IBIS Associates, Inc.

Vehicle Lightweighting: Mass Reduction Spectrum Analysis and Process Cost Modeling

Project ID # LM090

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Overview

Timeline

- Project Start: December 2014
- Project end: December 2015
- 100% Complete

Budget

- FY15-16 = $60 K (DOE)

Barriers

- Conflicting forces between vehicle lightweighting designs and materials with economics and consumer preferences
- Lack of comparative analysis of relative cost of mass reduction and risk level of alternative weight reduction strategies

Project Partners

- IBIS Associates, Incorporated
- Energetics Incorporated.
- Idaho National Laboratory (INL)

Relevance

- For every 10% reduction in vehicle mass, there can be a 7% improvement in fuel effeciency, directly impacting greenhouse gas emissions and energy security.

Objectives

- Assess the multiple strategies addressed in the earlier phases in terms of weight reduction, cost premiums, and risk factors in order to establish a prioritized spectrum of lightweighting opportunities.
- Apply process Technical Cost Models (TCMs) to priority lightweight material manufacturing technologies to evaluate cost structures and understand the relative leverage of key cost drivers. The processes targeted were aluminum extrusion, magnesium sheet forming, and carbon fiber composite molding.

Workplan to address barriers

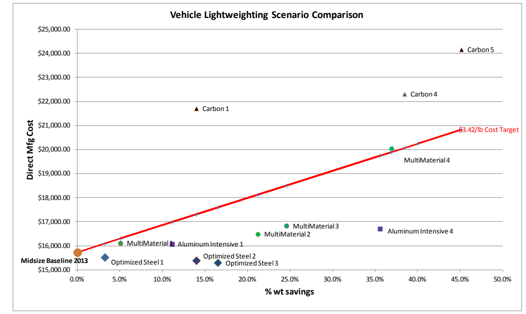
- 1.) Apply existing tools, knowledge base, and team structure form Years 1 an 2 towards meaningful cost spectrum
- 2.) Prioritize identified strategies by risk factor, cost of weight savings, and amount of weight saved
- 3.) Produce data map of mass reduction strategy adoption path
- 4.) Develop cost models for priority materials manufacturing processes

Approach: Task List and Milestones

- Develop Weight Reduction Path Scenarios 04/31/2015
  - *Review Previous AssessedTechnologies*
  - *Identify Data Collection Needs*
  - *Prioritize List by Impact and Cost*
- Develop Model Scenarios 05/31/2015
  - *Data Collection and Industry Review*
  - *Vehicle Model Update*
- Path Analysis and Optimization 09/31/2015
  - *Model Refinement and Analysis*
  - *Preliminary Results and Review*
  - *Present Results*

Approach: Scenarios and Strategies

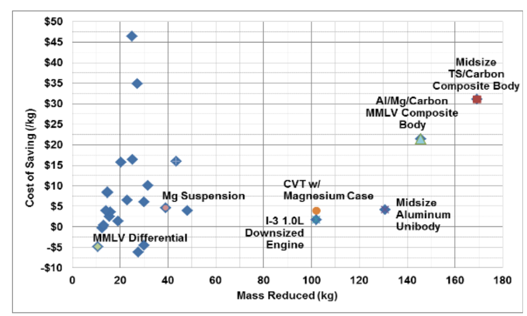
- Assessed multiple vehicle-level scenarios



