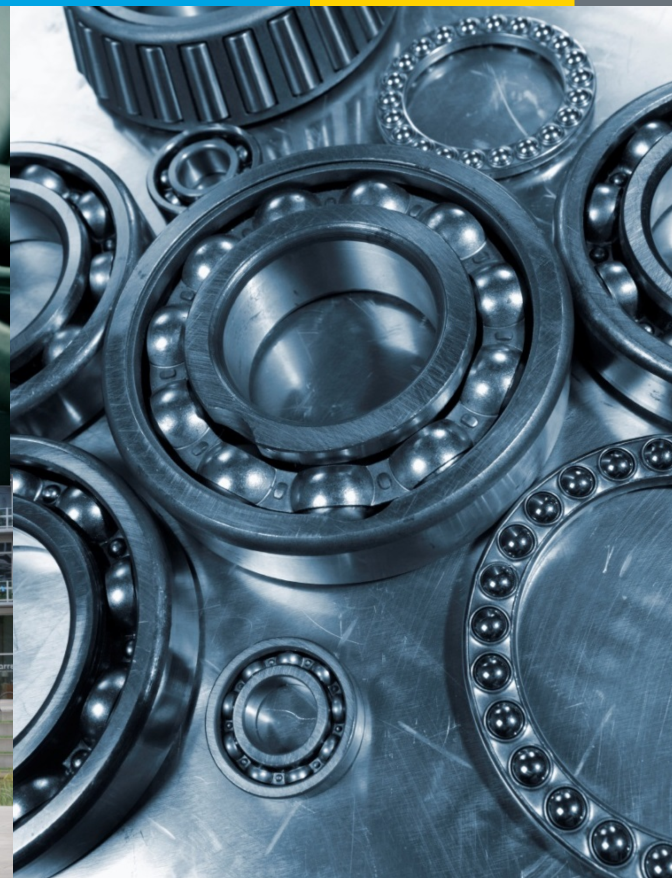


Lightweight Materials

Stephen Goguen
Carol Schutte
Will Joost

LM999

Materials Technologies

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

Values are FY15 enacted

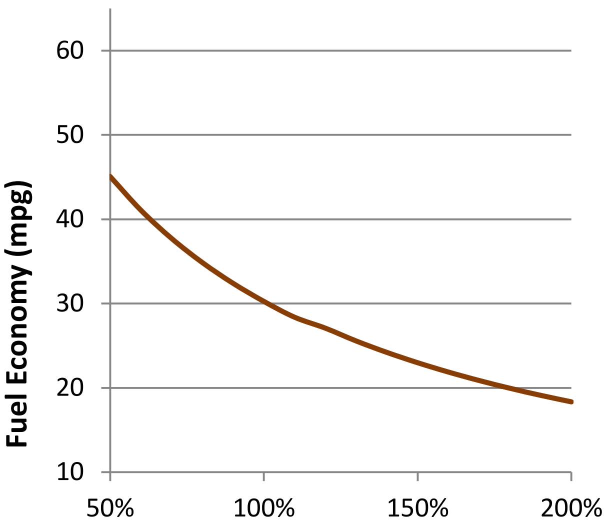
- **Materials Technologies $35.6 M**
  - **Lightweight Materials $28.5 M**
    - Properties and Manufacturing
    - Multi-material Enabling
    - Modeling & Computational Materials Science
  - **Propulsion Materials $7.1 M**
    - Engine Materials, Cast Al & Fe High Temp Alloys
    - Exhaust Sys. Materials, Low T Catalysts
    - Integrated Computational Materials Engineering

	Lightweight	Propulsion
FY13 Enacted	$27.5 M	$11.9 M
FY14 Enacted	$28.0 M	$8.9 M
FY15 Enacted	$28.5 M	$7.1 M

