Overview of Lightweighting Materials
Past, Present and Future

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Numerous supplier and university participants

Outline

- The Role of Lightweighting
- Past
- Present
- Summary and Thoughts on Future

Based upon paper in *Proceedings of the International Auto Body Conference*, Novi, Michigan USA, September 19, 2006

HISTORY

Materials Technologies

- 1970 (to present) – In response to environmental movements of the 1960's, the Clean Air Acts established standards for criteria emissions (carbon monoxide, hydrocarbons, nitrogen and sulfur oxides, and particulates) from transportation vehicles and other sources.
- 1975 to 1986 (and to present) - Energy Policy and Conservation Act of 1975 established Corporate Average Fuel Economy (CAFÉ) standards for light-duty vehicles.
- 1993-2002 – The Partnership for a New Generation of Vehicles (PNGV) between eight US government agencies and "Big Three" automakers, indicated that high-fuel efficiency (80 mpg, 33 km/l) family autos are probably technically viable at a slight cost premium (15%?) through use of alternate power plants (mainly diesel-electric hybrids), advanced design and lightweighting (40%), probably spurred automotive technology worldwide, and provided model for government-industry cooperation.

HISTORY - continued

- 2002 -- PNGV transitioned by President Bush to FreedomCAR with more emphases on fuel-cell vehicles, all varieties of light-duty vehicles ("CAR" stands for Cooperative Automotive Research, not "car") and limited to USCAR and DOE.

  -- Twenty-First Century Truck (21CT) Initiative also formed aimed at heavy-duty vehicles. Lightweighting thrusts eliminated in 2006-7.

- 2002-2007 – President Bush rejects Kyoto Treaty on economic bases but pledges large R&D efforts to provide technological solutions to climate change (e.g., *U.S. Climate Change Strategy*, 2/14/07; G-8 announcement, 5/31/07)

- 2003 – FreedomCAR expanded to include the Hydrogen Fuels Initiative, becomes FreedomCAR and Fuels Initiative, to **explore** technologies for producing and delivering hydrogen for transportation and other uses (the "hydrogen economy"). Energy-supply industry joins. International Partnership for the Hydrogen Economy formed.

Key Drivers and Technology Enablers

Externalities

"Safety" Focus

"Oil Shock"

"Hyper" Global Competition

"Personalized Design and Performance" Customer Experience

Product

Annual Model Change
Design Is King

Fuel Economy Drives Weight Reduction
Lightweight Material Use Intensifies

1950 1960 1970 1980 1990 2000

~300,000 Units/Models

Increasing Automation

50,000-100,000 Units/Models

Plant

Robots

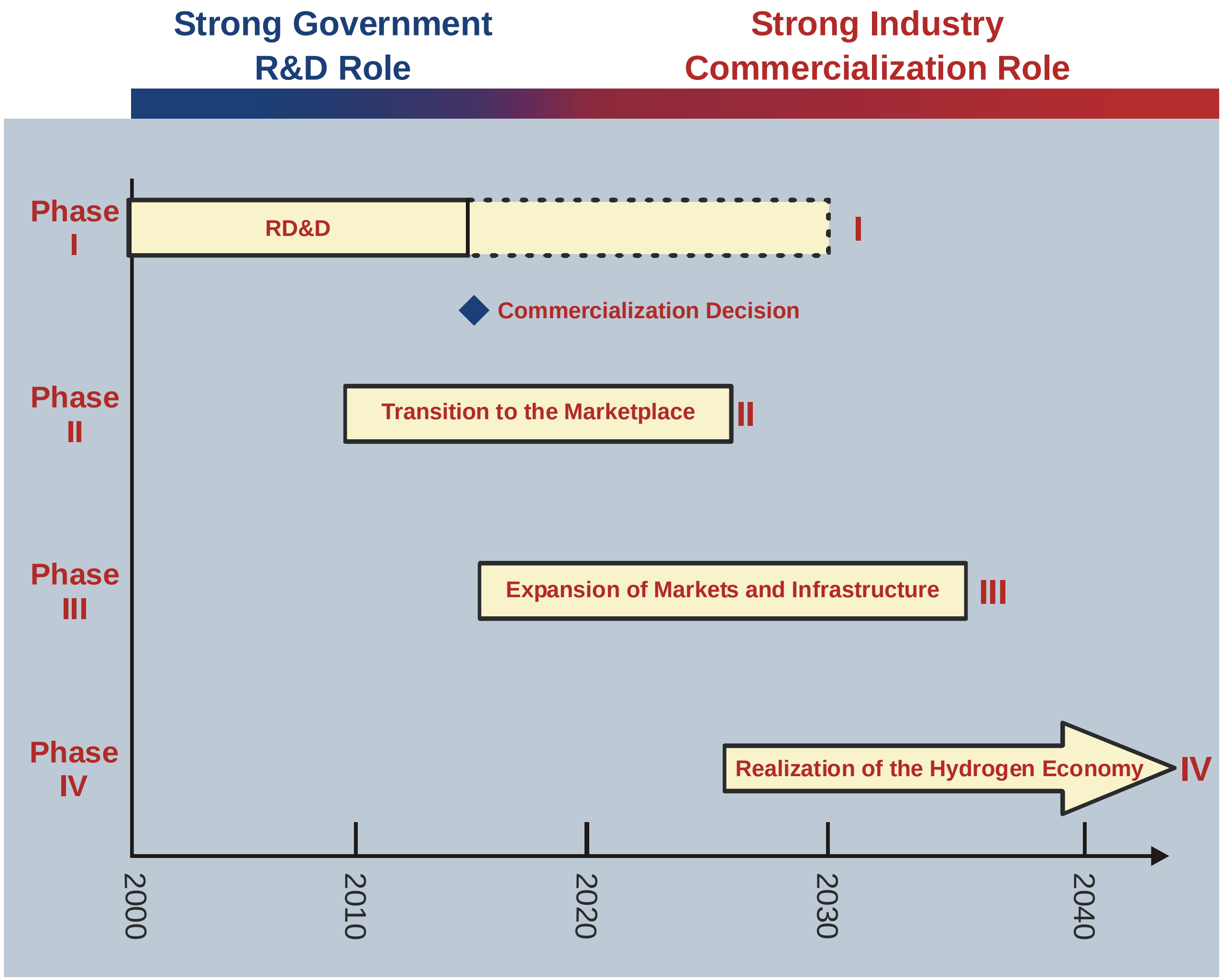
Lean Mfg.

CAD
CAM
CAE

Technology Enablers

Timeline

Materials Technologies



Transitional Phases

I. Technology Development Phase

II. Initial Market Penetration Phase

III. Infrastructure Investment Phase

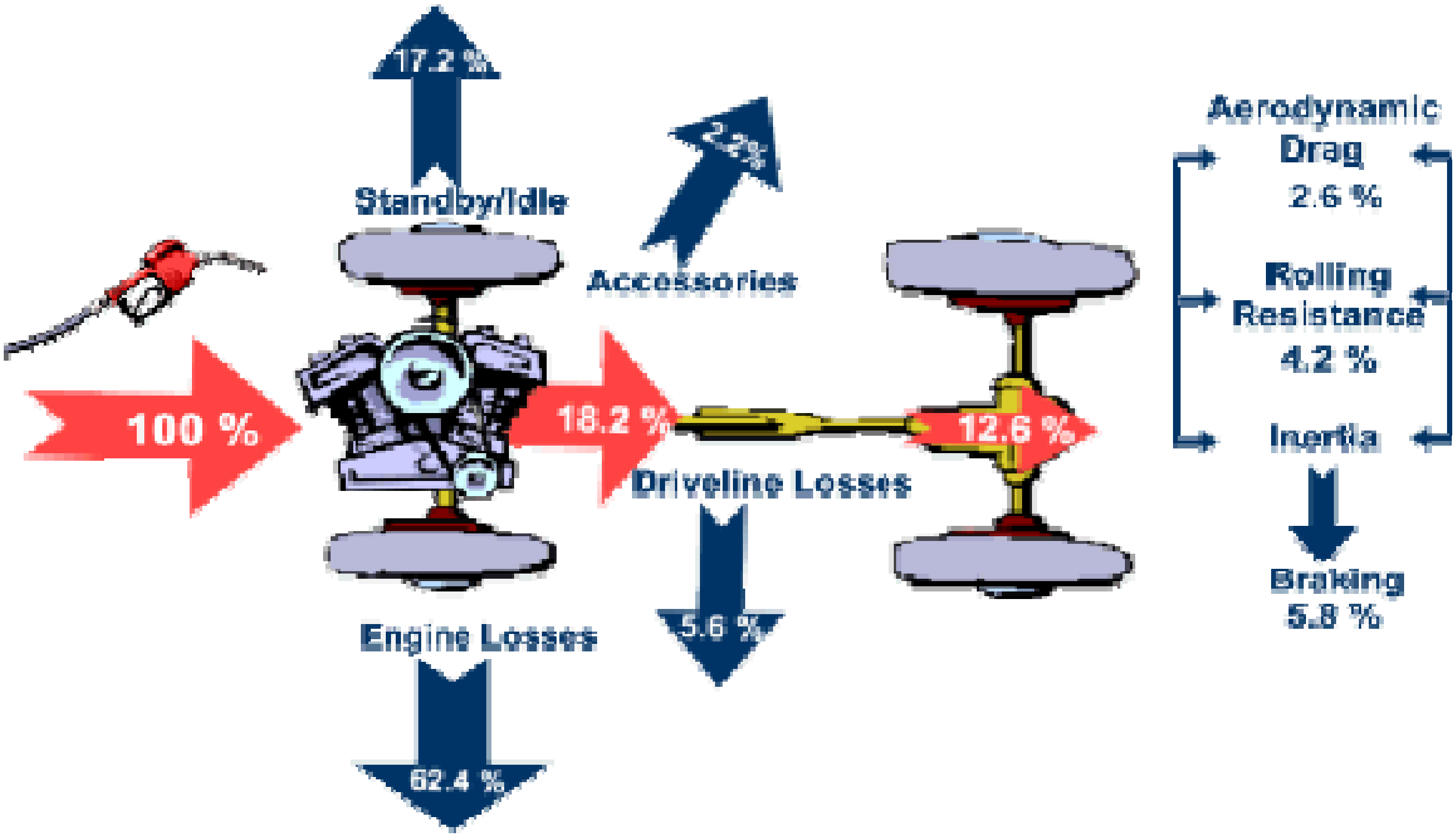
IV. Fully Developed Market and Infrastructure Phase

