CHALLENGES AND OPPORTUNITIES RELATIVE TO INCREASED USAGE OF ALUMINUM WITHIN THE AUTOMOTIVE INDUSTRY

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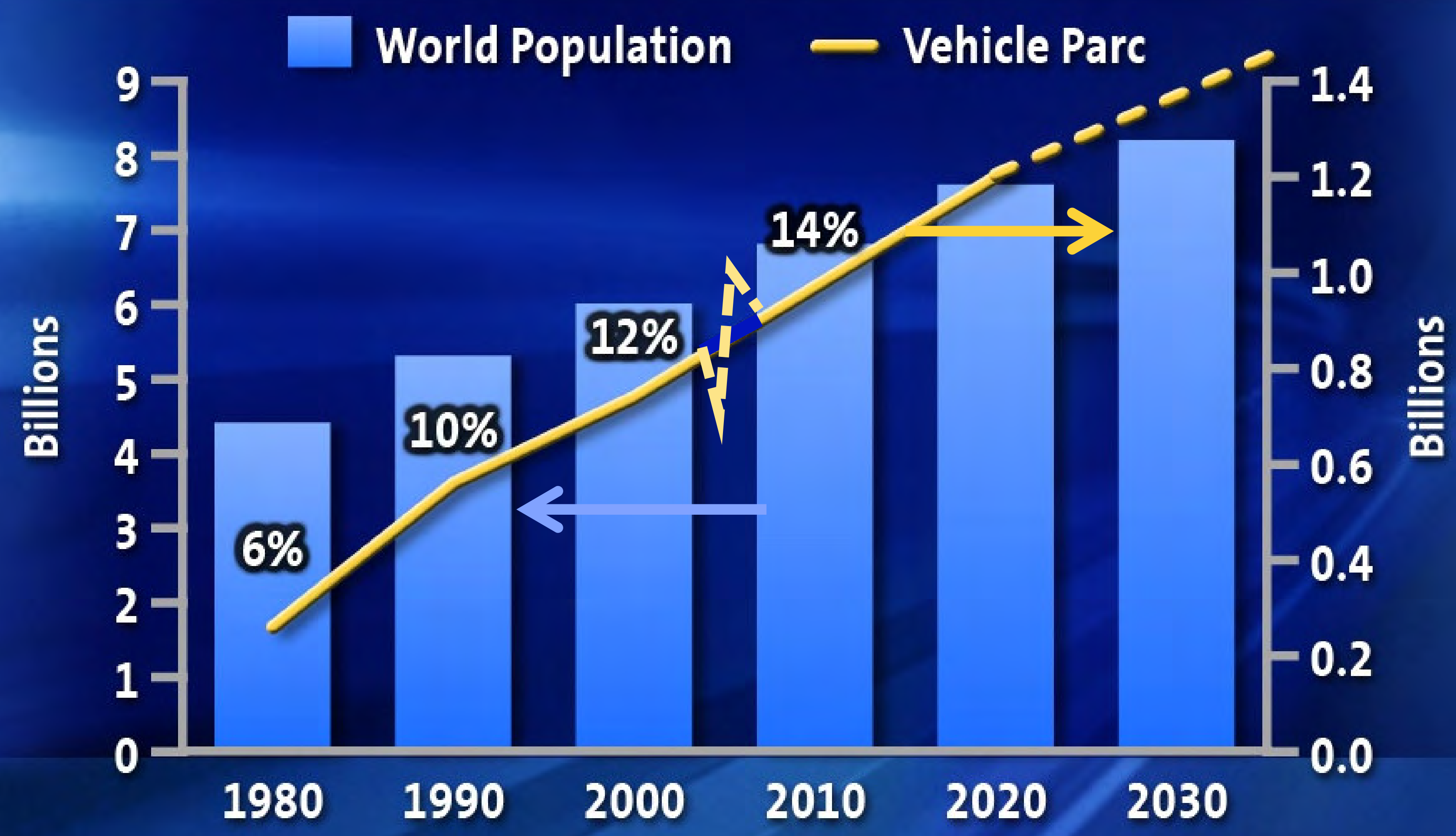
David Sigler, and
Mark Verbrugge (speaker)**

General Motors R&D, Warren, MI

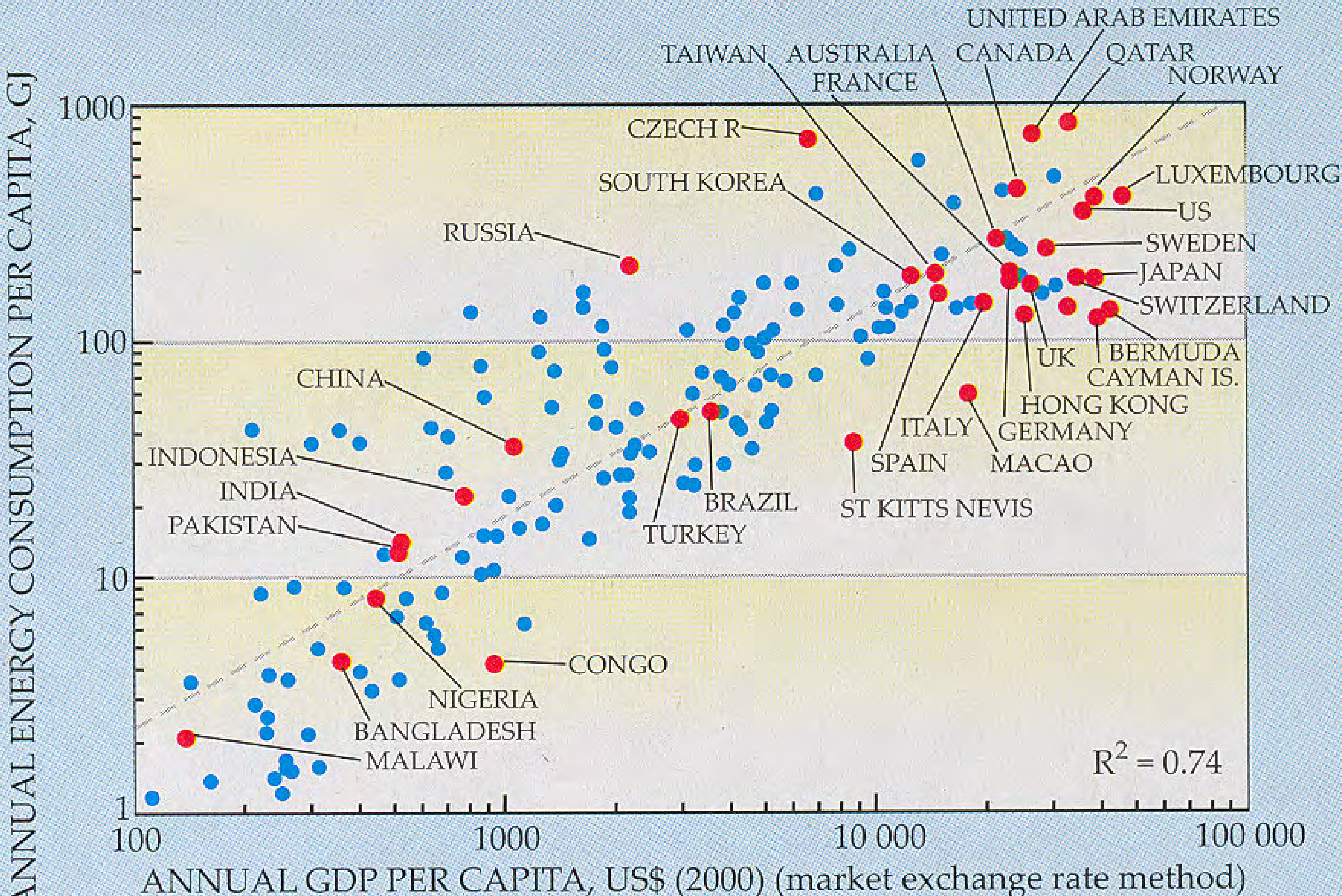
Outline

- Societal trends
- Automotive drivers
- Aluminum technology in automotive
  - Closure panels
  - Body structure
  - Chassis
  - Powertrain
  - Joining
  - Corrosion
- Open questions and potential enablers

World Population and Vehicle Parc



Data from U.S. Census Bureau and GM Global Market & Industry Analysis



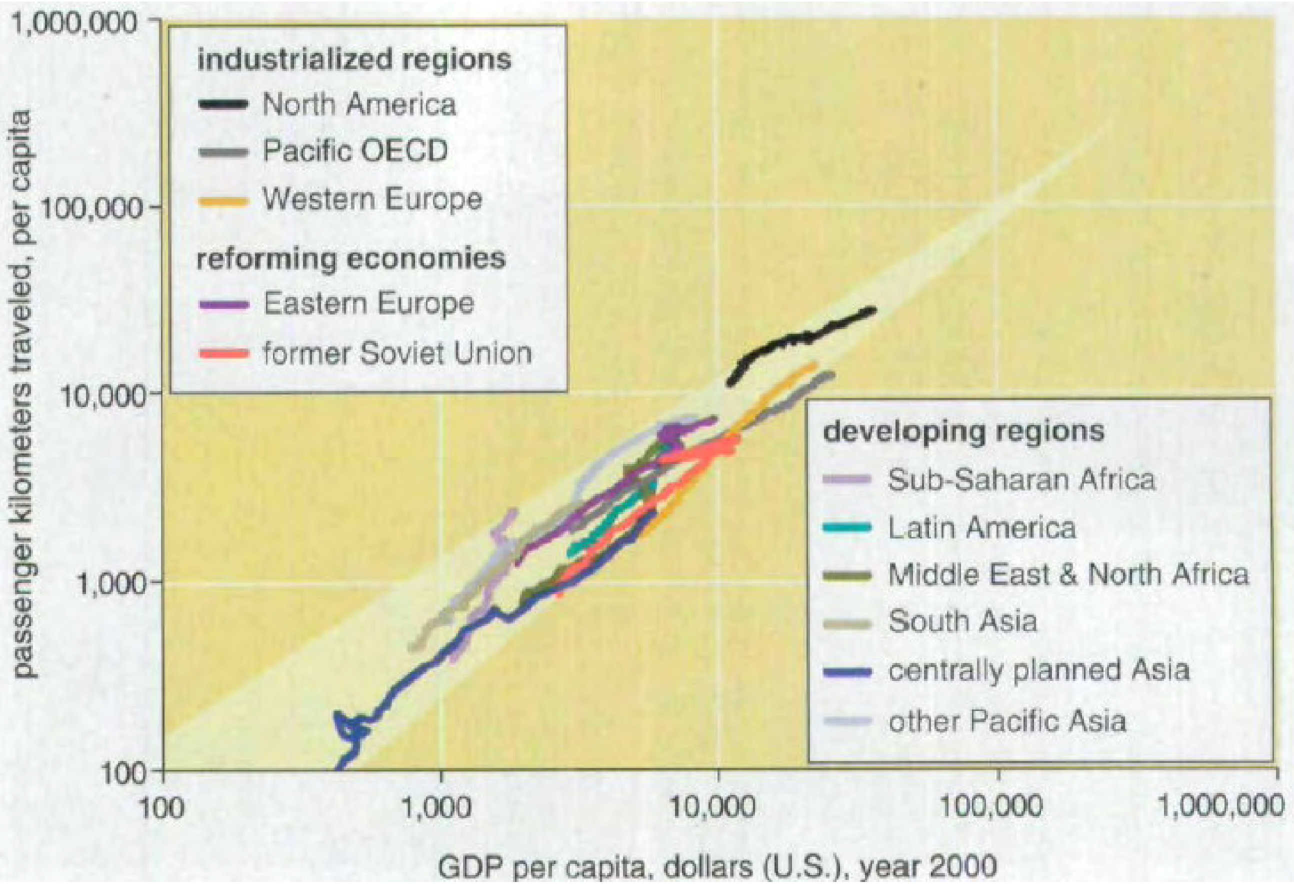
GDP per capita is related to income per capita

Source: Energy Information Administration, *International Energy Annual 2003*, Washington, DC (8 July 2005).

American Scientist, Nov-Dec 2009

The Other Climate Threat: Transportation

Andreas Schäfer, Henry D. Jacoby, John B. Heywood and Ian A. Waitz



Per-capita passenger-kilometers traveled (PKT) is correlated with economic development, shown as growth in per capita gross domestic product.

The 11 regional trajectories represent the years 1950 to 2005. The upper point of the shaded section is the theoretical highest mobility level, achieved when a population relies exclusively on the fastest mode of transport (aircraft) over the entire travel time budget (1.2 hours per person per day).

American Scientist, Nov-Dec 2009

The Other Climate Threat: Transportation

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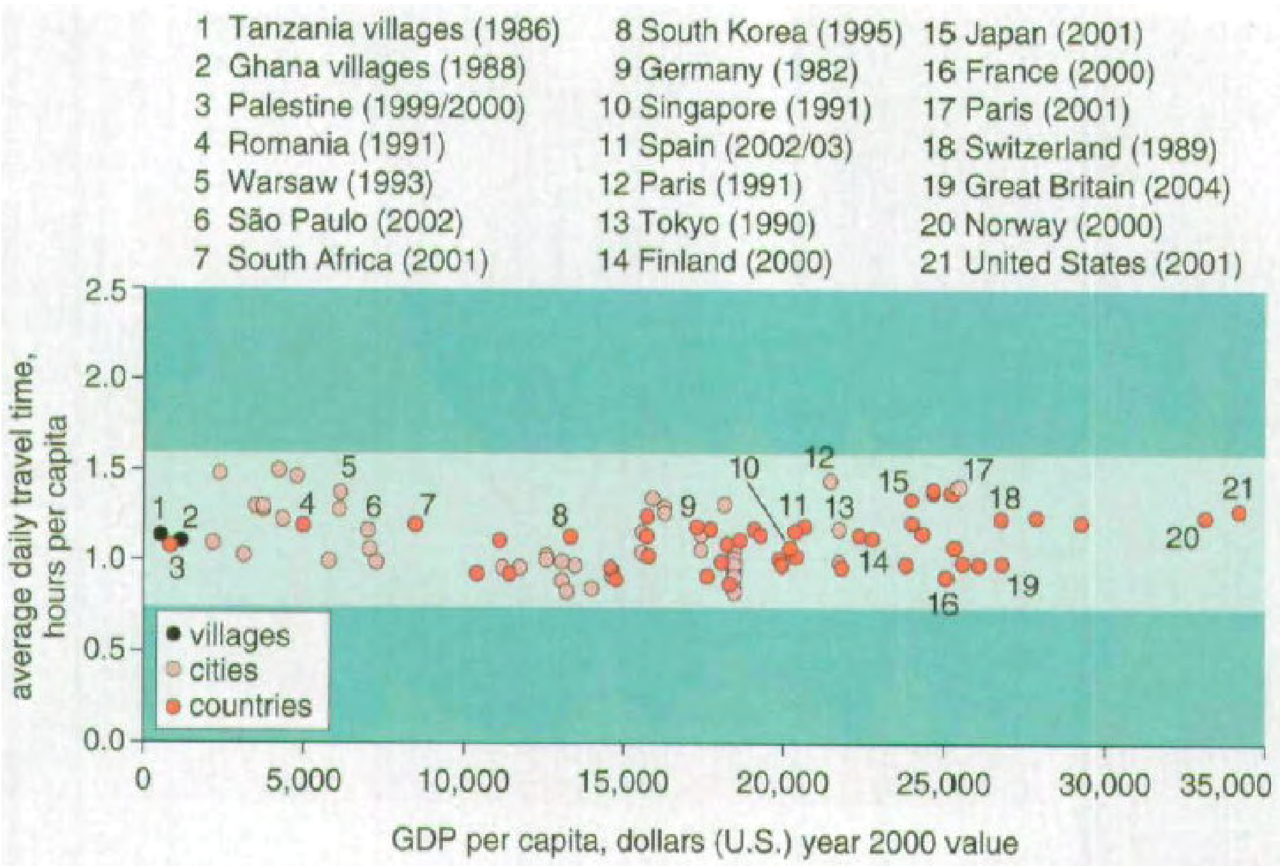
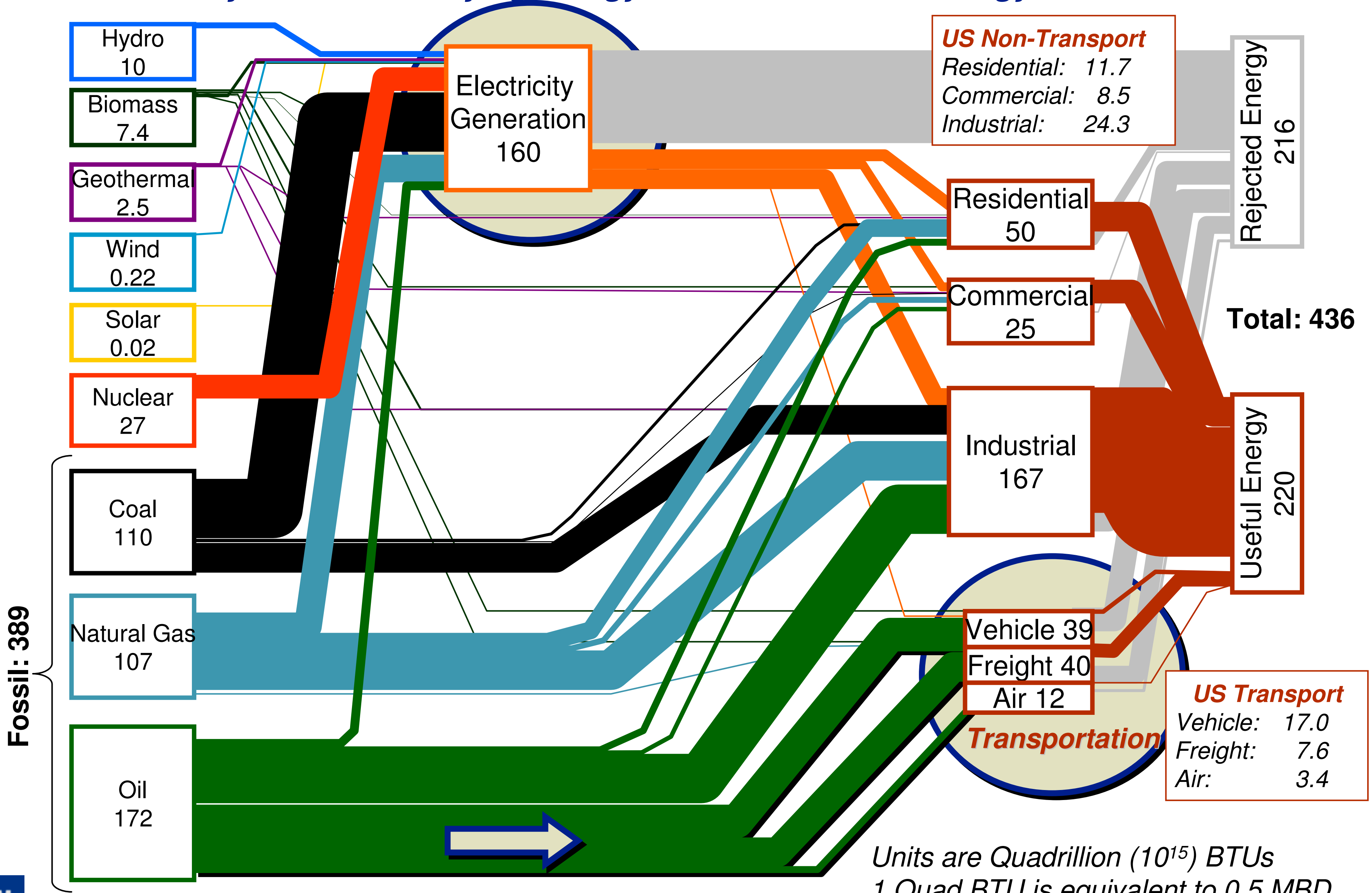


