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

Energy, Materials, and Vehicle Weight Reduction

Will Joost

Technology Area Development Manager
Lightweight Materials
Vehicle Technologies Program

Vehicle Technologies Program

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

Program Manager
Patrick Davis

Administration
Maxine Robinson
Bernadette Jackson
Johnathan Wicker

FreedomCAR and Fuel Partnership
Director – Christy Cooper
Yury Kalish

21st Century Truck Partnership
Director – Ken Howden

Chief Scientist
James Eberhardt

Analysis
Phil Patterson
Jake Ward

Education and Outreach
Connie Bezanson

Budget Program Analyst
Noel Cole

Supervisory General Engineer
Ed Owens

- **Hybrid Electric Systems**
  Team Lead – Dave Howell
  - **Vehicle Systems**
    Lee Slezak
    David Anderson
  - **Energy Storage**
    Tien Duong
    Brian Cunningham
    Peter Faguy
  - **Power Electronics & Electric Motors**
    Susan Rogers
    Steven Boyd
- **Materials Technology**
  Team Lead – Carol Schutte
  - **Lightweight Materials**
    Will Joost
  - **Propulsion Materials**
    Jerry Gibbs
  - **HTML**
    Carol Schutte

Supervisory General Engineer
Steve Goguen

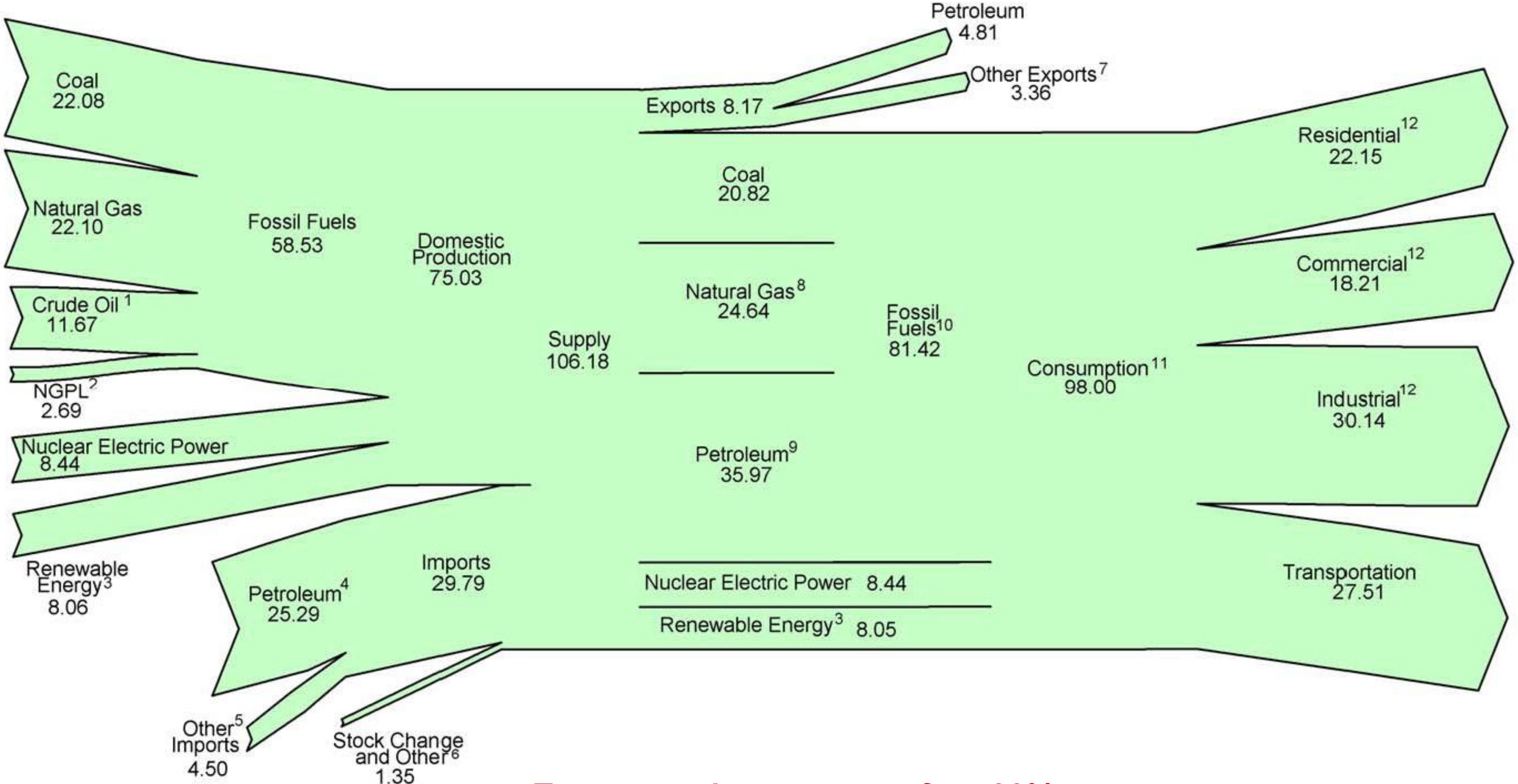
- **Fuels Technology**
  Team Lead – Kevin Stork
  - **Advanced Petroleum Based Fuels**
    Steve Przesmitzki
  - **Non-Petroleum Fuels**
    Dennis Smith
  - **Technology Integration/ Clean Cities**
    Dennis Smith
    Linda Bluestein
    Shannon Shea
    Mark Smith
  - **Legislation/Rulemaking**
    Dana O'Hara
- **Advanced Combustion Engine R&D**
  Team Lead – Gurpreet Singh
  - **Combustion & Emission Controls**
    Ken Howden
    Roland Gravel
  - **Solid State Energy Conversion**
    John Fairbanks

The Plan

- *Why reduce vehicle weight?*
- *What does weight reduction look like today?*
- *How can we move forward?*

U.S. Total Energy Flow (QBtu) - 2010

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

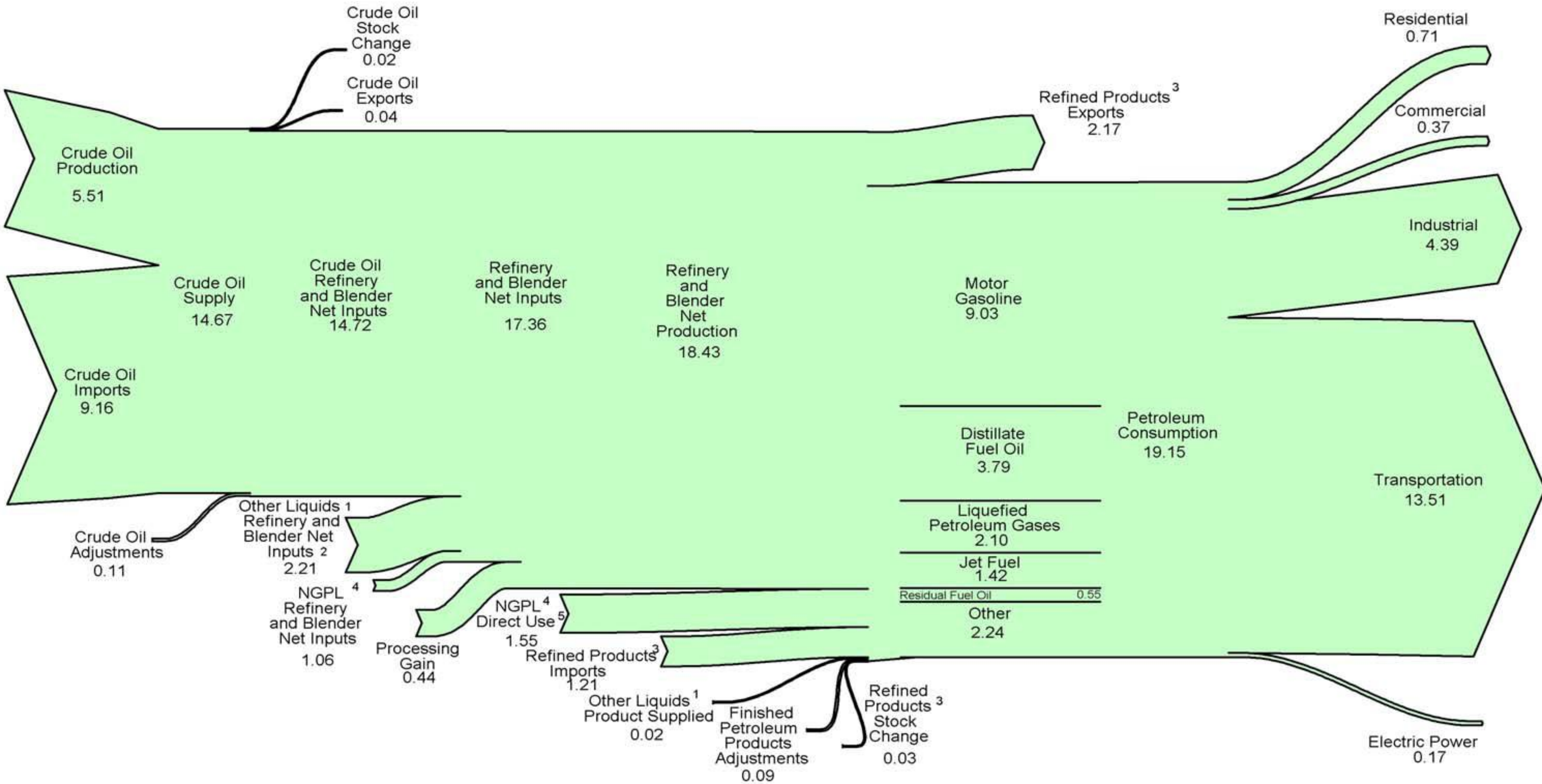


Transportation accounts for ~28% of U.S. energy consumption

Energy Information Administration (www.eia.gov)