Data Source	Ford	Ford/ Vehma	DOE	IBIS	IBIS	IBIS	IBIS	IBIS	IBIS	IBIS	IBIS	IBIS	IBIS	IBIS	IBIS	IBIS
Vehicle Scenario	2013 Ford Fusion	MMLV Mach 1	2013 Midsize Baseline	2013 Midsize Baseline	Optimized Steel 1	Optimized Steel 2	Optimized Steel 3	Aluminum Intensive 1	Aluminum Intensive 4	Multi Material 1	Multi Material 2	Multi Material 3	Multi Material 4	Carbon 1	Carbon 4	Carbon 5
Total Mass (kg)	**1,559.0**	**1,194.8**	**1,501.5**	**1,501.9**	**1,453.7**	**1,292.1**	**1,253.7**	**1,335.0**	**967.7**	**1,426.2**	**1,183.4**	**1,133.0**	**947.4**	**1,292.0**	**924.4**	**823.4**
Powertrain	**380.0**	**268.5**	**491.0**	**453.6**	**450.8**	**380.5**	**380.5**	**444.1**	**224.5**	**449.3**	**264.6**	**261.8**	**223.4**	**441.7**	**222.2**	**203.9**
Engine	121.0	54.9	157.0	157.0	157.0	127.0	127.0	157.0	55.0	157.0	55.0	55.0	55.0	157.0	55.0	55.0
Energy Storage	14.0	8.0	18.0	15.0	15.0	15.0	15.0	15.0	8.0	15.0	8.0	8.0	8.0	15.0	8.0	8.0
Fuel System	67.0	59.3	64.8	74.9	74.9	62.3	62.3	74.9	40.0	74.9	59.3	59.3	40.0	74.9	40.0	40.0
Transmission	88.0	77.0	110.4	88.8	86.1	67.1	67.1	79.4	62.0	84.5	74.8	72.0	60.9	76.9	59.7	40.6
Thermal Management	7.0	17.0	18.7	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	9.7
Driveshaft and Axle	18.0	14.7	28.2	25.1	25.1	23.5	23.5	25.1	14.7	25.1	14.7	14.7	14.7	25.1	14.7	14.7
Differential	1.0	0.0	12.9	10.9	10.9	10.9	10.9	10.9	0.1	10.9	0.1	0.1	0.1	10.9	0.1	0.1
Cradle	27.0	15.0	32.8	28.2	28.2	28.2	28.2	28.2	7.0	28.2	15.0	15.0	7.0	28.2	7.0	14.1
Exhaust System	22.0	16.3	22.7	22.7	22.7	15.5	15.5	22.7	16.3	22.7	16.3	16.3	16.3	22.7	16.3	15.3
Oil and Grease	4.0	4.0	12.3	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Powertrain Electronics	9.0	1.8	12.0	10.0	10.0	10.0	10.0	10.0	1.8	10.0	1.8	1.8	1.8	10.0	1.8	1.8
Emission Control Electronics	2.0	0.6	1.2	2.0	2.0	2.0	2.0	2.0	0.6	2.0	0.6	0.6	0.6	2.0	0.6	0.6
Body	**521.0**	**404.2**	**454.6**	**457.4**	**411.9**	**411.9**	**405.3**	**299.9**	**297.6**	**385.9**	**386.6**	**383.6**	**278.4**	**259.4**	**256.6**	**236.8**
Body-in-White	326.0	250.2	325.8	325.8	281.1	281.1	281.1	195.0	195.0	250.0	250.0	250.0	180.0	156.5	156.0	156.0
Closures	98.0	68.8	61.0	61.0	61.0	61.0	61.0	38.0	38.0	69.0	69.0	69.0	33.8	36.0	36.0	36.0
Front/Rear Bumpers	41.0	25.9	10.2	9.2	8.5	8.5	8.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	4.2
Glazing	36.0	24.9	22.2	36.8	36.8	36.8	32.8	36.8	22.0	36.8	25.0	22.0	22.0	36.8	22.0	22.0
Paint	8.0	7.7	12.2	11.0	11.0	11.0	11.0	11.0	7.7	11.0	7.7	7.7	7.7	11.0	7.7	8.0
Exterior Trim	4.0	21.4	11.1	3.7	3.7	3.7	3.7	3.7	21.4	3.7	21.4	21.4	21.4	3.7	21.4	3.7
Body Hardware	3.0	0.0	10.2	8.0	8.0	8.0	5.4	8.0	3.0	8.0	3.0	3.0	3.0	8.0	3.0	1.9
Body Sealers and Deadeners	5.0	5.3	2.0	1.8	1.8	1.8	1.8	1.8	5.0	1.8	5.0	5.0	5.0	1.8	5.0	5.0
Chassis	**328.0**	**251.0**	**306.7**	**301.2**	**301.2**	**210.0**	**210.0**	**301.2**	**233.4**	**301.2**	**242.4**	**242.4**	**233.4**	**301.2**	**233.4**	**189.6**
Suspension	121.0	101.1	135.8	122.5	122.5	79.9	79.9	122.5	83.5	122.5	92.5	92.5	83.5	122.5	83.5	83.5
Braking System	79.0	64.2	70.7	74.2	74.2	46.5	46.5	74.2	64.2	74.2	64.2	64.2	64.2	74.2	64.2	49.0
Wheels and Tires	106.0	66.0	58.4	82.0	82.0	62.9	62.9	82.0	66.0	82.0	66.0	66.0	66.0	82.0	66.0	38.6
Steering System	22.0	19.7	41.7	22.4	22.4	20.6	20.6	22.4	19.7	22.4	19.7	19.7	19.7	22.4	19.7	18.5
Interior	**250.0**	**196.2**	**214.7**	**214.8**	**214.8**	**214.8**	**189.1**	**214.8**	**139.1**	**214.8**	**214.8**	**172.1**	**139.1**	**214.8**	**139.1**	**143.2**
Instrument Panel	38.0	31.6	32.2	38.4	38.4	38.4	32.1	38.4	31.6	38.4	38.4	31.6	31.6	38.4	31.6	23.6
Trim and Insulation	40.0	38.4	41.5	53.9	53.9	53.9	53.9	53.9	38.4	53.9	53.9	38.4	38.4	53.9	38.4	38.4
Door Modules	50.0	42.5	30.2	22.6	22.6	22.6	22.6	22.6	22.6	22.6	22.6	22.6	22.6	22.6	22.6	20.9
Seating and	90.0	58.4	89.1	78.2	78.2	78.2	61.2	78.2	46.5	78.2	78.2	57.8	46.5	78.2	46.5	46.5
HVAC	32.0	25.3	21.7	21.7	21.7	21.7	19.3	21.7	0.0	21.7	21.7	21.7	0.0	21.7	0.0	13.8
Electrical	**56.0**	**53.0**	**24.3**	**51.0**	**51.0**	**51.0**	**44.9**	**51.0**	**49.0**	**51.0**	**51.0**	**49.0**	**49.0**	**51.0**	**49.0**	**26.0**
Interior Electrical	31.0	25.1	3.2	26.0	26.0	26.0	21.3	26.0	25.1	26.0	26.0	25.1	25.1	26.0	25.1	13.5
Chassis Electrical	15.0	19.0	3.2	15.0	15.0	15.0	14.1	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	6.7
Exterior Electrical	10.0	8.9	18.0	10.0	10.0	10.0	9.5	10.0	8.9	10.0	10.0	8.9	8.9	10.0	8.9	5.8

- Each scenario consisted of multiple lightweighting strategies from various vehicle mass reduction programs

- Data of each component or subsystem strategy was examined for individual contribution to weight reduction



Strategy: Overview

- Prioritize Mass Reduction Strategies
  - *Risk factor*
    - > Low – understood and in-use technology
    - > Medium – uncertainty of cost structure or performance equivalence
    - > High – economical high volume production yet to be demonstrated, or market acceptance of decontenting
  - *Cost per pound of weight savings*
  - *Amount of weight saved*
- Use vehicle cost model to assess the incremental adoption and replacement of strategies
- Map the path of adoption and compare amount of weight saved relative to the cost per pound of savings