The amount of time people around the world spend traveling is startlingly consistent, no matter whether they live in African villages, Europe, or the most affluent regions of Asia.

People in the industrialized world spend a larger share of their traveling time for leisure activities—about half—but they travel similar amounts of time on average each day nonetheless.

2005 Global Human-Activity Energy Flows

- *Transportation the only major industry dependent on only 1 energy supply chain*
- *Electricity serves as unifying energy carrier for diverse energy resources*



Units are Quadrillion (10^{15}) BTUs
1 Quad BTU is equivalent to 0.5 MBD

Source: Lawrence Livermore National Laboratory

GM

Global Energy Concerns (for every nation state)

Energy security

Secure

Environmental health

Clean

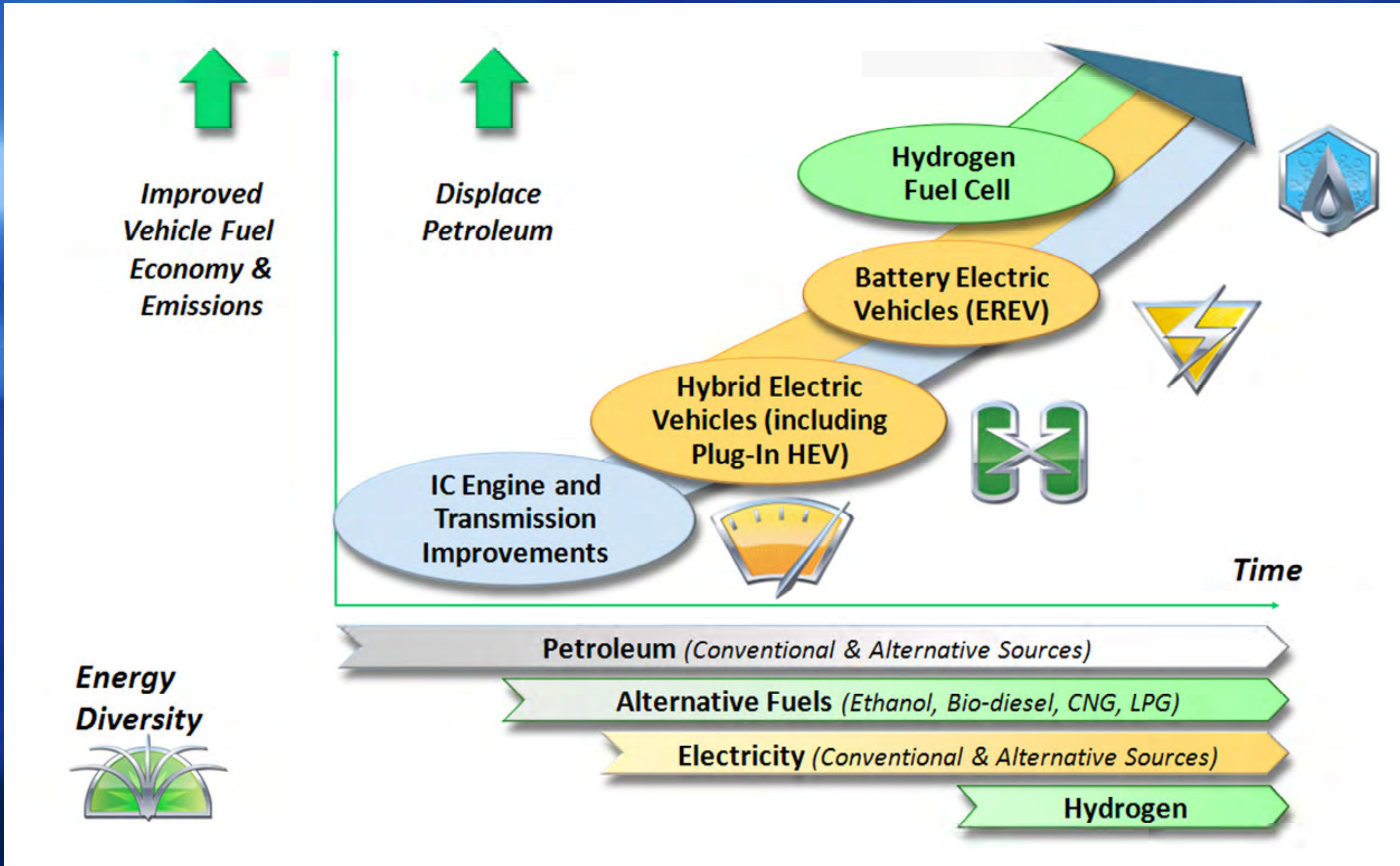
Economic competitiveness

Affordable

} Sustainability & National Security

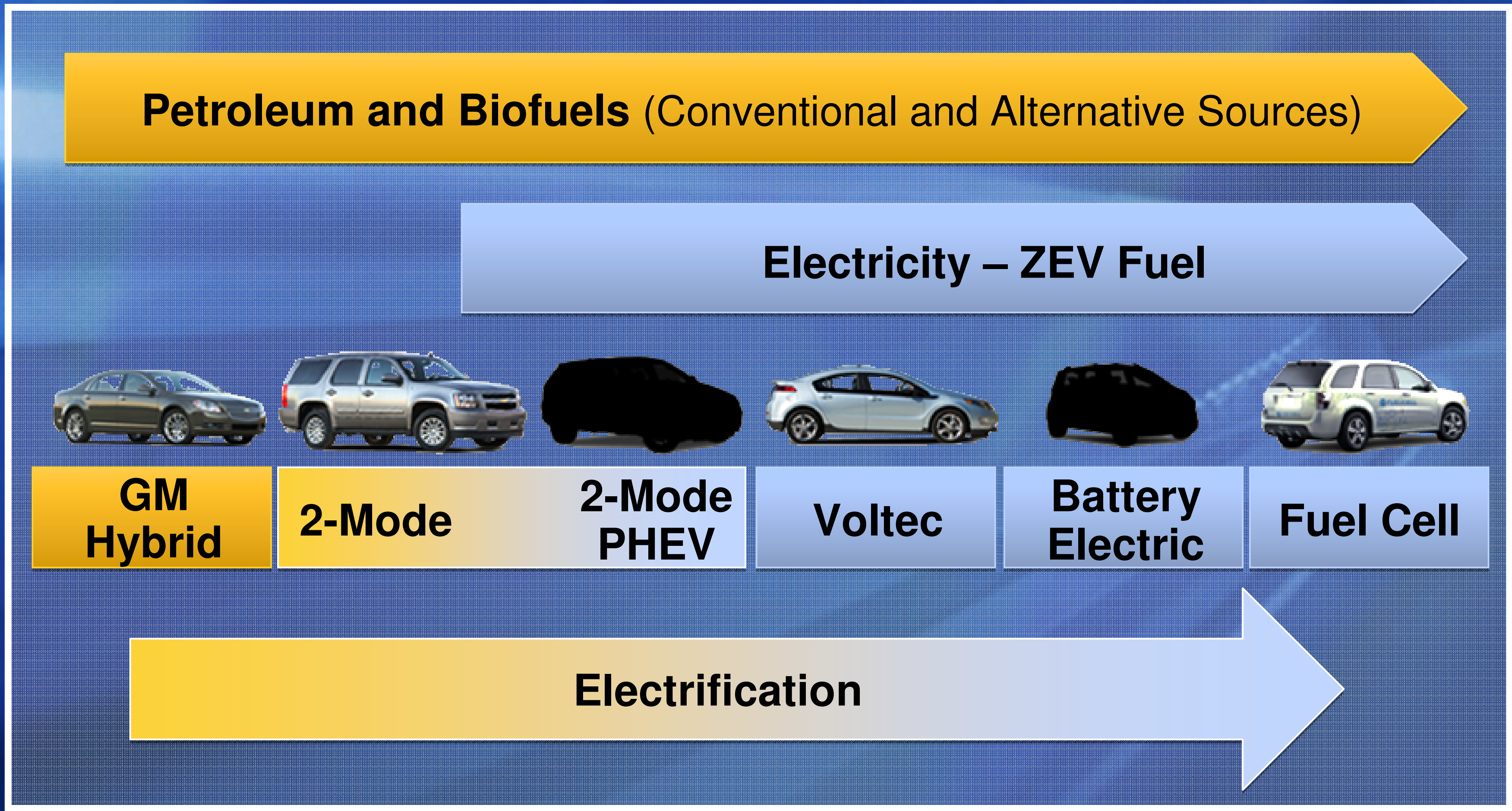
To some extent, we can reduce demand, but the ultimate solution will come out of advancements in science and technology.

GM Advanced Propulsion Strategy



GM VEHICLE ELECTRIFICATION STRATEGY

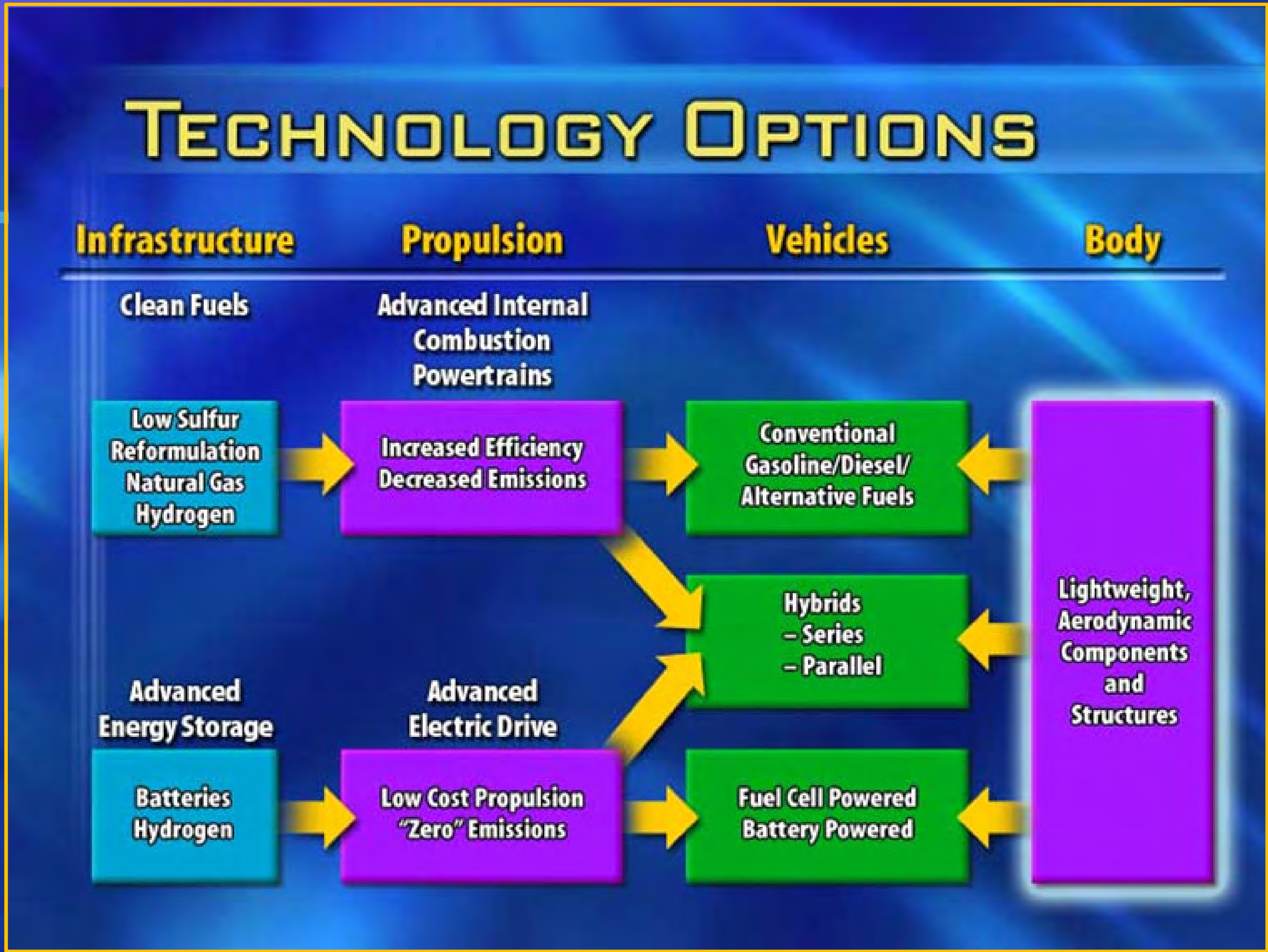
Portfolio of solutions for full range of vehicles that provide customer choice



GM'S PATH TO ELECTRIFICATION

	Conventional Powertrain	Mid Hybrid	Full Hybrid	Plug-in Hybrid	Extended Range Electric Vehicle	Battery Electric Vehicle & Fuel Cell
FUNCTIONALITY	Baseline	15-20%	30% RWD 50% FWD	FWD: 100% for 20 Miles, 50% After	40 Miles Pure EV	30 Miles Pure EV
DRIVE SYSTEM	Mechanical	Mechanical with Electric Assist			Electric with Mechanical Assist	All Electric

