II Design

The Mach II design demonstrates the lightweighting potential using materials and processes that have had some initial research, but are not ready for high volume production.

The Mach II design achieves a 50% full vehicle mass reduction, The 761 kg curb weight results from redesigning and lightweighting five vehicle systems: Body and Closures, Interior, Chassis, Powertrain and Electrical along with reductions in features and content from the 2013 Fusion.

Subsystem Description	2002 Taurus	2013 Fusion	MMLV Mach-I DESIGN FINAL	MMLV Mach-II DESIGN FINAL
Body Exterior and Closures (kg)	**574**	**594**	**456**	**308**
Body-in-White	n.a.	326	250	171
Closures-in-White	n.a.	98	69	51
Bumpers	n.a.	37	25	21
Glazings - Fixed and Movable	n.a.	37	25	18
Remainder - trim, mechanisms, paint, seals, etc.	n.a.	96	87	47
Body Interior and Climate Control (kg)	**180**	**206**	**161**	**100**
Seating	n.a.	70	42	34
Instrument Panel	n.a.	22	14	11
Climate Control	n.a.	27	25	10
Remainder - trim, restraints, console, etc	n.a.	88	80	45
Chassis (kg)	**352**	**350**	**252**	**165**
Frt & Rr Suspension	n.a.	96	81	55
Subframes	n.a.	57	30	17
Wheels & Tires	n.a.	103	64	42
Brakes	n.a.	61	49	34
Remainder - steering, jack, etc.	n.a.	33	29	18
Powertrain (kg)	**350**	**340**	**267**	**160**
Engine (dressed)	n.a.	101	71	63
Transmission and Driveline	n.a.	106	92	36
Remainder - fuel, cooling, mounts, etc.	n.a.	133	104	61
Electrical (kg)	**67**	**69**	**59**	**29**
Wiring	n.a.	28	25	14
Battery	n.a.	14	8	5
Remainder - alternator, starter, speakers, etc.	n.a.	27	26	9
Total Vehicle (kg)	**1523**	**1559**	**1195**	**761**
Weight Save Compared to 2013 Fusion			**23.3%**	**51.1%**
Weight Save Compared to 2002 Taurus			**21.5%**	**50.0%**

Mach II Design
BIW Technology Issues

Composite Material Information

- Composite material CAE cards for stiffness, durability, and fatigue analysis still not mature for accurate CAE predictions.
- Composite material CAE cards for safety cash analysis still not mature for accurate CAE predictions.
- Composite material and manufacturing infrastructure immature for automotive volumes.
- Critical joint analysis – mechanical fasteners and structural adhesives strategy still not mature for accurate CAE predictions. Joint technology still a gap for composite to steel/aluminum materials.

Carbon fiber and composites were deemed not feasible for “Class A” panels

- Requirements for appearance by all OEM’s would drive high cycle times to the composite process. Reviewing with many suppliers, it was determined that, even looking at a 2025 timeline, process cycle times would not meet the production volumes of 200,000 units/year with current OEM class be A requirements.
- Class A panels will be designed with aluminum or magnesium sheet products for the BIW and Closure applications.

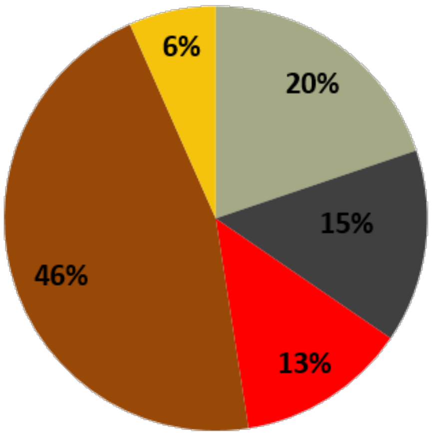
Recyclability and vehicle repair with carbon fiber