Vehicle Weight Reduction

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

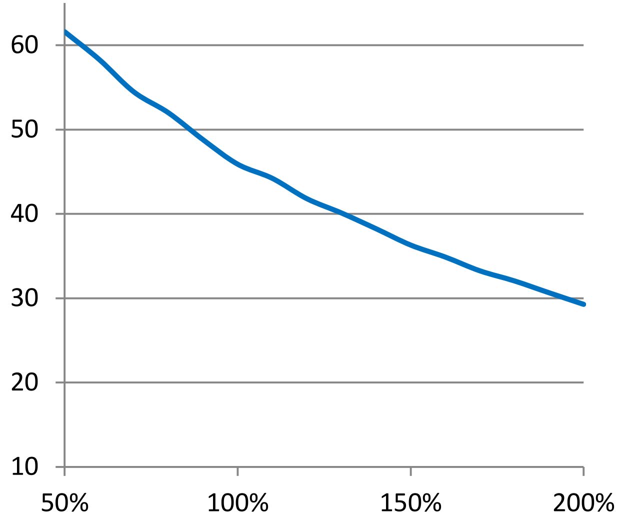
Conventional ICE



NREL 2011

6%-8% improvement in fuel economy for 10% reduction in weight

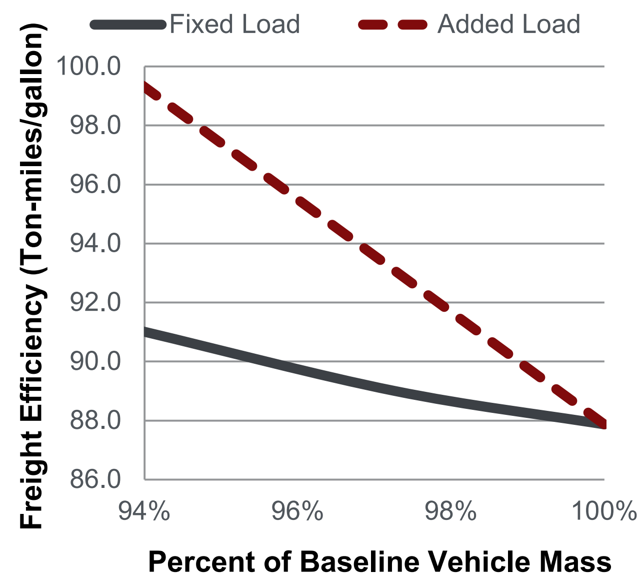
Hybrid/Electric Vehicles



NREL 2011

Improvement in range, battery cost, and/or efficiency

Commercial/Heavy Duty



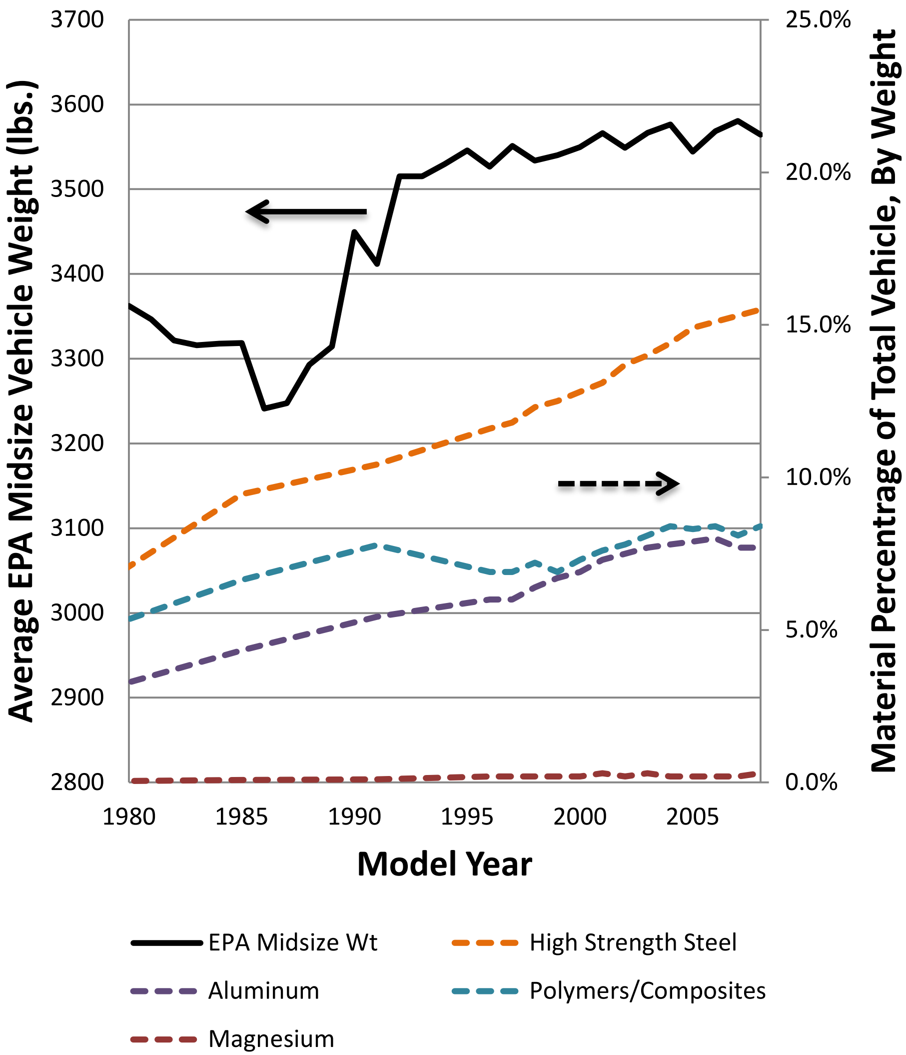
Ricardo Inc., 2009

13% improvement in freight efficiency for 6% reduction in weight

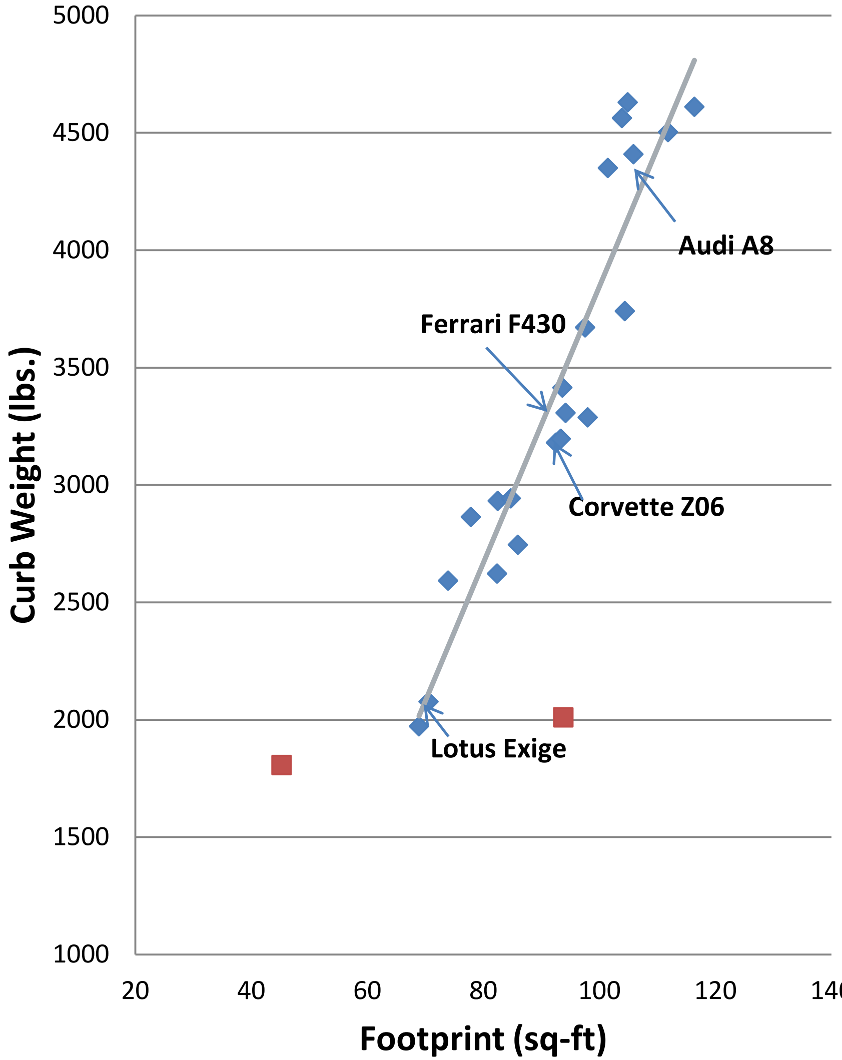
Trends in Vehicle Weight Reduction

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