INCREASING LEVELS OF ELECTRIFICATION AND EFFICIENCY

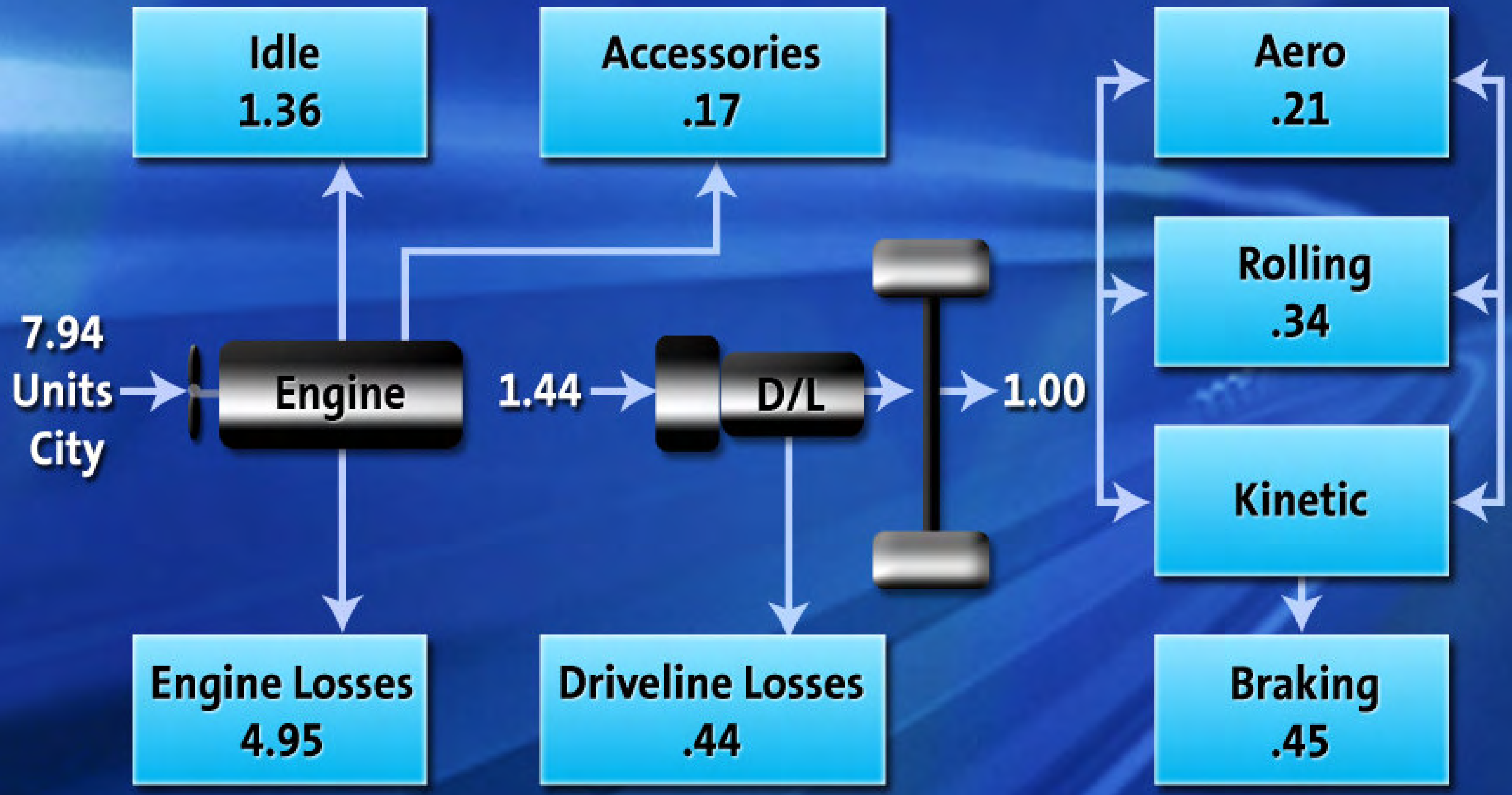


- **Key: Current and future vehicle architectures benefit from lightweighting**

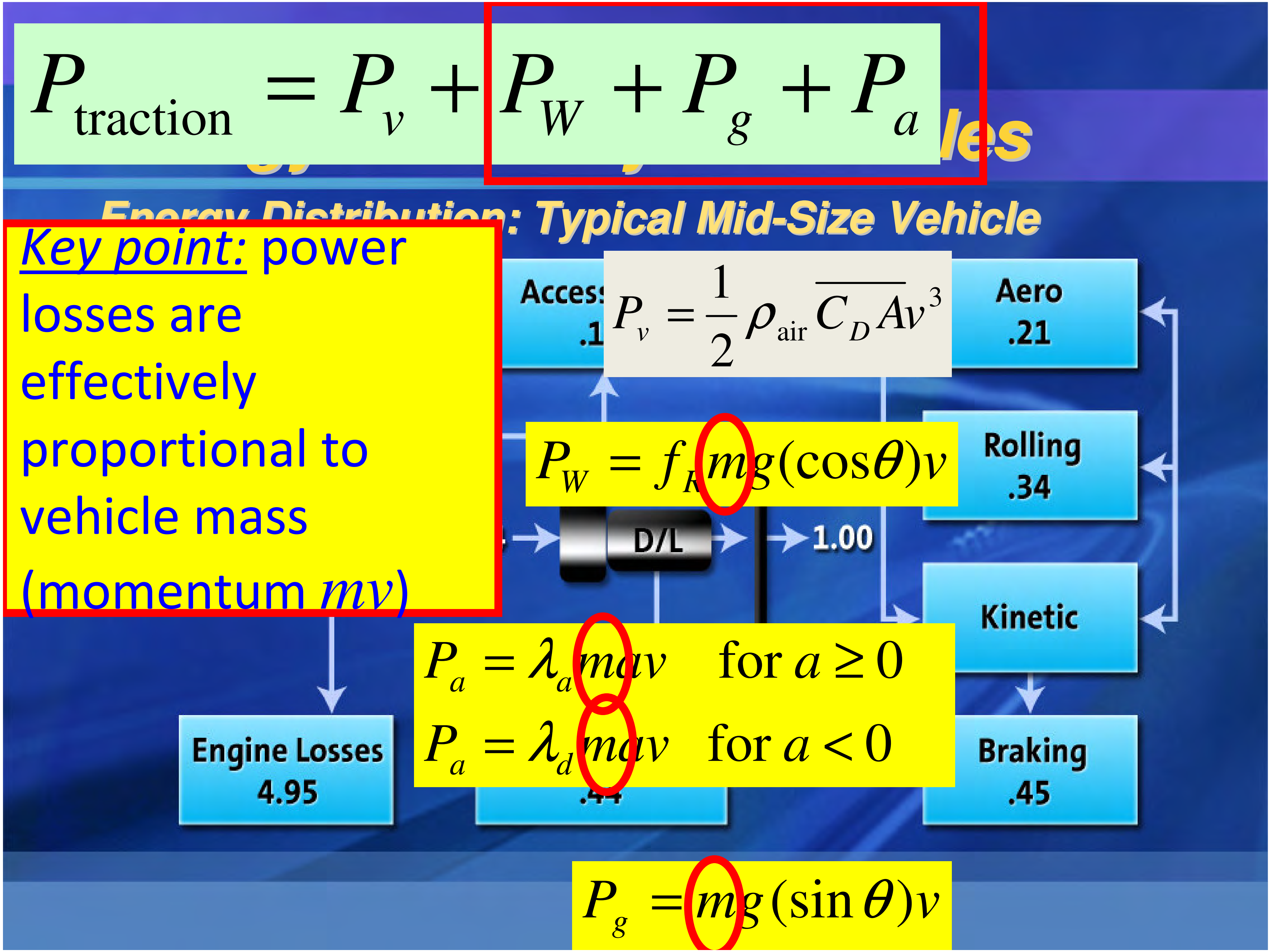
➢ *Systems engineering*: comprehensive look at metrics like $/Δmpg to balance imperatives across all vehicle systems!

Energy Efficiency of Vehicles

Energy Distribution: Typical Mid-Size Vehicle



$$P_{\text{traction}} = P_v + P_W + P_g + P_a$$



Key point: power losses are effectively proportional to vehicle mass (momentum mv)

$$P_v = \frac{1}{2}\rho_{\text{air}}\overline{C_D A v^3}$$

$$P_W = f_R m g(\cos\theta)v$$

$$P_a = \lambda_a m a v \quad \text{for } a \geq 0$$

$$P_a = \lambda_d m a v \quad \text{for } a < 0$$

$$P_g = m g(\sin\theta)v$$

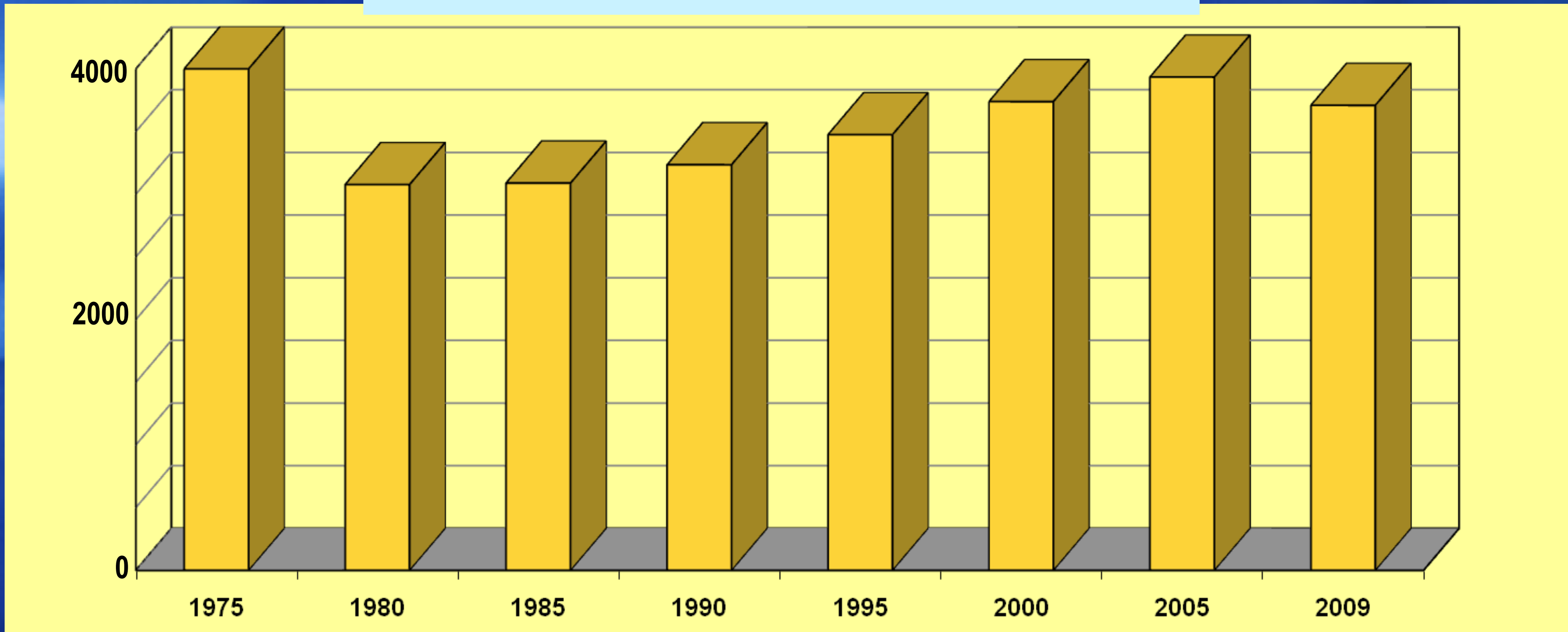
Potential Weight Reduction vs. Steel (%)

		Body Structure	Body Closures	Chassis
High-Strength Steel		25	15	25
Aluminum		40	45	50
Magnesium		55	55	60
Polymer Composite	Carbon	>60	>60	60
	Glass	25	25	35
Titanium		NA	NA	50
Metal-Matrix Composite		NA	NA	60

Vehicle Weight is Increasing

(Customer, Performance, Regulations & Safety)

Average Light Vehicle Weight in Pounds



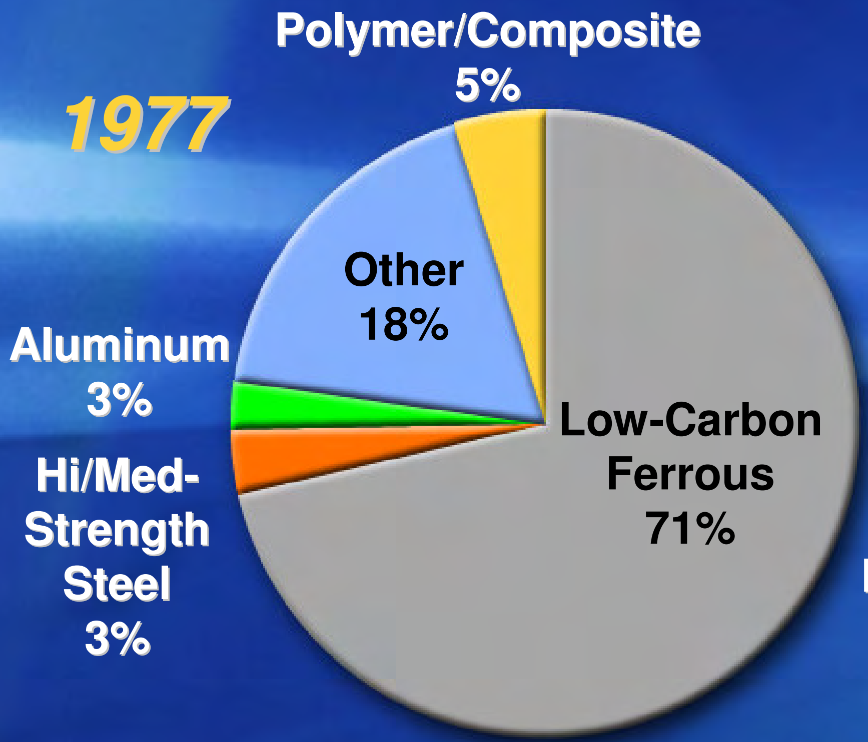
Safety
- ABS
- Airbags
- Crash Structure

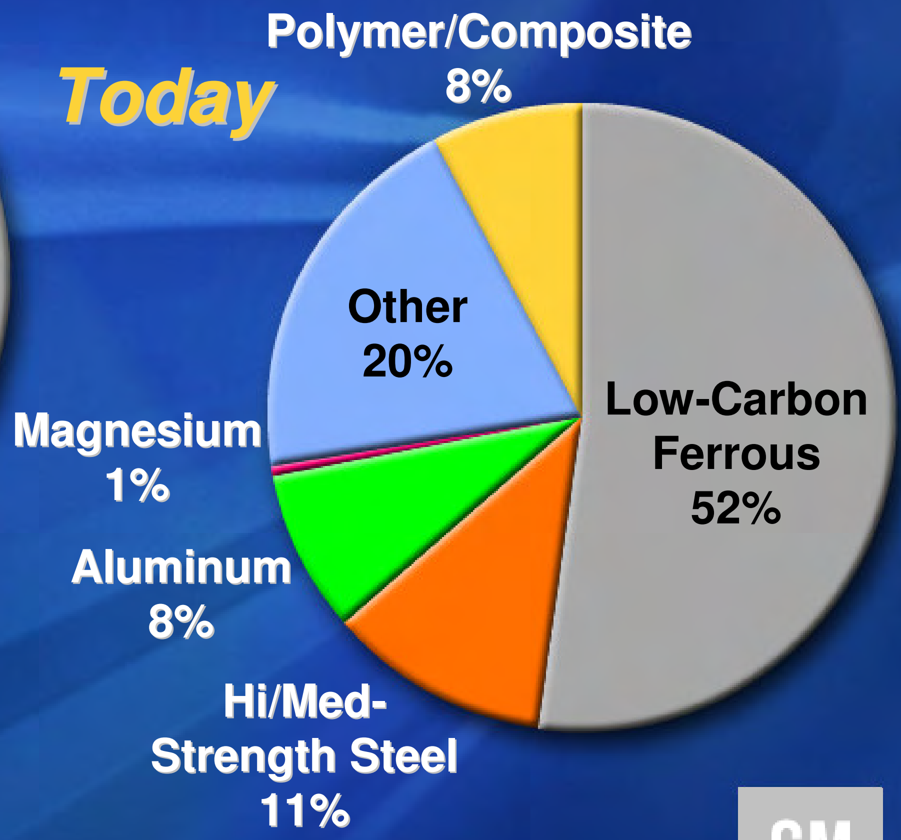
Extras
- Convertibles
- Power Accessories
- Electronics Devices