Component, Lightweighting Study (when Relevan	Vehicle Mass (lb)	Vehicle Cost	Total Weight Reduced (%)	Cost of Weight Reduction (/lb)
Baseline Vehicle	3,304	$15,723	0%	$0.00
Body-in-White, Lotus HSS Unibody	3,206	$15,723	3%	$0.00
Fuel System, HDPE	3,178	$15,723	4%	$0.00
Fuel System, MMLV	3,172	$15,723	4%	$0.00
Powertrain Electronics, MMLV Mach 1	3,154	$15,723	5%	$0.00
Emission Control Electronics, MMLV Mach 1	3,151	$15,723	5%	$0.00
Braking System, Al Brake Rotors, TS SS	3,129	$15,723	5%	$0.00
Cradle, Extruded Aluminum	3,100	$15,728	6%	$0.03
Wheels and Tires, Aluminum 15"	3,064	$15,787	7%	$0.27
Cradle, Extruded aluminum	3,062	$15,838	7%	$0.47
Body-in-White, MMLV Mach 1 Unibody	2,994	$16,366	9%	$2.07
Front/Rear Bumpers, Extruded Aluminum	2,986	$16,386	10%	$2.08
Corner Suspension, Aluminum	2,920	$16,566	12%	$2.19
Panels, Stamped Aluminum Mid	2,869	$16,715	13%	$2.28
Body-in-White, Aluminum Unibody	2,748	$16,728	17%	$1.81
Front/Rear Bumpers, FEV Lightweight	2,755	$16,719	17%	$1.81
HVAC, Subcompact	2,737	$16,719	17%	$1.76
Body Hardware, FEV MuCell/PolyOne	2,732	$16,719	17%	$1.74
Seating and Restraints, FEV Lightweight	2,694	$16,719	18%	$1.63
HVAC, FEV Lightweight	2,706	$16,719	18%	$1.67
Driveshaft/Axle, FEV Scalloped, Al & Poly Bearing C	2,703	$16,719	18%	$1.66
Corner Suspension, FEV Al, Mg, and St Tube	2,675	$16,539	19%	$1.30
Exhaust System, FEV Mubea Tubing	2,659	$16,537	20%	$1.26
Instrument Panel, FEV Mg Beam, MuCell	2,645	$16,537	20%	$1.24
Body Hardware, MMLV Mach 1 MuCell	2,640	$16,537	20%	$1.23
Interior Electrical, MMLV Mach 1	2,638	$16,537	20%	$1.22
Exterior Electrical, MMLV Mach 1	2,636	$16,537	20%	$1.22
Door Modules, LFIM PP	2,632	$16,537	20%	$1.21
Interior Electrical, FEV	2,623	$16,539	21%	$1.20
Chassis Electrical, FEV	2,622	$16,540	21%	$1.20
Wheels and Tires, Toyota Prius-based	2,615	$16,509	21%	$1.14
Exterior Electrical, FEV	2,616	$16,510	21%	$1.14
Trim and Insulation, MuCell and Foamed Plastic	2,582	$16,549	22%	$1.14
Glass, FEV Lightweight	2,573	$16,563	22%	$1.15
Transmission, FEV Mg Housing	2,525	$16,671	24%	$1.22
Transmission, CVT w/ Mg Case	2,467	$16,755	25%	$1.23
Steering System, FEV Lightweight	2,463	$16,765	25%	$1.24
Steering System, with Mg wheel, Col Assembly	2,458	$16,781	26%	$1.25
Glass, Lightweight Mix	2,435	$16,892	26%	$1.34
Seating and Restraints, Mg, MuCell, Structural Foam	2,427	$17,212	27%	$1.70
HVAC, None	2,385	$16,762	28%	$1.13
Body Hardware, Mg	2,382	$16,770	28%	$1.14
Engine, MMLV I-3 1.0L	2,158	$16,940	35%	$1.06
Corner Suspension, Al, Carbon, Hollow Springs	2,166	$17,120	34%	$1.23
Front/Rear Bumpers, Mg	2,157	$17,149	35%	$1.24
Instrument Panel, Carbon Fiber Beam	2,138	$17,272	35%	$1.33
Seating and Restraints, Carbon Fiber Seat Backs, Re	2,113	$17,272	36%	$1.30
Wheels and Tires, Carbon with Reduced Mass Whee	2,059	$17,940	38%	$1.78
Braking System, Carbon-Ceramic Brake Rotors and I	2,026	$18,351	39%	$2.06
Body-in-White, MMLV UHSS, AL, Carbon Composite	1,993	$20,932	40%	$3.97
Body-in-White, Carbon Composite Body	1,941	$23,068	41%	$5.39
Panels, Stamped Mg	1,932	$23,869	42%	$5.94
Panels, TS/Carbon Mid	1,937	$24,080	41%	$6.11
Interior Electrical, Internal Network	1,920	$24,678	42%	$6.47
Chassis Electrical, Internal Network	1,903	$25,277	42%	$6.82
Exterior Electrical, Internal Network	1,895	$25,576	43%	$6.99

Strategy: Risk Factors

- Costing performed as fully implemented, high volume processes, with automation and expected learning curve improvements (not as current developmental or low volume)
- Full detail of functionally equivalent, crashworthy designs for most advanced concepts were not available
- Potential reduced performance