FreedomCAR Strategic Approach

- Develop technologies to enable mass production of affordable hydrogen-powered fuel cell vehicles and assure the hydrogen infrastructure to support them

- Continue support for hybrid propulsion, advanced materials, and other technologies that can dramatically reduce oil consumption and environmental impacts in the nearer term

- Instead of single vehicle goals, develop technologies applicable across a wide range of passenger vehicles.



Source: http://www.fueleconomy.gov

Effect of Automotive Lightweighting

- 6-8% (with mass compounding) increase in fuel economy for every 10% drop in weight, everything else the same

and/or

- Offset the increased weight and cost per unit of power of alternative powertrains (hybrids, fuel cells) with respect to conventional powertrains (*Alice in Wonderland* syndrome)

Drivers

- Potentially higher prices of fuel.
- The hydrogen-fueled fuel-cell vehicle.
- Increasing “customer value” while staying within Corporate Average Fuel Economy (CAFÉ) limits

Barriers

- Historically low prices of fuel.
- Higher costs of lightweighting materials.
- Lack of familiarity with them.
- Sunk capital in steel-forming technologies.
- Preferences for large vehicles.
- Perceptions of safety.
- Recycling (plastics).

FreedomCAR Technology Specific Goals

Materials Technologies

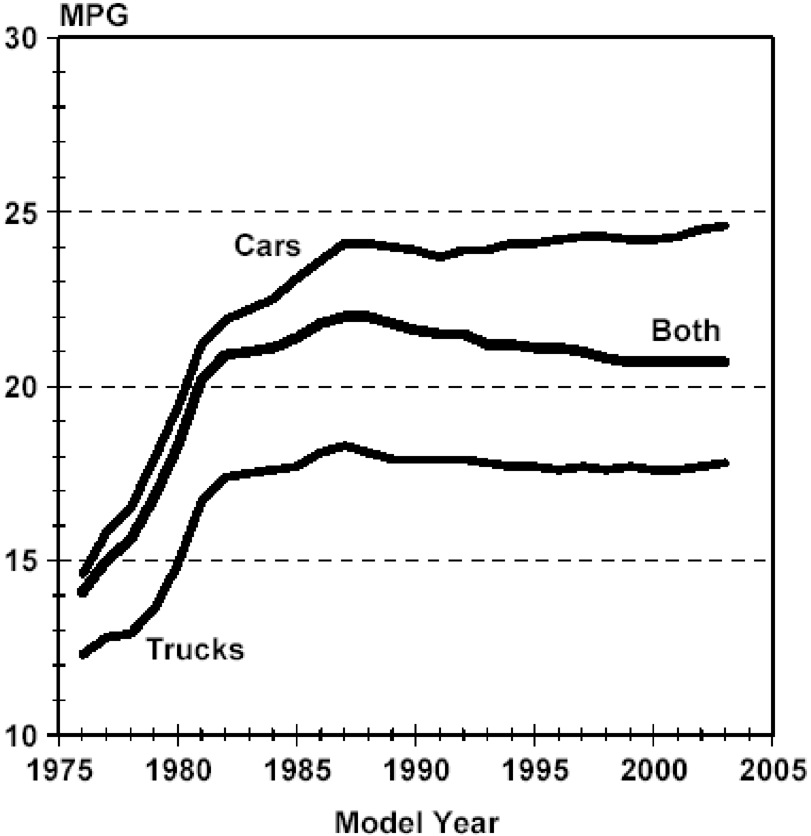
	Efficiency	Power	Energy	Cost*	Life	Weight
Fuel Cell System	60% (hydrogen) 45% (w/ reformer)	325 W/kg 220 W/L		$45/kW (2010) $30kW (2015)		
Hydrogen Fuel/ Storage/ Infrastructure	70% well to pump		2 kW-h/kg 1.1 kW-h/L	$5/kW-h $1.25/gal (gas equiv.)		
Electric Propulsion		$\geq$55 kW 18 s 30 kW cont.		$12/kW peak	15 years	
Electric Energy Storage		25 kW 18 s	300 W-h	$20/kW	15 years	
Materials				Same	Same	50% less
Engine Powertrain System**	45% peak			$30/kW	15 years	

* Cost references based on CY2001 dollar values

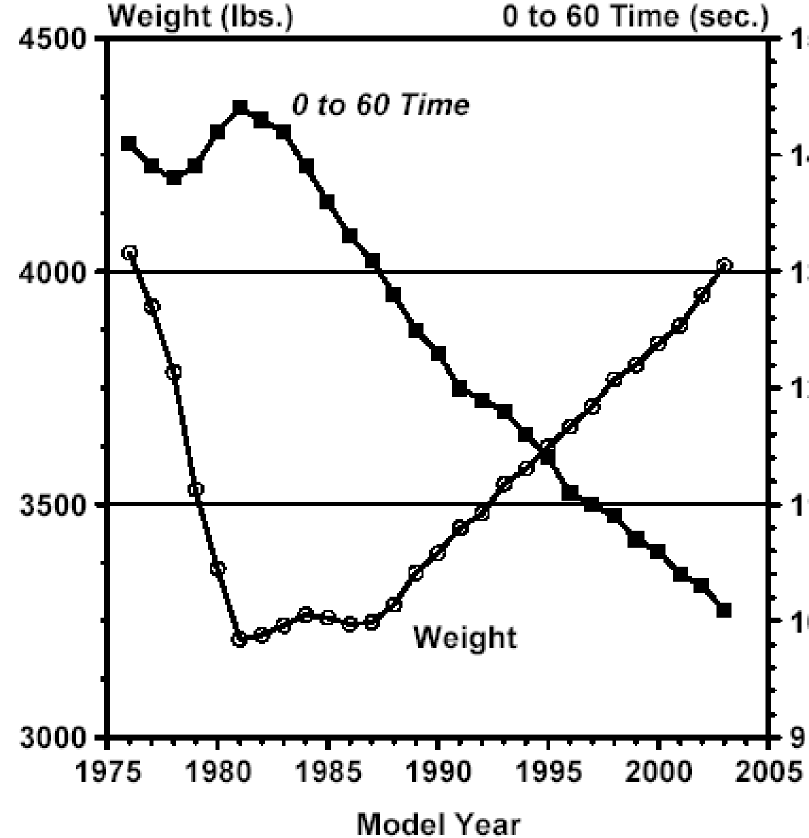
** Meets or exceeds emissions standards.