Average Vehicle Weight and Material Content

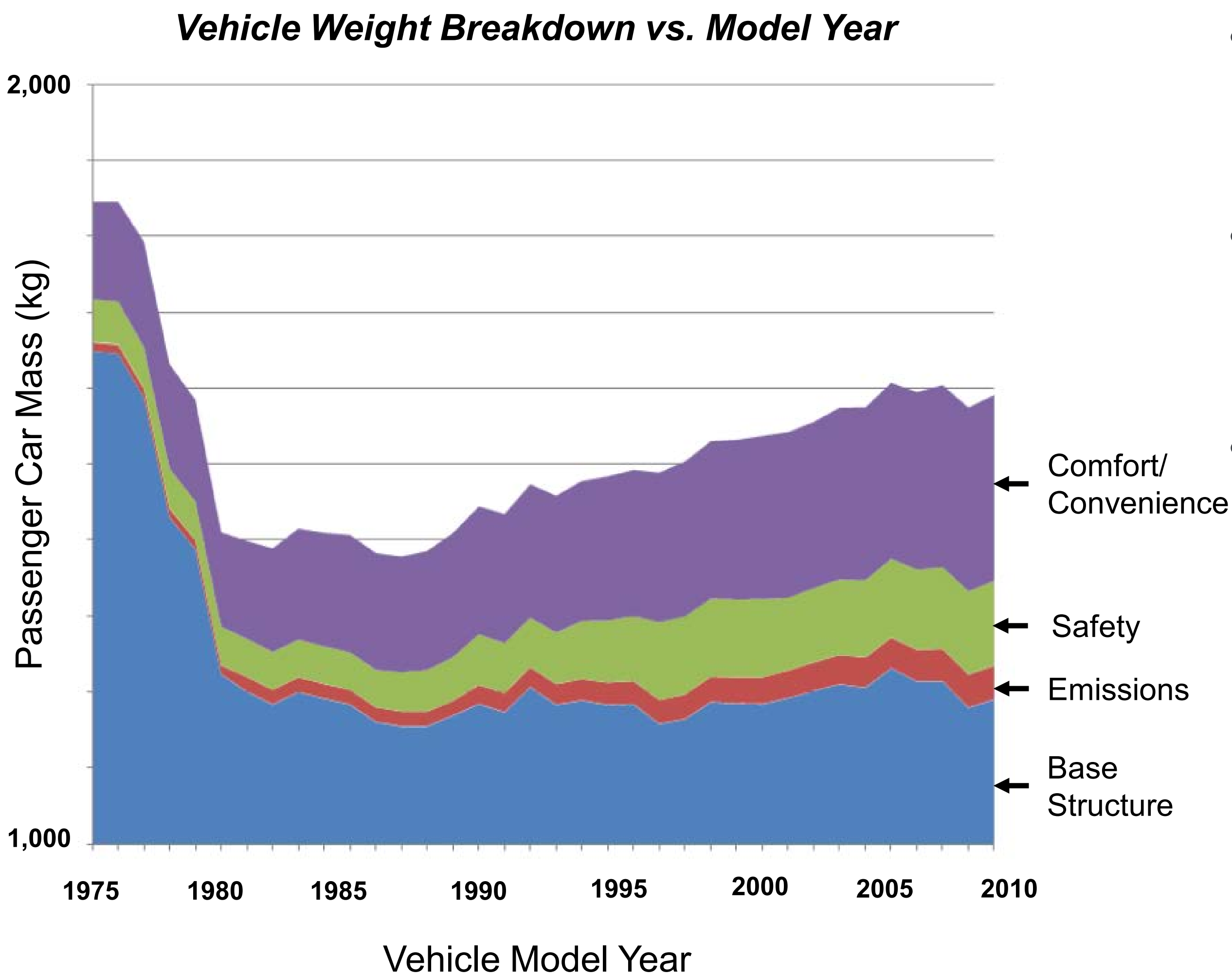


Vehicle Curb Weight vs. Footprint



Where's the Weight Reduction?

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



Stephen M. Zoepf "Automotive Features: Mass Impact and Deployment Characterization" MS Thesis, Massachusetts Institute of Technology, June 2011, page 36.

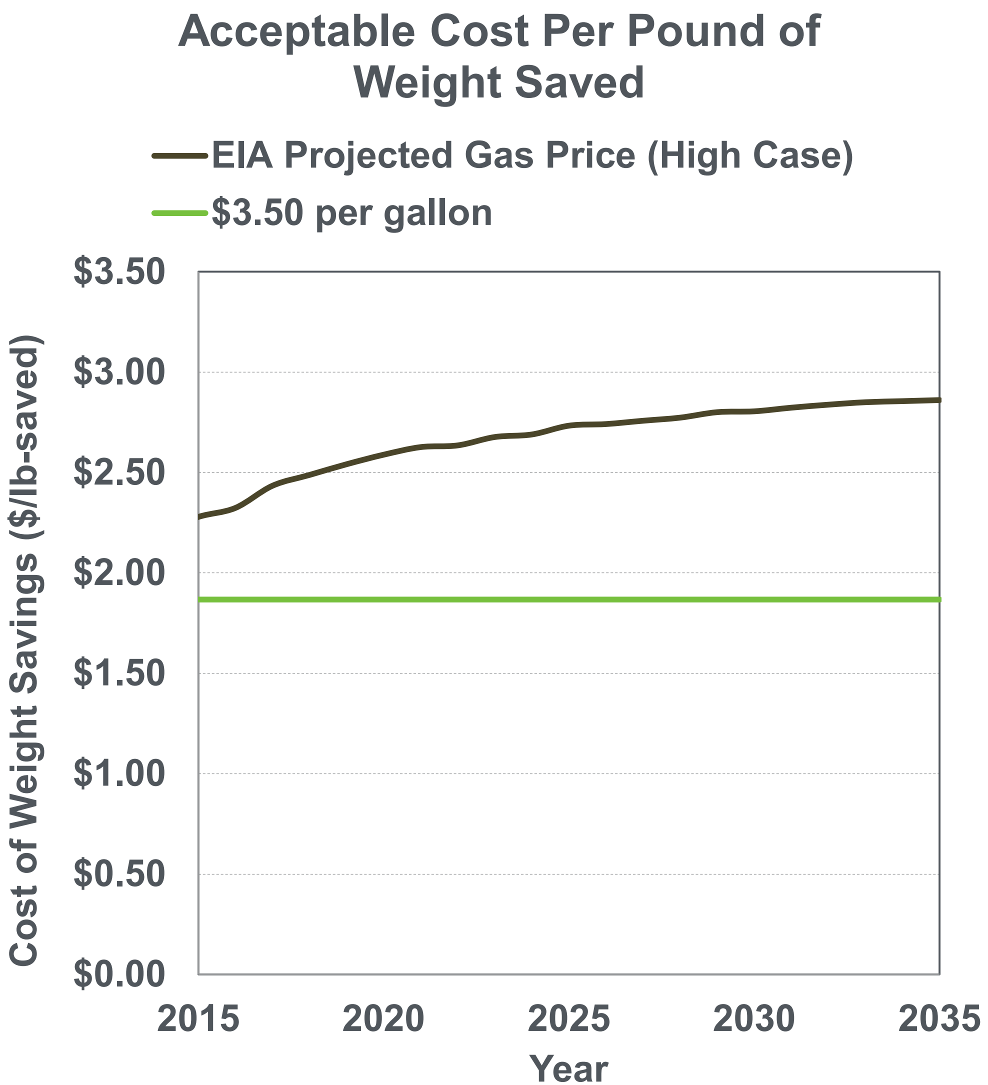
- Comfort, safety, and emissions control have all improved
- Base structure weight has decreased
- *System and component weight reduction has been applied to performance and comfort rather than total vehicle weight reduction*