NVH
- Stiffness
- Insulation

Performance
- 4W Drive
- Traction Control
- Powertrain Features

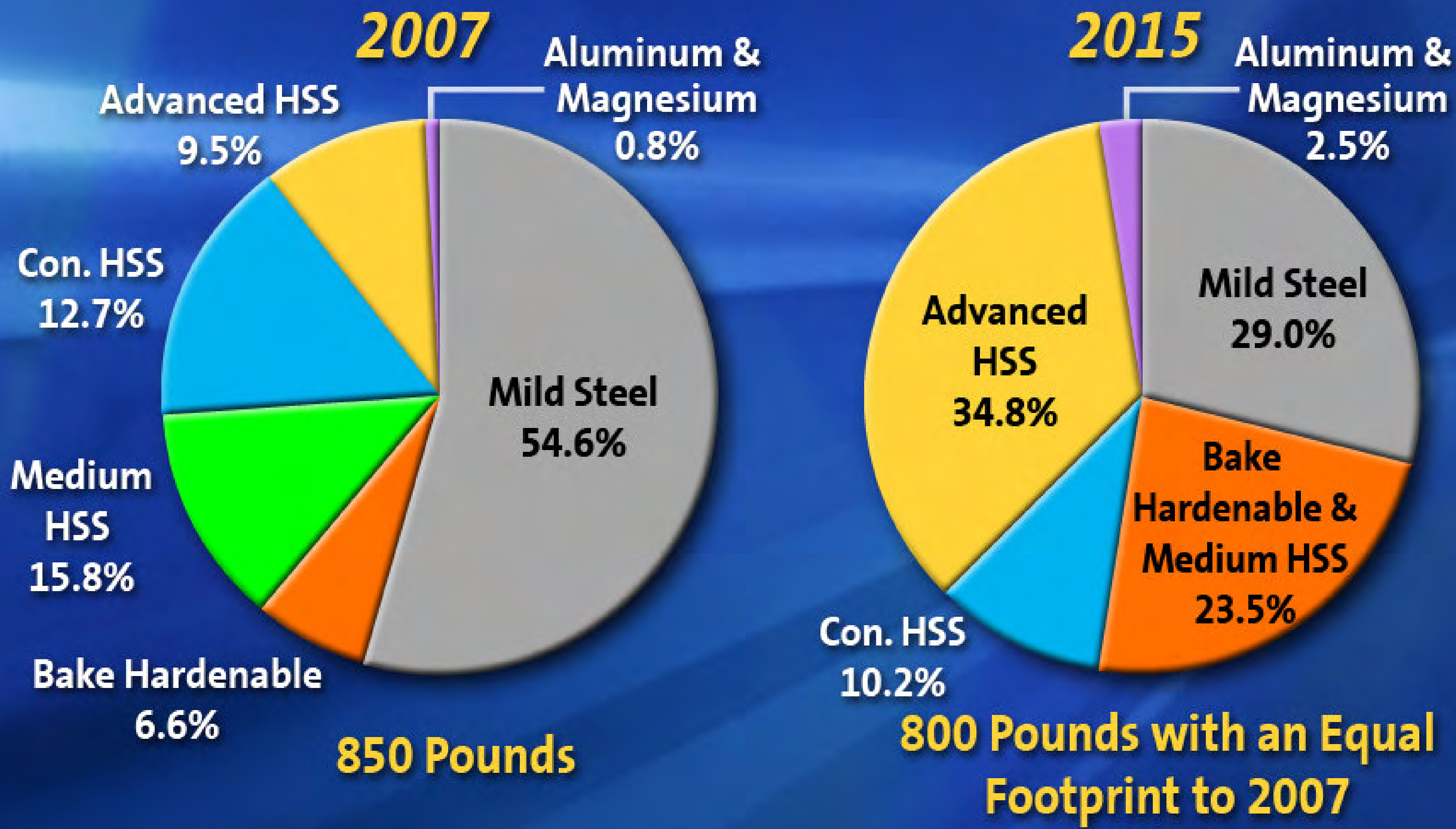
MATERIALS IN A TYPICAL VEHICLE





METALLIC MATERIAL TRENDS

Body and Closure Content by Type



Source: Ducker Worldwide

VEHICLE MASS AND FUEL ECONOMY

- About a 6% improvement in fuel economy for a 10% mass reduction
  – 0.4 mpg improvement per 100 lb for 3500 lb vehicle
  – 0.5 km/L improvement per 100 kg weight reduction for 1500 kg vehicle

Closure Panels

Vehicle mass contribution: ~5%
Mass correlation coefficient: ~0.02

- 100 kg reduction in vehicle mass leads to another 2 kg reduction in closure mass
- 20 kg reduction in closure mass leads to another (nearly) 20 kg reduction in the vehicle mass

Aluminum Closure Status

- Aluminum has been used extensively for "simple" closure panels like hoods on most large/luxury vehicles
- Industry standard for Al doors is multi-piece assembly
- Hot blow forming technologies are attractive at low volumes
- Significant redesign of steel panels is necessary to utilize conventional stamping
- No process is currently available to make high volume complex aluminum panels

Preform Annealing

Preform Annealing is a GM patented (US 7,260,972) process to enhance formability which includes an annealing step between a draw and redraw operation.

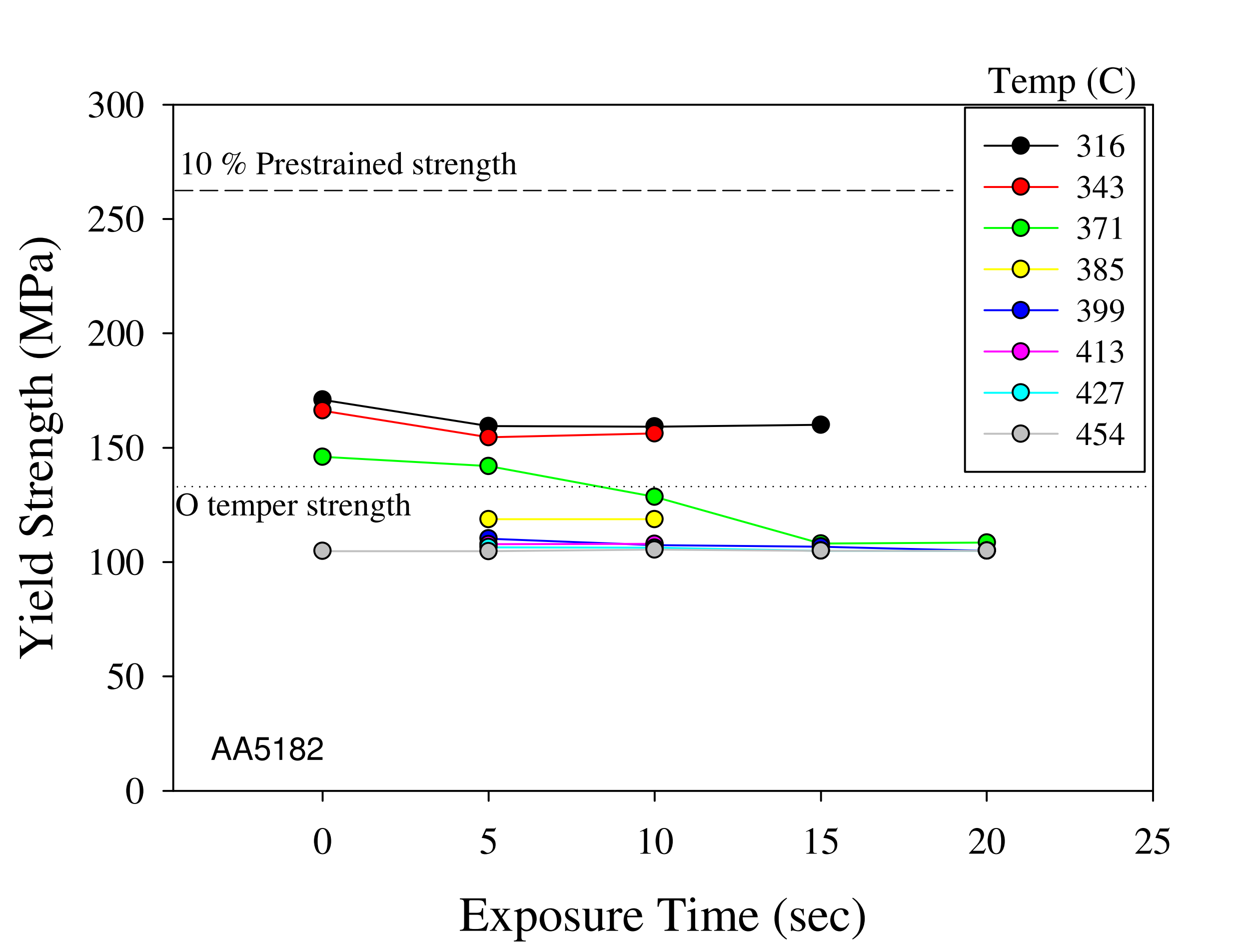
Preform

Anneal
350^{0}C

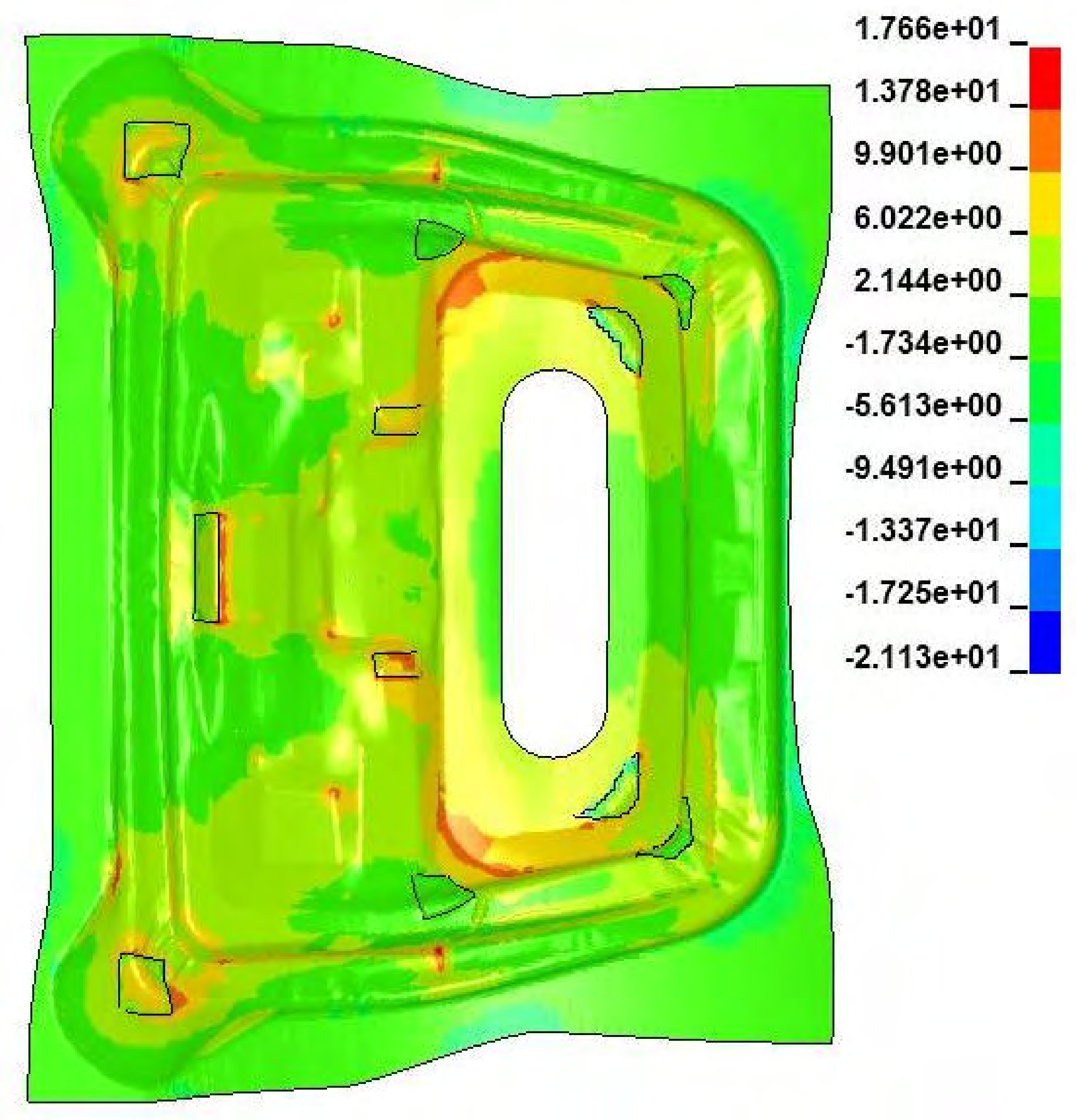
Forced
Air
Cool

Final Form

Rapid Annealing To Enable High Volume

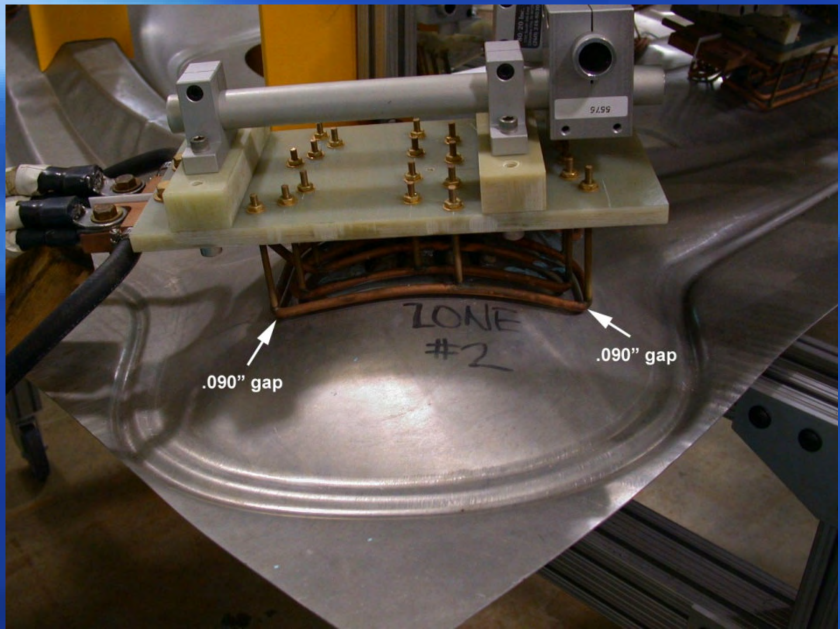


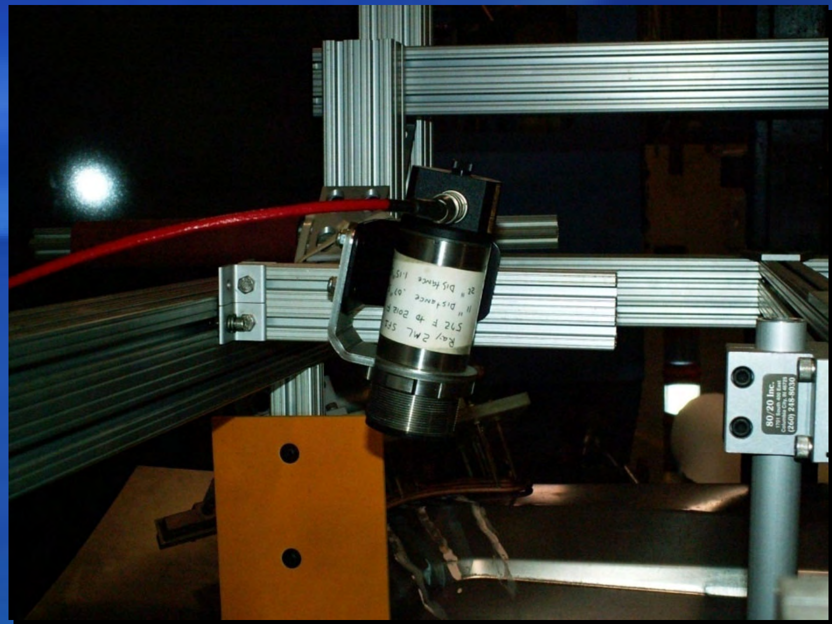
FEM to locate annealing needs



- End of first draw stage; stopped 24 mm from the bottom of the die.
- Thickness strain depicted
- Regions outlined: reset to O temper properties with annealing

Induction Coils Developed for Critical Regions





Location Specific Coils Manufactured

Infrared Camera Monitors Heat Cycle

Annealing Fixture Clamps/Heats Preform

O temper strength can be recovered in a matter of seconds

Preform Annealing Opportunities

- Identify optimum preform shape and annealing locations using FEM
- Build flexible coils & system to work in a press line and allow for quick die change between various parts
- Construct forming limit diagrams as a function of prestrain, annealing, and strain path
- Apply process to 6xxx series alloys

Aluminum Sheet Opportunities

Short term

- Global large sheet (2 m) capability for both 5xxx and 6xxx alloys providing acceptable class A surface quality
- Optimized recycling streams to capture maximum value from engineered scrap