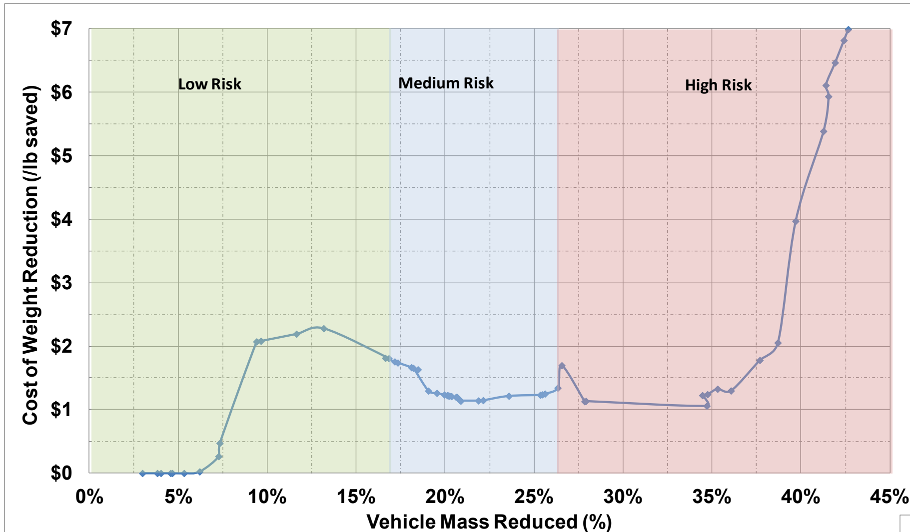
Particular to carbon:

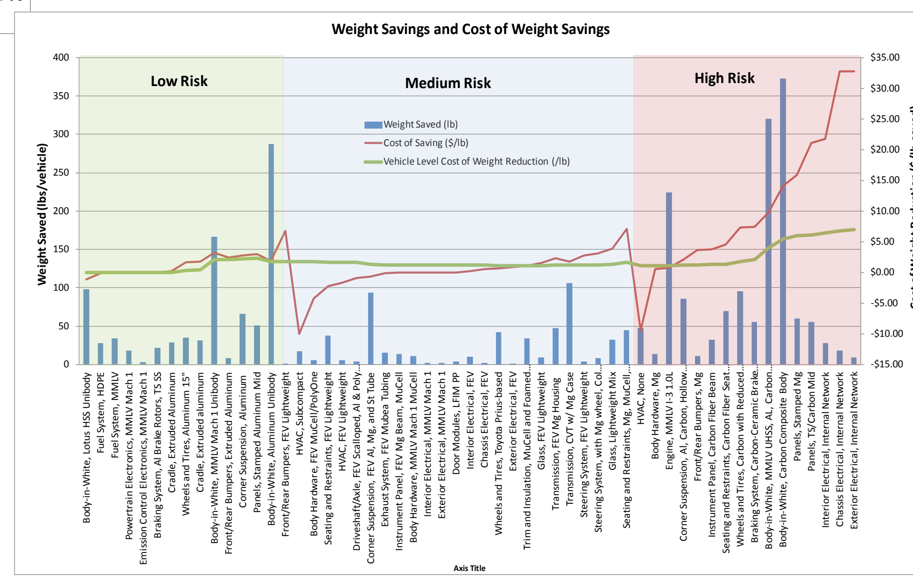
- Repairability
- Corrosion system unclear
- $/pound fiber actual vs $/lb required for targets
- $/pound finished part actual vs required
- (required $/lb amounts assessed in year 2)

Technical Accomplishments and Progress

- Developed framework for comparing 107 lightweighting strategies employed across multiple engineering studies on different vehicle platforms on a common basis. (FY2015)
- Applied framework to assess a coherent adoption path in terms of weight savings impact and cost reduction across different levels of technical and market adoption risk. (FY2015)
- Created Technical Cost Models (TCMs) for three lightweight material manufacturing operations (aluminum extrusion, magnesium sheet forming, and carbon fiber composite molding) in order to assess cost drivers and sensitivity to process improvements (FY2015)