Acceptable Cost – Societal View

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

Societal view: Fuel efficiency improvement must pay back lightweighting cost over vehicle lifetime

- Model Input
  - Baseline weight: 3500 lbs.
  - Baseline FE: 28.4 mpg
  - VMT per year: 12,000 mi.
  - Vehicle life: 15 yr.
  - FE improvement per weight saved: 7%/10%
  - Fuel Price
    - $3.50/gal
    - EIA projection
  - Discount rate: 7%



Total Vehicle Weight Reduction Potential

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

Sources of weight are from three categories:

Direct weight savings with lightweight materials

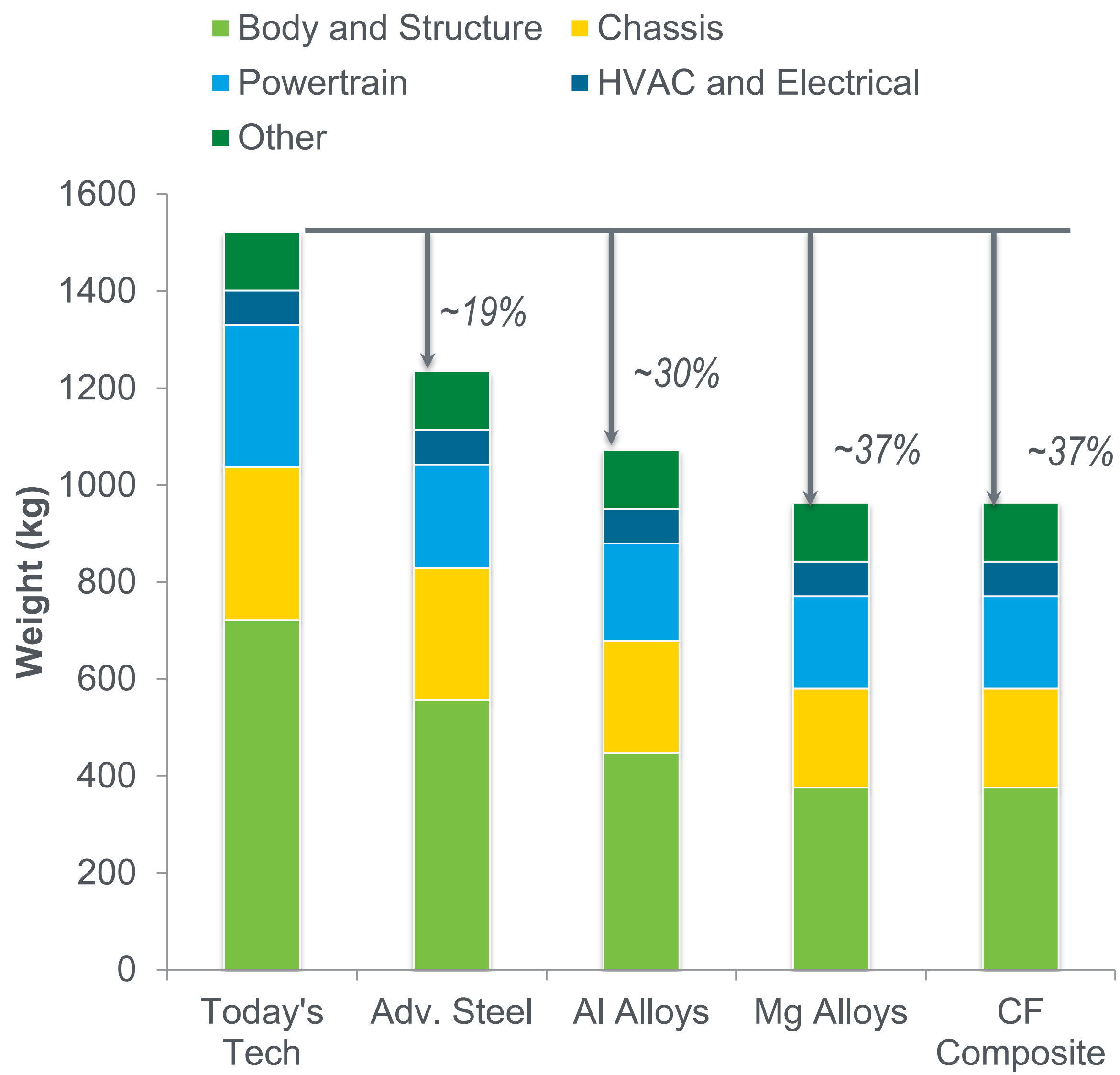
- *Body & Structure, parts of Chassis and Powertrain*

Indirect weight savings by reducing requirements

- *Lighter vehicle can use lighter brakes, lighter suspension, etc.*
- *"Mass Decompounding"*
- *Powertrain and Chassis*

No significant savings through lightweighting

- *Many systems are essentially a function of vehicle volume*
- *Windshield, wiring, headlights, HVAC, etc.*



Lightweight Materials Program

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

Light- and Heavy-Duty Roadmaps

Properties and Manufacturing

- Reduce cost
  - raw materials
  - processing
- Improve
  - performance
  - manufacturability

Multi-material Enabling

- Enable structural joints between dissimilar materials
- Prevent corrosion in complex material systems
- Develop NDE techniques

Modeling and Simulation

- Accurately predict behavior
- Tools to optimize complex processes efficiently
- ICME: Developing new materials and processes

Demonstration, Validation, and Analysis

Properties and Manufacturing

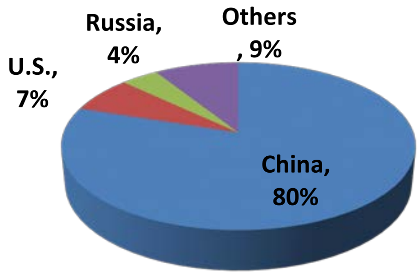
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Magnesium Alloys

When it "works" → 40-70% weight reduction

Otherwise → *Cost (~$3-10/ lb-saved)*

- Lack of domestic supply, unstable pricing
- Challenging corrosion behavior
- Inadequate strength, stiffness, and ductility
- Difficult to model deformation behavior



Aluminum Alloys

When it "works" → 25-55% weight reduction

Otherwise → *Cost (~$2-8/ lb-saved)*

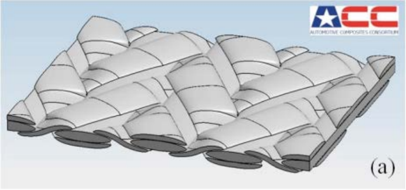
- Insufficient strength in conventional automotive alloys
- Limited room temperature formability in conventional automotive alloys
- Difficult to join/integrate to incumbent steel structures

