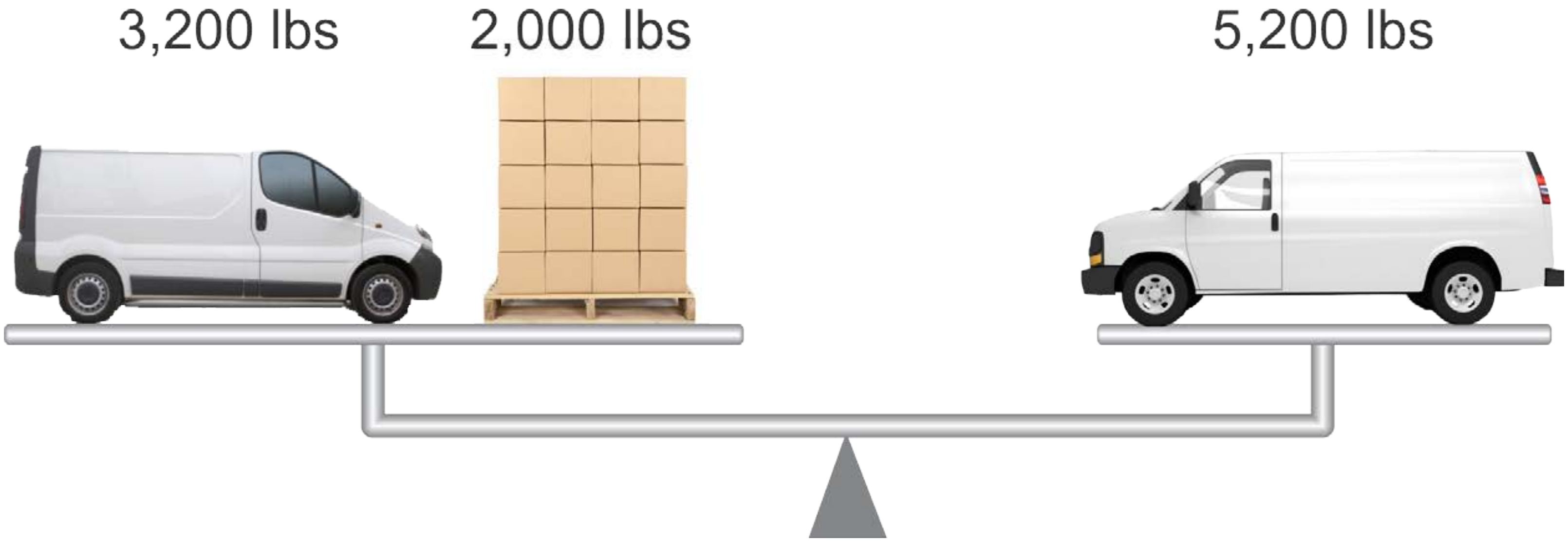
Lightweighting and Propulsion Materials Roadmapping Workshop Outbrief



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Vehicle Technologies Program
May 16, 2012

Workshop Particulars

Objectives: identify targets and technology gaps to overcome

- 135 participants representing
  light duty vehicles (LDV)
  and heavy duty vehicles (HDV):
  - OEMs **(36)**
  - Material & Tier 1 suppliers **(43)**
  - U.S. Government experts **(8)**
  - Canadian government **(4)**
  - Trade Organizations **(5)**

- Held March 2011 in Michigan

Workshop Participating Organizations

Workshop Team: Planning, Executing, and Analyzing

- DOE: Jerry Gibbs, William Joost
- Energetics: Michael Laughlin, Anand Raghunathan
- New West: Richard Bogacz, Peter Heywood, Peter McCallum, Daniel McKay, Jake Mello, Matthew Osterling, Rus Owens, Bryan Roy, Ken Weaver
- ORNL: Donna Balltrip, Ray Johnson, Philip Sklad, Kathi Vaughn, David Warren
- PNNL: Dean Paxton, Theresa Shoemaker, Mark Smith
- SRA –Sentec: Mary Apostolico, Steve Calandro, Abi Gaines, Steve Garon, Jon Hurwhich, Kenyon Larsen, Brian Pai, Phil Rizzi, Rich Scheer of Scheer Ventures, Lee Ann Tracy, Richard Ziegler

Workshop Considerations

Day 1

- Vehicle subsystems include:
  - Structural systems:
    - Body structure
    - Chassis structures
    - Suspension and drivetrain systems
    - Engine and transmissions
    - Turbo-machinery
    - Exhaust and cooling systems
  - Semi-structural and non-structural systems:
    - Appearance panels
    - Enclosures
    - Bumpers

Day 2

- Materials considered:
  - Advanced high strength steels
  - Cast iron
  - Aluminum
  - Magnesium
  - Carbon fiber composites
  - Glass fiber composites
  - Unreinforced plastics
  - Advanced materials such as:
    - Titanium
    - MMCs
    - Ni-based alloys

Weight Reduction Goals for LDV

LDV Component Group	2020	2025	2030	2040	2050
Body	35%	45%	55%	60%	65%
Power-train	10%	20%	30%	35%	40%
Chassis/suspension	25%	35%	45%	50%	55%
Interior	5%	15%	25%	30%	35%
Completed Vehicle	***20%***	***30%***	***40%***	***45%***	***50%***