Mass Reduction Spectrum Analysis Results





Results, Low Risk Factor

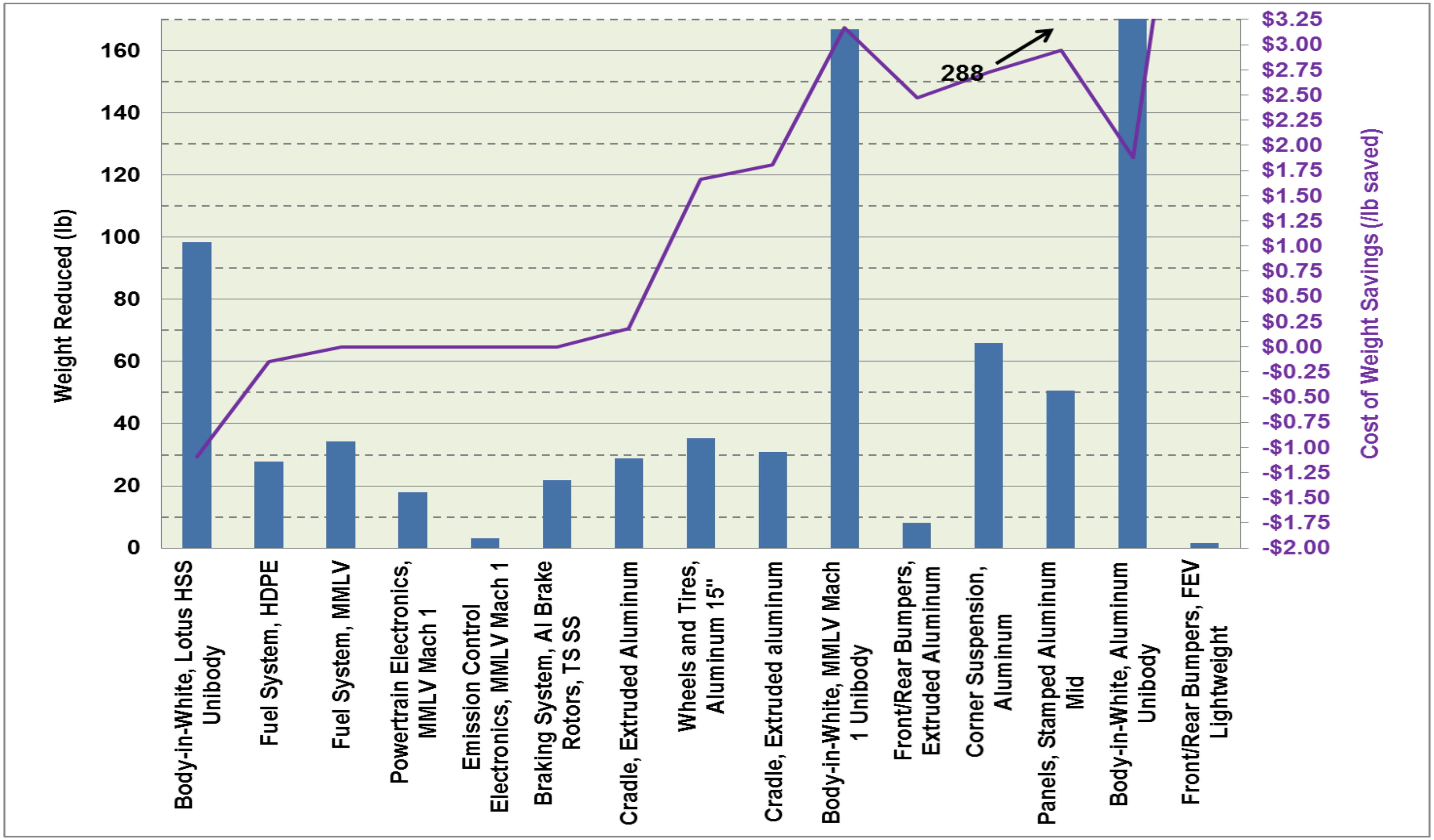


Figure : Weight Reduction Strategies by Risk Factor and Cost of Weight Savings (Low Risk)

Results, Moderate Risk Factor

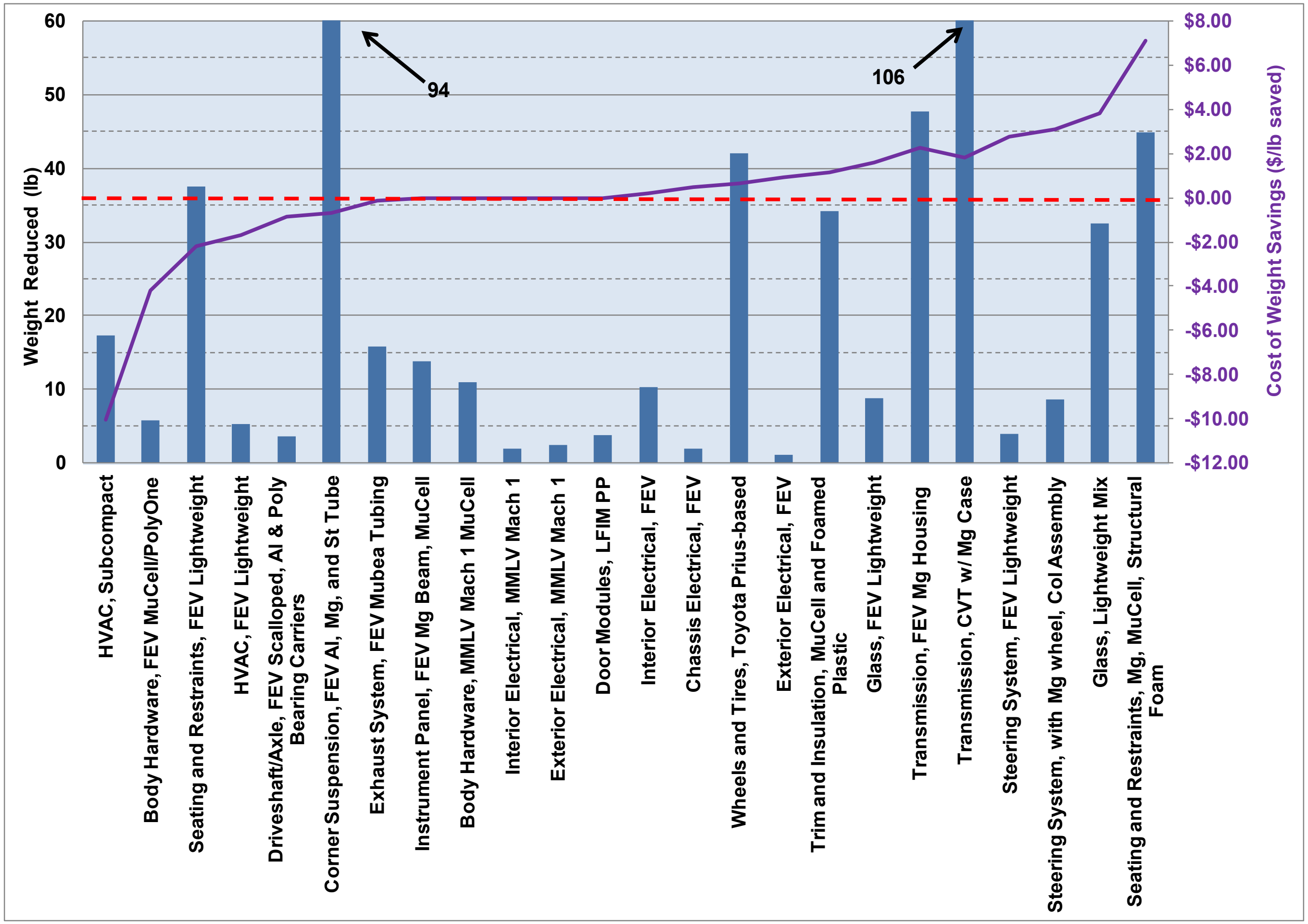


Figure : Weight Reduction Strategies by Risk Factor and Cost of Weight Savings (Moderate Risk)