Long term

- Joining technologies enabling mixed material structures (bonding Al to steel, magnesium, and composites)
- Low cost lubricants for elevated temperature forming processses which are compatible with painting and joining technologies
- 6xxx type alloy for elevated temperature forming

Body Structure

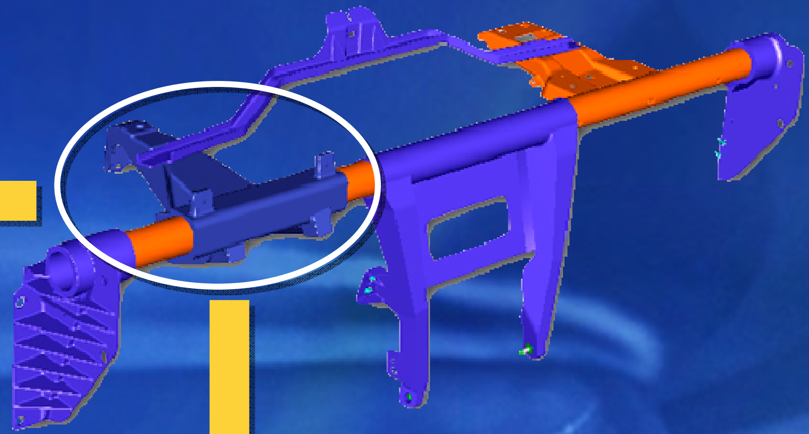
Vehicle mass contribution: ~23%
Mass correlation coefficient: ~0.25

- 100 kg reduction in vehicle mass leads to another 25 kg reduction in body-structure mass

➢ Significant new challenge to Al alloys: Mg alloys

OVERCASTING WITH DISSIMILAR MATERIALS

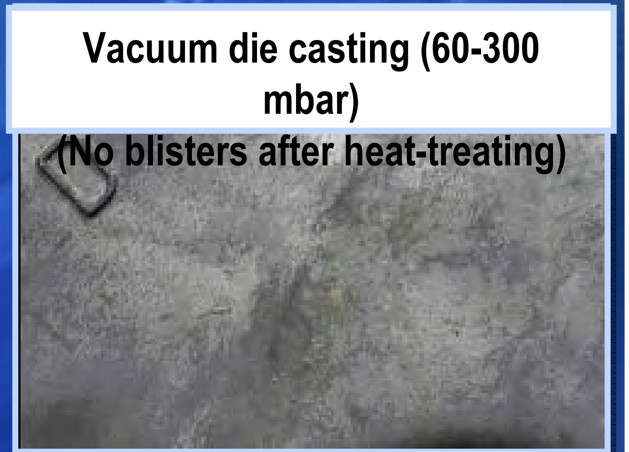
Steel Tube Overcast
with Al



VACUUM DIE CASTING: HEAT-TREATABLE AND WELDABLE

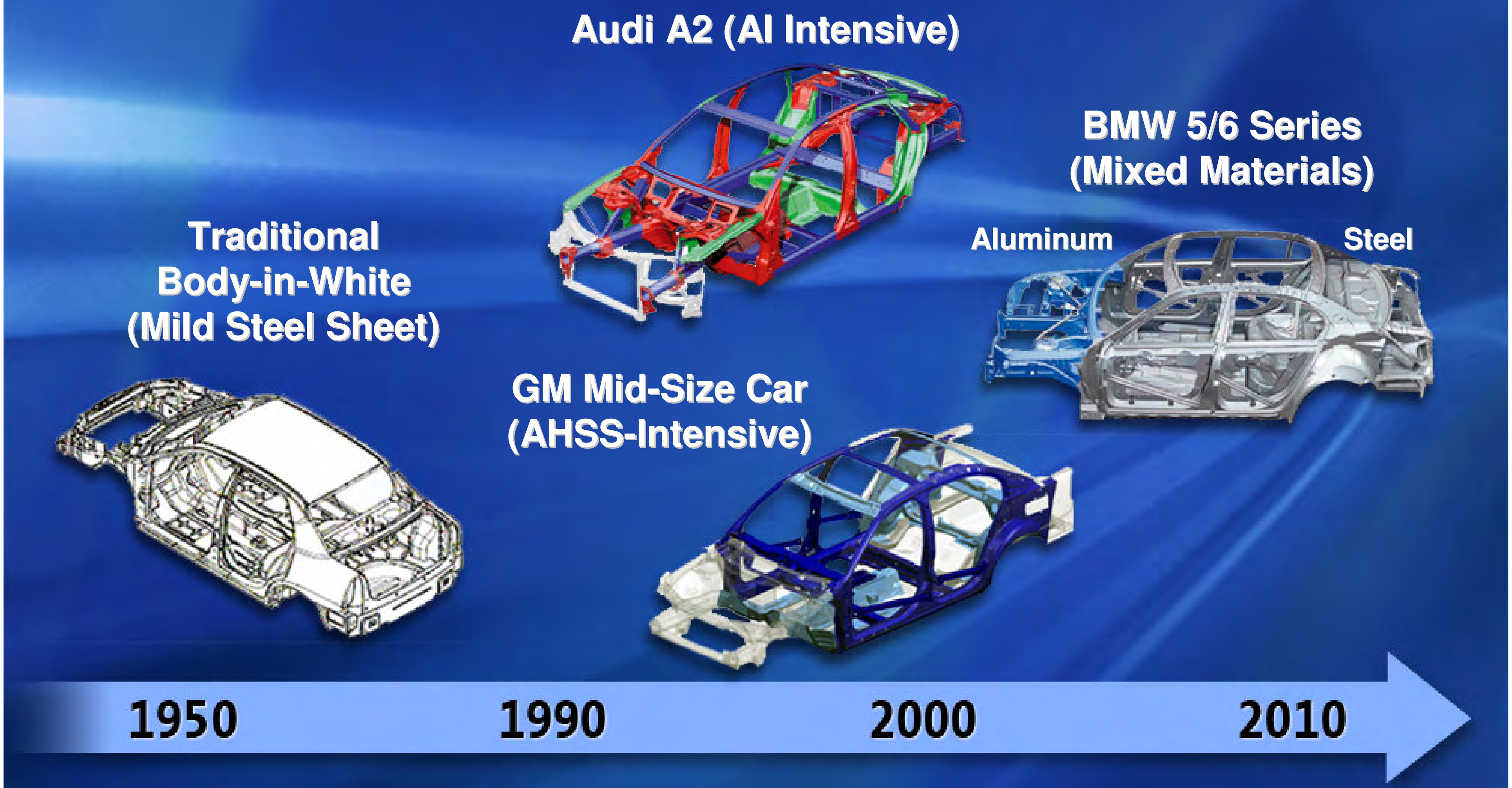
(Source: USAMP)

Alloy	UTS, MPa	YS, MPa	Elongation %
AM60B-SVDC	230	125	9
AM60B-HPDC	210	120	6



(Source: Alcan/Contech)

BODY STRUCTURE



INSTRUMENT PANEL BEAM

Mg Die Casting (1 part/6 kg)

Welded Steel Sheet Construction (30 parts/12 kg)

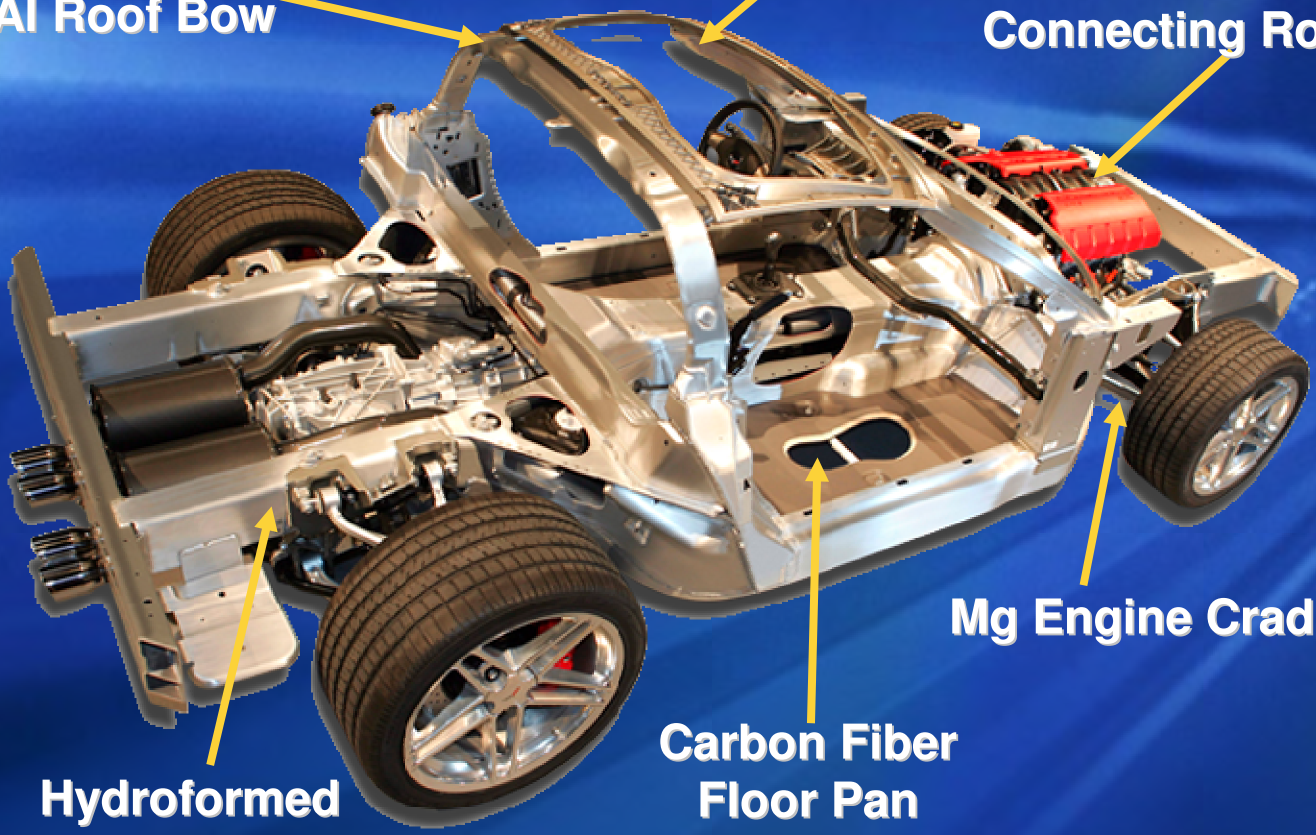
Steel Tube Design (15 parts/8 kg)

Mg Tubular Overcasting (2 parts/4 kg)

1950 — 1990 — 2000 — 2010

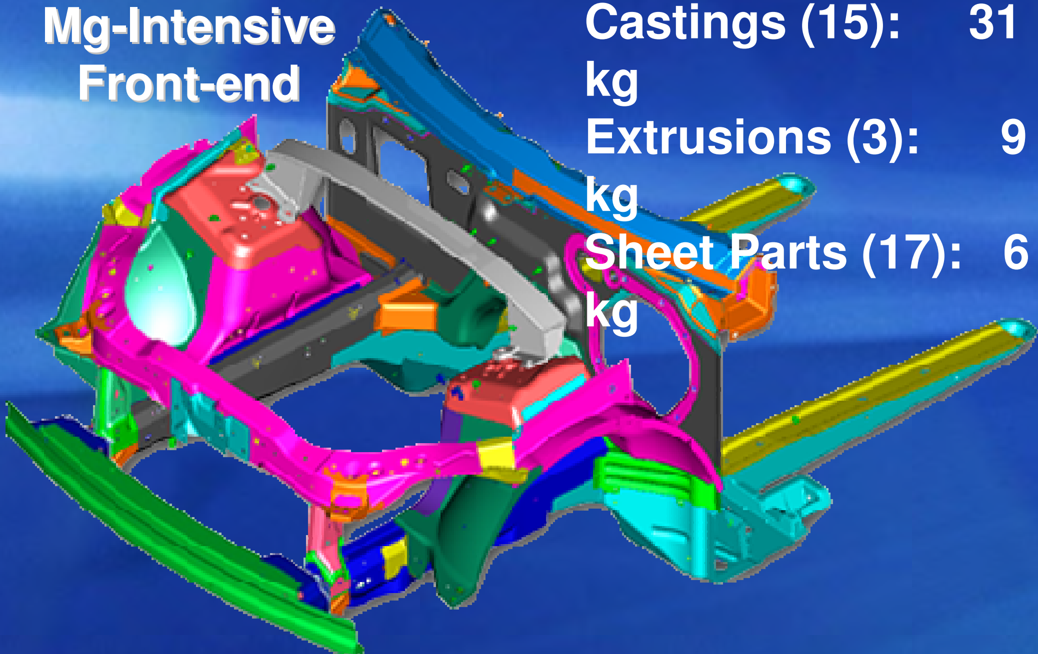
CHEVROLET CORVETTE Z0

0 to 60 mph in 3.7 s



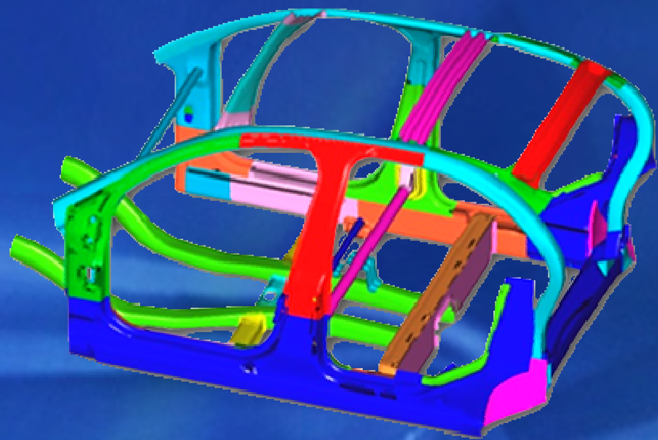
MULTI-MATERIAL BODY – THE FUTURE

Mg-Intensive Front-end

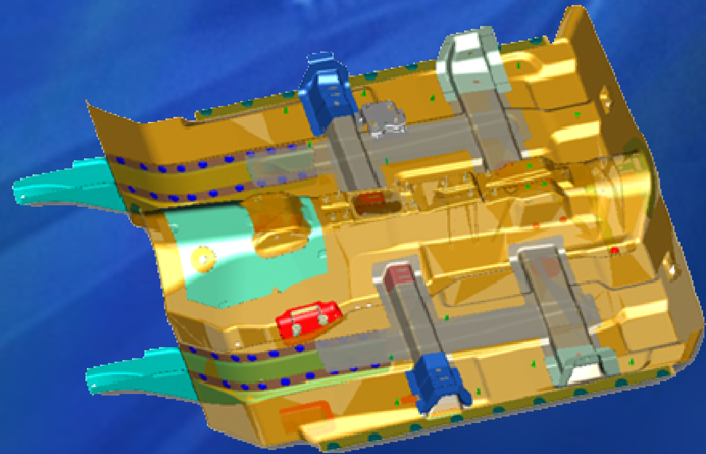


Castings (15): 31 kg
Extrusions (3): 9 kg
Sheet Parts (17): 6 kg

Steel: 79 Parts; 84 kg
Mg: 35 Parts; 46 kg
(Eliminate 44 Parts and Save 38 kg - 45%)