Weight Reduction Goals for HDV

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Class 8 Tractor Component Group	2020	2025	2030	2040	2050
Wheels and Tires	10%	20%	20%	25%	25%
Chassis/Frame	0%	10%	10%	20%	20%
Drivetrain & Suspension	0%	5%	10%	15%	20%
Misc. Accessories/Systems	5%	15%	25%	30%	35%
Truck Body Structure	15%	35%	45%	55%	60%
Powertrain	5%	10%	15%	15%	20%
Total Class 8 HDV	***6%***	***16%***	***22%***	***27%***	***31%***
Trailer (53 ft) Component Group					
Wheels and Tires	10%	20%	20%	25%	25%
Chassis/Frame	0%	10%	10%	20%	20%
Suspension	0%	5%	10%	15%	20%
Box/Other	5%	10%	15%	20%	25%
Total Trailer	***3%***	***9%***	***13%***	***19%***	***23%***
Truck and Trailer Combined Totals	**4.8%**	**13.2%**	**18.0%**	**23.6%**	**27.4%**

Overlap in Propulsion Materials Needs for LDV Engines & Transmission & HDV Engine and Engine Systems

Priority materials development requirements for LDV

- Absence of modified aluminum to satisfy needs of high specific output and high efficiency downsized engines
- Absence of new materials' property data limits their use in modeling & design
- Lack of lightweight and high capacity electrical energy storage devices

Overlap in materials shortcomings for LDV and HDV

Lack of cost-effective lightweight materials for engine rotating components e.g.:

- Durable low-cost coatings for thermal, corrosion, wear barriers

Limited affordable materials that exceed performance of traditional materials

Priority materials development requirements for HDV

Courtesy of Daimler Trucks North America

- Inability to produce cost-effective thin walled ferrous castings for engine blocks, heads, and exhaust manifolds
  - Capable of achieving thickness ≤2mm
  - Capable of withstanding pressures ≥ 300 bars

Engine/Transmission Metric Synergies LDV and HDV – 2025 and 2050

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	2010	2025	2050
Weight Reduction	Baseline - LDV Baseline – HDV	25% lighter - LDV 15% lighter - HDV	40% lighter- LDV 20% lighter- HDV
Power density **Fossil Fuel LDV ICE** **Fossil Fuel HDV ICE**	LDV Baseline Midsize Car -2.7L 196 HP (73.4 HP/L) LDT – 5L 308 HP (61 HP/L) 15L 475HP (32 HP/L) - HDV baseline	10% augmented –LDV 1.5L 196 HP (132 HP/L) 1.0L 139 HP (132 HP/L) 15% augmented -LDT – 2.6L 308 HP (119HP/L) 30% augmented –HDV 11L 475HP (45HP/L)	30% augmented – LDV 1.0L 196 HP (214 HP/L) 0.5L 98 HP (214 HP/L) 30% augmented -LDT – 1.6L 308 HP (192 HP/L) 40% augmented-HDV 9L 475HP (53 HP/L)
Efficiency **Waste heat recovery – LDV** **Thermal - LDV** **Thermal - HDV**	5% recovery – LDV Turbo Machinery LDV Thermal Baseline 30% efficiency 42% efficiency – HDV	20% recovery – LDV Turbo / Thermoelectric(TEs) LDV - 25% improvement (37% e) 50% efficiency- HDV	50% recovery – LDV Turbo/TEs/ Rankine Cycle LDV - 50% Improvement (45% e)/LD-ACE 50% e 60% efficiency- HDV
Exhaust Temperatures (Exhaust Valve to Turbo Inlet)	870 C - LDV 700 C- HDV	950 C - LDV 800 C - HDV	1000 C - LDV 900 C - HDV
Cylinder Peak Pressures	Baseline – LDV ~ 50 bar 190 bar - HDV	75-110 bar - LDV gasoline 193 bar - LDV diesel 250 bar - HDV	130-160 bar - LDV gasoline 200 bar – LD – HE/ACE 206 bar - LDV diesel 300 bar - HDV

Background Graphic Courtesy of Daimler Trucks North America

Technology Gaps and Priorities for both HD and LD Vehicle Systems

System	BIW & Cab	Propulsion	Chassis	Closures
Joining of Multi-materials	X		X	X
Optimized Performance (including matls for rotating parts, lower cost, improved strength etc)		X	X	X
Predictive Models	X			X
Optimized Manufacturing (including lower cost and larger parts)	X		X	
Design Tools	X			X
Cost and availability of Materials	X			
Corrosion				X

Overlap in Structural Materials Limitations for LDV Body-in-white & HDV Body & Cab

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Priority materials limitations for LDV

- Limited fiber reinforced polymer ductility
- Inability to meet crash requirements with magnesium
- Lack of high-strength, formable Al alloys with low processing cost
- Lack of next generation AHSS
- Limited multi-disciplinary process (e.g. Crash/Safety, etc..) for Steel, Aluminum, and Magnesium

Overlap in materials shortcomings for LDV and HDV

High cost and lack of lightweight materials

Limited knowledge of joining of dissimilar materials

Insufficient modeling and simulation engineering analysis tools for composites

Lack of low cost materials processing/ manufacturing

Inability to integrate composite parts into body-systems

Priority materials limitations for HDV

Insufficient new materials

- Alloying
- Sustainable materials and resins
- Recyclability
- Corrosion resistance