Results, High Risk Factor

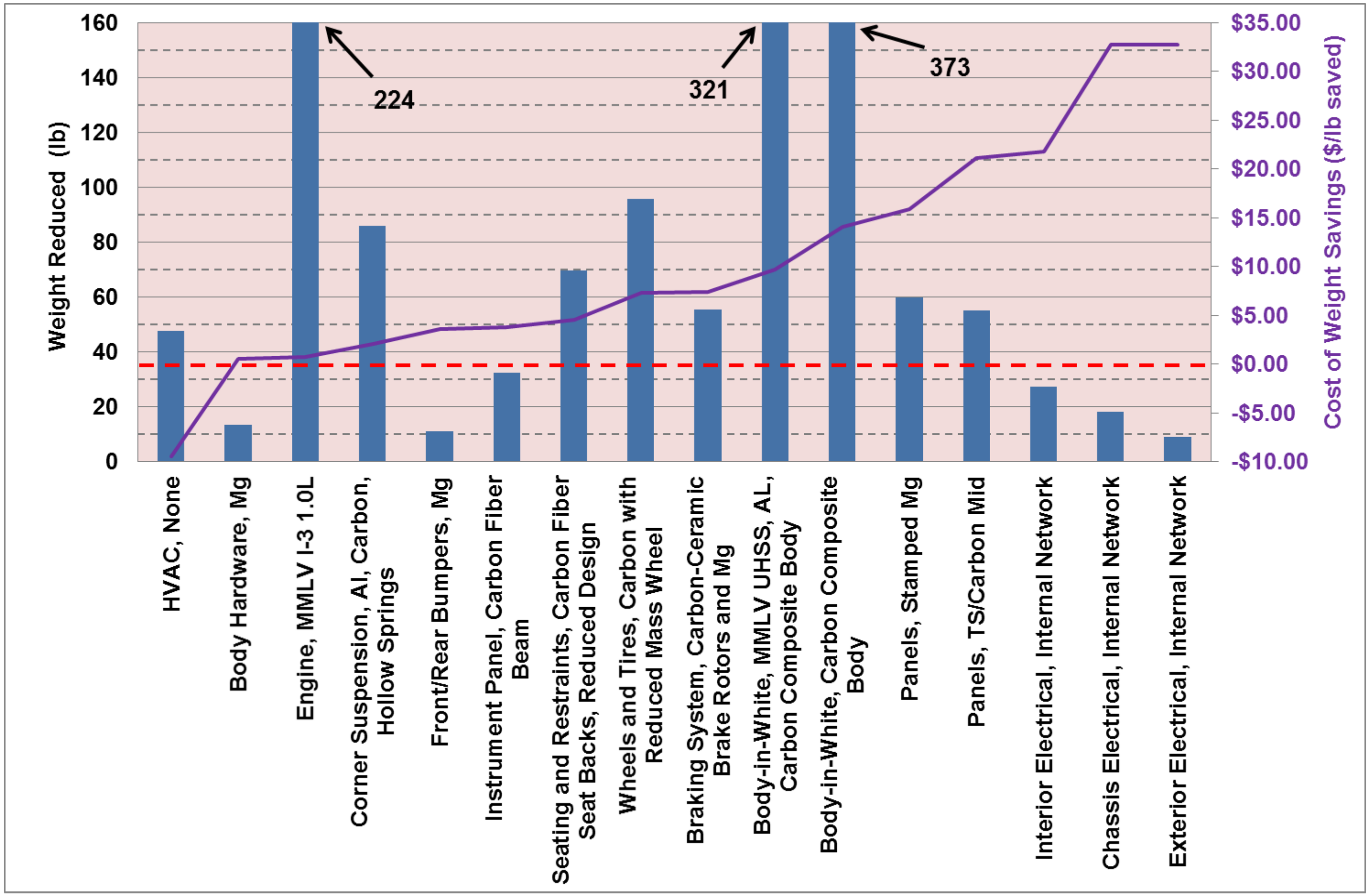


Figure : Weight Reduction Strategies by Risk Factor and Cost of Weight Savings (High Risk)

Response to Previous Year Reviewer’s Comments

These tasks were not presented at the 2015 AMR

Collaborations and Coordination

- IBIS Associates, Inc. and Energetics Incorporated - Developed analysis
- Vehma/Ford MMLV Team – Provided data, commentary, and advice
- DOE - Direction and assistance
  - *Carol Schutte, Materials Technology Lead, VTO*
  - *Gerry Gibbs, Propulsion Materials, VTO*

Proposed Future Activities / Ongoing Work

- The current scenario and process cost modeling tasking is completed. The Technical Cost Modeling approach and framework can be applied to perform in-depth cost analyses of specific vehicle subsystems and components (e.g., powertrain) to identify detailed optimal pathways for reducing weight in combination with increasing engine efficiency. So expanding the approach to investigate additional areas is being explored.