AHSS Passenger Compartment



Composite Floor Pan

USAMP
UNITED STATES AUTOMOTIVE MATERIALS PARTNERSHIP LLC

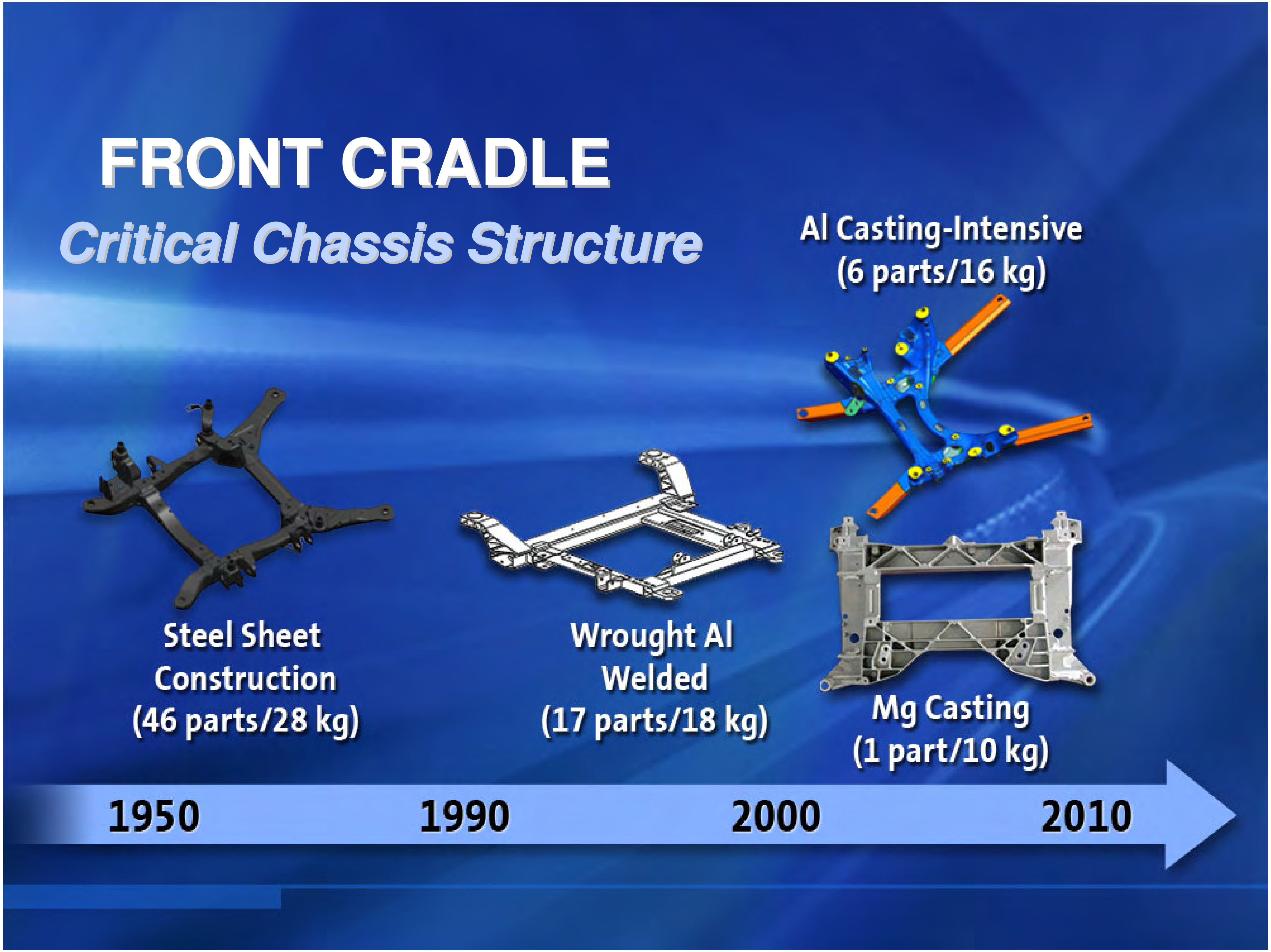
Chassis

Vehicle mass contribution: ~20%
Mass correlation coefficient

Suspension: ~0.3 (mostly metal components)

Steering, tires, wheels, electrical have lower mass correlation coefficients

- 100 kg reduction in vehicle mass leads to another 46 kg reduction in chassis mass


FRONT CRADLE
Critical Chassis Structure
Al Casting-Intensive
(6 parts/16 kg)
Steel Sheet
Construction
(46 parts/28 kg)
Wrought Al
Welded
(17 parts/18 kg)
Mg Casting
(1 part/10 kg)
1950
1990
2000
2010

ALUMINUM CRADLE – CADILLAC CTS

- Large hollow casting with welded extrusions
- Steel 27 kg; Al 16kg

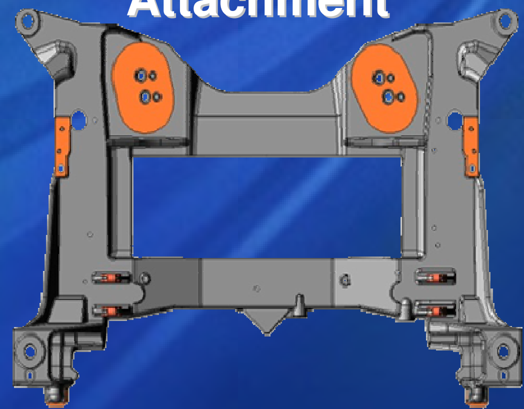
2008 AFS Casting of the Year Honorable Mention Award

DIE CAST MAGNESIUM ENGINE CRADLE

- One piece; first in industry
- 10.4 kg; 35% weight reduction compared to aluminum

AE44 Alloy

Aluminum Isolation Washers for Cradle-to-Body Attachment



2006 International Magnesium Association Application Award

Powertrain

Vehicle mass contribution: ~25%
Mass correlation coefficient

Engine: ~0.2 Transmission: ~0.1

Fuel system and balance: lower correlation

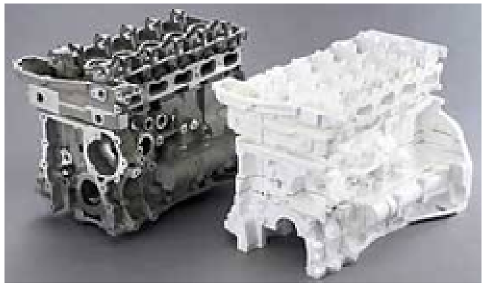
- 100 kg reduction in vehicle mass leads to another 30 kg reduction in engine + transmission mass

ENGINE BLOCKS

Cast Iron Block
(~68 kg)

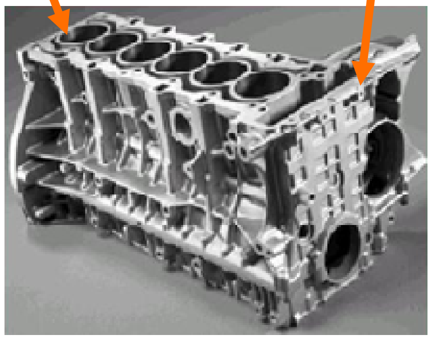
GM Die Cast Al Block
(~26 kg)

GM Lost Foam
Cast Al Block



BMW Mg/Al Block

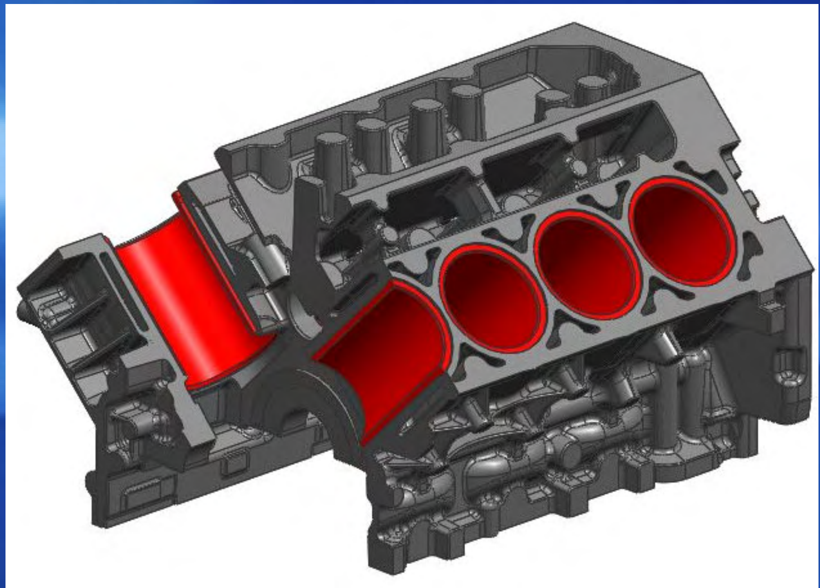
Al
Mg

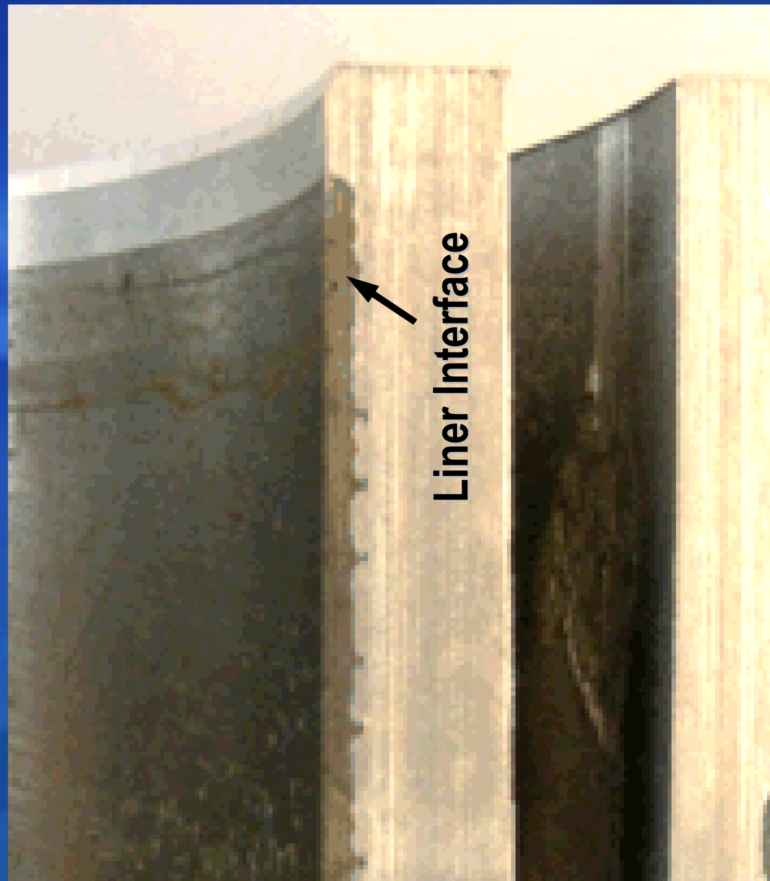


USCAR Mg Block

1950 — 1990 — Al ~50% weight reduction — 2000 — Mg ~25% weight reduction — 2010

Linerless Al engines





Benefits

- Improved heat transfer
- Higher combustion volume
- Eliminate liner mass and cost

PROTOPTYE DIE CAST MAGNESIUM OIL PAN FOR V8 ENGINE

Aluminum
(6.1 kg)

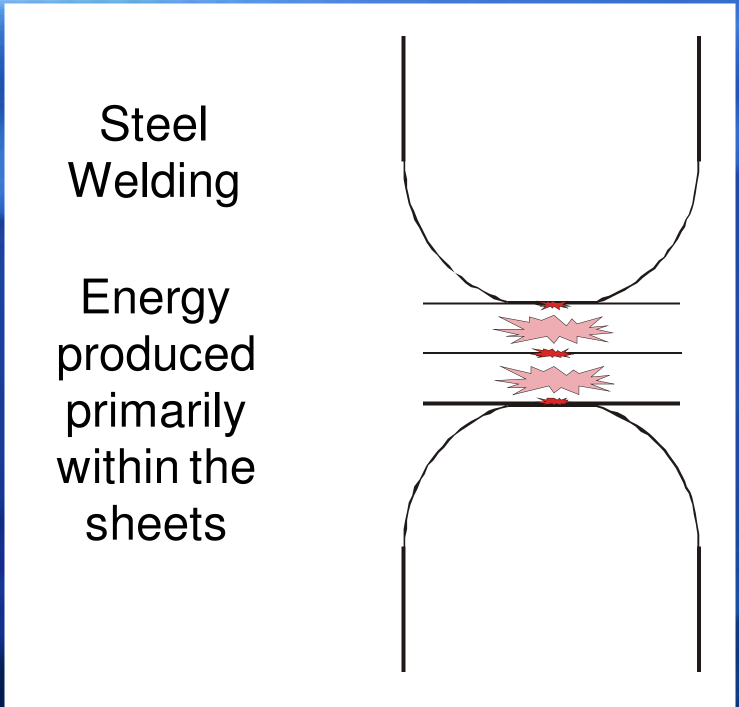
Magnesium
(4.2 kg; 30% Reduction)
AE44 Alloy

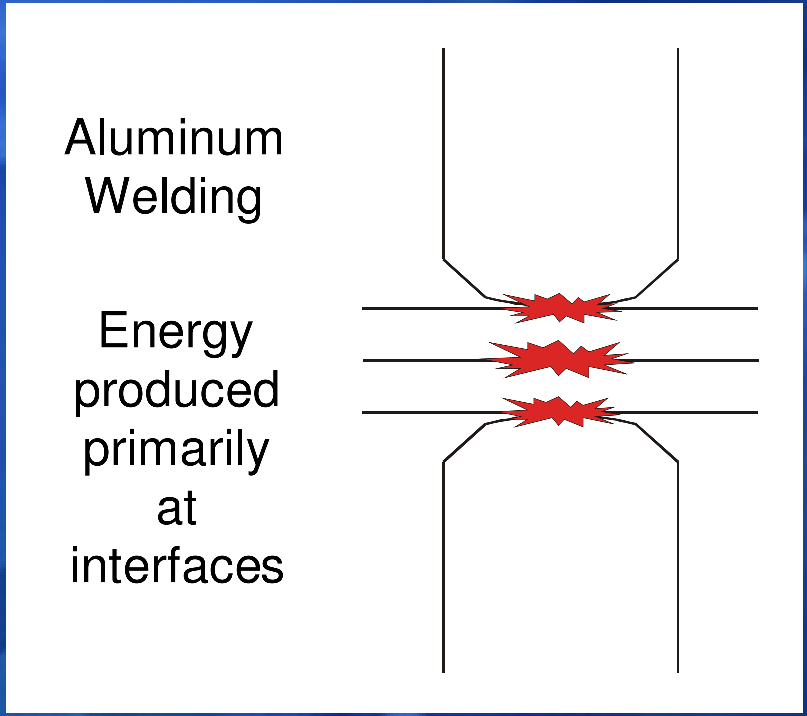
Joining

- Because of difficulties in spot welding of Al, many manufacturers have shied away from its use for high volume manufacturing, and instead have used rivets, adhesive, etc., to join aluminum structures.
- Properly implemented, spot welding may offer cost, productivity, and design flexibility advantages that are very attractive to auto manufacturers.

Energy Generated During RSW of Aluminum Compared to Steel

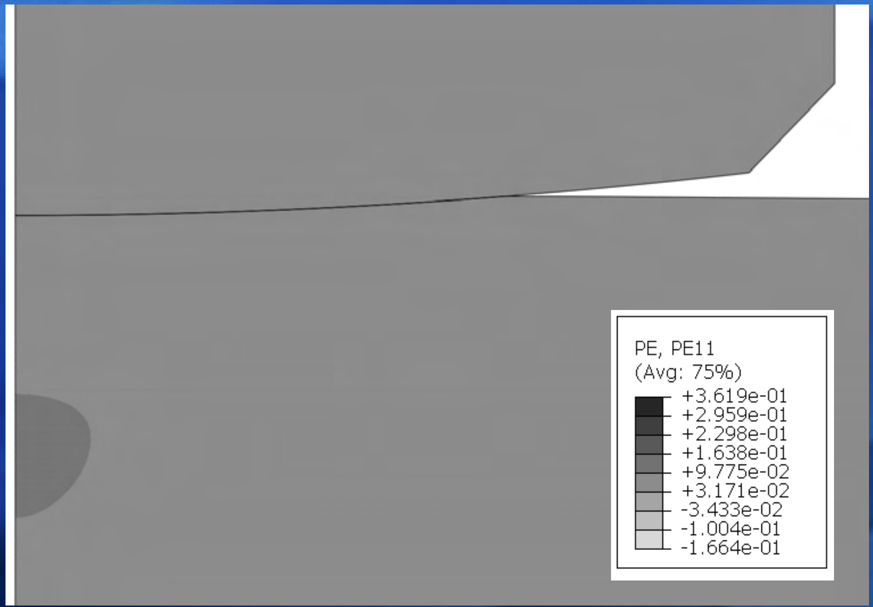
- Steel: heating within sheets
- Aluminum: heating at interfaces due to surface oxides