Body-in-white/ Body & Cab Metric Synergies LDV & HDV – 2025 and 2050

	2010	2025	2050
Weight reduction	Baseline of LDV & HDV	40-50% lighter by cost effective sustainable means	60-75% lighter by cost effective sustainable means
Low-cost manufacturing for composites	2-30 mins/part	1-3 mins/part	1 min/part
Structural modeling and simulations	Simulation based (not prediction based)	Durability, reliability prediction capability for lifecycle analysis	Materials by design – "mix material systems" to predict part properties in application
Design and performance	Steel-based	Composite-based – affordable materials with standardized material properties	Composite-based – commodity materials
Recyclability	Reclaim < 40% (no glass recovery)	Reclaim 85%	Reclaim 99%
Repairability	Mostly replacement	50/50 - repair to replace	Mostly repair

Overlap in Materials Limitations for LDV Chassis and Suspensions with HDV Chassis Structures & Components

Chassis and Suspensions for LDV

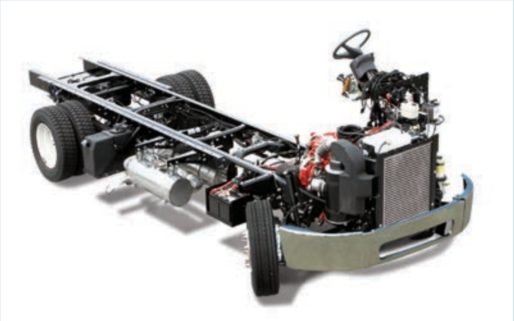
- Limited ability to mitigate corrosion in Mg
- Limited ability to produce casting with high integrity for both Al and Mg
- Limited infrastructure for casting High Pressure / Vacuum Casting (>2,500 ton)
- Limited ability for joining

Overlap in materials shortcomings for LDV and HDV

Lack of material development including large scale manufacturing

Limited capability in multi-material joining

Chassis Structures & Components for HDV



Courtesy of Daimler Trucks North America

- Limited material and assembly modeling
- Little collaboration among stakeholders in developing processes and software for optimizing vehicle systems -to the component level
- Unoptimized energy and efficiency processes

Chassis System Metric Synergies LDV & HDV – 2025 and 2050

	2010	2025	2050
Overall Weight Reduction	Materials mostly steel, Close to full optimization	20-35% lighter using advanced materials	50% lighter using new material & integration with other components
By Chassis Sub-system			
Front/rear cradles		Lighter by 35%	Lighter by 50% (EVs, front cradle major downsize)
Steering knuckles		Lighter by 25-35%	Lighter by 50%
Brakes		Lighter by 50%+	Lighter by up to 100% (regen. braking; using motor)
Wheels/tires		Lighter by 20%	Lighter by 50%
Stabilizers		Lighter by 50%+	Lighter by 75% (new composites)
Ladder frames		Lighter by 25%	Lighter by 35% (CF, CF/steel hybrid)
Springs		Lighter by 50%+	Lighter by 50%+
Fuel systems / exhaust		Lighter by 40% (30% + 10% from 10% EV penetration)	Lighter by up to 100% (all electric vehicles)

Background Graphic Courtesy of Daimler Trucks North America

Materials Limitations for LDV & HDV Closures, Fenders, and Bumpers

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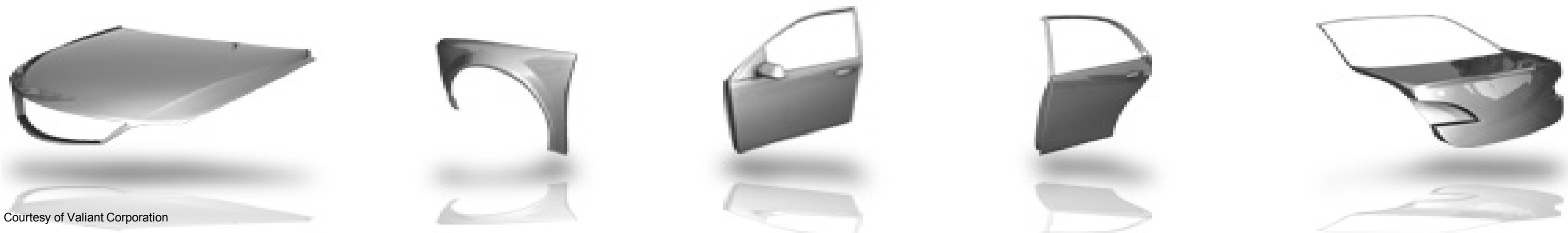
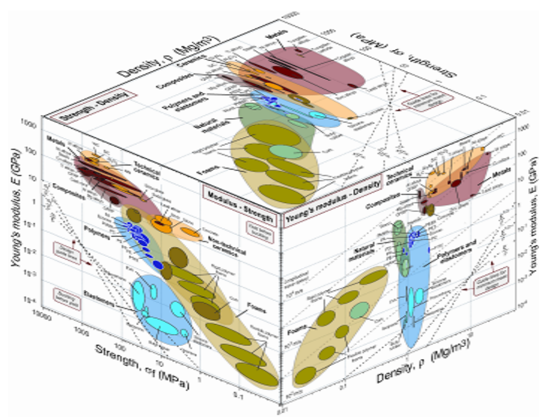

Courtesy of Valiant Corporation

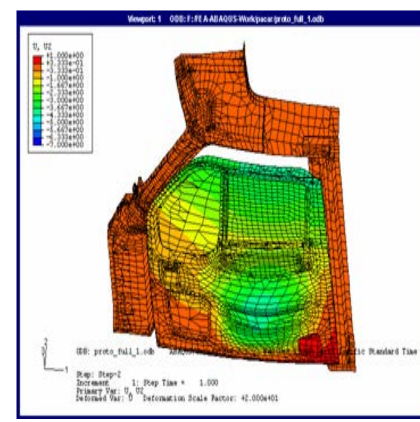
Materials shortcomings for closures

- Limited capability to:
  - Enduring material joints
  - Model, predict, mitigate corrosion issues, especially with new lightweight materials