U.S. Petroleum Flow (Mbpd) - 2010

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

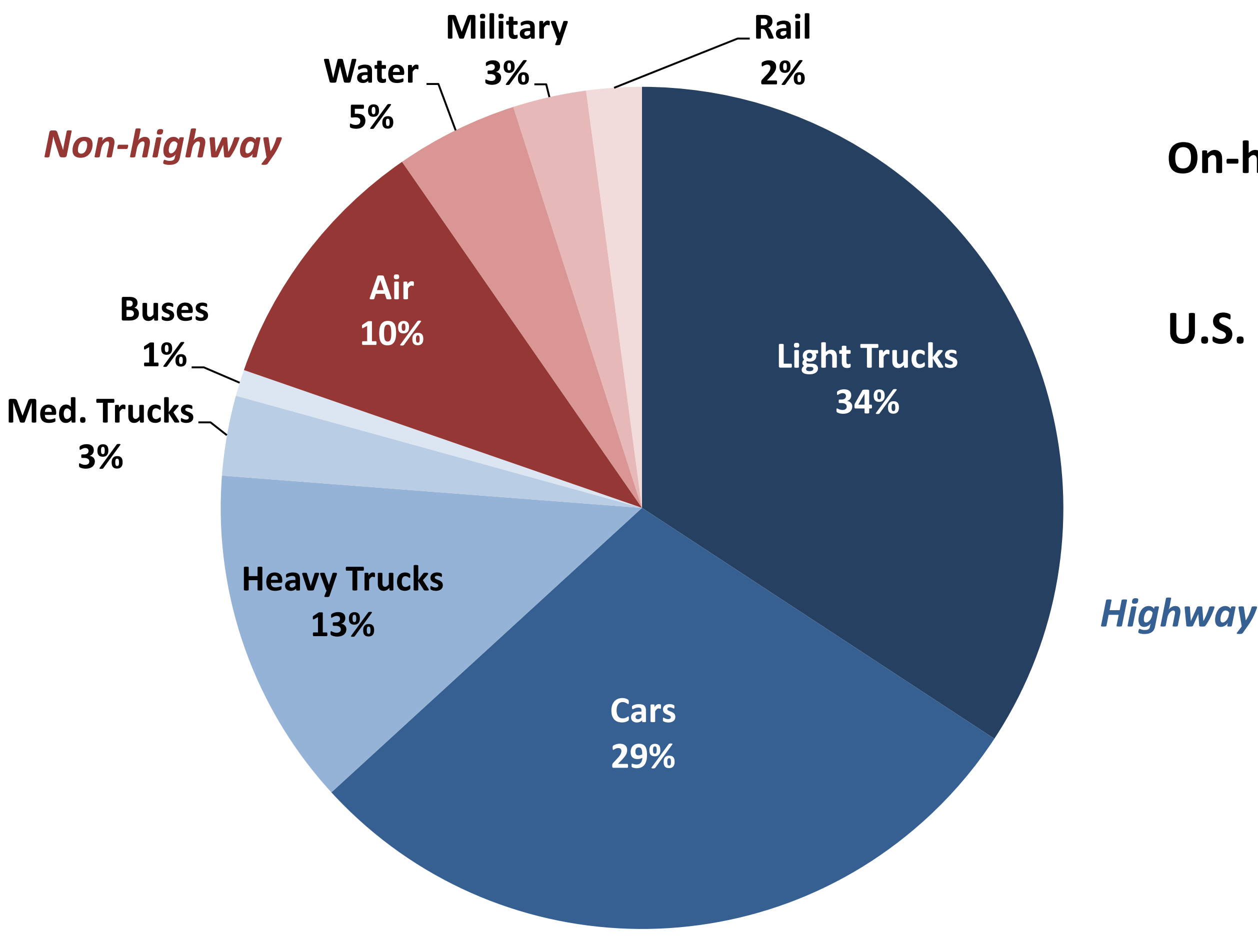


94% of transportation energy is from petroleum

71% of petroleum is used in transportation

Energy Information Administration (www.eia.gov)

Transportation Energy Consumption by Mode - 2009



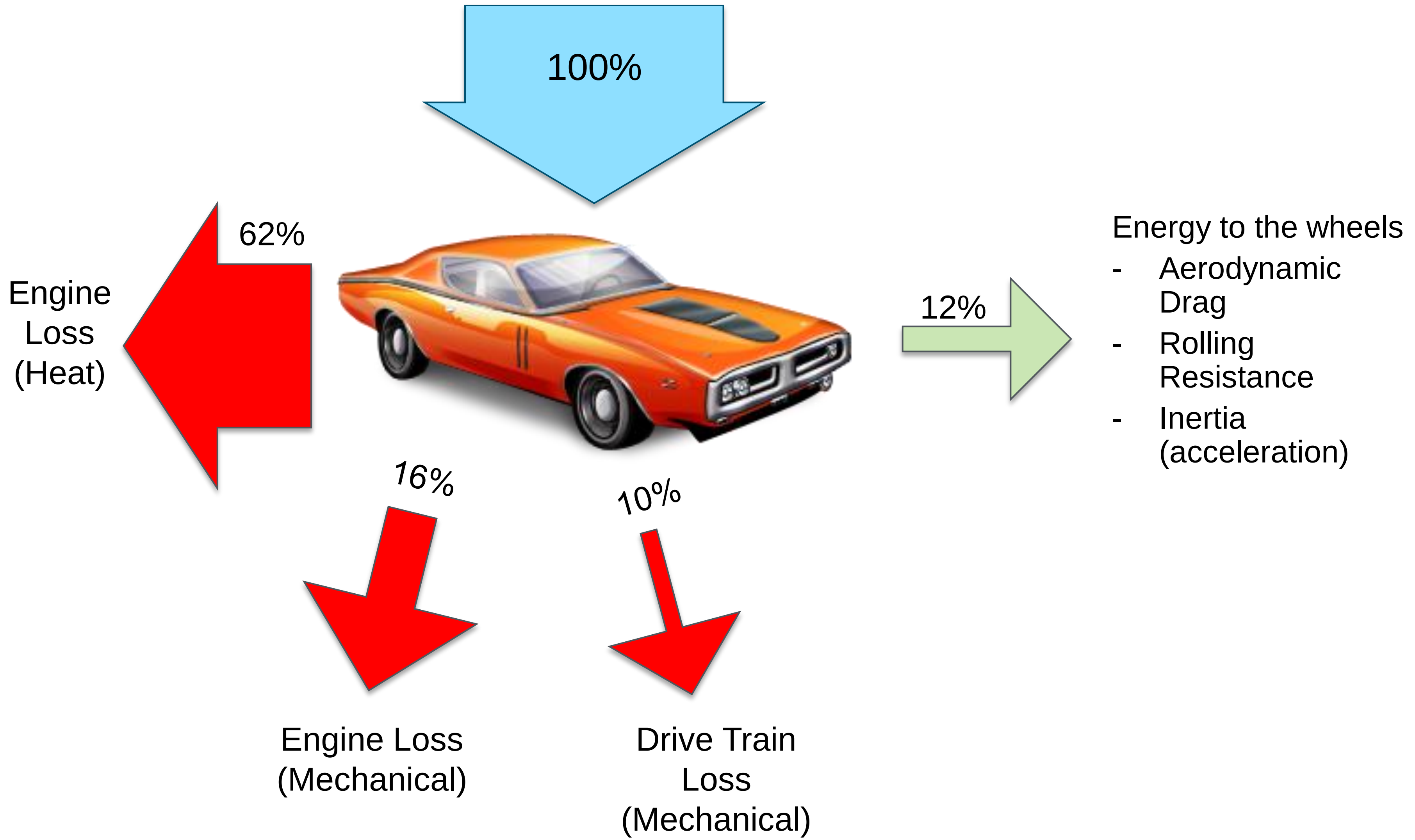
On-highway consumption → ~10.6 mbpd

U.S. domestic production → ~5.3 mbpd

Energy Information Administration (www.eia.gov)