Carbon Fiber Composites

When it "works" → 30-65% weight reduction

Otherwise → *Cost (~$5-15/ lb-saved)*

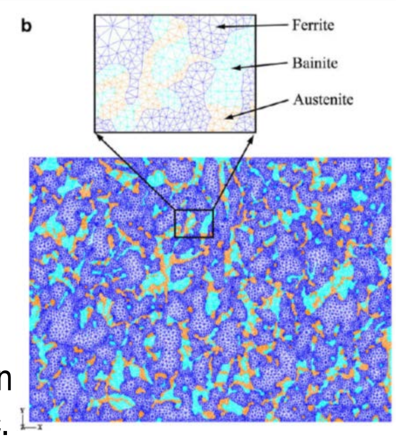
- High cost of carbon fiber (processing, input material)
- Joining techniques not easily implemented for vehicles
- Difficult to efficiently model across many relevant length scales



Advanced High Strength Steel

15-25% weight reduction→

- Inadequate structure/properties understanding to propose steels with 3GAHSS properties
- Insufficient post-processing technology/understanding
- What other relevant properties should be considered? Hydrogen embrittlement, local fracture, etc.



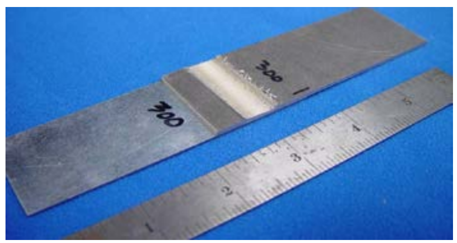
Choi et. al., Acta Mat. **57** (2009) 2592-2604

Multi-material Enabling

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

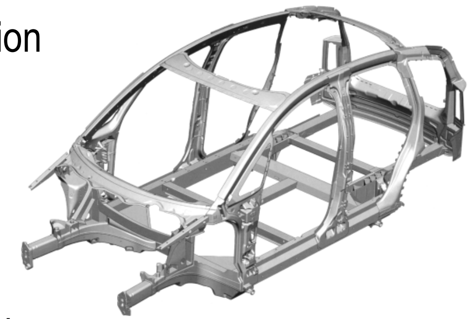
Magnesium Alloys

- Corrosion (galvanic and general)
- Difficulty Joining
  - Mg-Mg
  - Mg-X
  - Riveted Joints
- Questionable compatibility with existing paint/coating systems



Aluminum Alloys

- HAZ property deterioration
- Difficulty joining mixed grades
  - Joint integrity
  - Joint formability
- Difficulty recycling mixed grades



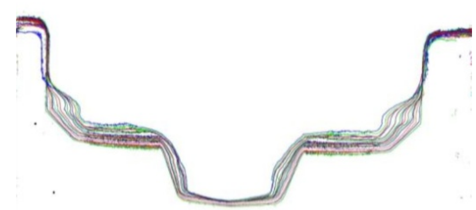
	Mg	Si	Cu	Zn
5182	4.0 - 5.0	< 0.2	< 0.15	< 0.25
6111	0.5 - 1.0	0.6 - 1.1	0.5 - 0.9	< 0.15
7075	2.1 - 2.9	< 0.4	1.2 - 2.0	5.1 - 6.1

Carbon Fiber Composites

- Corrosion and environmental degradation
- Some difficulty joining
- Questions regarding non-destructive evaluation

AHSS

- HAZ property deterioration
- Limited weld fatigue strength
- Tool wear, tool load, infrastructure



Modeling and Computational Materials Science

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

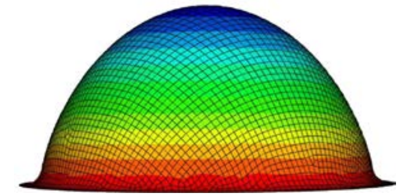
Magnesium Alloys

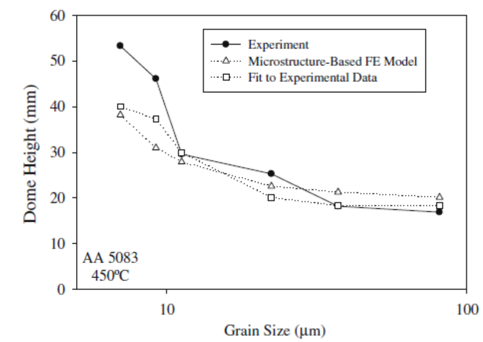
- Complicated deformation in HCP Mg alloys
  - Highly anisotropic plastic response
  - Profuse twinning
- Few established design rules for anisotropy
- Substantial gaps in basic metallurgical data

Q. Ma et al. *Scripta Mat.* **64** (2011) 813–816

Aluminum Alloys

- Basic metallurgical models are well established
- Substantial fundamental data is available
- Useful predictive models established for some conditions
- Truly predictive, multi-scale models are still lacking





P.E. Krajewski et al. *Acta Mat.* **58** (2010) 1074–1086

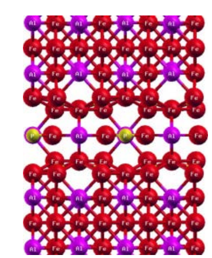
Carbon Fiber Composites

- Insufficient capability in modeling relationships between physical properties, mechanical properties, and ultimately behavior
- Lack of validated, public databases of CFC material properties
- Inadequate processing-structure predictive tools

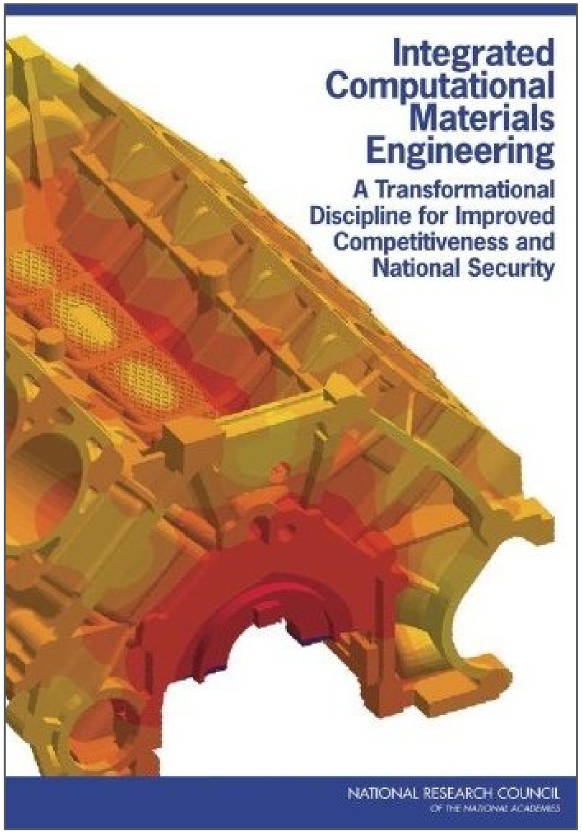
AHSS

- General lack of understanding on structures, phases, and deformation mechanisms to achieve 3GAHSS properties
- Very complicated structures, phases, and deformation mechanisms likely