Light-Duty Vehicle Trends

Adjusted Fuel Economy by Model Year
(Three-Year Moving Average)

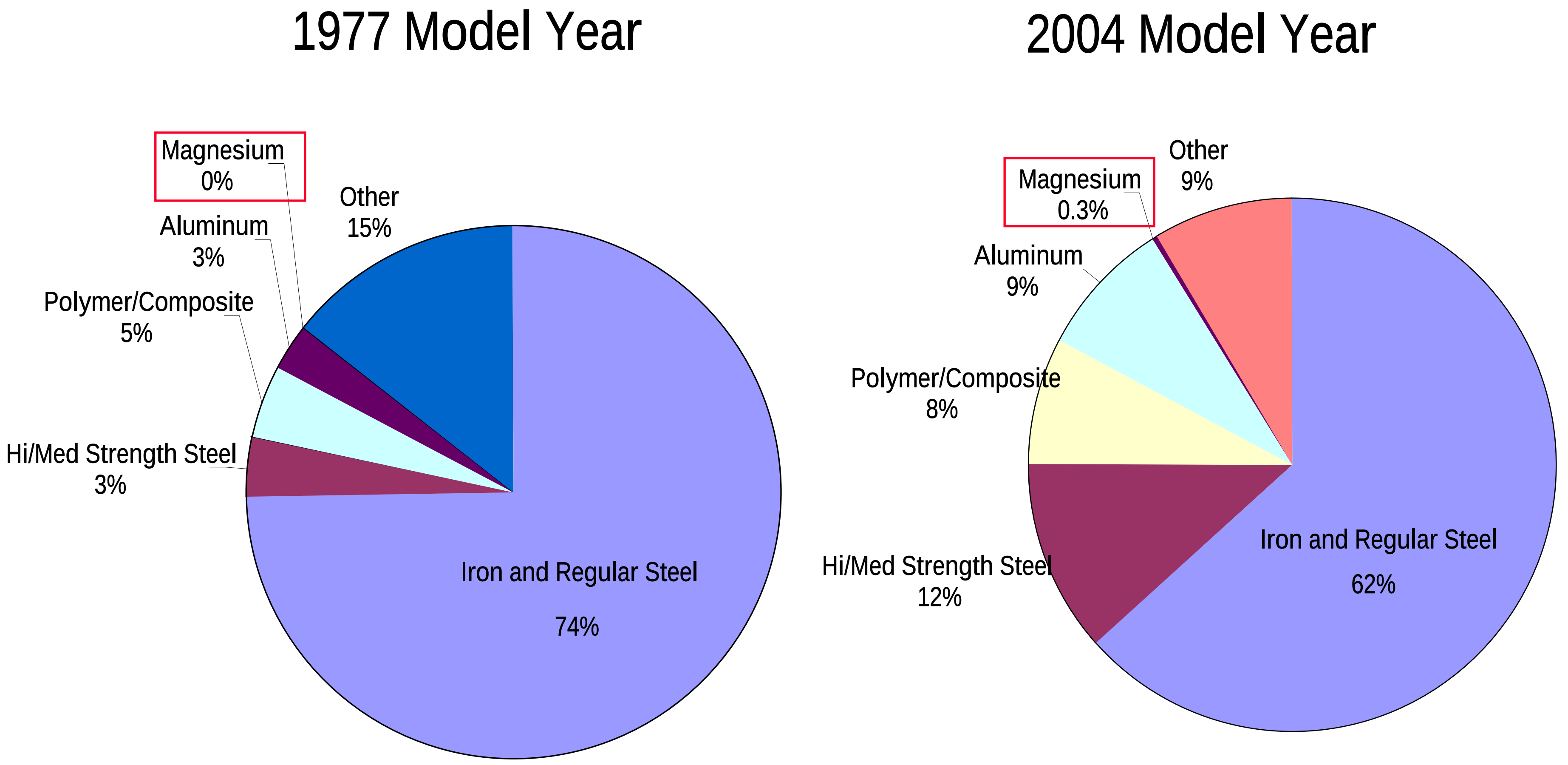


Weight and Performance by Model Year
(Three Year Moving Average)



Source: *Light Duty Automotive Technology and Fuel Economy Trends: 1975 through 2004*, U.S. Environmental Protection Agency, April 2004.

Materials in a Typical Family Vehicle



(Source: American Metal Market)

SAE 2005 WORLD CONGRESS

GM

Weight Savings and Costs for Automotive Lightweighting Materials

Lightweight Material	*Material Replaced*	*Mass Reduction (%)*	*Relative Cost (per part)**
High Strength Steel	Mild Steel	10 (25+?)	1
Aluminum (AI)	Steel, Cast Iron	40 - 60	1.3 - 2
Magnesium	Steel or Cast Iron	60 - 75	1.5 - 2.5
Magnesium	Aluminum	25 - 35	1 - 1.5
Glass-Fiber-Reinforced-Polymer (FRP) Composites	Steel	25 - 35	1 - 1.5
Carbon-FRP Composites	Steel	50 - 60	2 - 10+
Al Matrix Composites	Steel or Cast Iron	50 - 65	1.5 - 3+
Titanium	Alloy Steel	40 - 55	1.5 - 10+
Stainless Steel	Carbon Steel	20 - 45	1.2 - 1.7

•***Includes both materials and manufacturing.***

Ref: *William F. Powers, Advanced Materials and Processes, May 2000, pages 38 – 41.*

Lightweight Material Challenges

FreedomCAR & Fuel Partnership

Increasing Severity of Challenge ←

Increasing Impact on Mission ↑

Material	Critical Challenges				
Carbon-fiber Composites	Low-cost fibers	High-volume Mfg.	Recycling	Joining	Predictive Modeling
Aluminum	Feedstock Cost	Manufacturing	Improved Alloys	Recycling	
Magnesium	Feedstock Cost	Improved Alloys	Corrosion Protection	Manufacturing	Recycling
Advanced High-strength Steels	Manufactur-ability	Wt. Reduction Concepts	Alloy Development		
Titanium	Low-cost Extraction	Low-cost Production	Forming & Machining	Low-cost PM	Alloy Development
Metal-matrix Composites	Feedstock Cost	Compositing Methods	Powder Handling	Compaction	Machining & Forming
Glazings	Low-cost Lightweight Matls.	Noise, struc. models simulations	Noise reduction techniques	UV and IR blockers	
Emerging Materials and Manufacturing	Material Cost	Manufacturing	Design Concepts	Performance Models	

Automotive Lightweighting Materials

- Largest Focus Areas
  - Casting (Al and Mg)
  - Wrought (mainly Al and Mg sheet formation and fabrication)
  - Fiber-reinforced polymeric-matrix composites processing
  - Low(er)-cost carbon fiber production

- Smaller Focus Areas
  - Metal production (Al and Mg)
  - Metal(Al)-matrix composites
  - Ti metal production and fabrication
  - Steel
  - General manufacturing (joining and NDT)
  - Glazing (glass)
  - Crashworthiness
  - Recycling

Materials Portfolio Funding

DOE Automotive Lightweighting Materials - Operation

Shared Materials R&D Philosophy

Direct-funded Research

Materials Tech Team

- National Labs
- Universities
- Contractors

USAMP/DOE Cooperative Agreement

USAMP – Steering Committee

- **Automotive Metals Division (AMD)**
- **Automotive Composites Consortium (ACC)**
- **Auto/Steel Partnership (A/SP)**

[teams of OEM's, Suppliers, Universities]

LM Program
DOE Investment (Approx $22 M.)

Direct Funded Projects Approx $15 M	**USAMP Cooperative Agreement Approx.$7 M.**	**OEM and Supplier In kind Approx. $7 M**

Equal Match

Other Important Collaborators

- National Science Foundation
- Center for Advanced Vehicle Systems at Mississippi State University
- American Chemistry Council - Plastics Division (formerly the American Plastics Council – "Plastics make it possible")
- American Foundry Society
- North American Die Casting Association.
- CANMET – Materials Technology Laboratory of Natural Resources of Canada (Canadian equivalent of DOE)
- Ministry of Science and Technology of the Peoples Republic of China
- USAutoPARTS?
- National Center for Manufacturing Sciences?

Procedures for Development and Recommendation of New Thrusts and Proposals

- Materials Technical Team
  - Bubbled up from labs, OEMs, suppliers, universities, non-profits usually through extensive discussions with OEM “champions” in order to maximize likelihood of eventual implementation.
  - Prioritized for recommendation through rigorous language ladder-tree by entire MTT.

- USAMP
  - Bubbled up from AMD, ACC, A/SP and various Working Groups
  - Reviewed and approved for recommendation by USAMP Steering Committee.

- Predictive Modeling of Polymer Composites Processing and 3rd Generation of Advanced High-Strength Steels.
  - Workshop between NSF, DOE and industry.
  - NSF “Dear Colleagues” (informal) solicitation.

Stage definition for USAMP cone:

DRAFT USAMP CONFIDENTIAL

Concept Feasibility | **Technical Feasibility** | **Demonstrated Feasibility**

Concept Feasibility

Definition:

- Specific Idea to solve problem or to create something new
- Projects should address issues within scope of research “cone”
- Project should be small, short and exploratory
- Should provide a Y/N answer re: value of idea
- Project should have
  - Research plan
  - Budget
  - Timing
- Can be either with or without gov’t funding
- Typically < 200 K and 1-2 yrs. duration

Kill Criteria:

- Technical failure
- Preliminary Cost
- Preliminary Business Case

Technical Feasibility

Definition:

- Idea with proven merit or potential
- Projects identify key barriers and ways to overcome them.
- Defined research plan should only focus on overcoming key barriers
- Defined OEM/Industry supplier participation and pull
- Larger, longer term projects
- Typically 1-2 million dollars and 2-3 yrs.duration

Kill Criteria:

- Failure to overcome barriers
- Cost
- Business Case

Demonstrated Feasibility

Definition:

- Validation projects
- Much larger scale
- May involve component or system fabrication and test

Technology Planning Process

Procedures for Reviews of Progress

- Materials Technical Team and USAMP
  - Usually reviewed extensively by OEM and lab working groups and as-needed by entire MTT or USAMP Steering Committee.
  - Results presented annually to OEMs at USCAR fall "Off-Sites"
  - Informal semi-annual and formal published annual.

