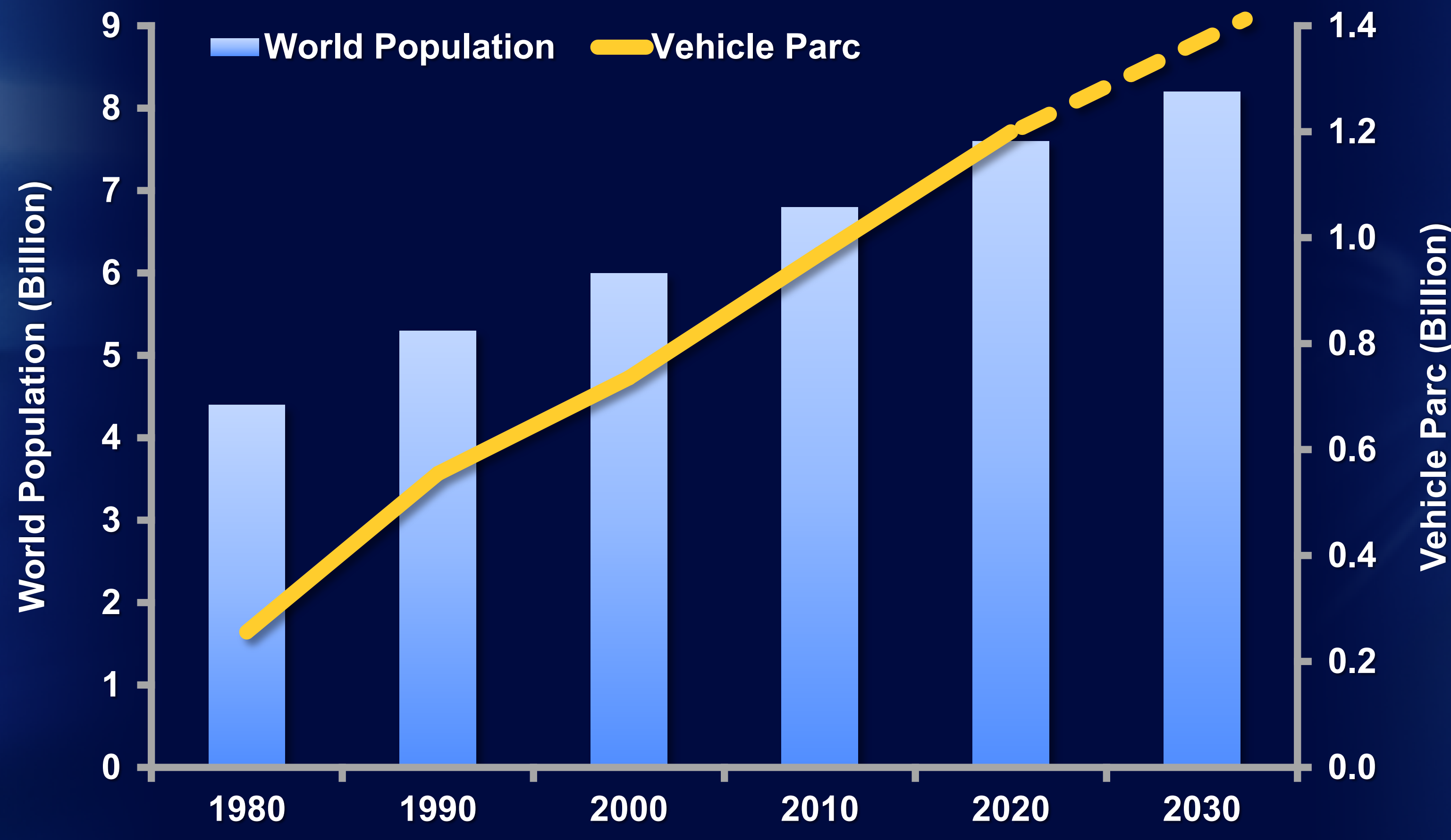
"Addressing The Transportation Energy Challenge"

DOE Merit Review
June 16, 2014

ALAN TAUB
Professor, University of Michigan
CTO, American Lightweight Materials Manufacturing Institute (ALMMII)




PERSONAL MOBILITY MUST BE REINVENTED FOR THE 21st CENTURY



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

2013 AND BEYOND

The World Can Afford >1 Billion Operating Vehicles
… But Is It Sustainable?

WHY ARE WE HERE?