N.I. Medvedeva et al. Phys. Rev. B **81** (2010) 012105



Integrated Computational Materials Engineering (ICME) Materials Genome Initiative (MGI)



ICME: A growing discipline in materials science and engineering

Replace and/or augment conventional techniques with integrated experimentation and computation to generate material properties used for engineering analysis

MGI: A White House Office of Science and Technology Policy (OSTP) Initiative

Advance and integrate experimental tools, computational tools, and data to reduce the time from discovery to deployment for new materials

The Materials Genome Initiative (MGI)

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

Integrating experimentation, modeling, and theory

- Developing new models
- Implementing models to develop new tools
- Integrating tools to develop new frameworks

Building the foundation for a materials data infrastructure

- Developing best practices and standards for materials data
- Enabling and supporting data infrastructure

Driving a fundamental shift in materials research culture

- Emphasizing cross-discipline, cross-agency, and industry-academic research
- Promoting data sharing, distribution, and citation

Equipping the next-generation materials workforce

- Connecting early-career researchers with industry
- Developing curricular and training programs
- Establishing co-op/intern/detail opportunities

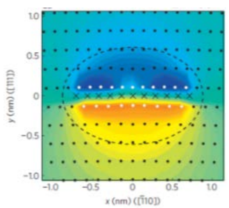
Integrated Computational Materials Engineering (ICME)

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

Start

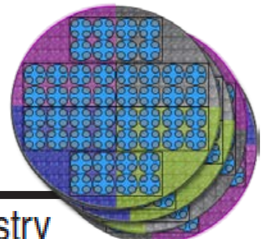
"We want to reduce weight of a shock tower by 15% using Mg alloys while costing no more than $18.50 to produce and integrate into the vehicle"

Atomic Scale Models



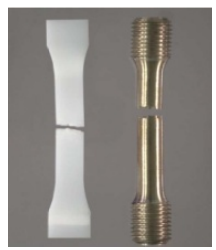
J. Allison, *JOM*, ***63***, *15-18, 2011.*

Material Property Measurements

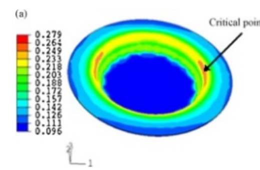


Chemistry
Thermodynamics
Diffusion

Bulk Measurement



Macro-scale Models



Manufacturing Process Simulation

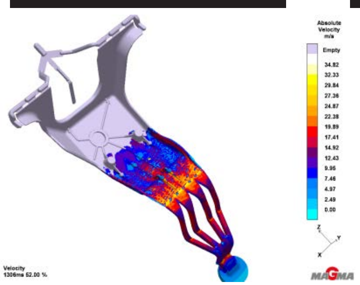
Quantitative Processing-Structure Relationships

Quantitative Structure-Property Relationships

Constitutive Models

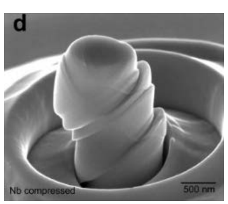
Engineering Product Performance Analysis

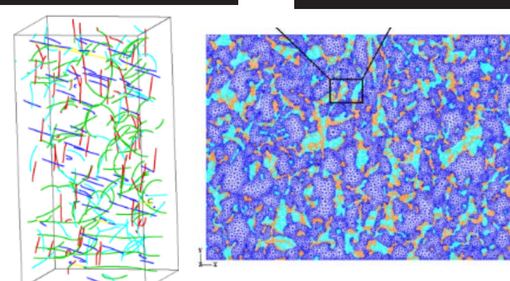
- Process & product optimization
- Innovation



Manufacturing Process Models

Fine-scale Measurement



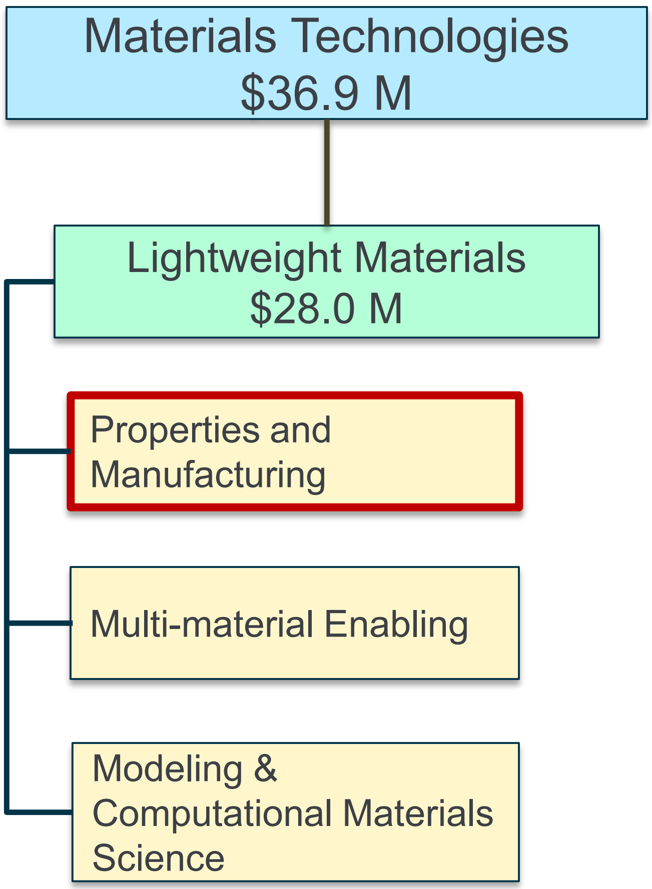


Crystal/Grain Scale Models

System Level Model

Lightweight Materials – Properties and Manufacturability

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



- Carbon fiber (CF)
  - **ORNL**: Advanced oxidation and stabilization of PAN-based carbon precursor fibers
- Light Metals
  - **U. Michigan, PNNL, Ohio State U., Arizona State U., Mississippi State U., ORNL**: Building the scientific foundation for advanced magnesium alloys
  - **INFINIUM**: Scale-Up of low-cost zero-emissions magnesium by INFINIUM electrolysis
  - **PNNL**: Processing an property improvements for aluminum and magnesium alloys, advanced steel microstructure development
  - **USAMP**: Mg Intensive vehicle front end R&D
  - **Xtalic:** High-strength electroformed nanostructured Al for lightweight automotive applications

DOE Vehicle Technologies – Supporting the MII

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

Objectives: Generate thermodynamic, kinetic, and corrosion data for automotive Mg die casting alloys to fill significant gaps in the reported properties and to enable design of high performance alloys. Partner with NIST to structure data and deliver via NIST Dspace repository.