- NSF
  - Annual Grantees Conference
  - Formal published annual report.

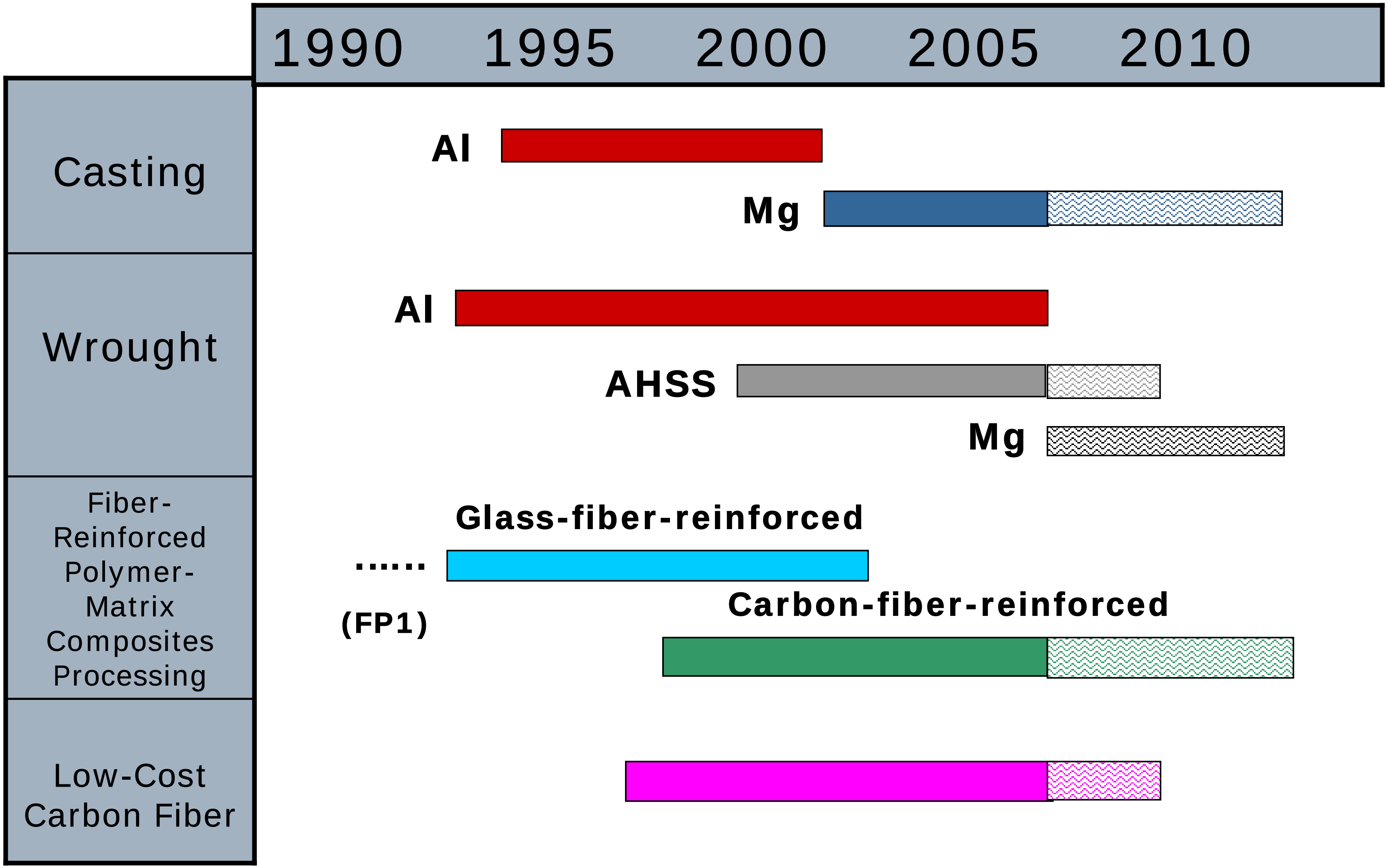
Procedures for Tech Transfer

- Materials Technical Team and USAMP

  - Results presented annually to OEMs at USCAR fall "Off-Sites"
  - Formal published annuals.
  - Conference presentations and open-literature publications.
  - Participation by OEMs and suppliers (probably most effective)

- A/SP
  - Active marketing.

ALM Historical Timeline – Main Efforts



Design & Product Optimization for Cast for Cast Light Metals

Cooperative Resources

- USAMP
- ORNL
- AFS
- SNL
- WMT&R
- LLNL
- Entelechy
- DOE
- Geo. Tech.
- 32 Suppliers & Big 3

Technology for Rapid Application of Light Metal Structural Castings

Customers: OEM's and Suppliers

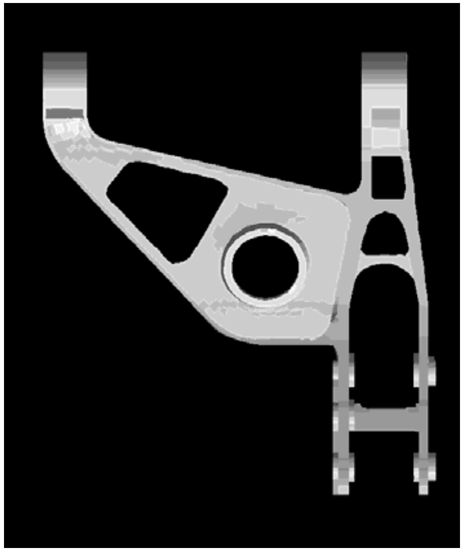
Design & Product Optimization for Cast for Cast Light Metals

Material & Technology

Using New Technology to Further Reduce Component Weight

Original - Nodular Iron
16 lbs.

Conversion to Cast
Aluminum 6.7 lbs.



Application of Simulation
Tool 5.4 lbs..

58% Savings

20% Savings

Component Weight Reduction

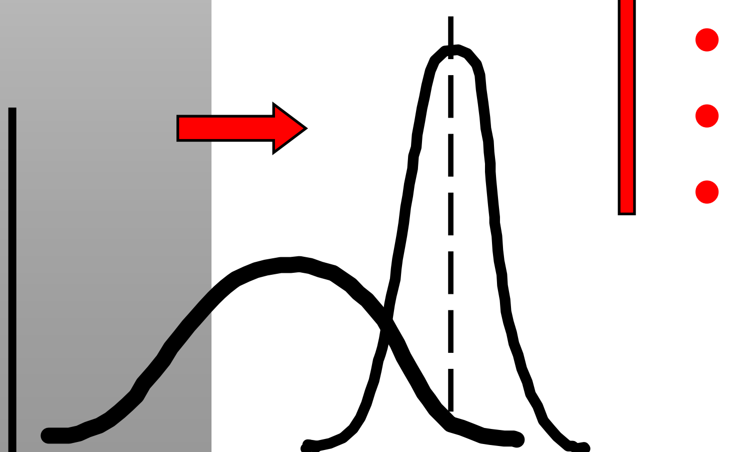
Design & Product Optimization for Cast for Cast Light Metals

Property Influence

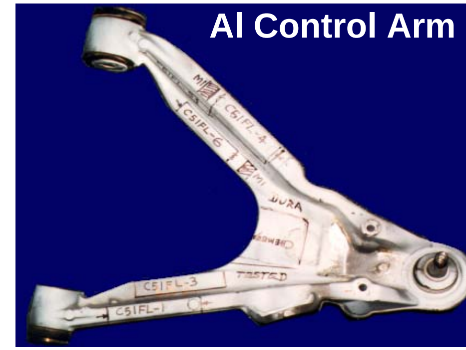
Reduced material property variation combined with an increasing mean leads to …… = Lower Cost & Weight

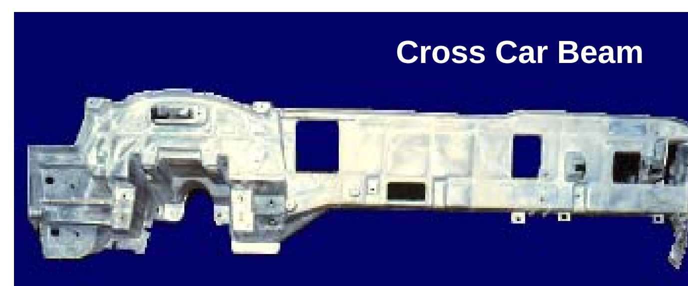
Material Properties

- YS
- UTS
- Ductility
- Fat.Str.