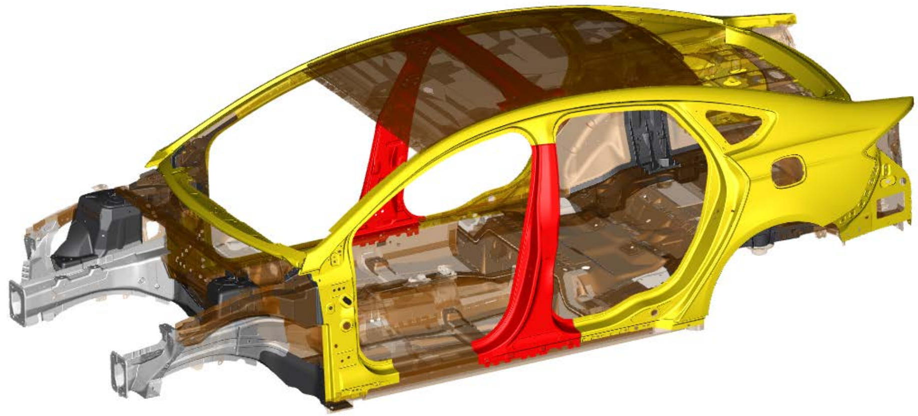
- Recycling of carbon fiber is an area that will need further investigation
- Repair of body components will be an area that will need further investigation

Mach II Design
Mixed Material BIW & Closures

Multi-Material Lightweight Vehicle
MMLV

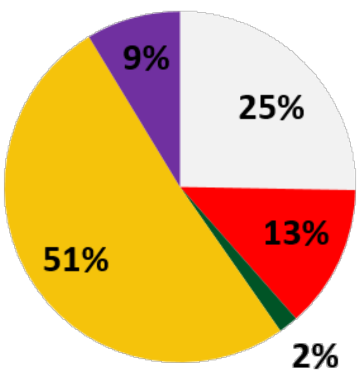
Body-in-White (BIW) 155 kg mass reduction from baseline (47.5%)





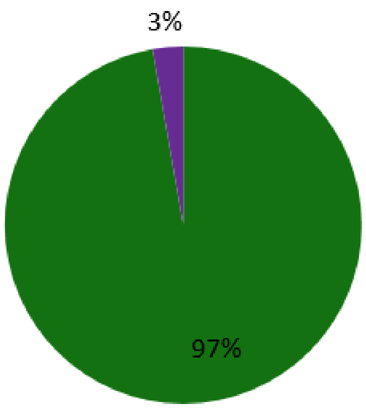
ALUMINUM SHEET	ALUMINUM EXTRUSION	COMPOSITE	MAGNESIUM EXTRUSION
ALUMINUM CASTING	HOT STAMPING	MAGNESIUM SHEET	MAGNESIUM CASTING

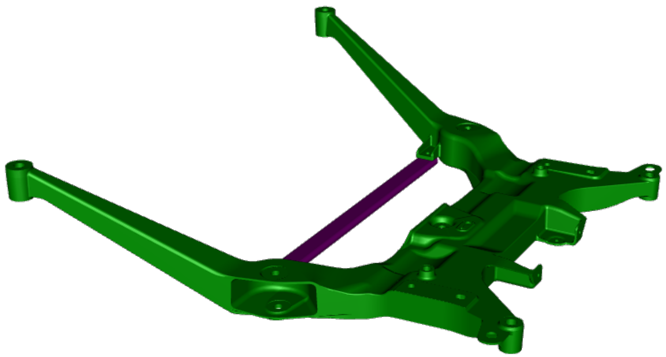
CLOSURES 47.0 kg mass reduction from baseline (48.0%)

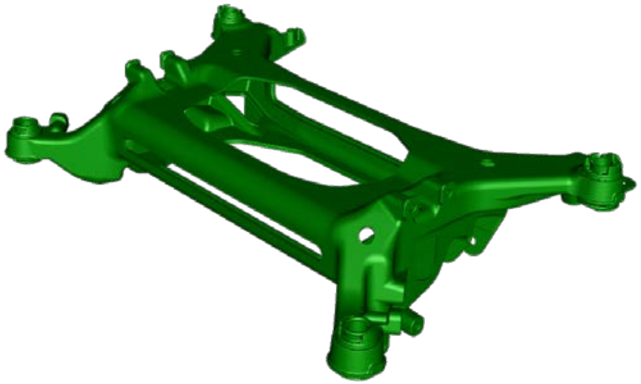


Mach II Design
Subframes and Bumpers

SUBFRAMES 40 kg mass reduction from baseline (70.0%)