- Complete material database & design knowledge does not fully exist
  - Limits the design & manufacturing of novel parts with current/future materials

- Supply and affordability challenges for materials – new and existing alike


Courtesy of Granta Design www.grantadesign.com



LDV & HDV Closures, Fenders, Bumpers Material Metrics – 2025 & 2050

	2010	2025	2050
Maintain Functionality (Safety, Appearance, Impact Performance, NVH, etc.)	• 10% lower weight than 2002 in metal components • Net gain in weight since 2002	Maintain Today's Functionality	Maintain Today's Functionality
Weight Savings	• Premium of ~$1 per lb shed in bumpers • Premium >$1/lb in other components	• More than 50% weight savings • Weight Savings at a Cost of <$1 per lb • Small Cost Increases	• More than 75% weight savings • Weight Savings at a Cost of <$1 per lb • Small Cost Increases

Materials Technology Gap Priorities

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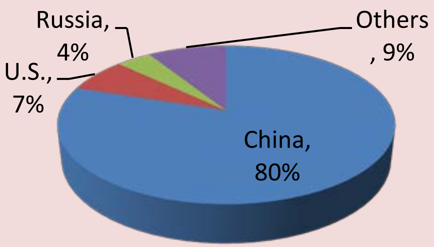
Material	Mg	Carbon Fiber	CF composites	GF composites	AHSS	Al	Advanced Metals – (Ti, Ni)
Lack of Predictive Models	X	X	X	X	X	X	
Optimized Manufacturing (lower cost)		X	X	X	X	X	X
Optimized Performance (lower cost, improved strength etc)	X	X		X	X		X
Design Tools		X		X			X
Raw Material Supply	X						X
Multi-material Joining			X			X	
Damage Detection			X				
Corrosion	X						

Representative Workshop Output – Magnesium

- Weight reduction potential of magnesium vehicle components (vs. conventional, steel intensive structures) ~ **60-75%**

- Barriers to pervasive use of Mg in contemporary vehicles:

Limited Domestic Production

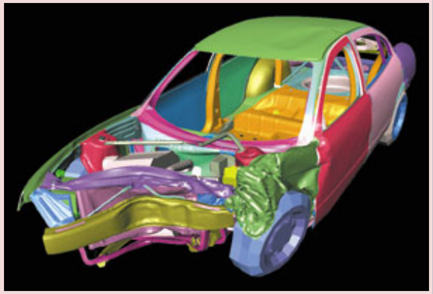


Magnesium Market Review - April 2011
USGS Magnesium Commodity 2011

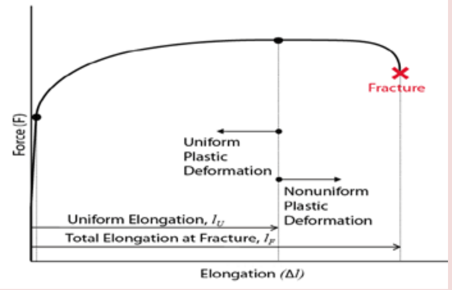
Corrosion Control and Resistance

Graphic courtesy of STAMPING Journal and the Center for Precision Forming, The Ohio State University, Columbus, Ohio