Energy flow in a typical ICE vehicle

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



Mass and Fuel Consumption

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

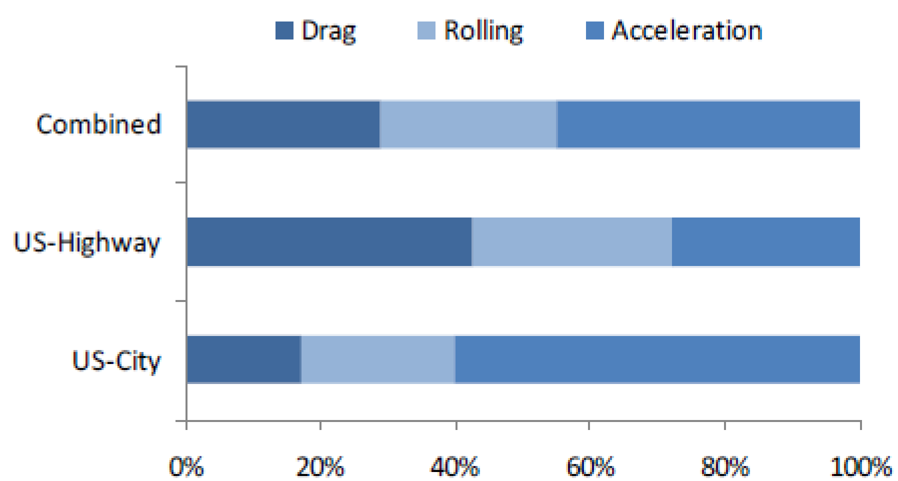
$$\text{Fuel Consumed} = \frac{\int b \cdot \left(\frac{F_T \cdot V}{\eta}\right) dt}{\int V dt}$$

b = **Specific Fuel Consumption (Heat/Mech Loss)**

F_T = **Tractive Forces (Drag, Inertia, Rolling)**

η = **Drivetrain Efficiency (Mechanical Loss)**

$$F_T = F_{ROLL} + F_{ACCEL} + F_{AERO} = (fmg) + (ma) + \left(\frac{1}{2} C_D \cdot \rho_{AIR} \cdot V^2 \cdot A\right)$$



Cheah, L. Cars on a Diet: The Material and Energy Impacts of Passenger Vehicle Weight Reduction in the U.S., 2010.

The Mass Effect

- We know that mass affects tractive forces
  - Rolling resistance, inertial forces
- The relationship between mass and energy consumption is complicated by a variety of factors
  - Averages/fleet mix
  - Mass compounding
  - Vehicle design
  - Powertrain resizing
  - Material energy content

- *So how does vehicle mass affect vehicle efficiency?*

What can weight savings do for you?

Improve performance

- Fuel economy
- Acceleration
- Gradability
- Handling/Feel
- Safety?

Increase freight efficiency

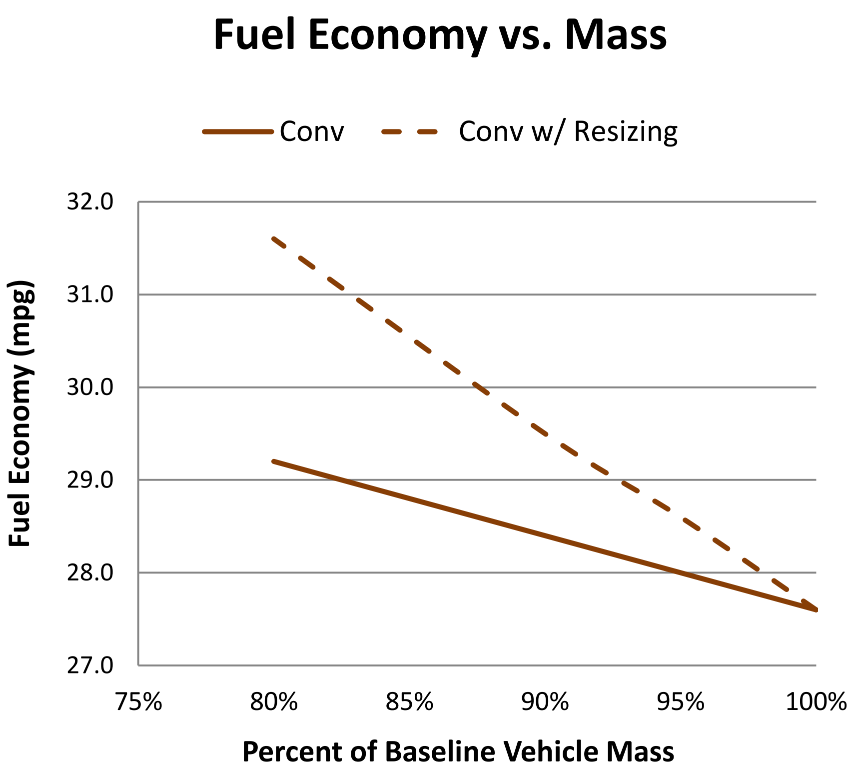
- Freight efficiency when weight limited
- Fuel efficiency when volume limited

Extend electric range

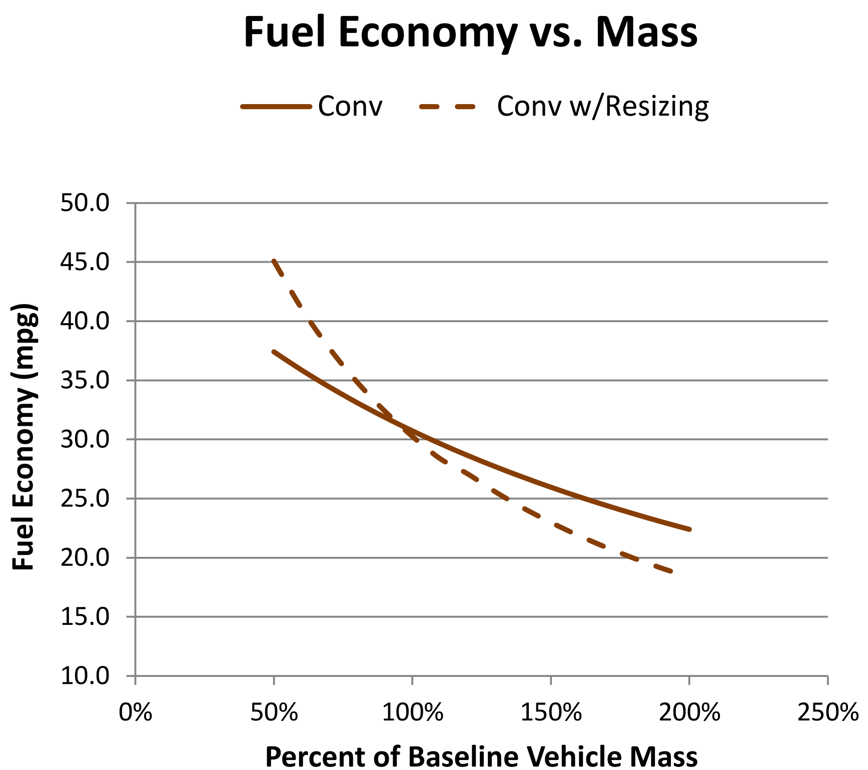
- Increase range with existing battery
- Maintain range with smaller battery
- Optimize for requirements