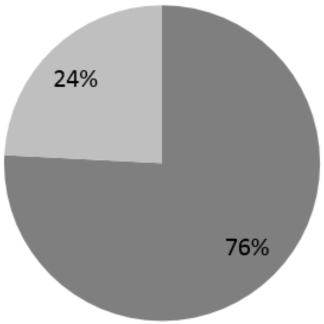


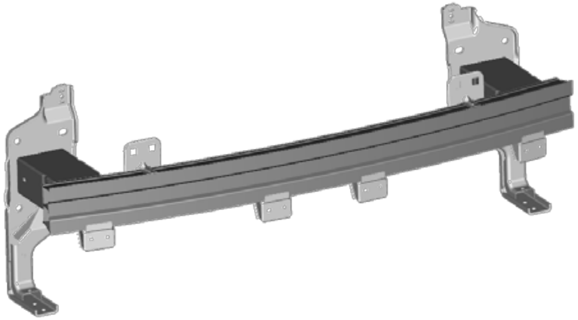




ALUMINUM SHEET	ALUMINUM EXTRUSION	COMPOSITE	MAGNESIUM EXTRUSION
ALUMINUM CASTING	HOT STAMPING	MAGNESIUM SHEET	MAGNESIUM CASTING

BUMPERS 16.0 kg mass reduction from baseline (43.0%)





Mach II Design Vehicle Summary

Multi-Material Lightweight Vehicle MMLV

U.S. DEPARTMENT OF ENERGY · Ford · MAGNA

Body & Closures

- Composite intensive mixed material body
- Magnesium intensive closures
- Reduced thickness windows

Interior & Climate Control

- Carbon fiber seats with reduced function
- Carbon fiber composite instrument panel
- Reduced content; no bins, center console, etc.
- Eliminate air conditioner

Chassis

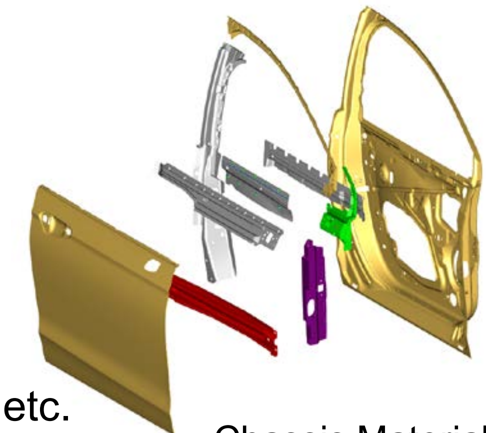
- Cast magnesium subframes
- Composite coil springs
- Reduced capacity components for reduced weight, cargo and towing

Powertrain

- Naturally aspirated 1.0 liter 3-cylinder engine
- Reduced capacity manual transmission

Electrical

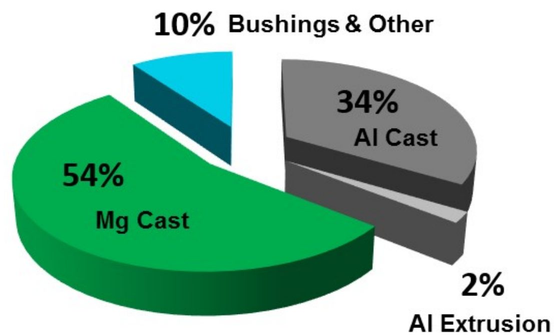
- Eliminate content and features
- Reduced battery, alternator, wiring



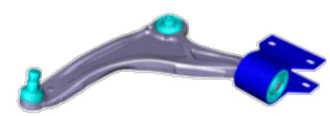
Front Door Materials

- HOT STAMPING
- ALUMINUM SHEET
- MAGNESIUM SHEET
- MAGNESIUM CASTING
- MAGNESIUM EXTRUSION

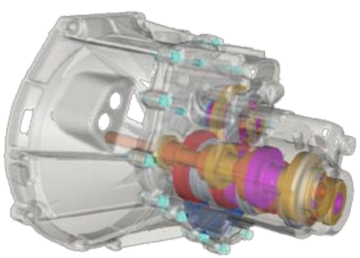
Chassis Materials



FRC Coil Spring



Remove: turbo charger, intercooler
Material Change: Most components



Mach II Design
Vehicle Evaluation - ESTIMATED PERFORMANCE

Safety
- CAE-based assessments OK, with uncorrelated material models
- Maintained all airbags