Lack of Predictive Models Comparable to Fe or Al



Elongation Limits / Lack of Uniform Properties in Castings



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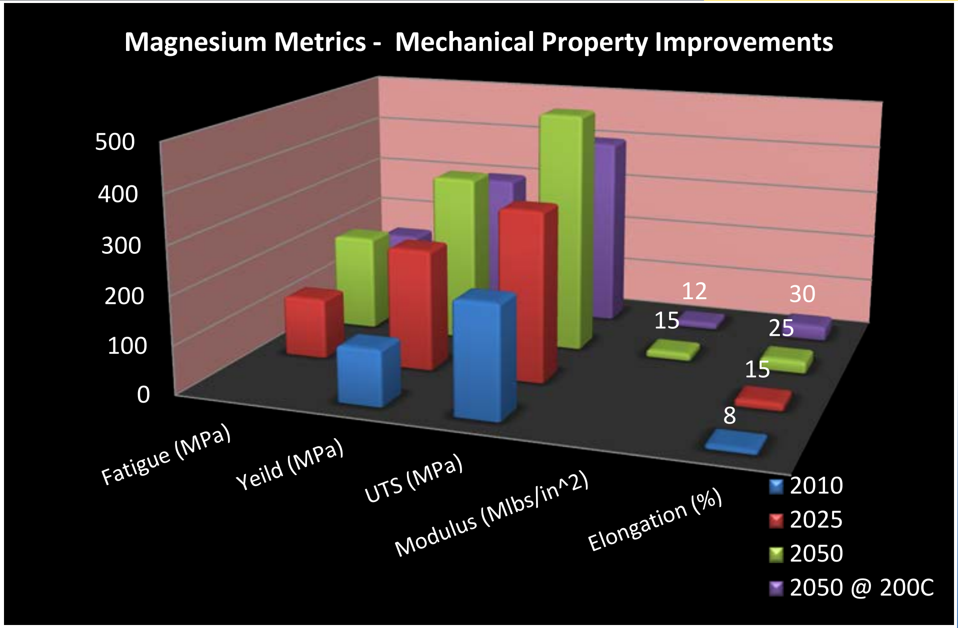
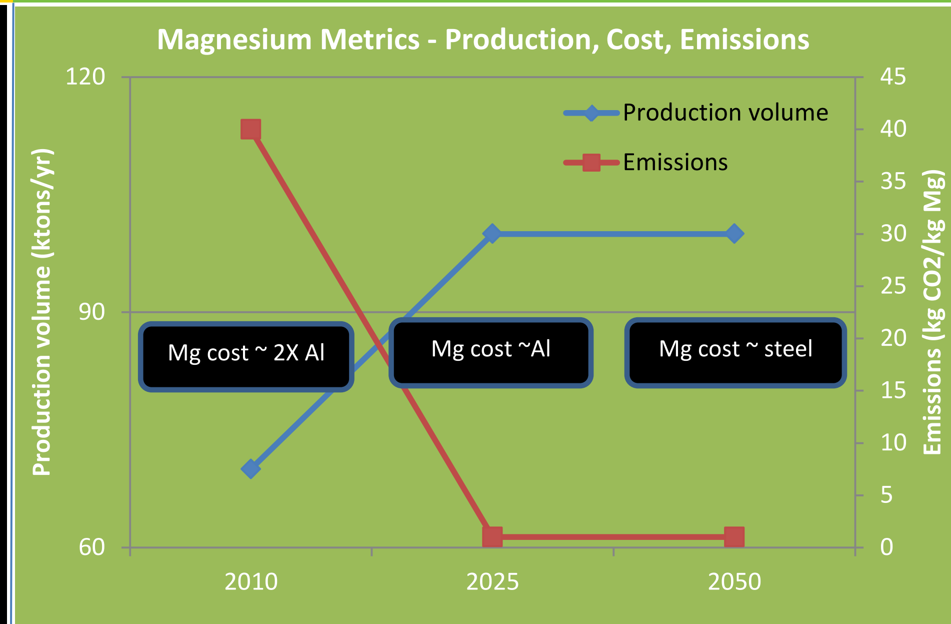
Magnesium Material Metrics – 2025 and 2050

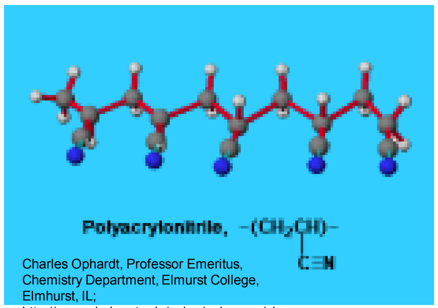




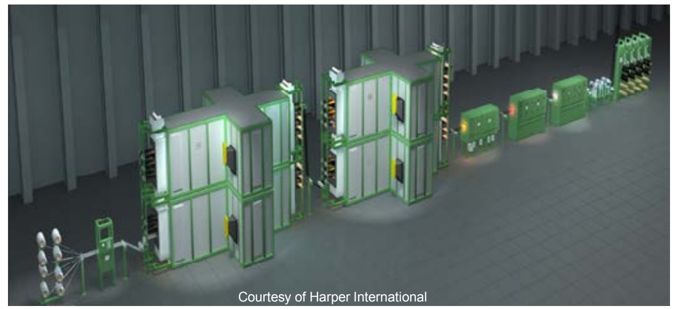
	2010	2025	2050
Corrosion Prevention and Joining	Corrosion, joining and compatibility shortfalls	Eliminate galvanic corrosion issues when joining magnesium with dissimilar materials	Universal one step pretreatment compatible with aluminum, steel
Alloy Development – (expand types of optimized alloys)	Significant shortfall of Mg alloys	Increase alloy availability by 2X compared to 2011	Increase alloy availability by 4X compared to 2011

Representative Workshop Output - Carbon Fiber

- Weight reduction potential of carbon fiber composite (CFC) vehicle components (vs. conventional, steel intensive structures) ~ **50-60%**
- Barriers to pervasive carbon fiber (CF) use in contemporary vehicles:



Charles Ophardt, Professor Emeritus, Chemistry Department, Elmurst College, Elmhurst, IL; http://www.elmhurst.edu/~chm/onlcourse/chm110/outlines/images/polyacry.GIF



Courtesy of Harper International

Barriers	**Limited Data on Structure/ Property Relationship**	**Limited Processing & Manufacturing Understanding**	**Limited Knowledge of CFC Behavior in Use**	**Limited Design Knowledge & Training System for CF Work**
	• Incomplete interfacial CF chemistry-to-composite property relationships • Incomplete precursor –to-CF-structure-property relationships • Inadequate predictive engineering tools for CF	• Costly alternative carbon-fiber precursors • Insufficient knowledge on manufacturing with high cycle formability and joining • Low efficiency of CF conversion (energy/environmental)		

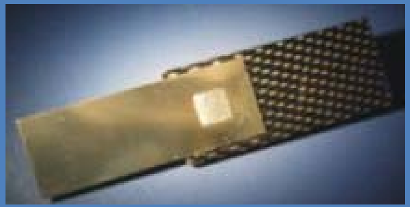
Carbon Fiber Material Metrics – 2025 and 2050

2010	2025	2050
• Carbon Fiber Cost~ $9/lb	• Carbon Fiber Cost ~ $3/lb	
• Poly acrylonitrile precursors: ▪ <2/1 yield ▪ low throughput ▪ high emissions	• New precursor chemistries: ▪ >2/1 yield ▪ high rate conversion ▪ low emissions • Precursor - 100% petroleum based • Stable conversion at temperatures 800-1500°C	• Precursor based on 100% recyclable materials • 100% sustainable process for making & using CF materials with emissions reduced by 80% compared to 2010