PETROLEUM SUPPLIES…

35%
OF WORLD'S ENERGY

96%
OF TRANSPORTATION ENERGY

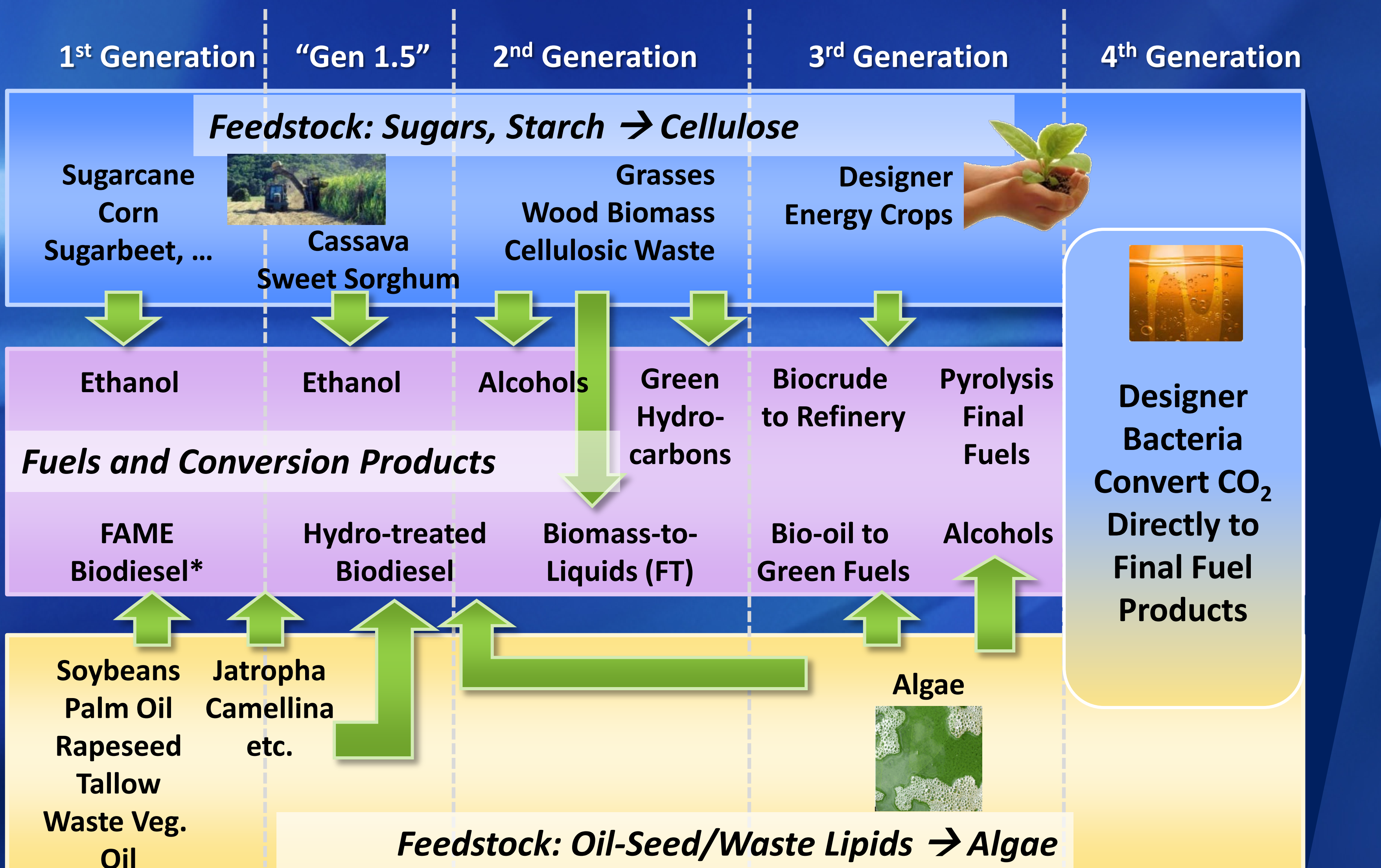
TYPICAL VEHICLE-LEVEL ENERGY BREAKDOWN

Compact Sedan with Four-cylinder Engine and Automatic Transmission
(U.S. Federal Test Procedure, Composite City-Highway Drive Cycle)

Fuel Input
100%

TO THE ROAD
17%

BIOFUELS TECHNOLOGY ROADMAP



ENERGY DIVERSITY – CNG AND LPG





- **10 CNG & 18 LPG global applications**
- **15% CO_2 reduction**
- **Gasoline-equivalent cost**
  - **CNG: 40% lower**
  - **LPG: 22% higher**