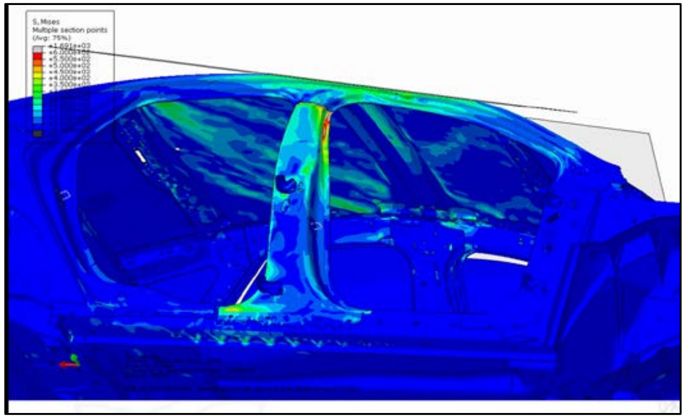
Durability & Fatigue
- CAE-based assessments marginal, with uncorrelated material models
- Low confidence in load cases

Noise, Vibration & Harshness
- Large degradations in all metrics!
- Removed all sound absorption materials
- Reduced body and chassis stiffness
- Reduced mass increases loudness

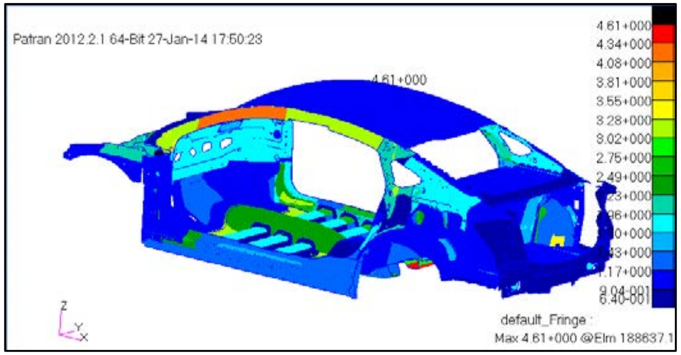
Corrosion
- Significant challenge with carbon fiber composites,magnesium and mixed material joints

Manufacturing
- Unknown processes for high volume production
- Challenges with joining, surface treatments, Class-A exterior paint, thermal expansion, dimensions & tolerances

Roof Crush Simulation



Composite thickness layups for optimal stiffness



GAPS Identified by MMLV Project

Steel:

- Improved coatings on ultra high strength steels for multi material applications.

Aluminum:

- Increased die life and bi-metallic (inserts, etc.) for Al die castings plus low cost 7xxx aluminum sheet and extrusions

Magnesium:

- High volume warm forming, hemming, class-A finish, plus improved die life and bi-metallic inserts in high pressure vacuum die casting.

Carbon Fiber Composites:

- Material characterization for CAE, joining, corrosion, paint, class-A finish.

Multi Material Vehicles:

- Corrosion mitigation strategy including universal equivalent of phosphate (or equivalent) bath for any mix of steel, aluminum and magnesium before e-coat and paint.
- Joining methods with corrosion mitigation.
- Aluminum rivet, high hardness, high strength.
- Alternative NVH treatments for lightweight panels sheet metal and glazings
- Design for disassembly, end of life, for reclaiming, recycling

Next Steps

Remaining Work

- Final Report
- All Technical Work has been COMPLETED

Component Testing Completed May 2015

- Engine dynamometer testing
- Lithium-Ion starter battery load testing

Documentation and Technology Transfer

- SAE 2015 Government/Industry Meeting, Washington DC
- SAE World Congress 2015, Detroit, 14 technical papers
- TMS 2015, Orlando, 3 technical papers
- Automotive Megatrends USA 2015, Dearborn
- Automotive Engineering Expo 2015, Germany,
- Strategies in Car Body Engineering 2015, Germany
- Over 25 web, magazine and other articles

MMLV Summary

Weight Reduction is a System Level Exercise

- Must address and integrate all vehicle systems
- Customer expectations for cargo, towing, features can limit the amount of weight reduction