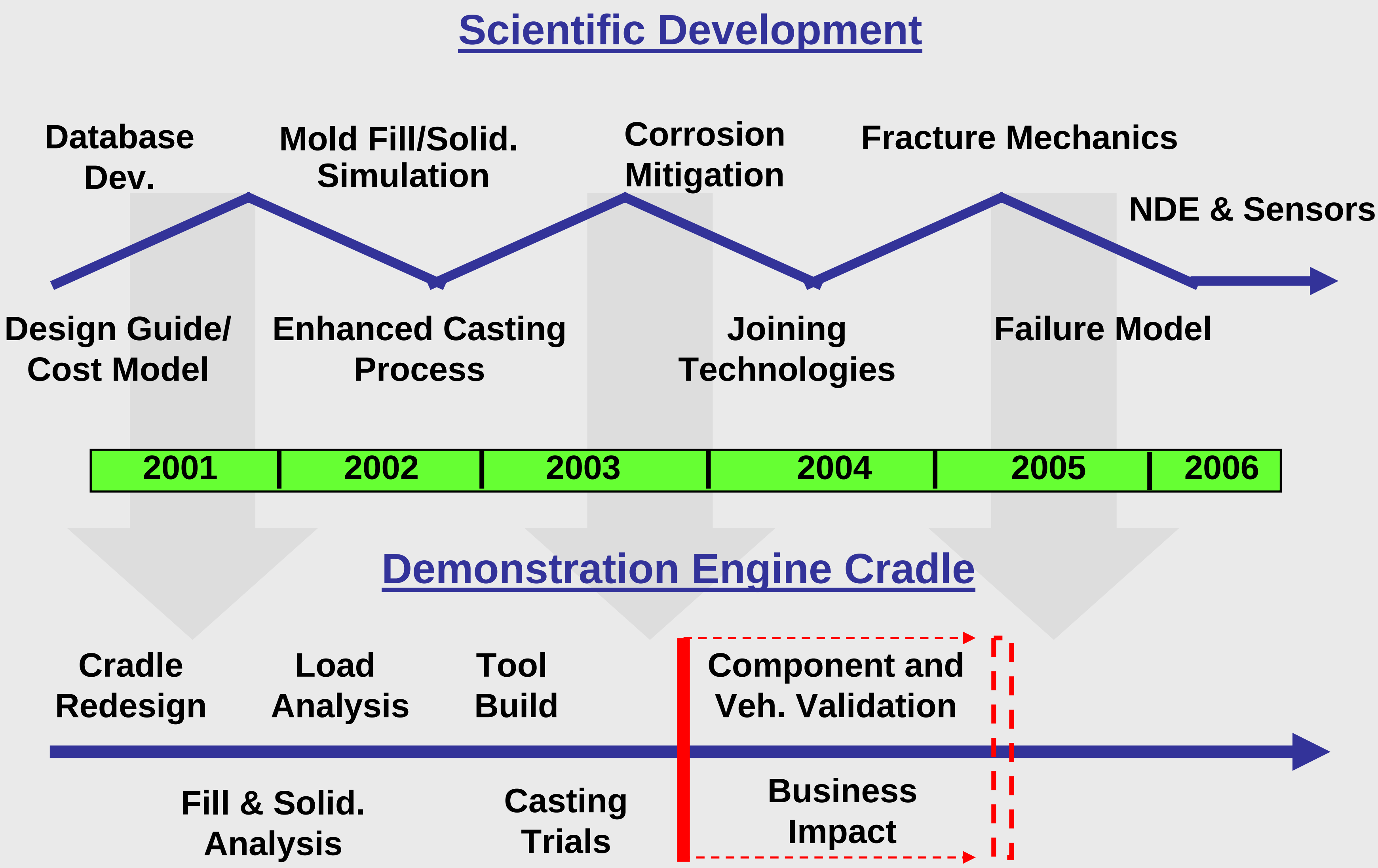


mean





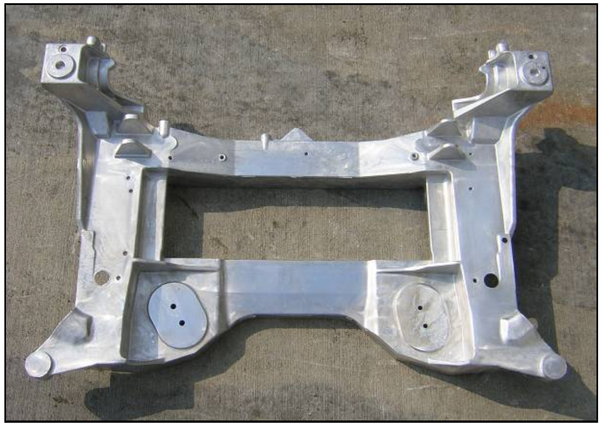
Structural Cast Magnesium Development - Dual Activities



Mg Cradle on 2006 Corvette Z06

Benefits:

- Mass Reduction: Mass savings of 5.6 kg (34%)
  - Mass Delta: 16.4 kg (Al) to 10.8 kg (Mg)
- Improved vehicle performance
- Avoidance of $1000/car gas guzzler tax
- Very high visibility