Summary

Low Risk

strategies that involve well-understood materials and processes can be employed in the near-term to reduce the overall vehicle weight of a conventional North American midsize vehicle by up 17% with cost of weight savings from $0 - $2.00 per lb.

Achievable with:

- Increased aluminum
- Moderate price premium
- Low technical risk

Medium Risk

strategies can be used to reduce the overall vehicle weight up to a total of 27% with a best case cost of weight savings still about $2.00 per lb.

Extensive lightweighting needed:

- increased magnesium
- component redesign,
- system downsizing
- lightweight interior materials and glazings.

High Risk

Strategies are needed to achieve the highest levels of weight reduction that approach 45% overall vehicle weight savings with cost of savings up to $7.00 per lb. under optimum conditions.

Requires:

- Carbon fiber at significantly reduced cost per pound
- Extensive use of Mg
- Advanced electrical & interior systems
- Consumer acceptance of some decontenting

Technical Back-up Slides

Process Cost Modeling – Aluminum Extrusion

	Part Cost ($/part)	Annual Cost ($/year)	Percentage of Total Cost
VARIABLE COST ELEMENTS			
Material Cost	$2.58	$258,373	69.4%
Labor Cost	$0.29	$29,437	7.9%
Utility Cost	$0.01	$1,298	0.3%
FIXED COST ELEMENTS			
Equipment Cost	$0.32	$32,032	8.6%
Tooling Cost	$0.11	$10,901	2.9%
Building Cost	$0.01	$1,032	0.3%
Maintenance Cost	$0.17	$16,570	4.5%
Overhead Labor Cost	$0.05	$4,745	1.3%
Cost of Capital	$0.18	$17,948	4.8%
TOTAL MANUFACTURING COST	$3.72	$372,338	100%
Cost per Unit Weight ($/lb)	$1.69		

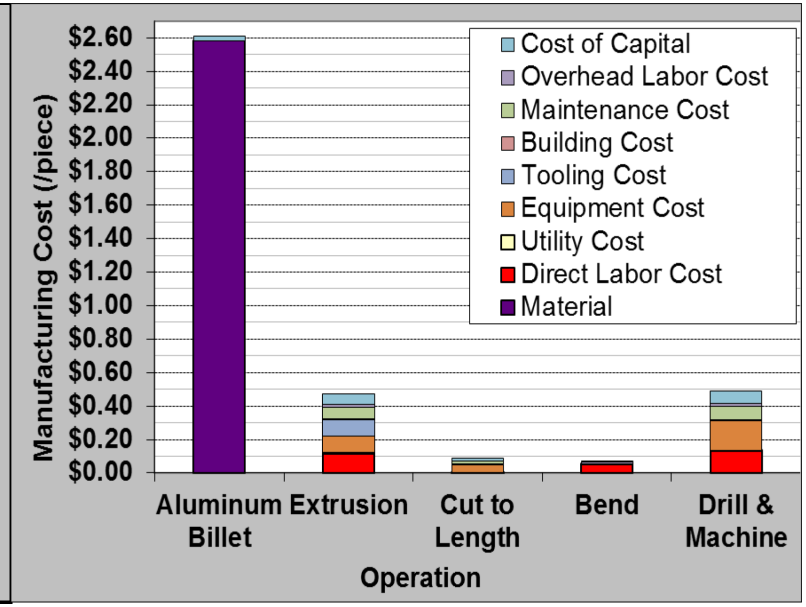
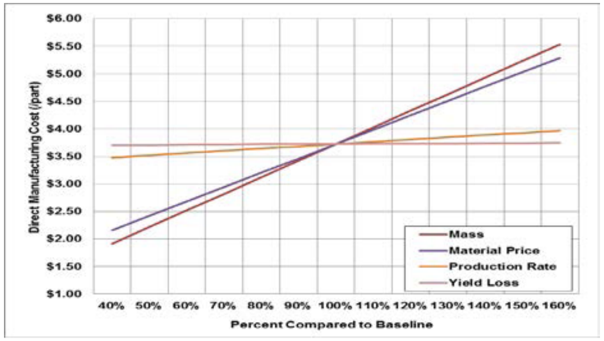
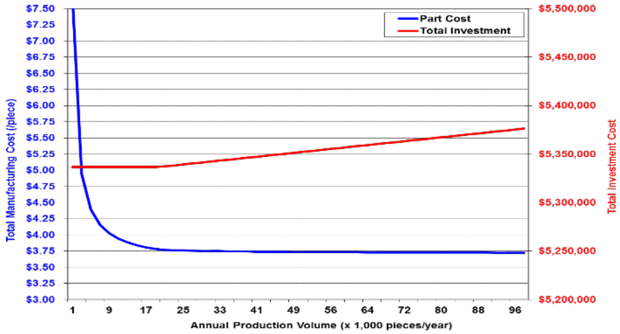


Figure : Aluminum Extrusion (Complex) Cost Summary by Element and Part Cost Breakdown by Operation





Process Cost Modeling – Mg Sheet Forming

	Part Cost ($/part)	Annual Cost ($/year)	Percentage of Total Cost
VARIABLE COST ELEMENTS			
Material Cost	$15.91	$1,591,111	74.8%
Labor Cost	$1.07	$106,516	5.0%
Utility Cost	$0.06	$5,658	0.3%
FIXED COST ELEMENTS			
Equipment Cost	$0.57	$57,003	2.7%
Tooling Cost	$1.93	$193,105	9.1%
Building Cost	$0.02	$2,184	0.1%
Maintenance Cost	$0.73	$73,262	3.4%
Overhead Labor Cost	$0.17	$17,169	0.8%
Cost of Capital	$0.82	$82,338	3.9%
TOTAL MANUFACTURING COST	$21.28	$2,128,346	100%
Cost per Unit Weight ($/lb)	$5.40		