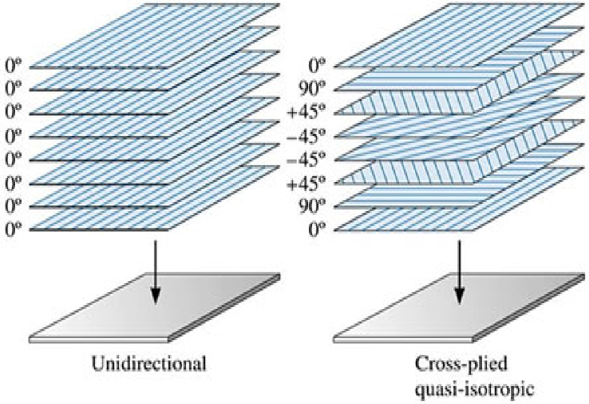
Representative Workshop Output - Carbon Fiber Composites (CFCs)

- Weight reduction potential of CFCs vehicle components (vs. conventional, steel intensive structures) ~ **50-60%**
- Barriers to pervasive CFC use in contemporary vehicles:

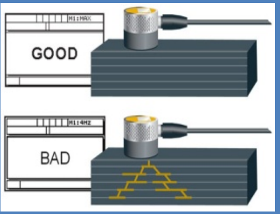
Joining



- Difficulty joining with other materials
- Joint durability –CFC & other material

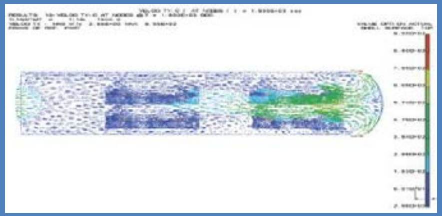


Damage Detection & Recycling



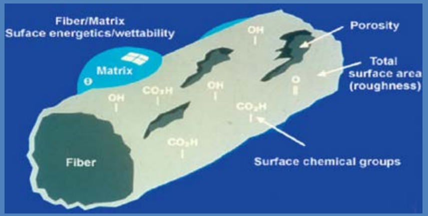
- Lack of damage detection tools and repair technology
- Inadequate CFC recycling

Modeling



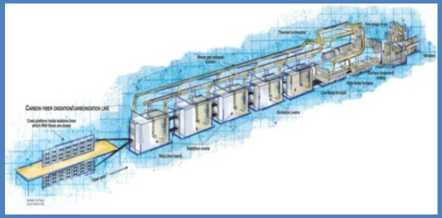
- Lack of predictive modeling capability for CFC and joints
- Inadequate materials database

Matrix Materials



- Limited options to improve CF adhesion to matrix
- Limited CF-compatible resin matrix materials

Manufacturing

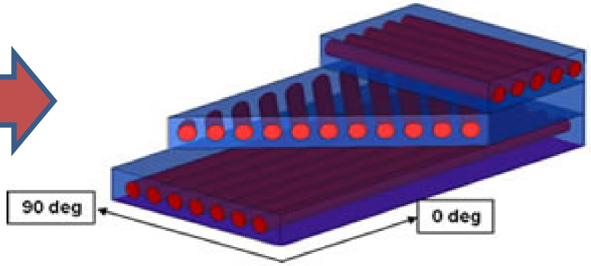


- Fiber/resin systems not optimized for manufacturing
- High cost/limited supply of CF
- Long cycle times

Carbon Fiber Composites Material Metrics – 2025 & 2050

	2010	2025	2050
Utilization	<40K LDV/yr No use HDV	5% of vehicle mass	15-25% of vehicle mass
Cost	$12/lb	<$5/lb	<$2.5/lb
Modeling		Predictive with CAE &FEM	
Design		50% of theoretical limits	
Raw materials		Non-petroleum based materials (precursors, fibers, resins)	
Joining		Joining technology for CF-CF and CF-metal at cost & time ~steel design	
Recycling		100% recycled, 25% renewable precursor 25% reduced carbon footprint	100% recycled 50% renewable precursor 75% reduced carbon
Repair	0% detection 0% repair	100% detection 25% repair	100% detection 50% repair

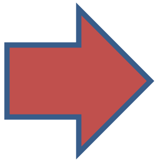

Courtesy of the Oak Ridge National Laboratory, managed for the US Department of Energy, Photographer: Jason Richards.




Courtesy of Road Race Motorsports

Representative Workshop Output – Glass Fiber Composites

- Weight reduction potential of GFCs vehicle components (vs. conventional, steel intensive structures) ~ **25-30%**
- Barriers to pervasive glass fiber composite (GFC) use in contemporary vehicles:
  - Limited reinforcement technologies to improve mechanical properties and durability of GFCs
  - Incomplete material property database & design knowledge
  - Modeling and simulation software is immature
  - Process cycle times are lengthy



Glass Fiber Composites Material Metrics – 2025 & 2050 (1 OF 2)

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	2010	2025	2050
Material Property Database & Modeling	Baseline not comprehensive for all material properties	A comprehensive database	Predictive modeling & correlation with field data
Stiffness	• Stiffness dependent on • Variables ranges are large	30% improvement in material stiffness	Same stiffness as Aluminum
Appearance	• Class 'A' appearance possible • Low fill levels, stiffness ~steel	Parity with steel (painted)	Same as 2050
Recycling, Chemical & Energy Recovery	• Typically no recycling • Potential exists	Achieve 50% recyclability & recovery	Eliminate LDV & HDV-related landfill load composites/plastics
Fiber Characteristics	Processes tend to break fibers	Improved predictive fiber characteristics	• Aluminum-like thermoplastics • Low CLTE & isentropic properties