Weight Reduction and Fuel Economy

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



Ricardo Inc., 2008

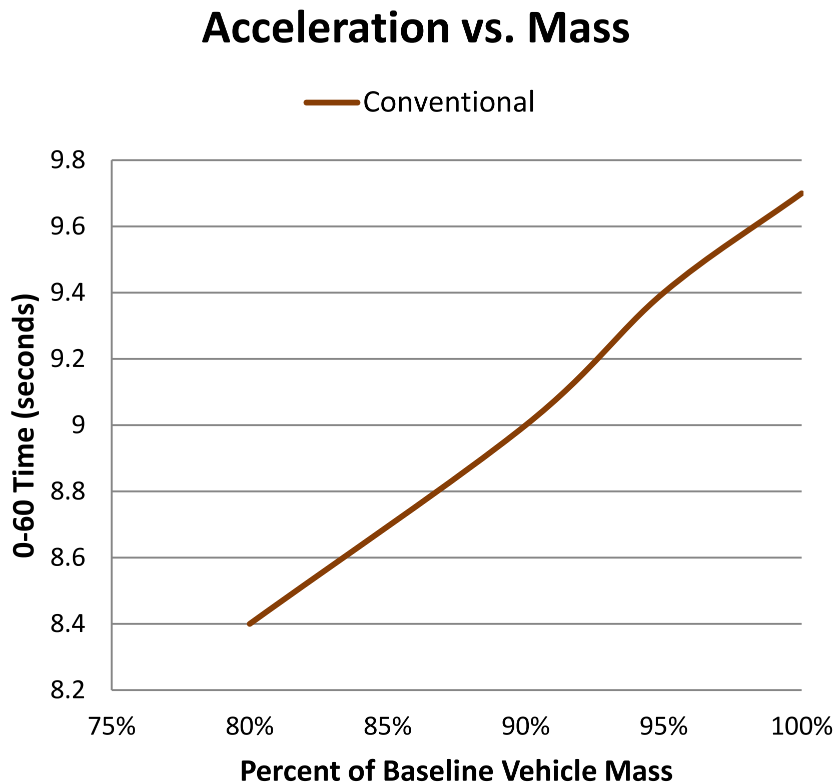


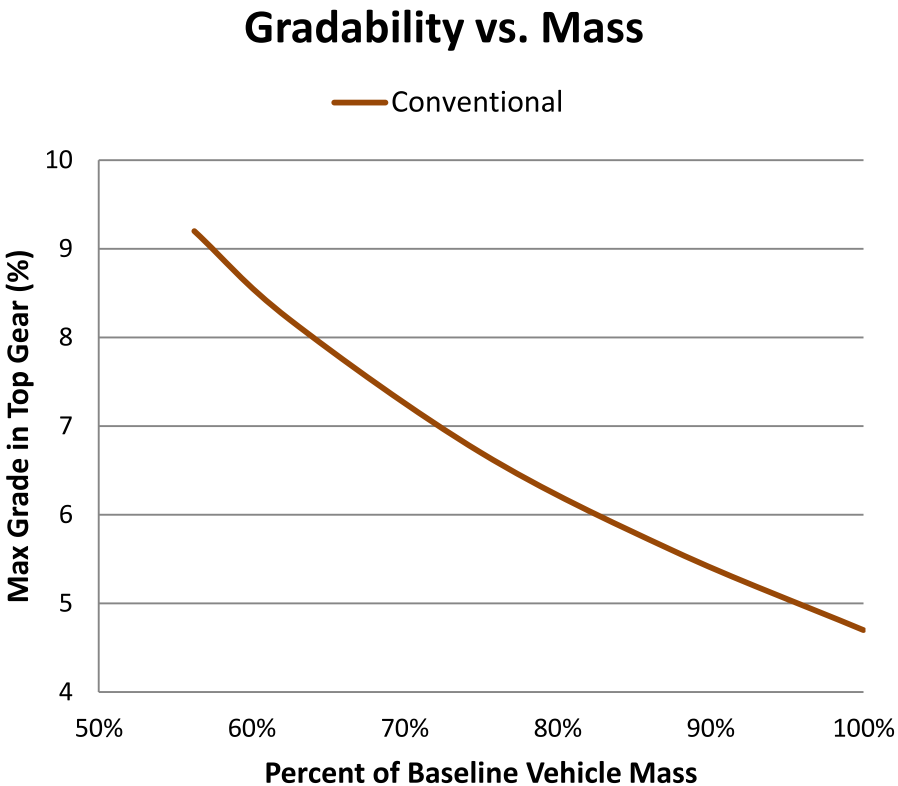
FAST Model, NREL 2011

Conv. Midsize Sedan: 6.8% improvement in fuel economy for 10% reduction in weight

Conv. Midsize Sedan: 6.9% improvement in fuel economy for 10% reduction in weight

Weight Reduction and Performance





Ricardo Inc., 2008

Conv. Midsize Sedan: 7% improvement in 0-60 time for 10% reduction in weight

Conv. Midsize Sedan: 25% improvement in gradability for 10% reduction in weight

Performance improvements compete with resizing → design objectives

Heavy Duty Vehicles

+

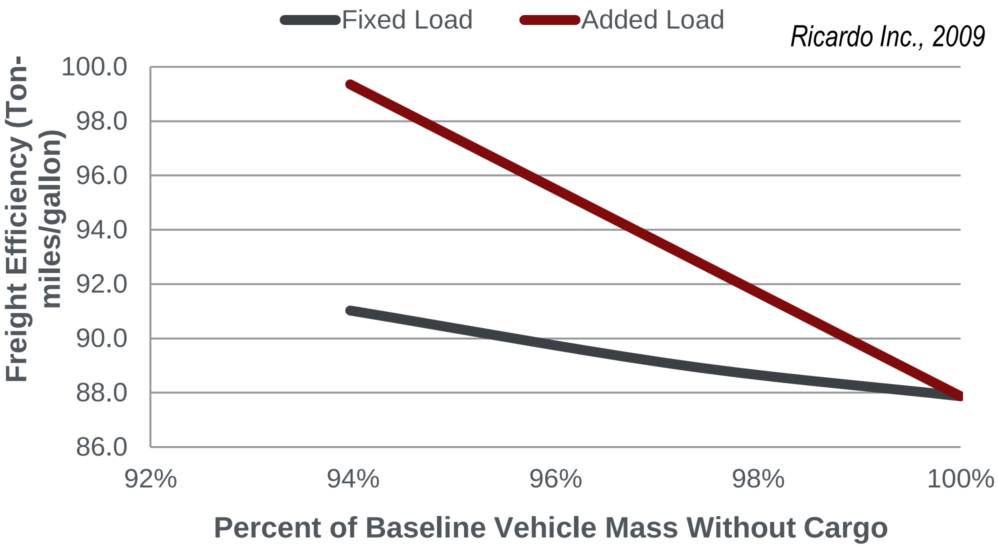
= **80,000 lbs**

Empty Trailer
13,000 lbs (16%)

Tractor
16,000 lbs (20%)

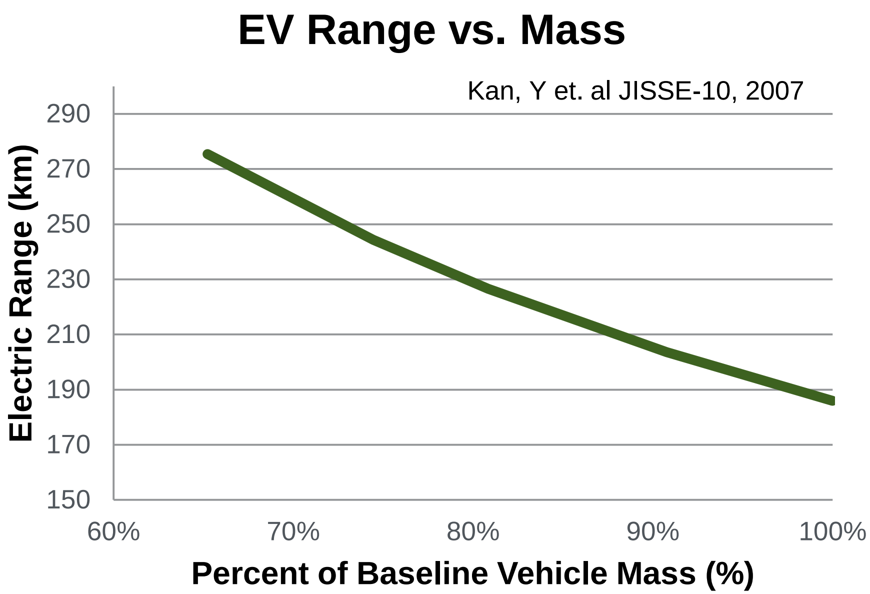
Cargo
51,000 lbs (64%)

- 50% reduction in tractor/trailer weight
  - → 23% reduction in total weight
- You can't "lightweight" cargo
  - → You can increase freight efficiency



Weight Reduction and "Electric Vehicles"