Commercial Applications of Aluminum SPF in Automotive

Oldsmobile Aurora 4.0L

SPF Aluminum Rear Hatch and Truck Lid Structures

Cadillac SRX

Malibu Max

Focal Project II - Glass Fiber

Vehicle Systems

MATERIALS | JOINING | ENERGY MANAGEMENT | PROCESSING

Compared to Steel Baseline

25% lighter — Greater Durability

Equal cost — Equal Safety

1 part every 4 min achieved

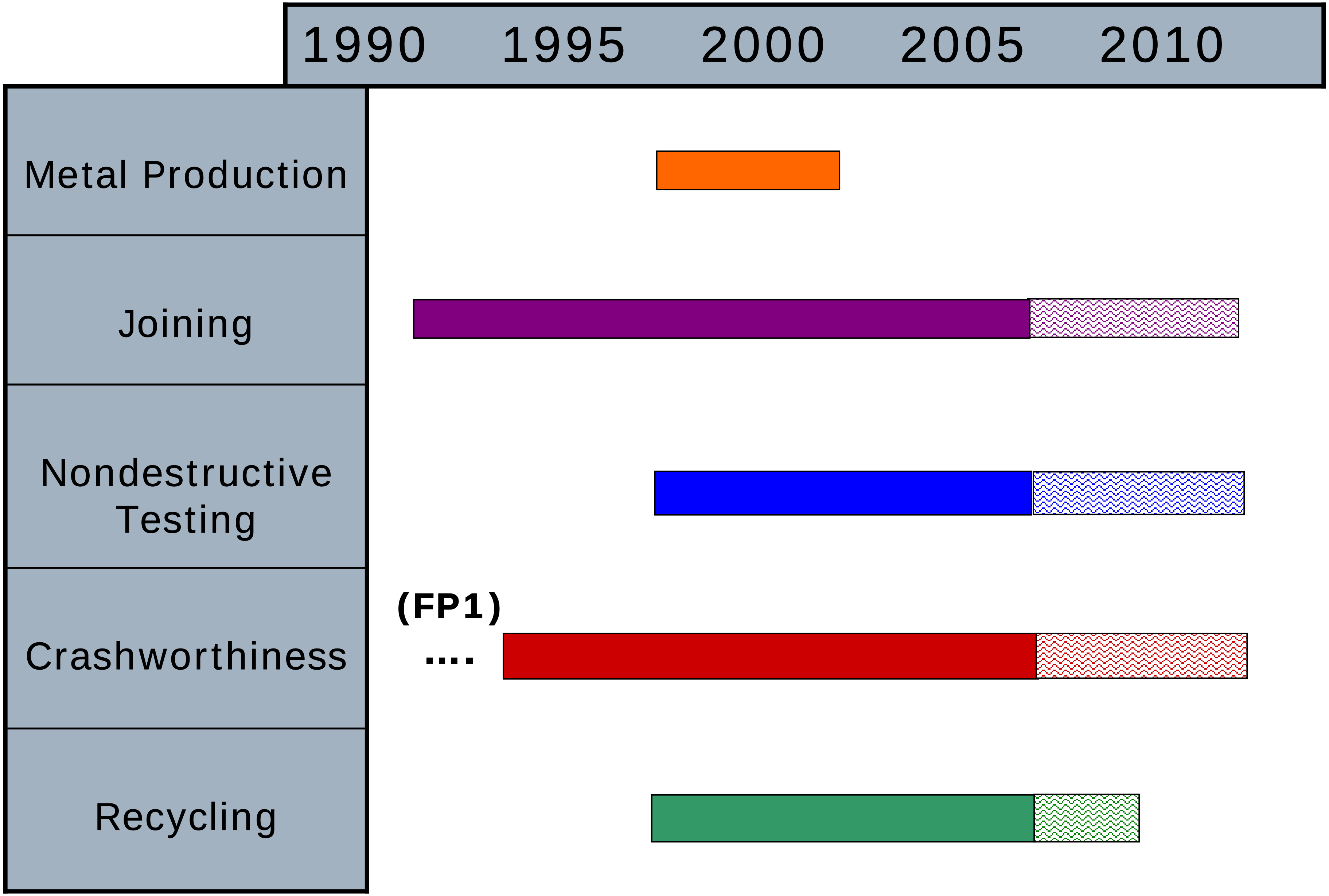
50 lb lighter - 15 lb lighter tailgate

No painting necessary

Impact and Corrosion Resistant

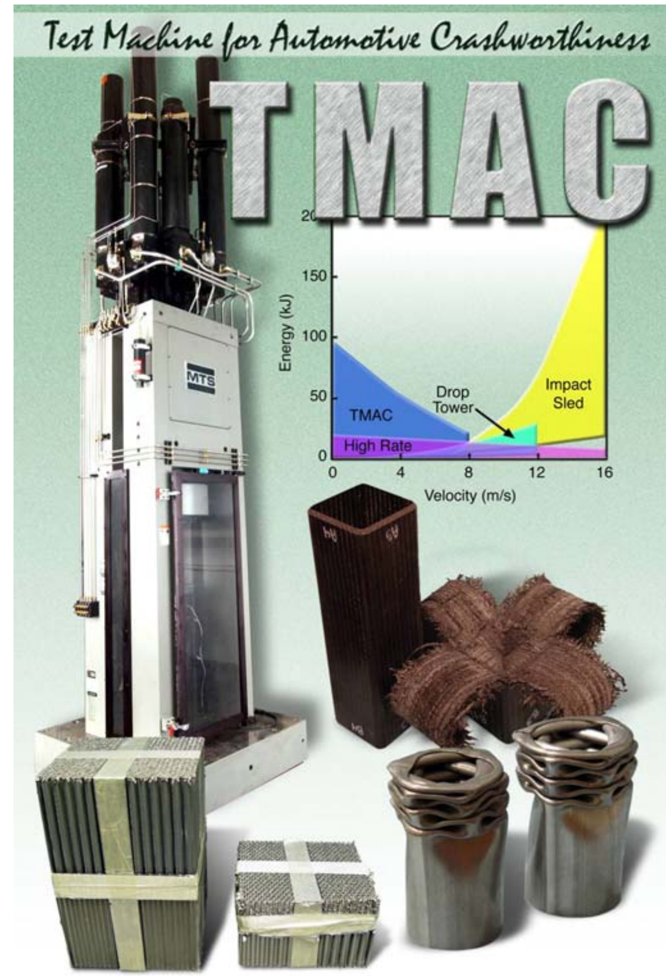
Tailgate Load Capacity 1000lb vs 600lb steel

ALM Historical Timeline - General Manufacturing

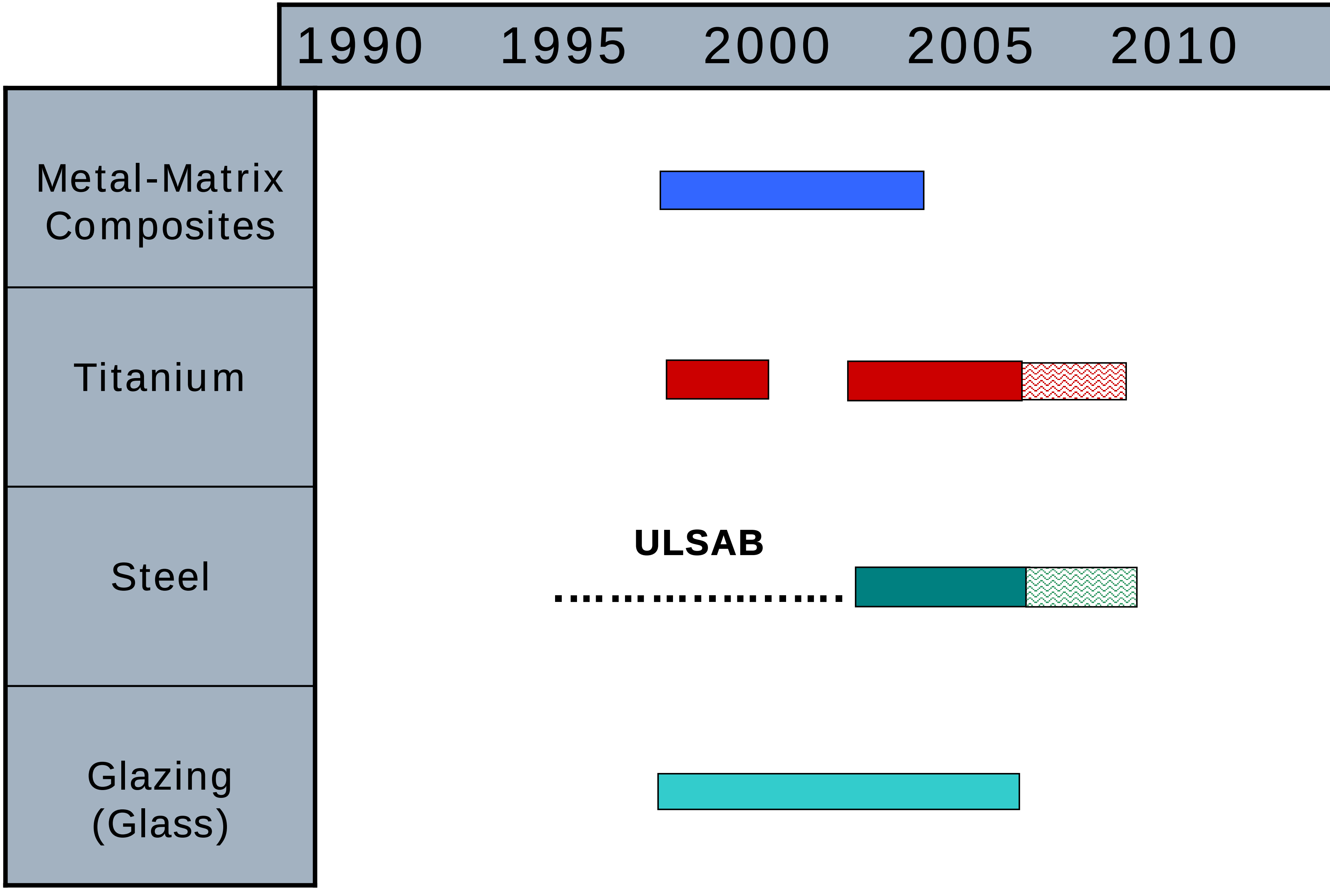


Test Machine for Automotive Crashworthiness (TMAC) for Intermediate Rate Crush Studies

- **<u>Accomplishment</u>**
  - Completed design, build and installation of TMAC at National Transportation Research Center (NTRC) in Oak Ridge, TN.
  - Demonstrated capability to conduct controlled, progressive crush experiments at constant velocity (±10%), high forces (0-267kN), and intermediate rates (0-8m/s).
- **<u>Importance / Significance</u>**
  - This machine permits–for the first time–progressive crush experiments at high force levels and constant intermediate velocities. This data, previously unobtainable, is critical for the development of predictive crash models.



ALM Historical Timeline



Recent ALM Steel Projects

- "Enablers" - Applied Fundamentals Studies

  Die Face Engineering for Advanced Sheet Forming (AMD 408).
  Enhanced Forming (A/SP 040).
  High Strength Steel Stamping (A/SP 050).
  Active Flexible Binder Control for Robust Stamping (AMD 301).
  Tribology (A/SP 230).
  Hydroform Materials and Lubricants (A/SP 060).
  High-Strength Steel Tailor-Welded Blanks (A/SP 210)
  Sheet Steel Joining (A/SP 070).
  Friction Stir Spot Welding of High-Strength Steels (ORNL and PNNL).
  Forming Limits of Weld Metal in Al and AHSSs ((PNNL).
  Ultrasonic Phased Array System for Resistance Spot Weld Inspection (AMD 409 and LBNL).
  NDE Inspection of Adhesive Bonds in Metal-Metal Joints (SNL).
  In-Line Resistance Spot Welding Control and Evaluation System Assessment for Light Weight Materials (AMD 605 and PNNL)
  Strain Rate Characterization of Steels (A/SP 190 and ORNL).
  Dynamic Characterization of Spot Welds for AHSSs (AMD ??? (USoCar) and ORNL).
  Evaluations of Manufacturing Effects on TRIP Steels (PNNL).
  Characterization of Thermomechanical Behaviors of AHSSs (ORNL and PNNL).
  Sheet Steel Fatigue (A/SP 160).