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USCAR
UNITED STATES COUNCIL FOR AUTOMOTIVE RESEARCH LLC

USDRIVE
DRIVING RESEARCH AND INNOVATION FOR VEHICLE EFFICIENCY AND ENERGY SUSTAINABILITY

FreedomCAR & Fuel Partnership

PNGV SM
PARTNERSHIP FOR A NEW GENERATION OF VEHICLES

1993

The most well-known goal of the partnership is ***to develop technology that can be used to create vehicles that can achieve up to triple the fuel efficiency*** of today's vehicles with very low emissions, but without sacrificing affordability, performance or safety.

USCAR
UNITED STATES COUNCIL FOR AUTOMOTIVE RESEARCH LLC

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FreedomCAR

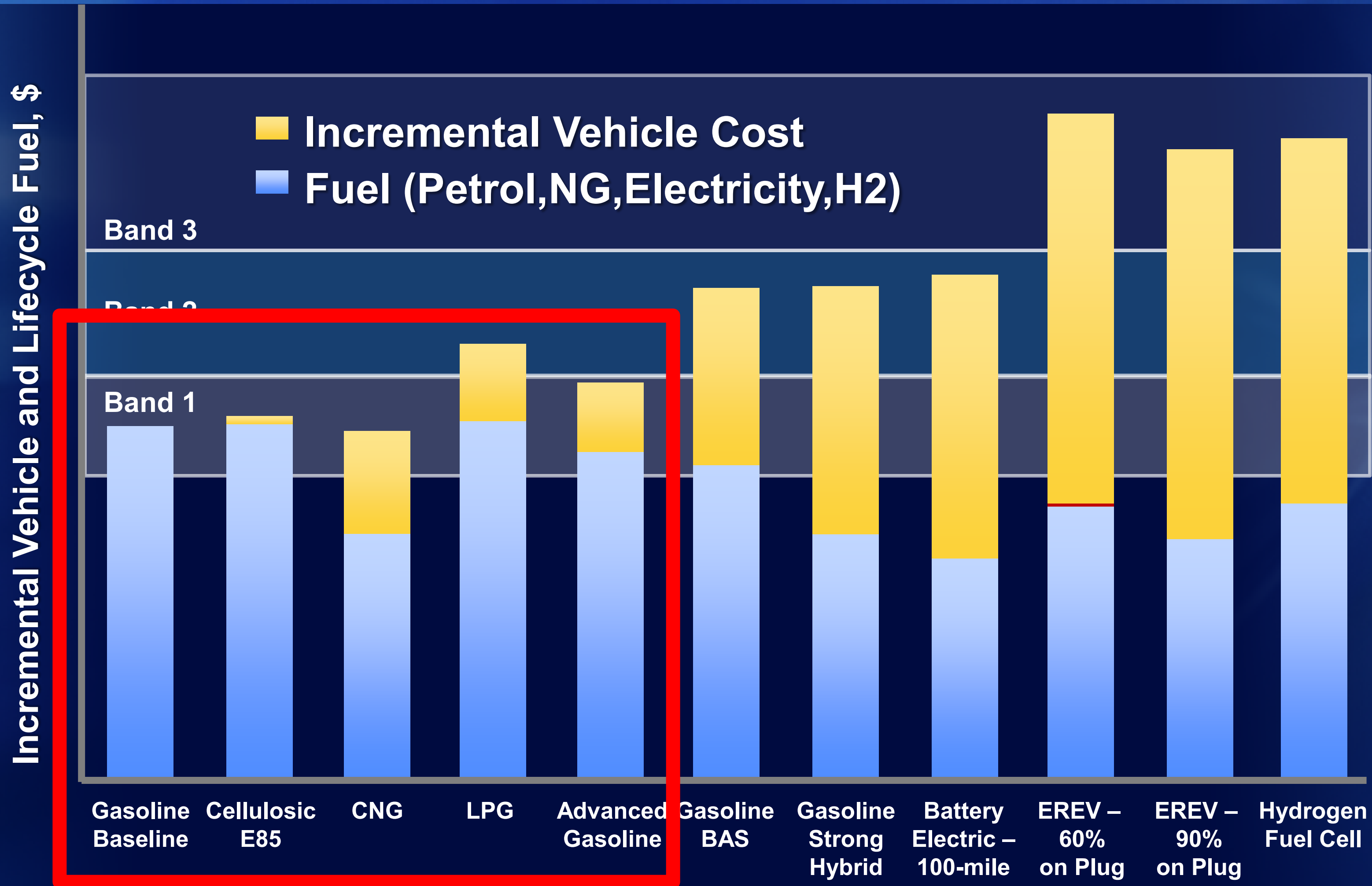
PARTNERSHIP FO

Concept Cars Unveiled In 2000

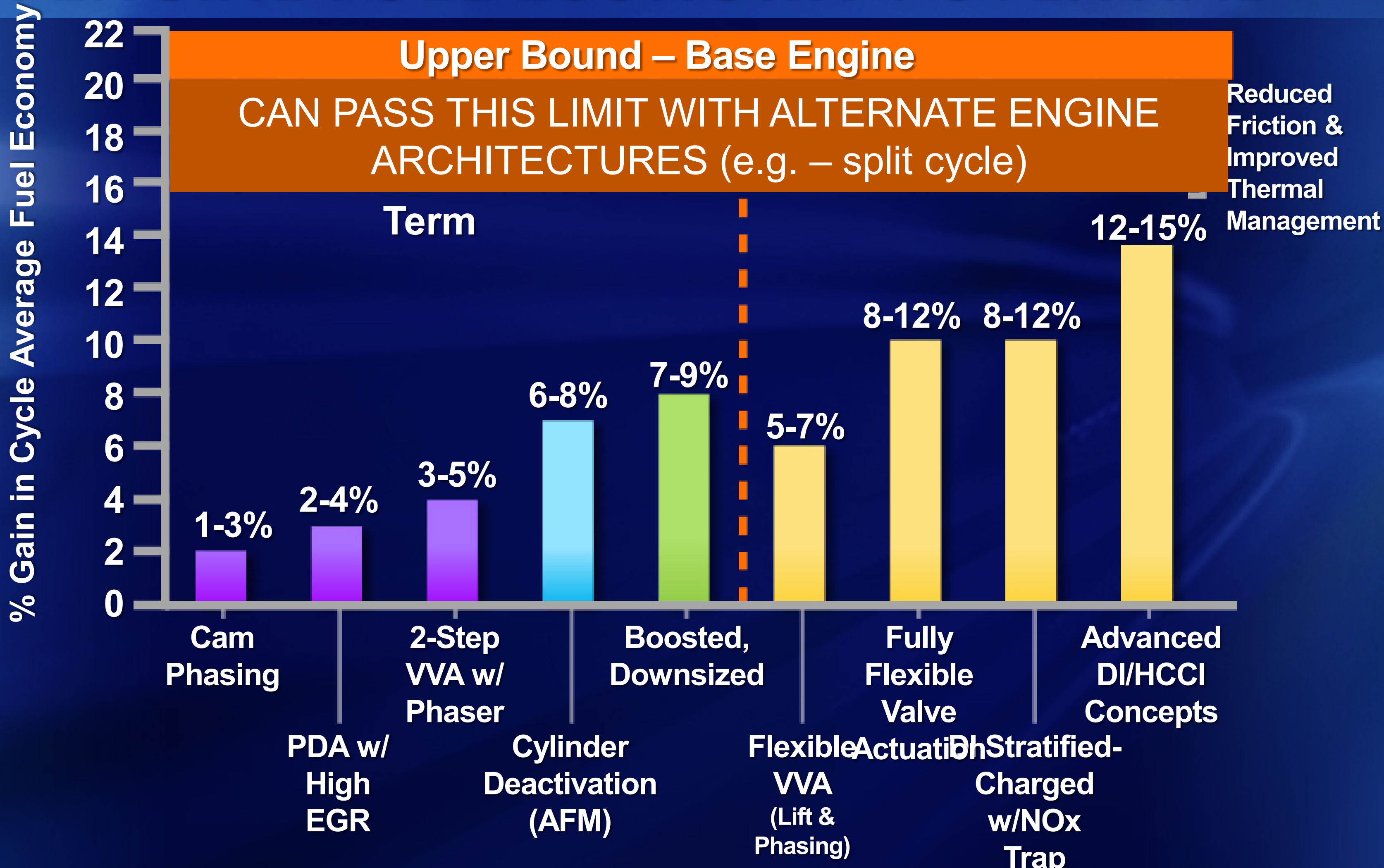
	GM Precept	Ford Prodigy	DaimlerChrysler ESX3
			