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

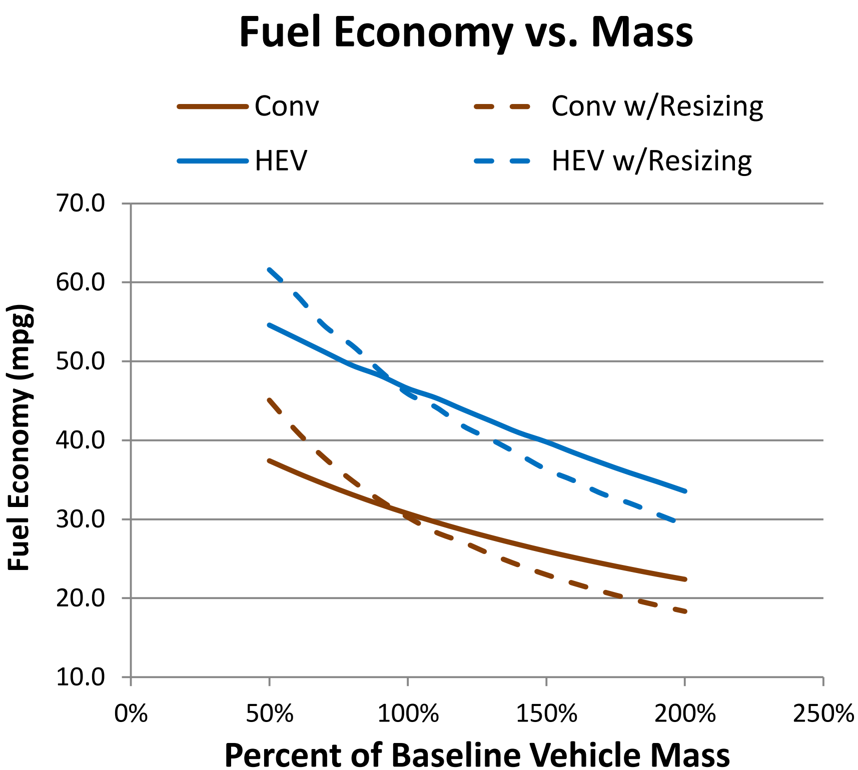


BEV Midsize Sedan: 13.7% improvement in electric range for 10% reduction in weight

Battery Cost Savings

- $/kWh fixed
- Fewer kWh to maintain range

… Design balance including cost!



FAST Model, NREL 2011

HEV Midsize Sedan: 5.1% improvement in fuel economy for 10% reduction in weight

The Mass Effect

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

- Directly calculating the impact of vehicle weight reduction on energy consumption is difficult
  – Complicated by mass compounding, design, material energy content, etc.
- Mass reduction does provide improvements
  – Typical ICE Vehicles → Efficiency, performance, and optimization
  – Heavy Duty Vehicles → Freight Efficiency
  – HEV/PHEV/BEV → Range, battery size, and cost

- Impact on Energy Consumption
  – Nearer term: 30% light duty wt. reduction, 15% heavy duty wt. reduction → Potentially more than 2 QBtu per year saved!
  – Longer term: 45% light duty wt. reduction, 25% heavy duty wt. reduction → Potentially more than 3.5 QBtu per year saved!

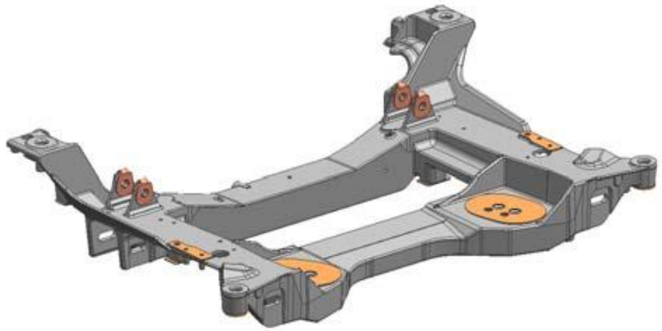
Weight Reduction Potentials

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

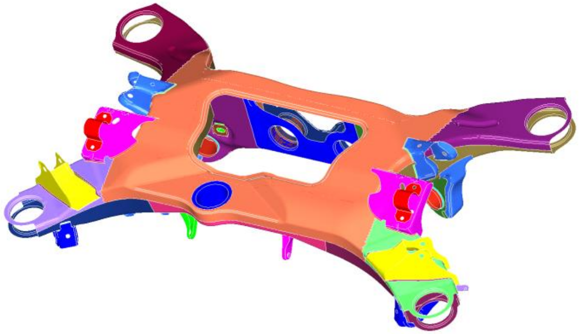
Lightweight Material	Material Replaced	Mass Reduction (%)	Relative Cost Per Part
Magnesium	Steel, Cast Iron	60 - 75	1.5 - 2.5
Carbon Fiber Composites	Steel	50 - 60	2 - 10+
Aluminum Matrix Composites	Steel, Cast Iron	40 - 60	1.5 - 3+
Aluminum	Steel, Cast Iron	40 - 60	1.3 - 2
Titanium	Steel	40 - 55	1.5 - 10+
Glass Fiber Composites	Steel	25 - 35	1 - 1.5
Advanced High Strength Steel	Mild Steel	15 - 25	1 - 1.5
High Strength Steel	Mild Steel	10 - 15	1

Example Component Lightweighting

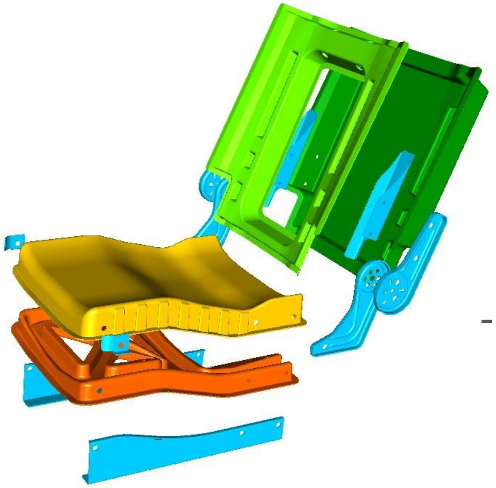
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy



- Mg engine cradle for Corvette Z06
- 35% lighter than Al
- Single piece Mg casting vs. multi-piece steel assembly



- AHSS rear cradle for RWD vehicles
- 27% lighter than conventional design, no loss of stiffness
- Cost neutral

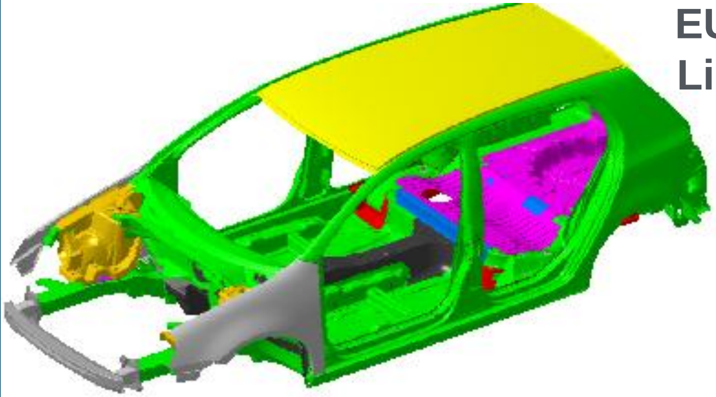


- Carbon Fiber Composite seat structure
- 58% lighter than standard design

- Mg engine block, bedplate, oil pan, and engine cover
- 28% lighter than Al version

Example System Lightweighting

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



EU Super Light Car

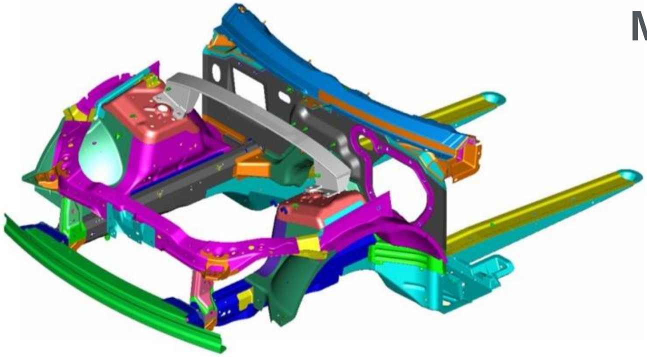
- Multi-material vehicle, Al intensive
- 30% weight reduction for BIW