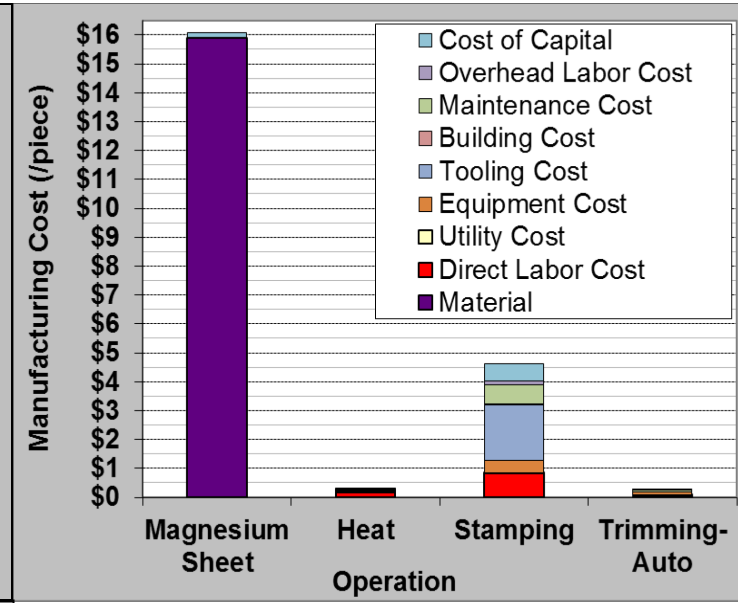
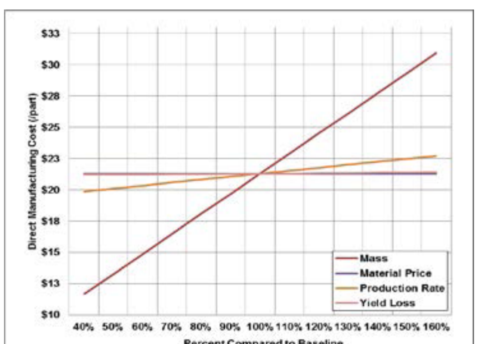
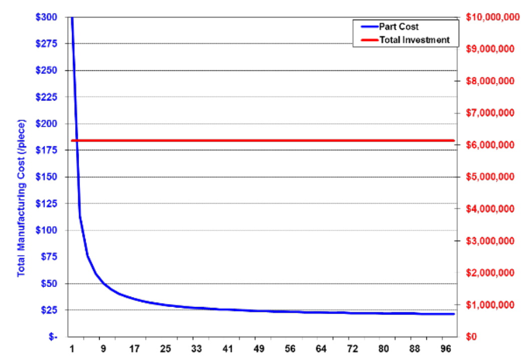


Figure : Magnesium Sheet Forming Cost Summary by Element and Part Cost Breakdown by Operation





Process Cost Modeling – Carbon Fiber Comp.

	Part Cost ($/part)	Annual Cost ($/year)	Percentage of Total Cost
VARIABLE COST ELEMENTS			
Material Cost	$309.78	$30,977,778	47.7%
Labor Cost	$69.46	$6,946,452	10.7%
Utility Cost	$3.26	$326,075	0.5%
FIXED COST ELEMENTS			
Equipment Cost	$171.74	$17,173,678	26.4%
Tooling Cost	$1.18	$118,165	0.2%
Building Cost	$0.65	$65,353	0.1%
Maintenance Cost	$43.56	$4,355,637	6.7%
Overhead Labor Cost	$8.08	$808,391	1.2%
Cost of Capital	$42.10	$4,209,551	6.5%
TOTAL MANUFACTURING COST	$649.81	$64,981,081	100%
Cost per Unit Weight ($/lb)	$21.07		

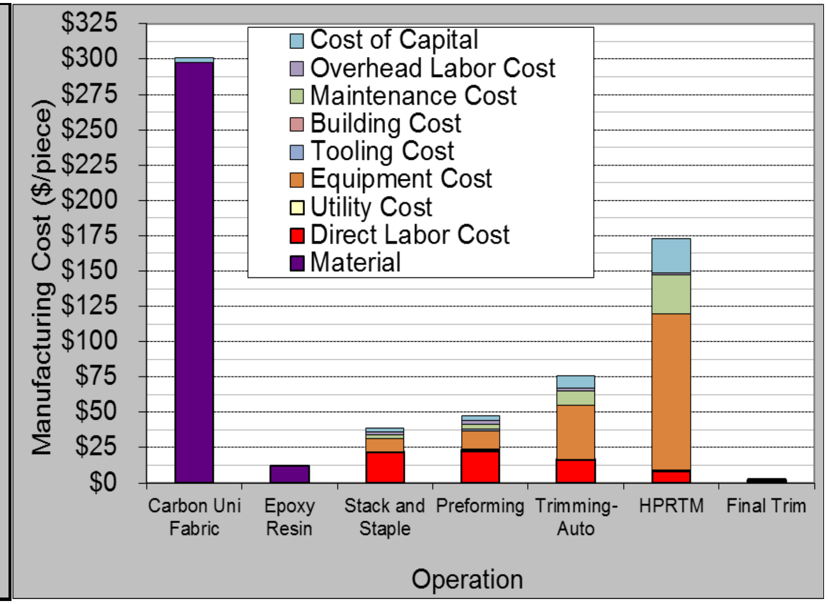


Figure : Carbon Fiber Composites (Side Inner Panel) Cost Summary by Element and Part Cost Breakdown by Operation