Glass Fiber Composites Material Metrics – 2025 & 2050 (2 OF 2)

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	2010	2025	2050
Joining of Composites	Many methods, few standards.	More methods and available data Standards for multimaterial joining	Continued technology – methods & standards- advancement
System Cost Parity	SMC $1-2 / lb	Parity with Steel	Same as 2025
Reduced Part Weight via Design Optimization or Reduced Density		30% part weight reduction relative to composite components	50% part weight reduction relative to composite components
Regulatory Standards -VOC emissions	Baseline today's standards	50% from baseline	95% from baseline
Process	Shrink/Warp due to fiber orientation	Eliminate warp	Continued advancement

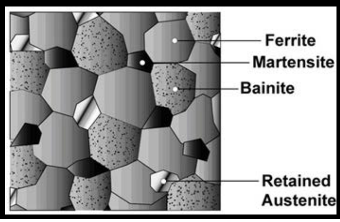
Cycle Time Metrics for GFCs

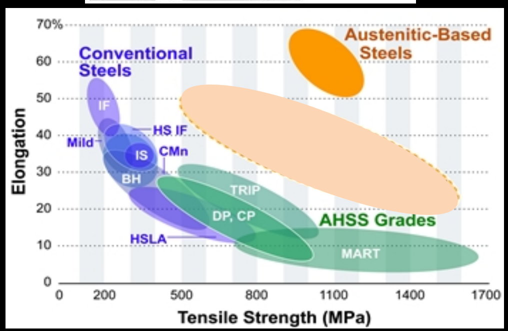
	2010	2025	2050
Liquid Thermoset Resin/Continuous Fiber	10 min	<5 min	<2min
SMC Thermosets	1.5 min	<1 min	30 sec
Thermoplastics	~1 min	30 sec	<10 sec
Metal Stamping	10 sec	-	-

Representative Workshop Output – Advanced High Strength Steel (AHSS)

- Weight reduction potential of AHSS vehicle components (vs. conventional, steel intensive structures) ~ **15-25%**
- Barriers to pervasive AHSS use in contemporary vehicles:

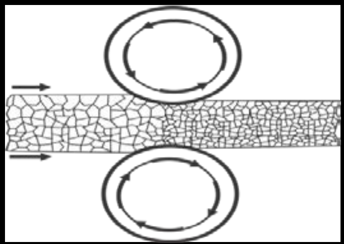
Structure-property relationship





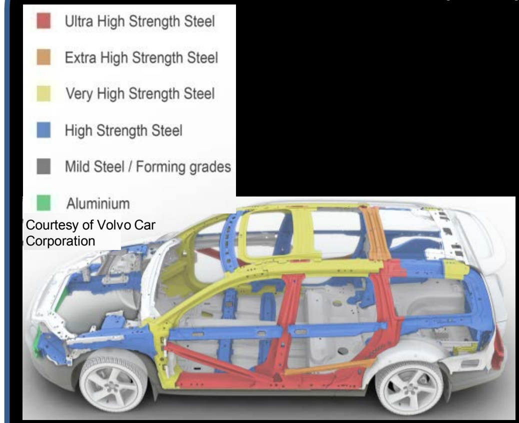
Limited knowledge of:
- grade μstructure with improved strength-ductility relationship
- impact with fillers: in situ nanoparticles, whiskers

Lack of post processing knowledge



- Limited knowledge from rolling and forming
- Inability to mitigate corrosion, limit galvanic bonding, bond steel sheets

Models & Simulations (MS)



Lack of MS tools & material parameters for predicting:
- Properties utilizing physics based models
- Microstructures
  - Morphology & properties
  - Link to failure modes
- Manufacturability & performance

Advanced High Strength Steel Material Metrics – 2025 & 2050

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	2025	2050
Tensile strength and elongation	• 1,500-2,000 MPa UTS • 20% elongation	• 2,500-3,000 MPa UTS • 20% elongation
Density	5% density reduction	10% density reduction
Modulus	10% increase	20% increase
Gauge and width	• Reduce gauge to 0.5mm • Increase width to 1,800mm	• Reduce gauge to 0.4mm • Increase width to 1,800mm
Reliable joining processes for mixed materials	Mechanical properties equivalent to steel-to-steel spot welding	Seamless 3-D construction of multi-material structures
Increase modeling capabilities across the board (cost, crash, fatigue, formability, corrosion, etc.):	Models achieve 75% confidence in correlation	Models achieve 90% confidence in correlation

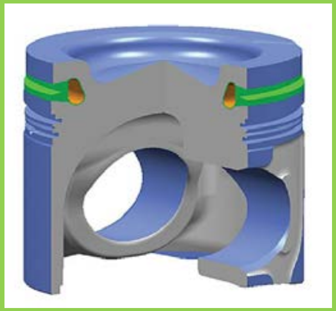
Representative Workshop Output – Aluminum & Aluminum Matrix Composites

- Weight reduction potential of Aluminum vehicle components (vs. conventional, steel intensive structures) ~ **40-60%**
- Barriers to pervasive Aluminum use in contemporary vehicles:

Multi-material Joining

- Inadequate predictive modeling of joint performance
- Inadequate knowledge of how to optimize integrity of joints
- Lack of adhesives for multi-material joining

Modeling & Simulations



- Lack of tools for design and CAE to optimize performance
- Lack of models to predict failure
- Limited tools to optimize manufacturing processes
- Limited database for public reference

Inability to Cast High Quality Complex Parts

Courtesy of Nelson Competition Inc Pinellas Park Fl.