Energy Foundation - Lotus

- AHSS intensive vehicle
- 16% weight reduction for BIW

PNGV

- Multi-material vehicles
- ~25% overall vehicle weight reduction

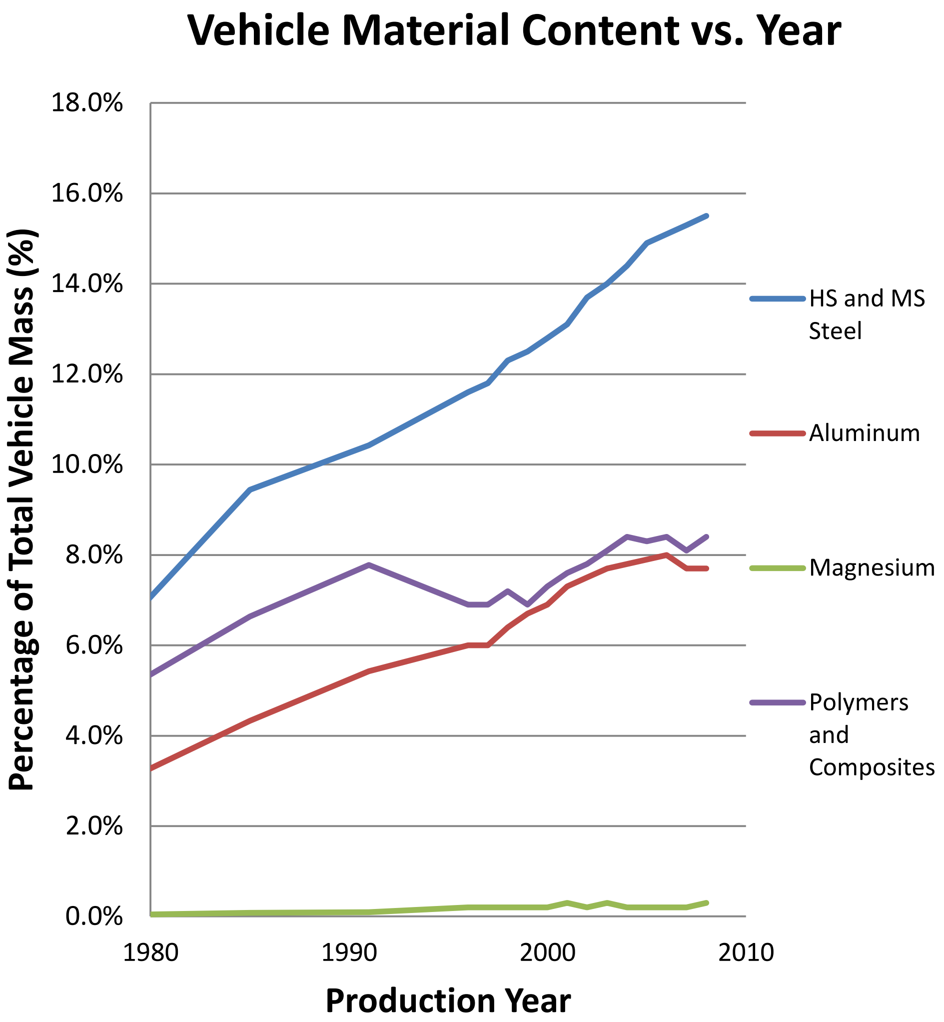


Mg Front End

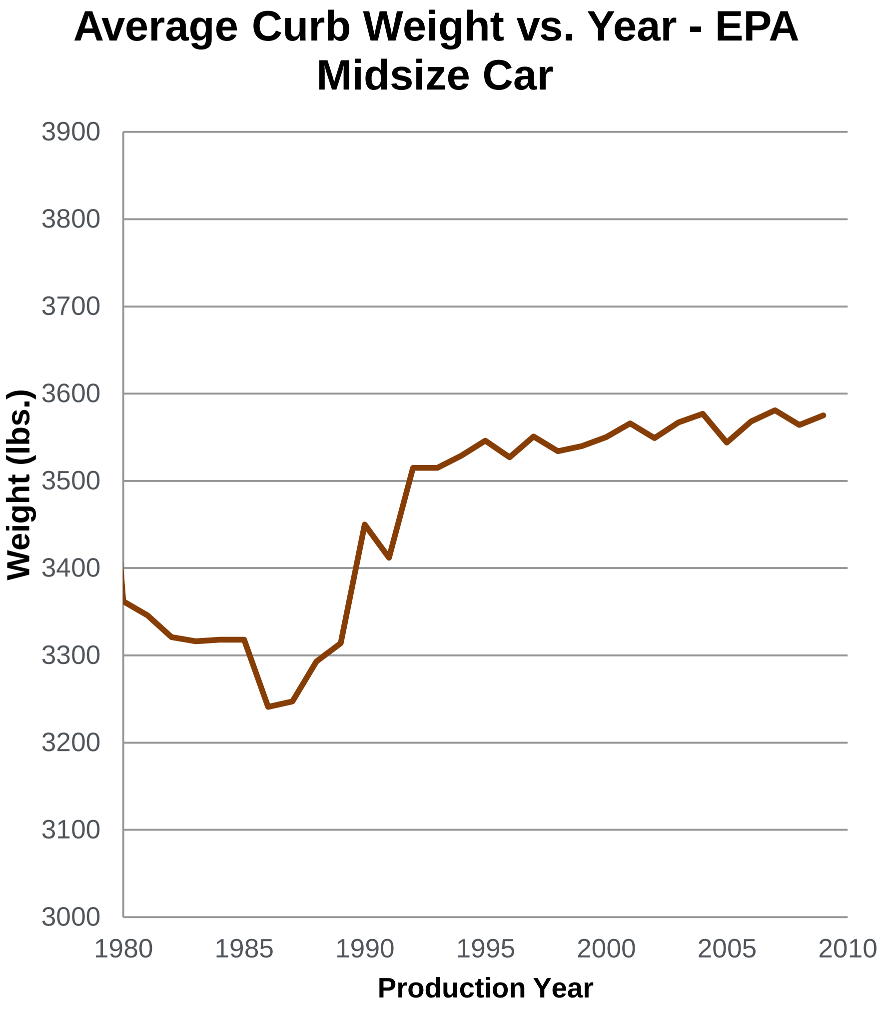
- Mg intensive front end structure
- 45% weight reduction compared to steel
- 56% reduction in part count

Characteristics of Production Vehicles

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



Wards, American Metals Market



EPA

Advanced Material Vehicles

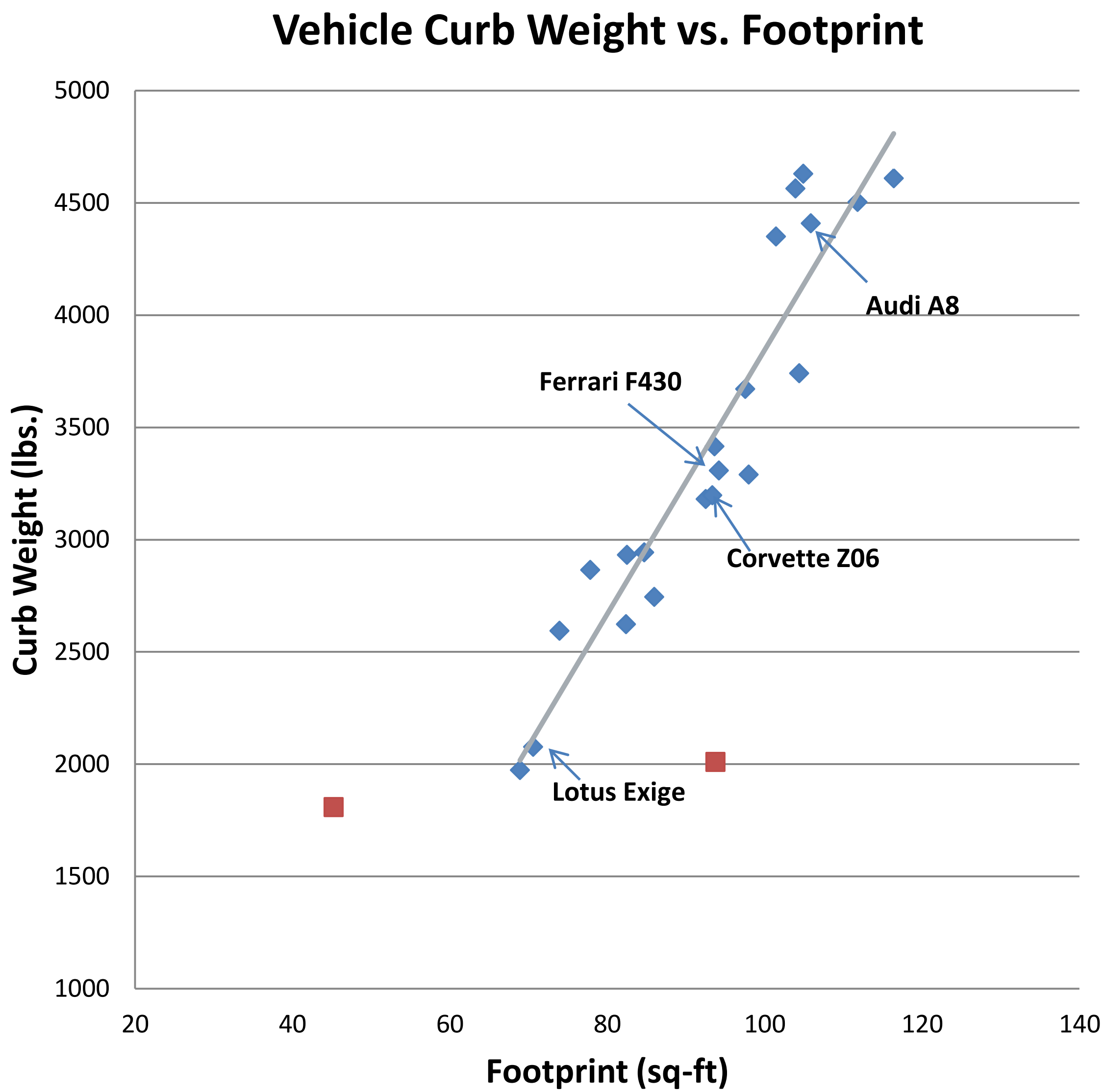
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

- Some advanced material use is "tactical"…

  …hoods, interior pieces, etc.