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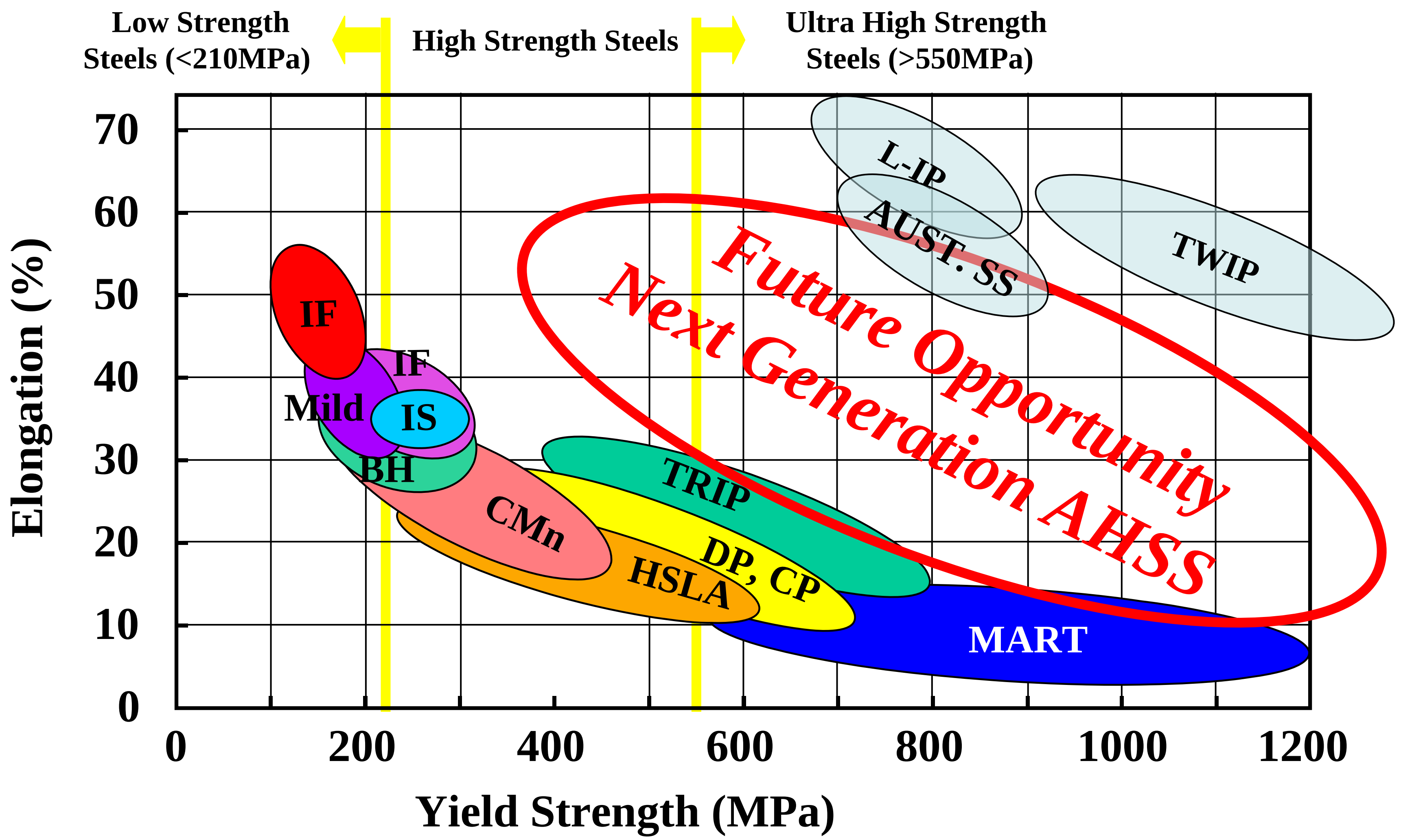
- "Focals" – Validation of and Guidance for Enablers' Technologies

  Lightweight Closures (A/SP 090).
  Lightweight Front End Structures (A/SP 110).
  Future Generation Passenger Compartment (A/SP 240).
  Lightweight Rear Chassis Structures (A/SP 601).



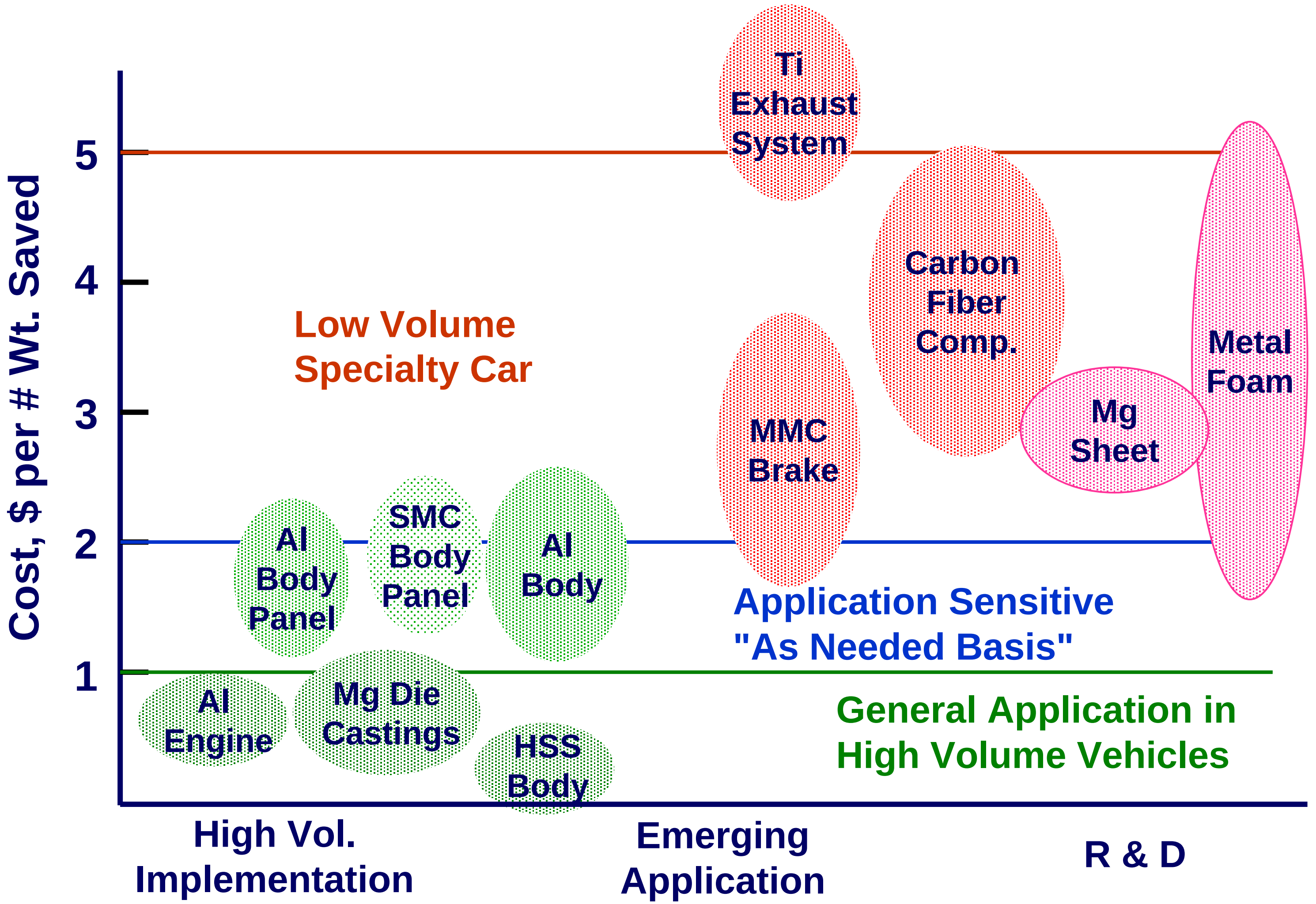
Low Strength Steels (<210MPa)
High Strength Steels
Ultra High Strength Steels (>550MPa)
Elongation (%)
70
60
50
40
30
20
10
0
0
200
400
600
800
1000
1200
Yield Strength (MPa)
IF
Mild
IF
IS
BH
CMn
HSLA
TRIP
DP, CP
MART
L-IP
AUST. SS
TWIP
Future Opportunity
Next Generation AHSS