MPG (gasoline)	80	72	72
Heat Engine	1.3 liter 3-cylinder diesel	1.2 liter 4-cylinder diesel	1.5 liter 3-cylinder diesel
Key Lightweight Material	Aluminum	Aluminum	Thermoplastics
Aerodynamic Coefficient of Drag	0.163	0.199	0.22
Weight (Pounds)	2,593	2,387	2,250
Battery	NiMH or Lithium polymer	NiMH	Lithium ion
Acceleration Time (0-60 sec.)	11.5	12.0	11.0

TECHNICAL HURDLES REMAIN BUT BIGGEST CHALLENGE IS *COST*

INCREMENTAL VEHICLE AND 10-YEAR FUEL COST – EXAMPLE ANALYSIS

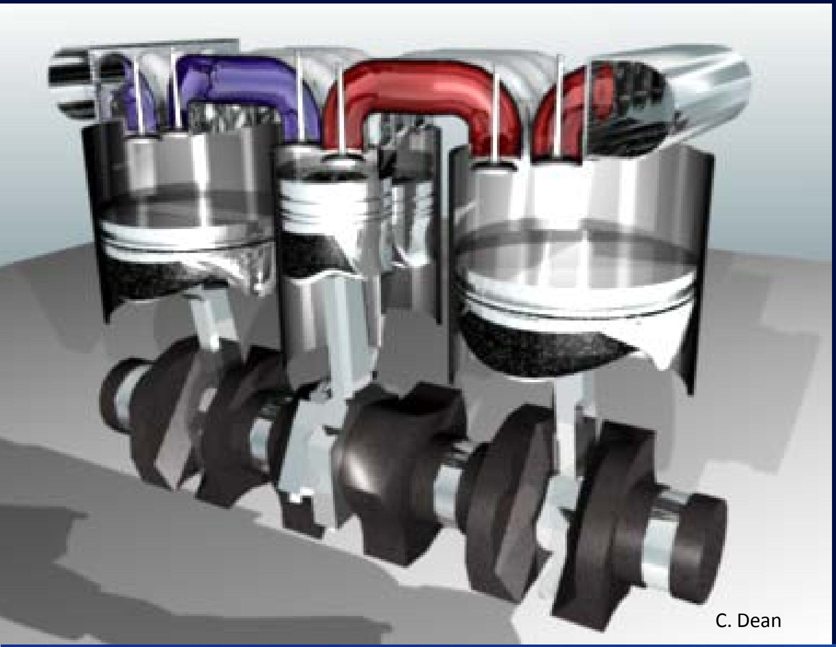


SI ENGINE FUEL ECONOMY POTENTIAL



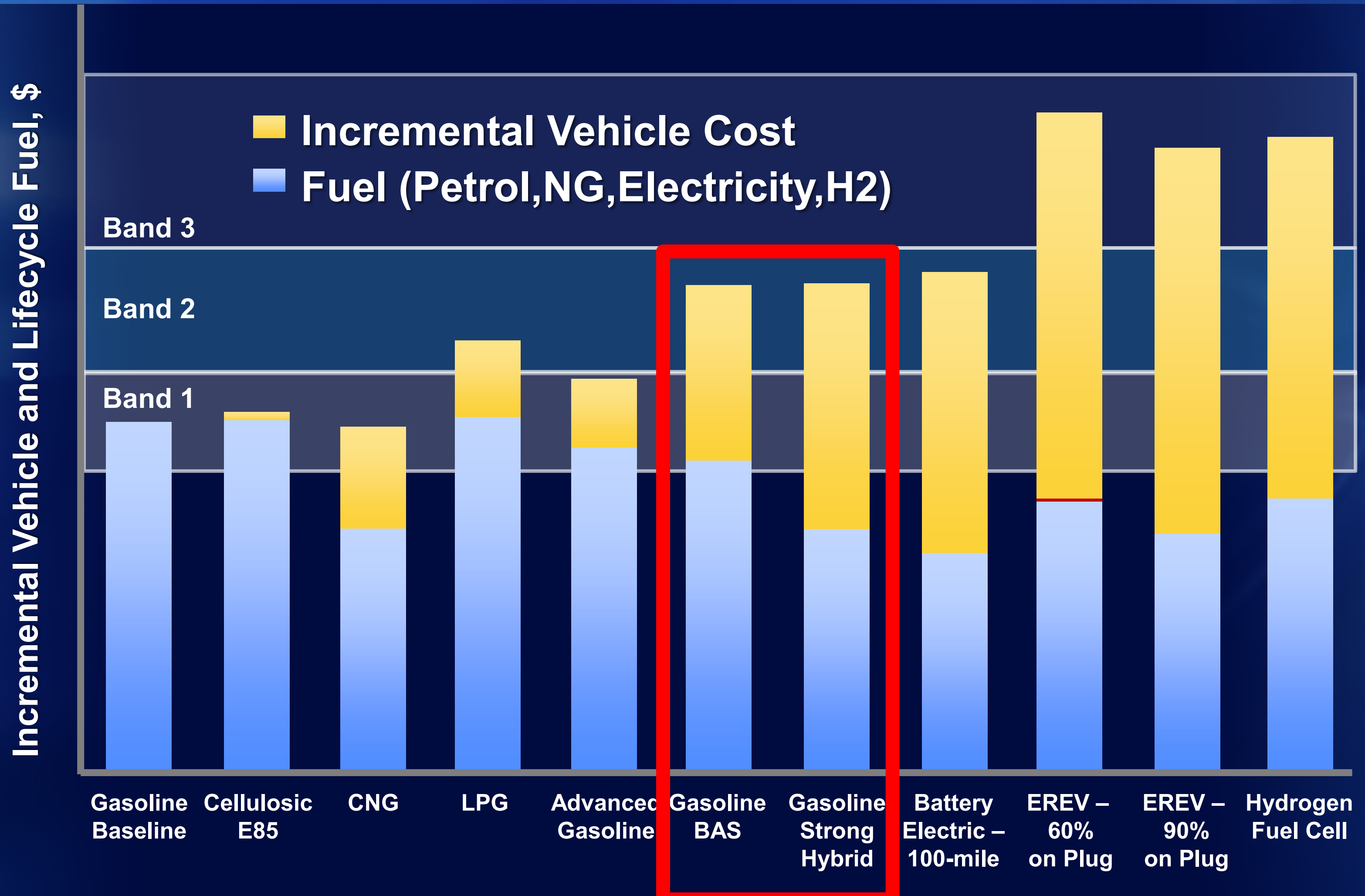
ADVANCED IC ENGINES

ONE POTENTIAL HIGH-EFFICIENCY DCDE MANIFESTATION

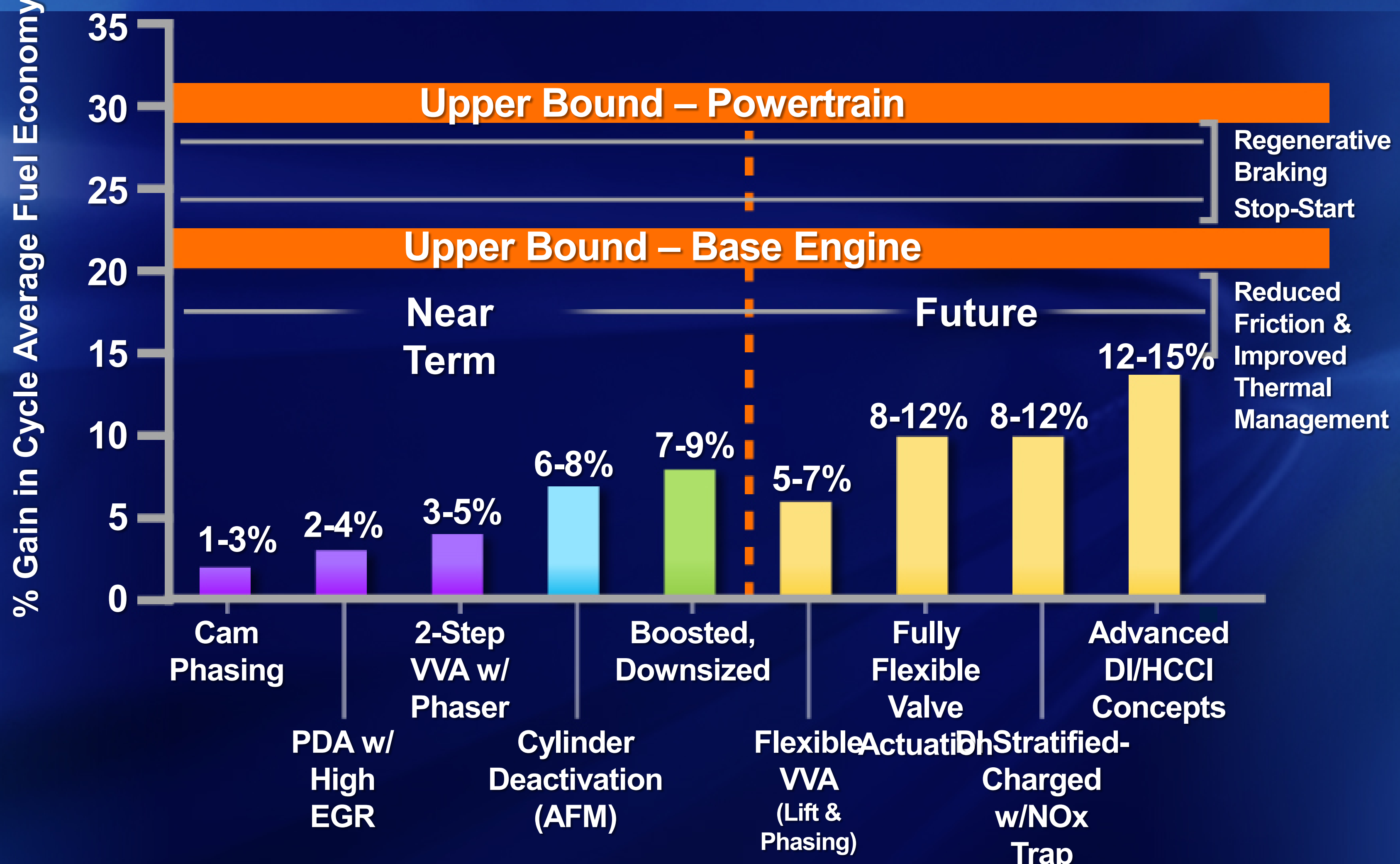