- A few vehicles use advanced materials at a full-vehicle level…

  …but do not save considerable weight!



The Weight Reduction Story

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

- Lightweight materials have found increased application in production vehicles

- Weight reduction doesn't always result in weight reduction
  - Offset by the addition of new features
  - Offset by improving performance, comfort, design
  - Offset by improving safety and crashworthiness

The materials and design toolbox is growing

Lightweight Materials Strategy

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

Light- and Heavy-Duty Roadmaps

Properties and Manufacturing

- Reducing the cost
  - raw materials
  - processing
- Improving
  - performance
  - manufacturability

Multi-material Enabling

- Enabling structural joints between dissimilar materials
- Preventing corrosion in complex material systems
- Developing NDE techniques

Modeling and Simulation

- Predicting the behavior accurately
- Optimizing complex processes efficiently
- ICME: Developing new materials and processes

Demonstration, Validation, and Analysis

Properties and Manufacturing – Non-Ferrous

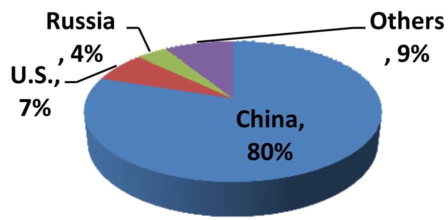
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Magnesium

When it "works" → *Cost (~$2-5/ lb-saved)*

Otherwise →

- Lack of domestic supply, unstable pricing
- Difficulty forming sheet products at low temperatures
- Limited energy absorption in conventional alloys



Aluminum

When it "works" → *Cost (~$1-3/ lb-saved)*

Otherwise →

- Difficulty casting complex, high strength parts
- Insufficient strength in conventional automotive alloys
- Non-conventional alloys benefit from non-automotive heat treatment

Carbon Fiber Composites

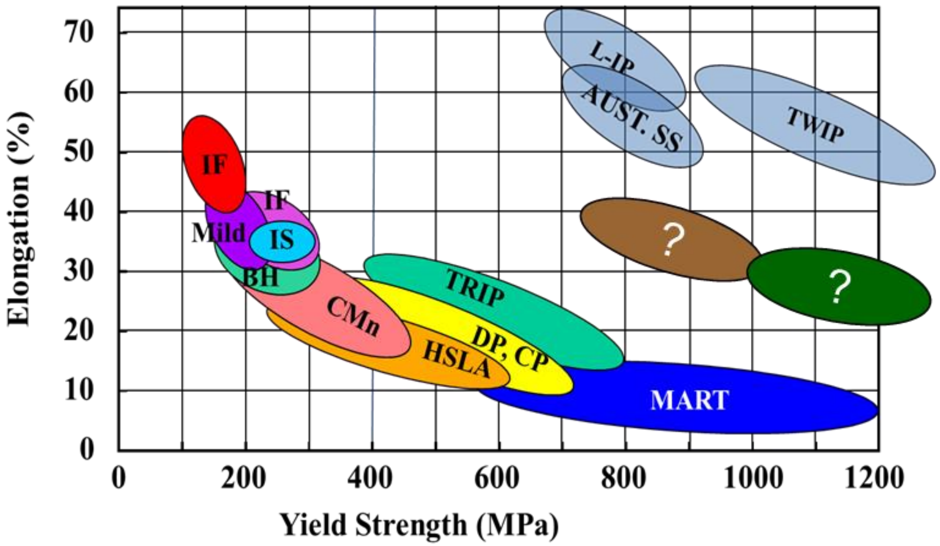
When it "works" → *Cost (~$3-6/ lb-saved)*

Addressing Cost →

- Producing carbon fiber from low cost feedstock (~50% of carbon fiber cost
- Graphitizing carbon fiber more rapidly/efficiently (~23% of carbon fiber cost)

Properties and Manufacturing – AHSS

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



Beating the banana curve

- What other relevant properties should we consider?
- What are the microstructural options to achieve 3G properties?
- Can this be compatible with existing infrastructure? Should it be?

3G…now what?

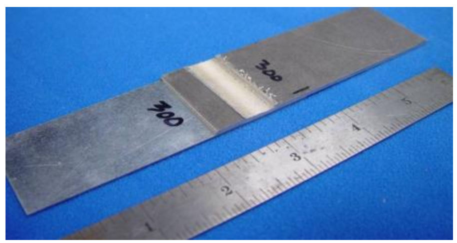
- How do you turn sheet into components?
- How will the steel behave in a crash event?
- What is the system-level weight reduction potential of these steels?
- Does it have to be stamped sheet?

Multi-material Enabling

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

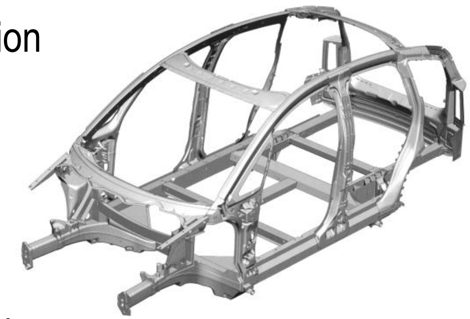
Magnesium

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



Aluminum

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



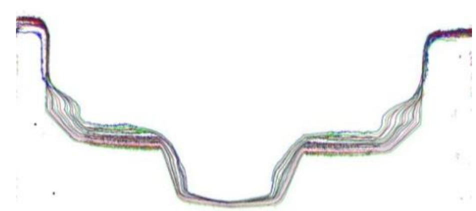
	Mg	Si	Cu	Zn
5182	4.0 - 5.0	< 0.2	< 0.15	< 0.25
6111	0.5 - 1.0	0.6 - 1.1	0.5 - 0.9	< 0.15
7075	2.1 - 2.9	< 0.4	1.2 - 2.0	5.1 - 6.1

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



Multi-material Enabling

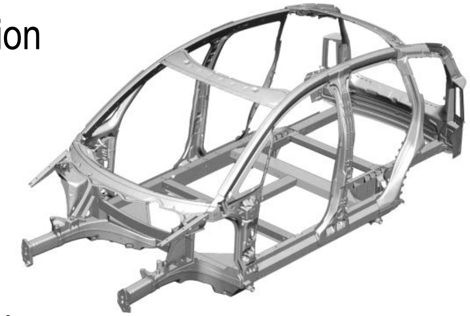
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Magnesium

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

Aluminum

- HAZ property deterioration
- Difficulty joining mixed grades
  - Joint integrity
  - Joint f[illegible]ility
- Di[illegible]g mixed grad[illegible]

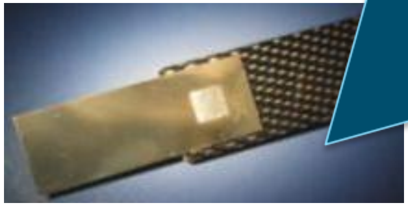


	[illegible]	Si	Cu	Zn
[illegible]	4.0 [illegible] .0	< 0.2	< 0.15	< 0.25
[illegible]11	0.5 - 1.0	0.6 - 1.1	0.5 - 0.9	< 0.15
[illegible]075	2.1 - 2.9	< 0.4	1.2 - 2.0	5.1 - 6.1

?