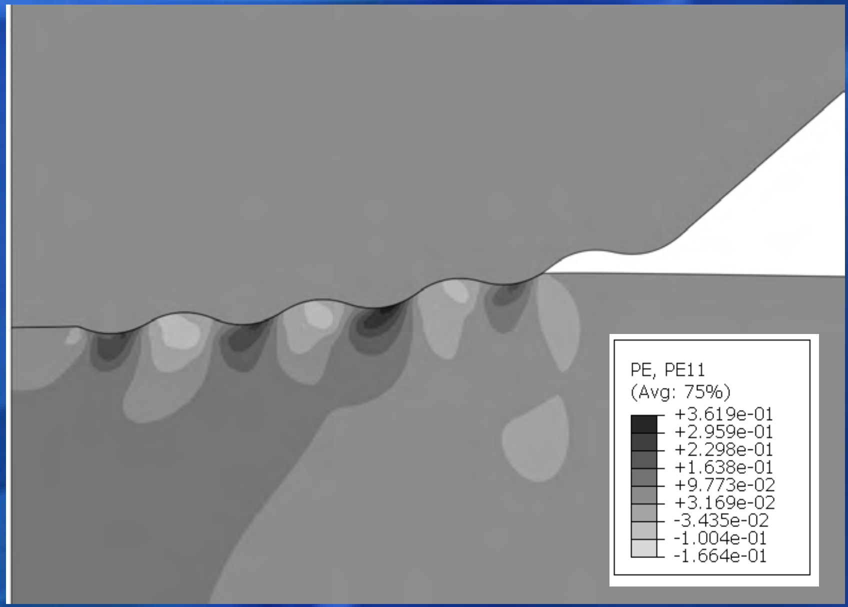




Conventional vs Macro-Featured Electrodes for Aluminum Welding

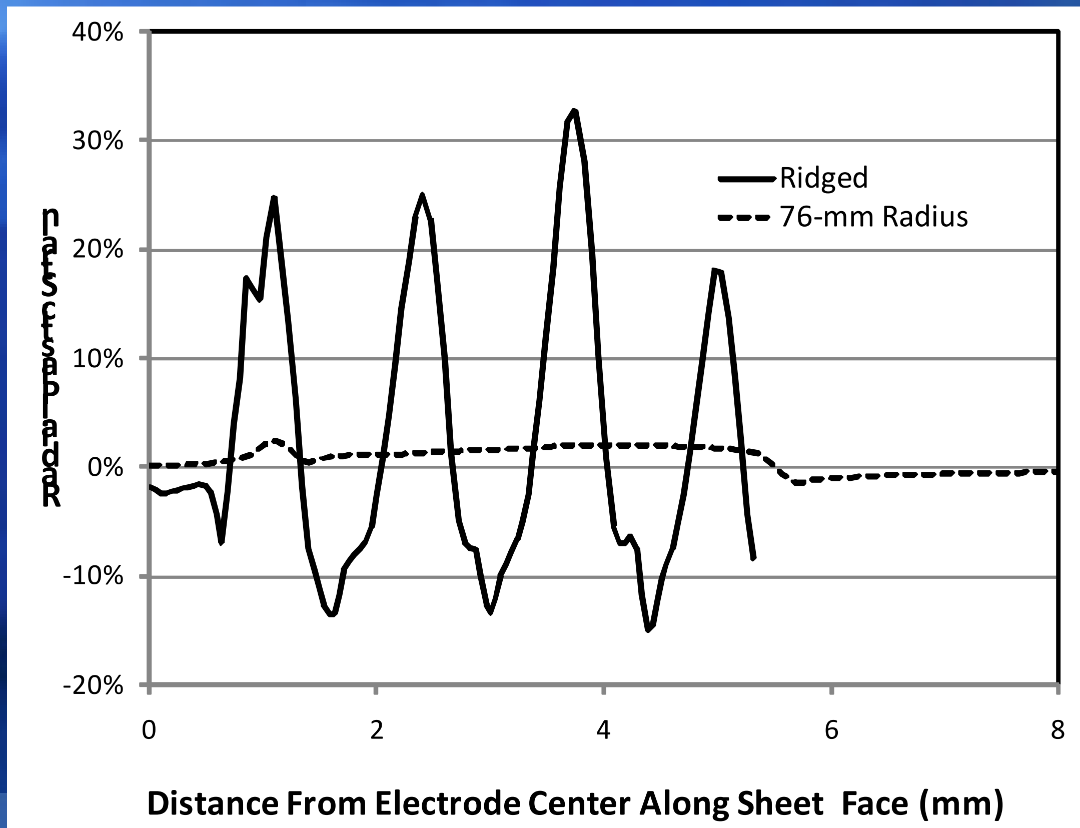
- Radial strain following indentation as proxy for oxide fracture and penetration
  - 75-mm radius electrode: strains <3%
  - Featured electrode: local strains >20%





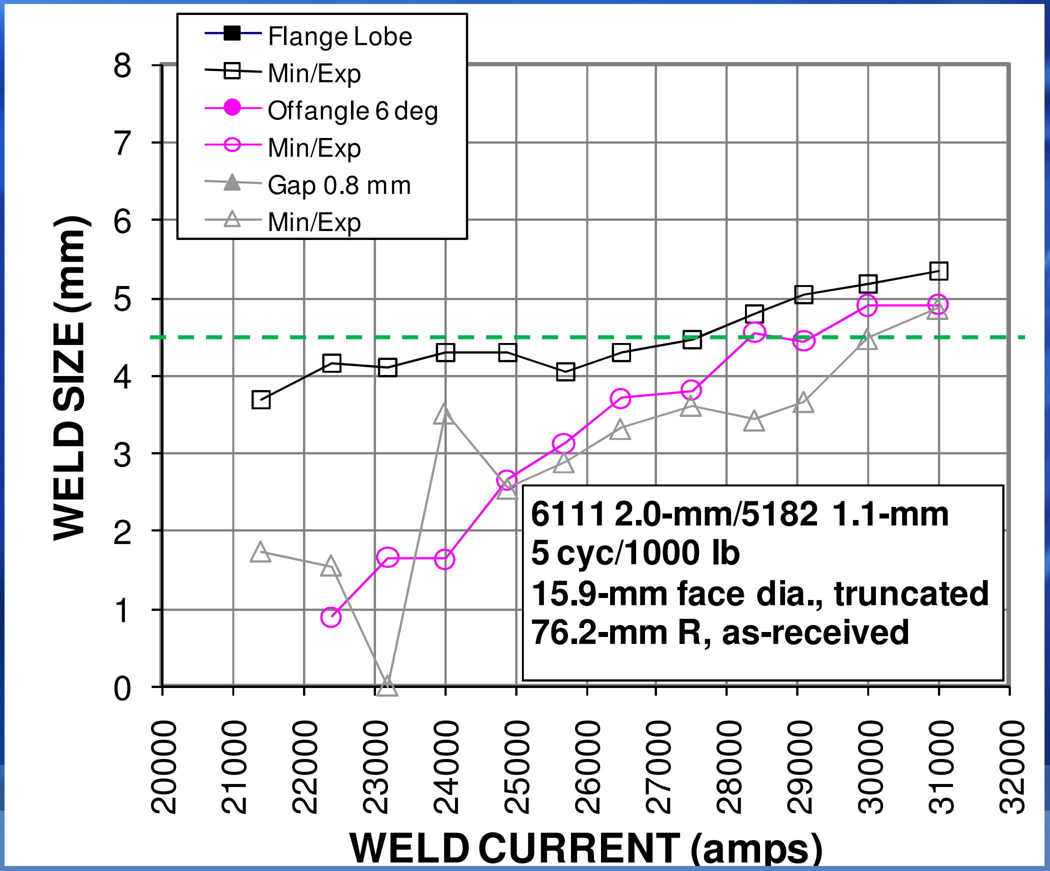
Conventional vs Macro-Featured Electrodes for Aluminum Welding

- FEA predictions of surface strains at the aluminum sheet surface

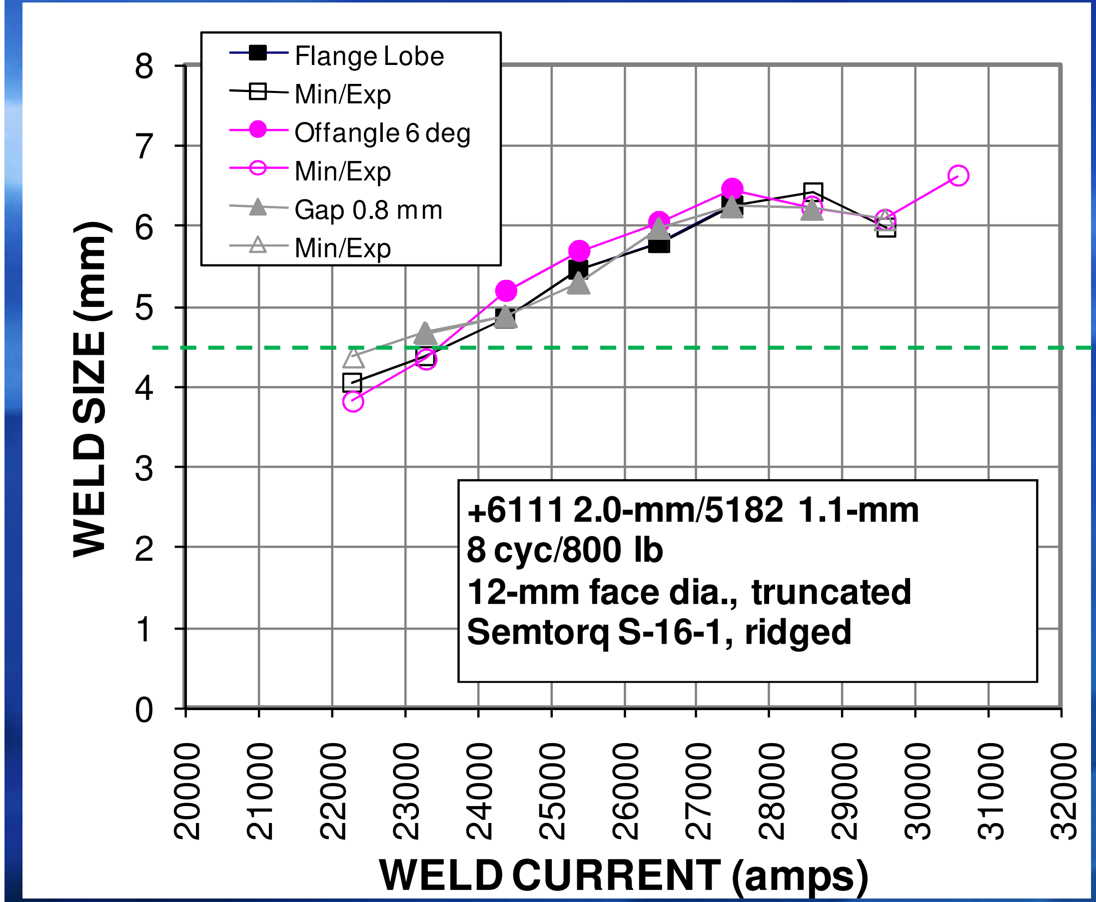


Aluminum Welding Behavior with Conventional Electrodes

- Narrow range of conditions to achieve satisfactory weld size (>4.5mm)
- Behavior degrades with poor fit-up and offangle conditions



Aluminum Welding Behavior with Macro-Featured Electrodes



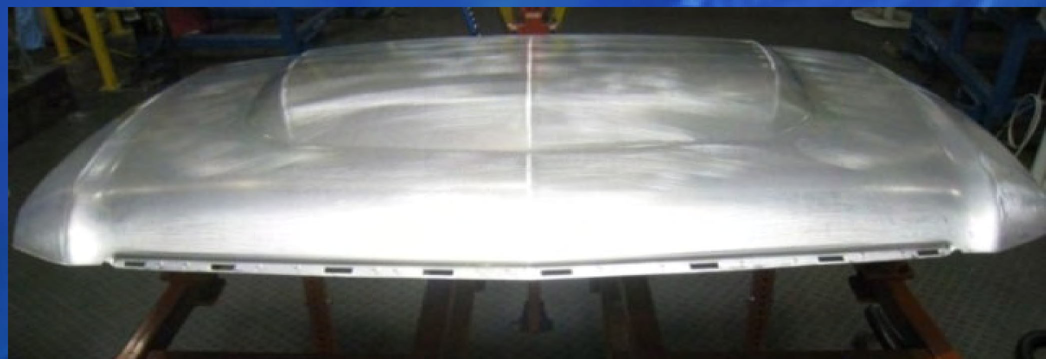
- Broad range of conditions to achieve adequate weld size (> 4.5mm)
- Behavior insensitive to poor fit-up and off-angle conditions
- Enablers for macro-featured welding system: scale implementation of mid-frequency DC welding and rotary electrode dressing systems.

2008 Hybrid Tahoe Aluminum Liftgate

- Liftgate is resistance spot welded with macro-featured electrodes
- Electrode surfaces maintained with a rotary dressing operation

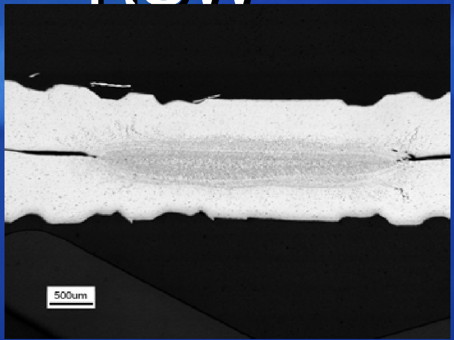
2009 Cadillac CTS-V Aluminum Hood

- Narrow front flange (10.5-mm weld flat) is resistance spot welded with macro-featured electrodes
- Conventional aluminum RSW not capable for this geometry

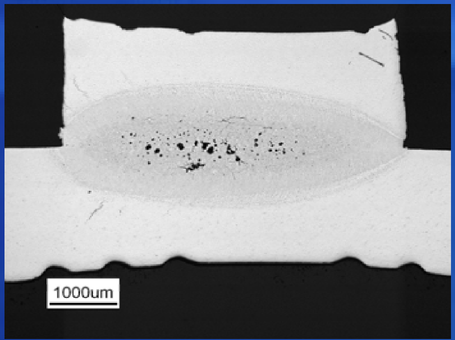


Macro-Featured Electrodes Weld Both Aluminum and Steel

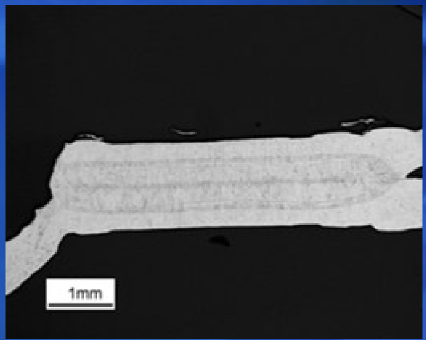
- Common electrode can be used for Al/Al and Fe/Fe welding
- Required aluminum currents reduced vs historic RSW



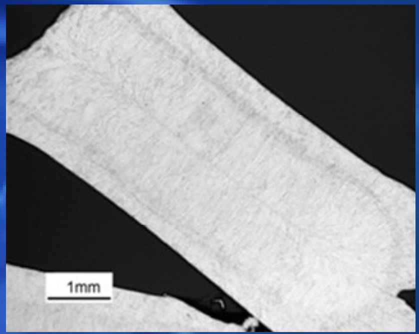
0.8 to 1.0 mm
6111-T4 Al



2.0 to 2.0 mm
5754-0 Al



0.75 to 0.75 mm
HDG (hot dip galvanized) low carbon steel



1.5 to 1.5 mm
HDG low carbon steel

Corrosion

- Filiform Corrosion is of concern for closure panels
- Dissimilar joints (Al-Steel) …concern over galvanic coupling
- Alternative fuels (e.g., E85) can induce corrosion in Al engines

Filiform Corrosion

- Filiform corrosion…most common corrosion challenge for Al panels
- Another current manufacturing challenge…cross-contamination of steel to Al during metal finishing of closures
- Cathodic intermetallic particles (Al_3Fe) increase corrosion rate. Conversion coatings can provide protection but are costly.