- Inability to cast high performance parts reliably
- Need improved properties for specific applications

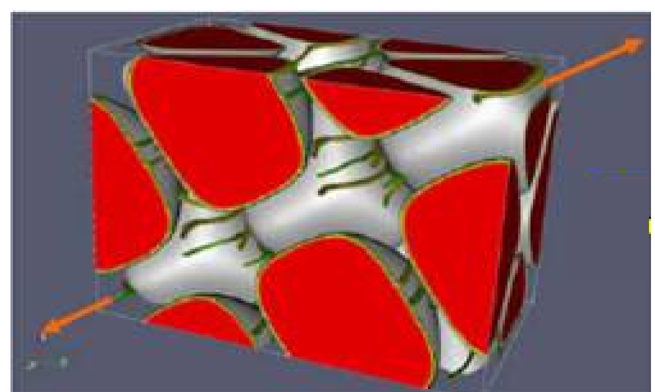
Aluminum Material Metrics – 2025 & 2050

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

	2010	2025	2050
Mechanical Properties (strength, fatigue, creep, ductility, corrosion resistance)	Current standards for cast and wrought products	40% improvement	200% improvement
Aluminum joining with dissimilar materials	• Slow, expensive, • Can't be modeled	50% less fasteners, easier to model	Near zero use of fasteners
Parts Cost – inability to cast complex shapes reliably	Not cost competitive	25% lower	40% lower
Design Techniques	• Incomplete understanding of system properties; • Significant prototyping	50% reduction in design time	Zero prototyping
Recyclability	• 90% overall • 0% high performance alloys	• 90% overall • 50% of high performance alloys being reused for high performance alloys	• 90% overall • 100% of high performance alloys being reused for high performance alloys

Advanced Materials – Titanium, Nickel, etc..

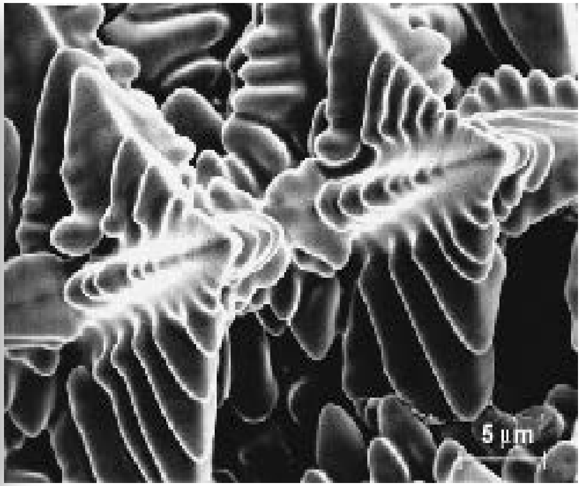
- Weight reduction potential of advanced materials vehicle components (vs. conventional, steel intensive structures) ~ **<u>40-60%</u>**
- Barriers to pervasive advanced materials use in contemporary vehicles:
  - Limited Near-Net-Shape for mass production of titanium parts
  - Insufficient tolerance to temperature extremes (-40 – 1050°C) for advanced materials, including superalloys and MMCs
  - Lack of mass production capability for titanium raw materials
  - Lack of processing capability for intricate component shapes
  - Lack of low temperature ductility for MMCs
  - Inadequate design database for advanced materials



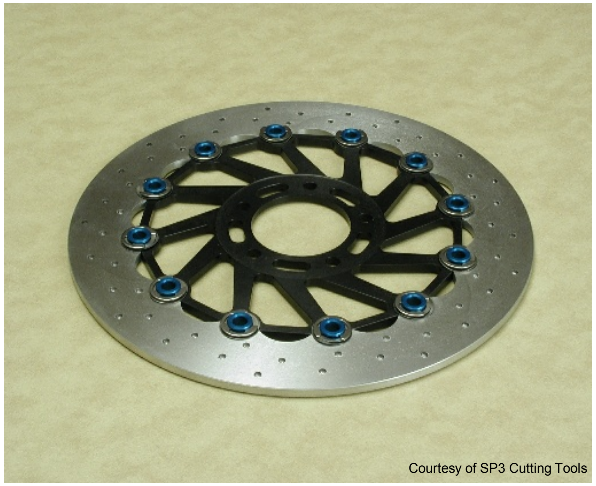
Advanced Materials Metrics – 2025 & 2050

	2010	2025	2050
Titanium – Cost vs. Performance	Cost Prohibitive	50% reduction from current levels	Parity with aluminum alloy
Nickel alloys - Cost vs. Performance	4X cost of stainless steel	• 2X cost of stainless steel • Temperature capability ≥ 1050° C.	1.5X cost of stainless steel


Courtesy of Vanguard Performance



Mel M. Schwartz, Edward M. Breinan, K. K. Wang, William F. Gale, S. S. Babu, J. M. Vitek, S. A. David, "Welding and cutting of materials," in AccessScience, ©McGraw-Hill Companies, 2008, http://www.accessscience.com


Courtesy of SP3 Cutting Tools

Thank You!

Questions?

www.vehicles.energy.gov

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