Carbon Fiber Composites

- Corrosion and environmental degradation
- Some difficulty joining
- Questions regarding non-destruct[illegible]n



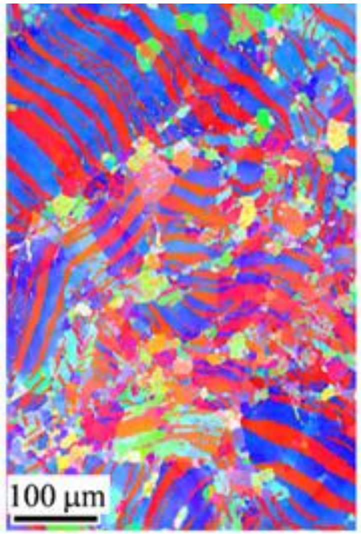
[illegible]SS

- [illegible] property deterioration
- [illegible]veld [illegible]tigue strength
- To[illegible]ad, infrastructure

Modeling and CMS – Non-Ferrous

Magnesium

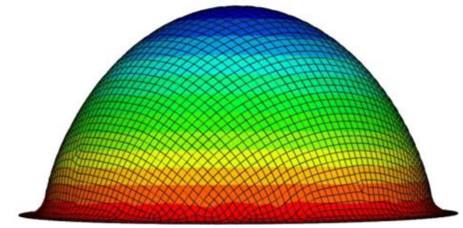
- Complicated deformation in HCP Mg alloys
  - Highly anisotropic plastic response
  - Profuse twinning
- Few established design rules for anisotropy
- Substantial gaps in basic metallurgical data

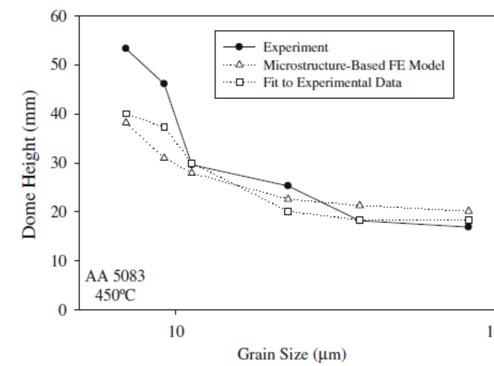


Q. Ma et al. *Scripta Mat.* **64** (2011) 813–816

Aluminum

- 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

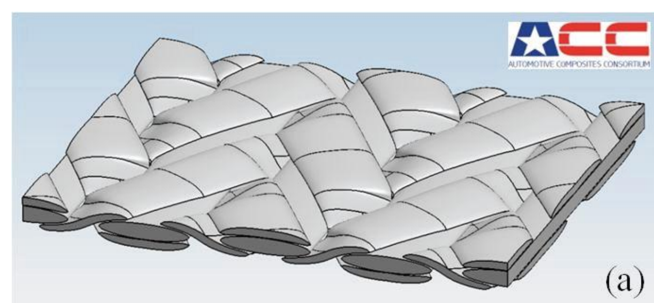




P.E. Krajewski et al. *Acta Mat.* **58** (2010) 1074–1086

Carbon Fiber Composites

- Process-structure models:
  - Difficult to predict fiber orientation and length in long-fiber injection molding
- Structure-property models:
  - Complicated micro/meso/macrostructures make efficient simulation of structural and crash performance difficult



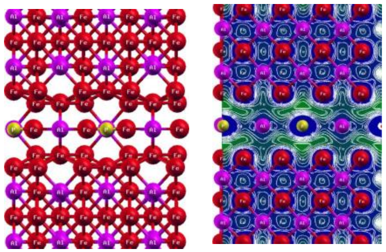
http://www1.eere.energy.gov/vehiclesandfuels/resources/fcvt_reports.html

Modeling and CMS - AHSS

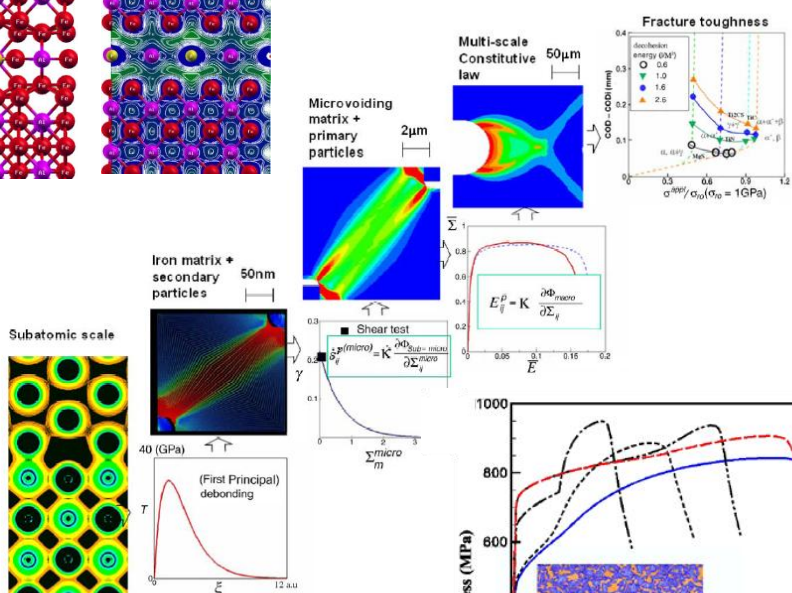
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Beating the banana curve

- There are many paths towards new, advanced properties
  - How can we efficiently optimize the existing approaches?
  - How can we efficiently discover new approaches?

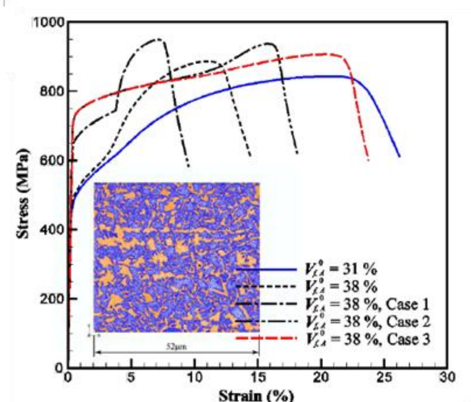


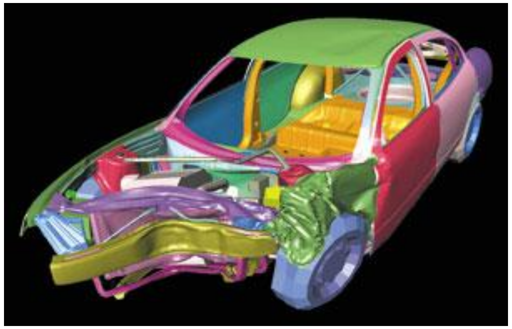
N.I. Medvedeva et al. Phys. Rev. B **81** (2010) 012105



S. Haw at al. Compt. Meth. Appl. Mech. Eng. **193** (2004) 1865-1908

http://www1.eere.energy.gov/vehiclesandfuels/pdfs/merit_review_2010/lightweight_materials/lm020_sun_2010_o.pdf





Predictive Engineering

- Can we apply these techniques to solve engineering problems?
  - Prediction/design for manufacturing?
  - Prediction/design for performance?

Big Picture

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

Energy and Vehicle Weight Reduction

- U.S. transportation energy accounts for 28% of total consumption
- 94% of transportation energy is from petroleum
- The relationship between weight and energy savings is complicated…
- …but significant fuel economy and energy savings are likely

Vehicle Weight Reduction Today

- Lightweight materials (including steels) have seen wider application in vehicles…
- …but vehicle weight has increased!
- Demand for improved safety, comfort, emissions control, etc. has offset weight reduction
- Development of lightweight materials provides a strong foundation for future weight reduction

Moving Forward with Lightweight Materials

- Steel, Aluminum, Magnesium, Carbon Fiber Composites, and other materials will likely play a roll in continued weight reduction
- Significant unanswered questions exist in properties, manufacturing, multi-material enabling, and modeling/simulation of these materials
- **Where does steel need to go from here?**

Mass Reduction, Vehicles, and Energy:

- Cheah, L.W. Cars on a Diet: The Material and Energy Impacts of Passenger Vehicle Weight Reduction in the U.S. Ph.D. Dissertation, Massachusetts Institute of Technology, Cambridge, MA, 2010.
- Lutsey, N. Review of Technical Literature and Trends Related to Automobile Mass-reduction Technology, Institute of Transportation Studies, UC Davis, 2010.

EERE Vehicle Technologies Program Resources:

- Annual Reports

  http://www1.eere.energy.gov/vehiclesandfuels/resources/fcvt_reports.html
- Annual Review Presentations

  http://www1.eere.energy.gov/vehiclesandfuels/resources/proceedings/index.html
- Annual Merit Review

  May 16 – 18, 2012, Crystal City (Arlington), VA

william.joost@ee.doe.gov