- Different stages of the cycle can be separated into different working volumes
- Possible to optimize each stage individually, potential for heat loss management and exhaust energy recuperation
- Initial modeling shows potential for very high thermal efficiency

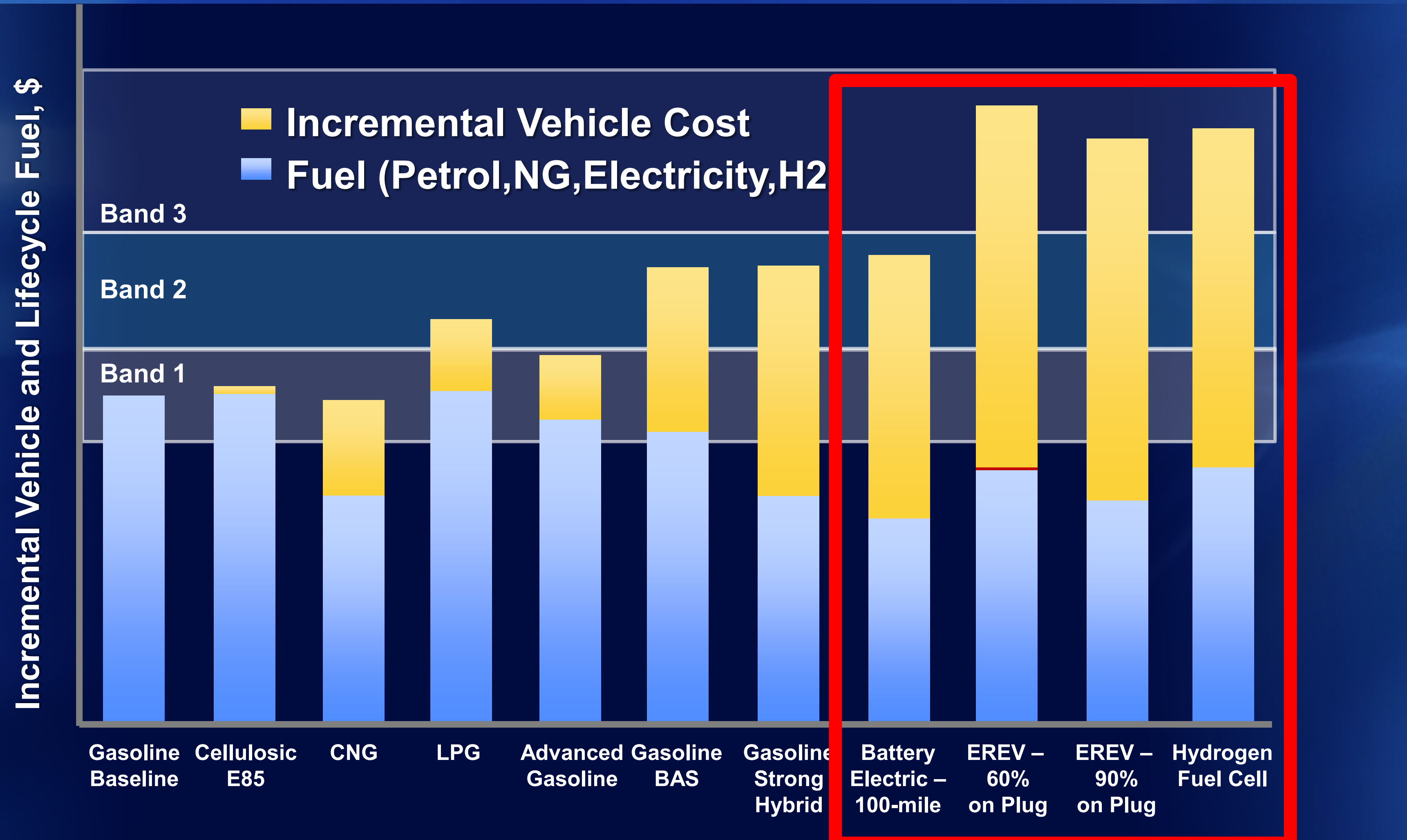
INCREMENTAL VEHICLE AND 10-YEAR FUEL COST – EXAMPLE ANALYSIS