UNIVERSITY OF MICHIGAN

PI: J. Allison
Coupled modeling and experiment to determine liquid- and solid-state kinetics in die castings
DOE Funding: $600k

ASU

PI: K. Sieradzki
Synthetic microstructures and atomistic modeling to explore microstructure effects on bulk corrosion
DOE Funding: $500k

OHIO STATE

PI: J.C. Zhao, A. Luo
High-throughput measurement of binary, ternary, and quaternary Mg alloy kinetics in liquid and solid
DOE Funding: $600k

M STATE

PI: M. Horstemeyer
Model development and experimental validation for coupled H_2 evolution and corrosion damage model
DOE Funding: $500k

Pacific Northwest NATIONAL LABORATORY

PI: A. Rohatgi
Dynamic-TEM measurement of Mg liquid- and solid-state kinetics with ~500ns resolution
DOE Funding: $500k

OAK RIDGE National Laboratory

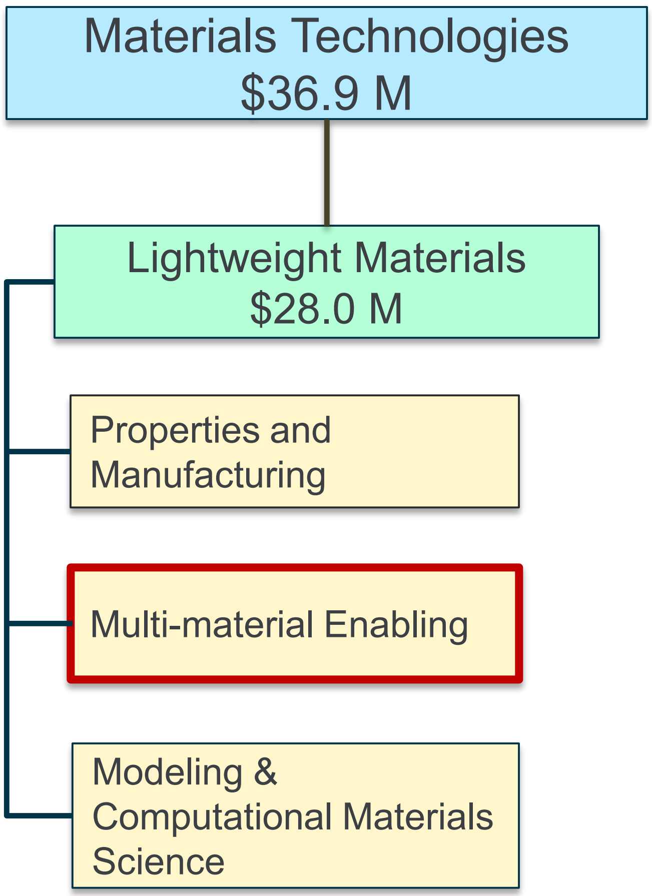
PI: G. Song
Systematic experimental test of passivation behavior for wide range of Mg-X solid solutions
DOE Funding: $600k

NIST National Institute of Standards and Technology U.S. Department of Commerce

- All PIs will work with NIST to determine best format, content, and meta-data
- All PIs will upload project data to a NIST repository where it will be publicly available, searchable, useable, etc.
- All data will be assigned a persistent identifier for citation and connection with publications

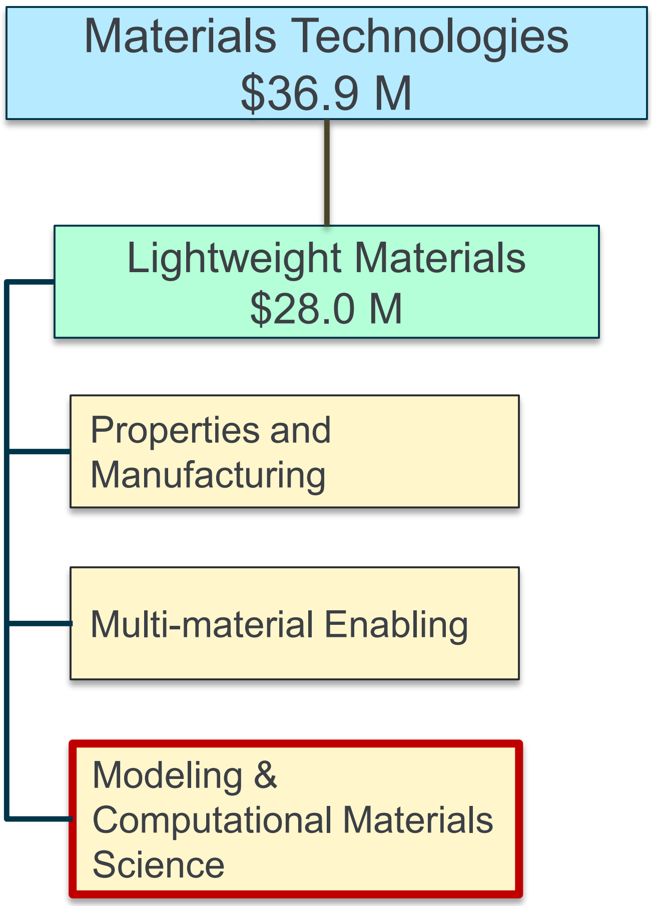
Lightweight Materials – Multi-Material Enabling

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



- Cross-cutting
  - **Vehma and Ford**: Multi-materials lightweight vehicle
  - **IBIS** : Technical cost modeling of lightweight vehicles
- Light Metals
  - **Chrysler, Ohio State, Johns Hopkins, ORNL, Michigan State**: Breakthrough concepts in multi-material joining
  - **ORNL:** Fundamentals of Mg corrosion in automotive-relevant environments
  - **ORNL**: Demonstrating techniques for AHSS and mixed material joining
  - **PNNL**: Demonstrating techniques for Al and Mg joining

Lightweight Materials – Modeling and Computational Materials Science



- Carbon fiber (CF) and carbon fiber composites (CFC)
  - **USAMP** : Validation of material models for automotive carbon fiber composites
- Light Metals
  - **PNNL** : Mechanistic-based ductility predictions for complex Mg castings
  - **USAMP** : ICME development of advanced steel for lightweight vehicles