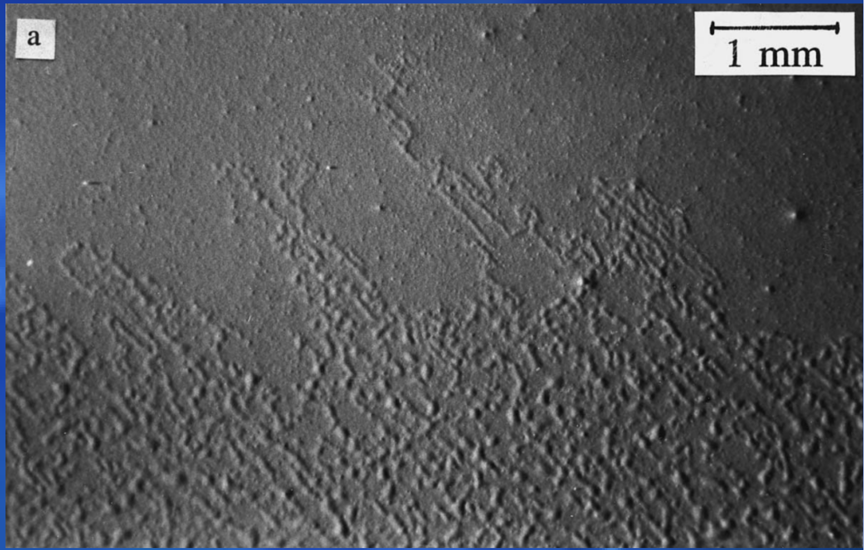
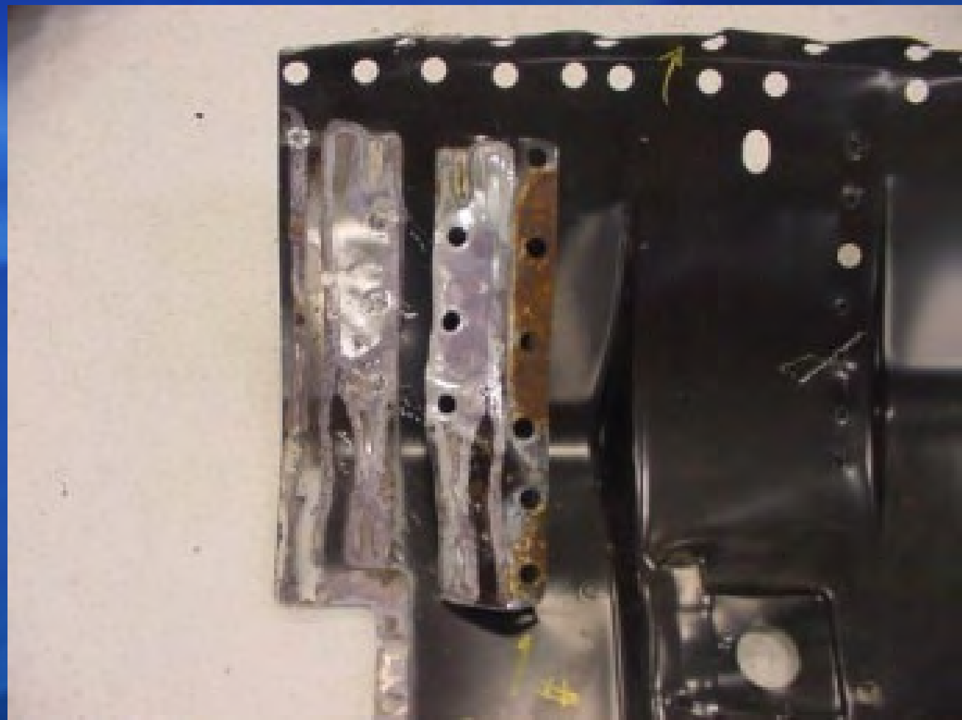


Photo from Leth-Olsen & Nisancioglu, 1998

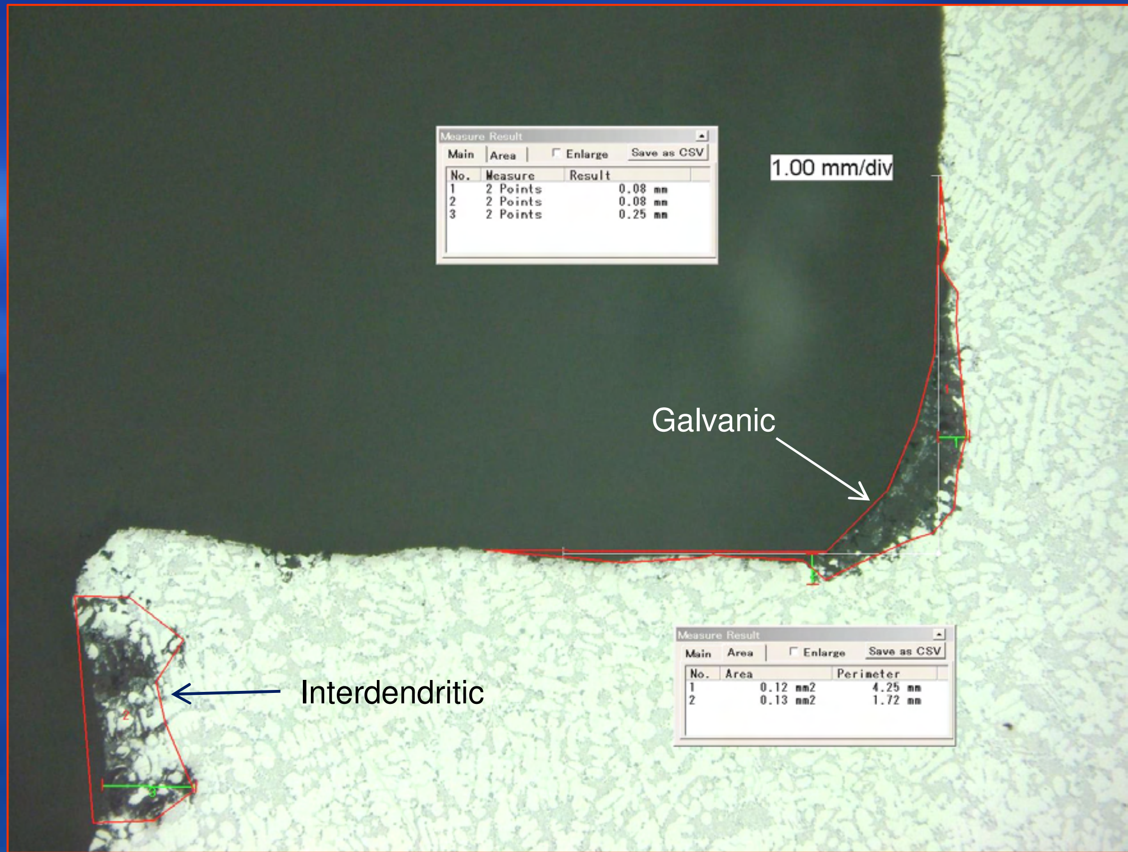
Aluminum – Steel Interfaces

- Adhesive typically used as isolation strategy
- Patchy adhesive layers can lead to poor phosphate & electro-coat (ELPO) corrosion protection



E85 Induced Corrosion between Valve Seat & Al 319 Cylinder Head

Pressed in Steel
Valve Seat



Opportunities for Aluminum in Structures

Short term

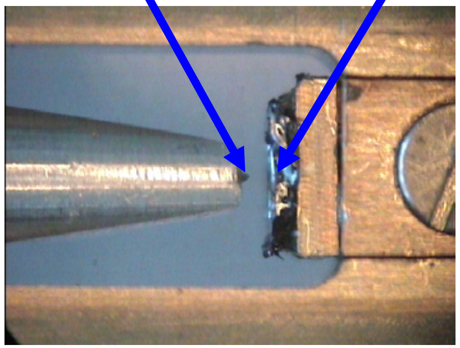
- Large, thin wall, and hollow castings
- High strength/toughness and weldable castings in load paths

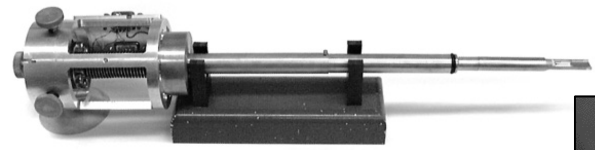
Long term

- Linerless engines
- Mixed materials subsystems, including joining
- Galvanic corrosion mitigation

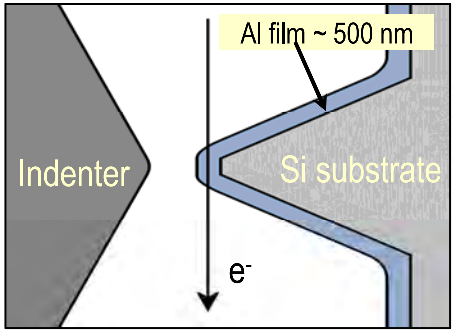
Future enablers

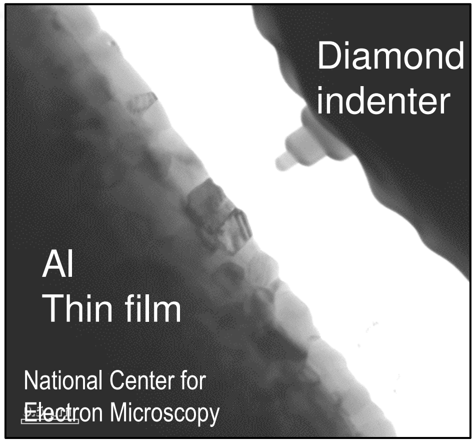
In-Situ Nanoindentation inside a Transmission Electron Microscope

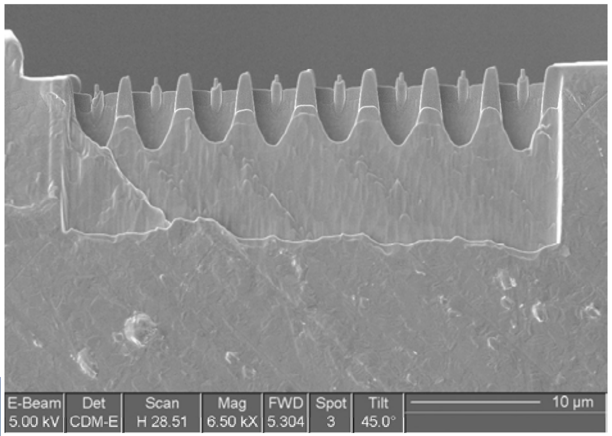


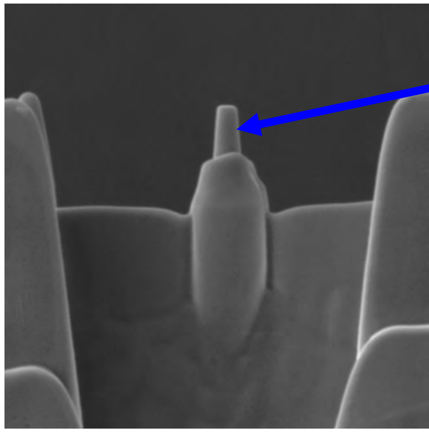


Wall and Dahmen, *Microscopy and Microanalysis*, **3**, 1997







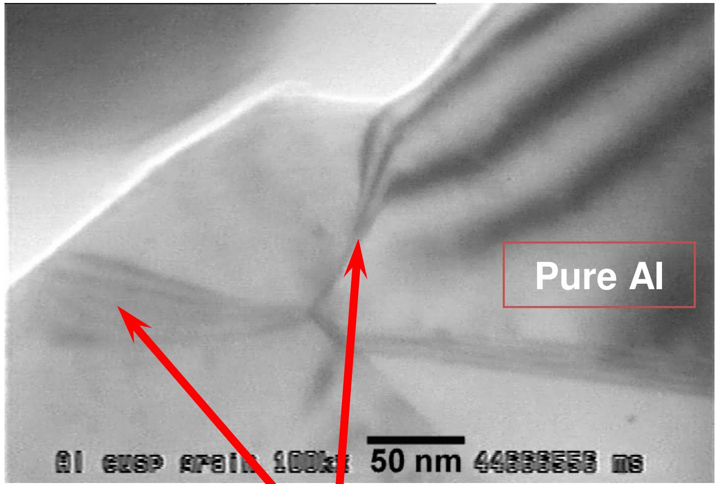


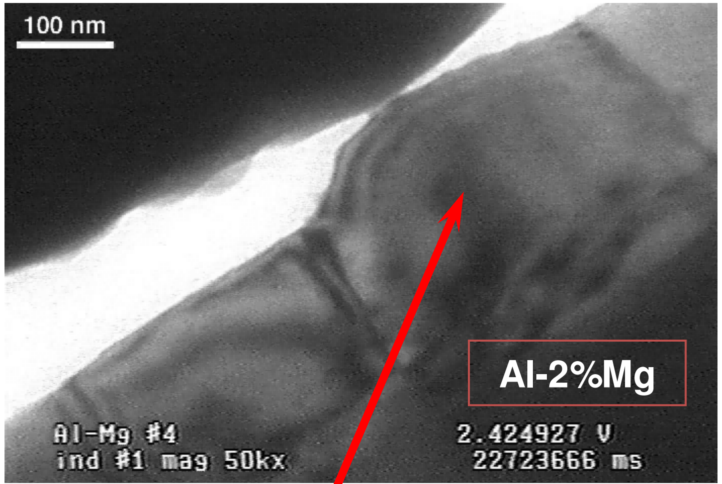
Pillar Fabrication

- 160-200 nm diameter
- 600-800 nm long
- 3-5º taper

Work of LBL and colleagues

Grain Boundaries in pure Al and Al-Mg



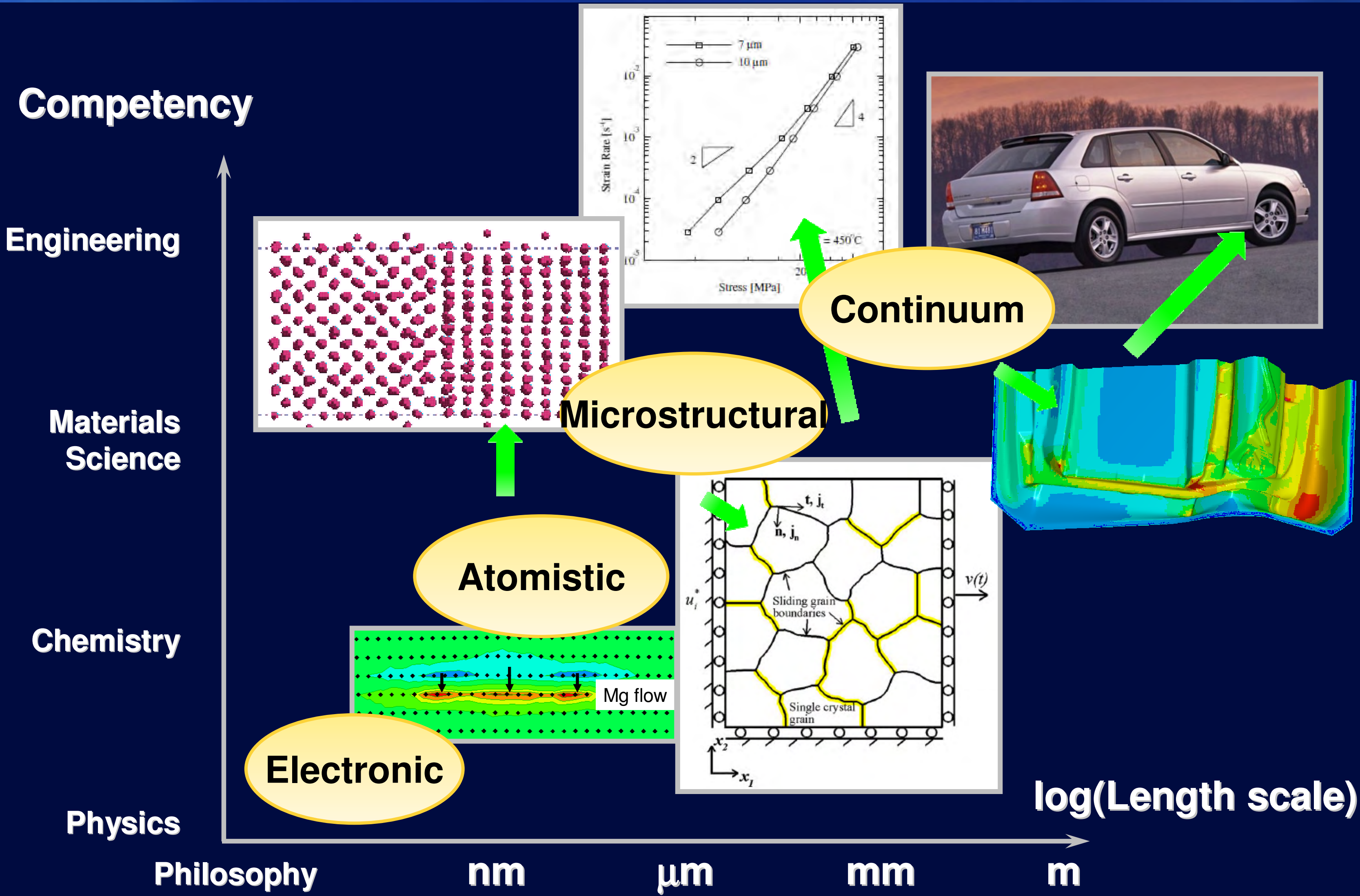


High angle boundaries are mobile since there are no solutes to pin them

Mg pins the high angle boundaries and make them immobile. Dislocations thus accumulate inside the grain to cause hardening

Work of LBL and colleagues

MULTI-SCALE MODELING OF ELEVATED TEMPERATURE DEFORMATION



SUMMARY

- GM's focus…design, build and sell the world's best vehicles
- Mass-reduction technologies are key to reinventing the automobile for tomorrow
- *Affordable, formable/castable, and robust aluminum components and subsystems are of great interest for automotive applications*