FreedomCAR Automotive Lightweighting Materials Highlights

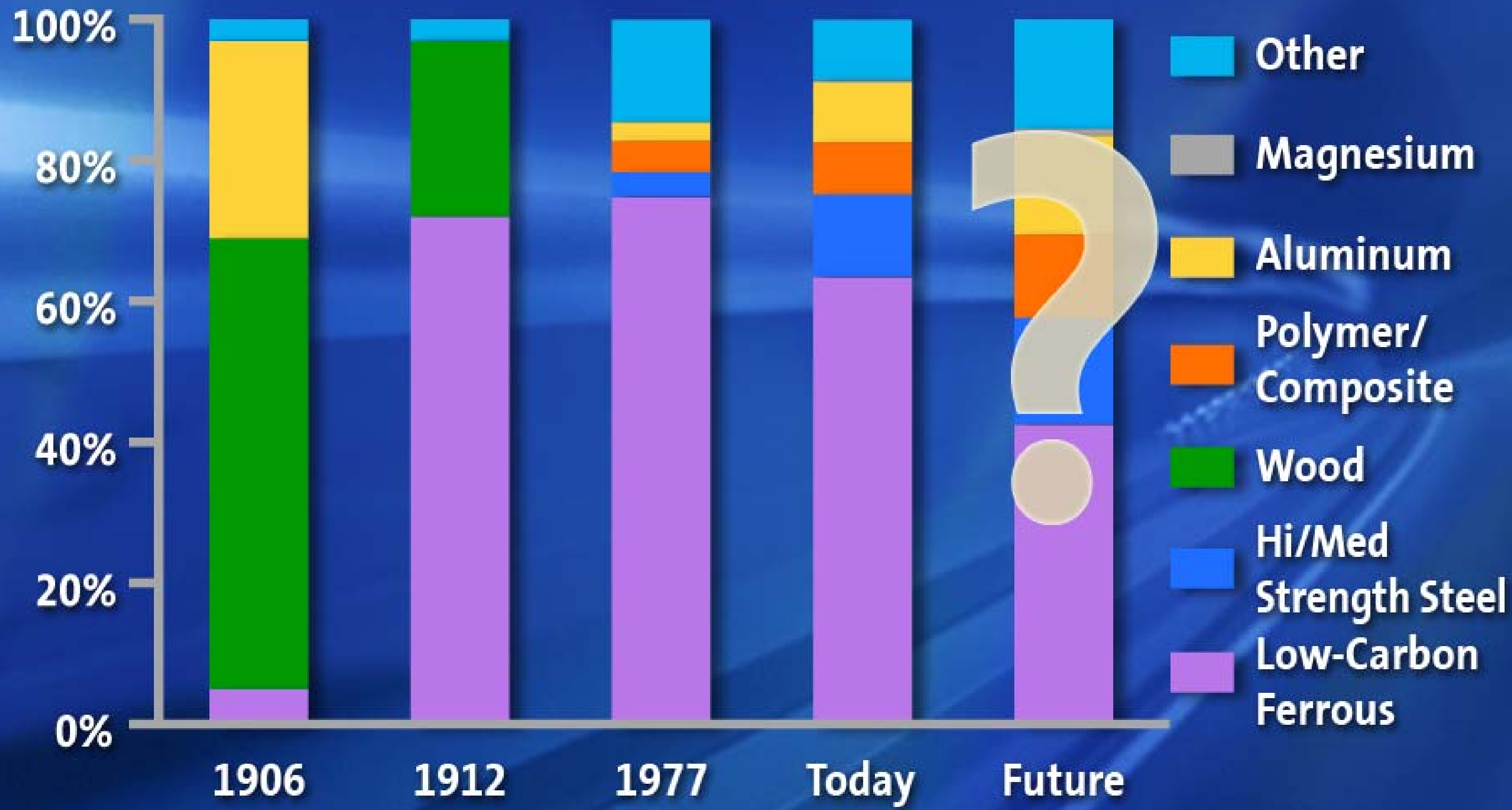
Transportation Materials

- Superplastic Forming of Aluminum (GM's Quick Plastic Forming)
- Programmamble Powdered Preform Process (P4) for Automotive Composite Structures
- Initial Automotive Composites Durability Guidelines
- Optimization of Al Castings
- Mg Casting for Structural and Powertrain Applications
- Initial (?) Identification of Emerging Lower-Cost Ti Production Processes

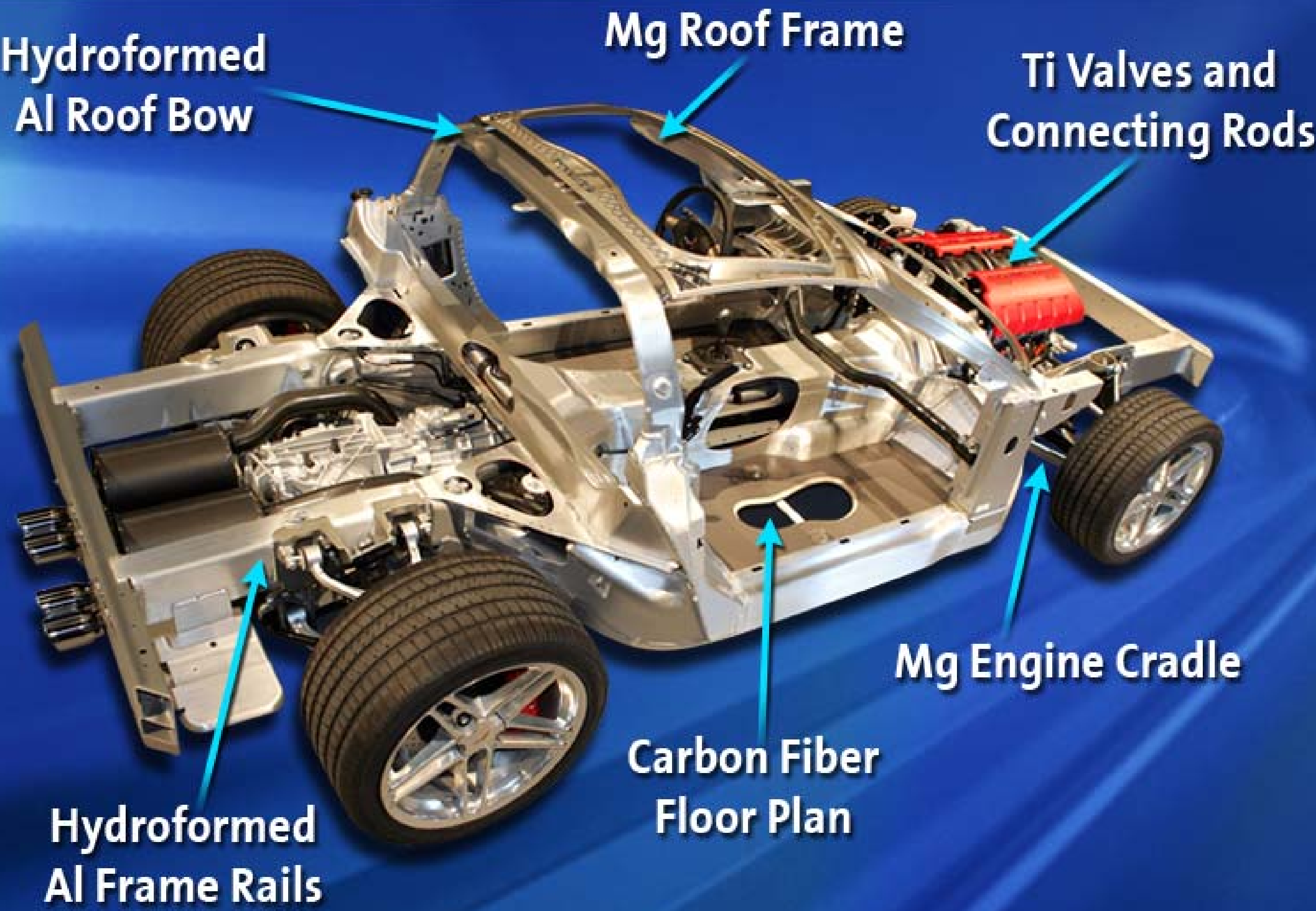
Lightweight Automotive Materials - Market Penetration vs. Cost



Materials in a Typical NA Vehicle



2006 Chevrolet Corvette Z06



Present

- $22,331K in FY 2008 (up from $18,650K in FY 2007)

  - Composites: 36% (16% LCCF, 20% Design and Processing)
  - Metals : 35% (4% Al, 14% Mg, 14% Steel, 3% Ti)
  - Recycling : 15%
  - Joining : 8%
  - NDE : 4%
  - Cross-Cut : 2%

  - National Labs: 68% (34% ORNL, 17% PNNL, 15% ANL, 2% SNL)
  - USAMP : 30% (+ equal match)
  - NSF : 2% (+ equal match)

- 86+ Projects

Future

- Continue LCCF, composites, Mg.
- Redirect steel work to 3rd Generation.
- Continue transition from focus on components and subassemblies to whole multi-material structures
- MTT more top-down (like USAMP)?
- More validation?
- More fundamental applied work to restock the pipeline?

Summary and Thoughts

- Has the $220M + spent by FreedomCAR and PNGV on automotive lightweighting been worth it?
  - Commercial implementations and formal evaluations would indicate "yes."
  - Probably served to increase R&D pressure
  - Too early to tell quantitatively?
  - At least we know the technical and costs parameter spaces better

- Qualitatively, the greatest value may have been in fostering government-industry collaborations.
  - Industry brought their "A Teams"

For Further Information

USDOE Vehicle Technologies

http://www.eere.energy.gov

US Council for Automotive Research

http://www.uscar.org