2014 Accomplishments

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

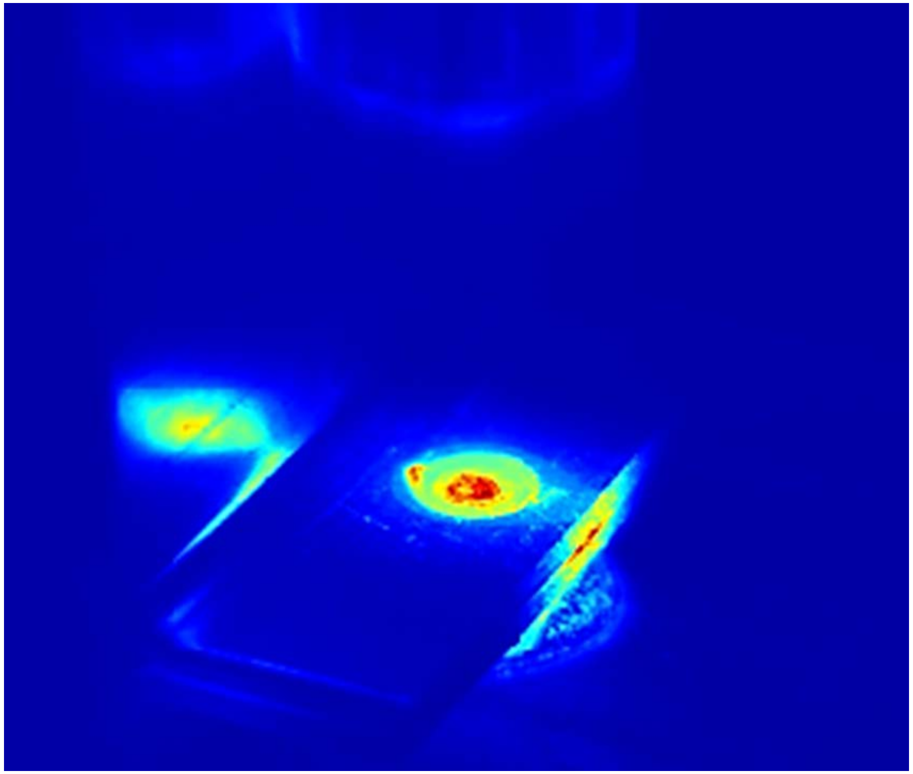
Developed and deployed Al friction stir welded tailor welded blank process technology with weight reduction potential of up to 60% versus conventional techniques

This technology is now implemented in production at the TWB facility in Monroe, MI, with capacity of up to 250,000 parts per year

Pacific Northwest National Lab, General Motors, Alcoa, TWB LLC

2014 Accomplishments

Developed a non-contact, non-destructive infrared weld inspection technology suitable for use in a production environment. This technology is licensed by ALPAIR Manufacturing Systems for development into a commercial product.

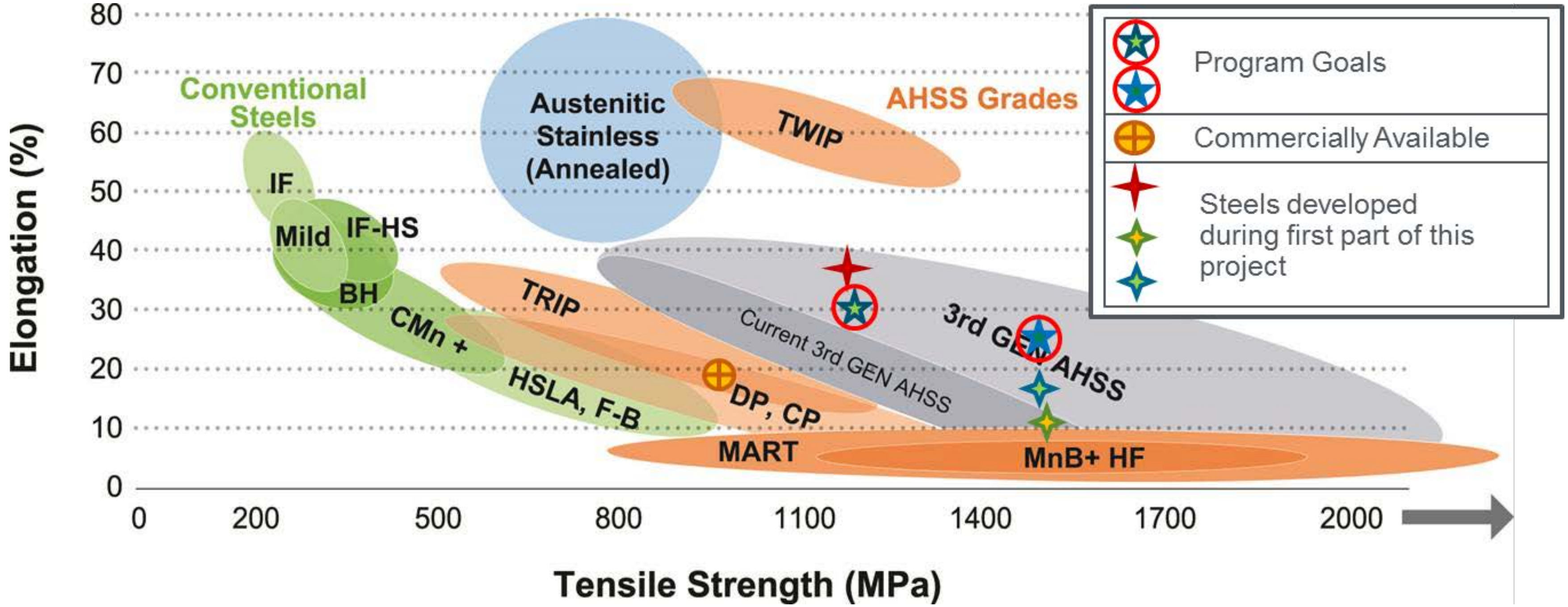


Oak Ridge National Laboratory

2014 Accomplishments

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

Demonstrated the first version of new advanced high strength steels nearly meeting the program targets and enabling significant weight reduction



USAMP, AS/P, Brown U., Clemson U., Colorado School of Mines, Michigan State U., U. Illinois, PNNL, EDAG, LSTC

2014 Accomplishments

Completed prototype design, build, and testing of a multi-material lightweight vehicle (MMLV) demonstrating:

- ***More than 23% weight reduction***
- ***16% reduction in GHG and primary energy in Life Cycle Analysis***
- ***Safety testing and consumer comfort requirements show promising results***
- ***2013 Ford Fusion baseline vehicle***

Investigations and early testing of the MMLV carbon fiber wheels helped speed the development of the carbon fiber wheel for the new Mustang Shelby GT350R

VEHMA, Ford Motor Company

Contact Information

- Stephen Goguen
  - stephen.goguen@ee.doe.gov
- Jerry Gibbs (Propulsion Materials)
  - jerry.gibbs@ee.doe.gov
- Carol Schutte (Lightweight Materials)
  - carol.schutte@ee.doe.gov
- Will Joost (Lightweight Materials)
  - william.joost@ee.doe.gov