SI ENGINE FUEL ECONOMY POTENTIAL



INCREMENTAL VEHICLE AND 10-YEAR FUEL COST – EXAMPLE ANALYSIS



ENERGY CARRIER PROPERTIES: ONBOARD STORAGE

WHY IS PETROLEUM THE DOMINANT TRANSPORTATION FUEL?

Weight & Volume of Energy Storage System for 500 km Range

Diesel

System
Fuel

43 kg
33 kg

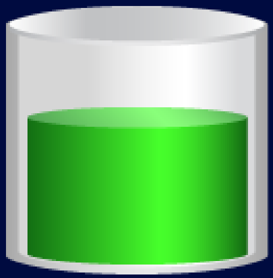
46 L
37 L

Lithium-Ion Battery

100 kWh electrical energy

System
Cell

830 kg
540 kg

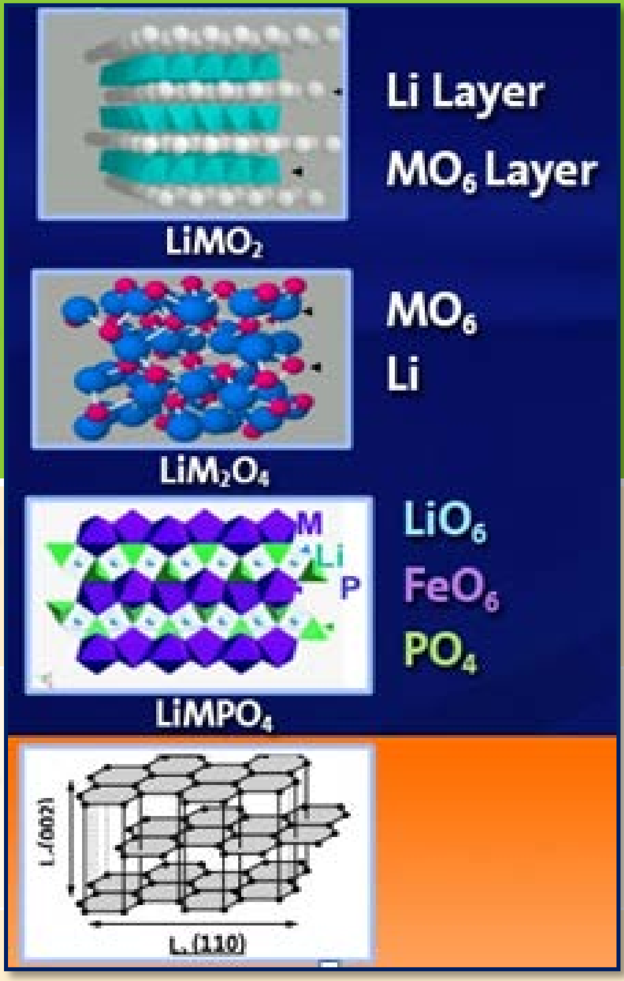


670 L
360 L

GLOBAL LITHIUM BATTERY MATERIALS TECHNOLOGY

Cathode (+) Oxides

- **Layered – $LiCoO_2$, $LiNiO_2$**
- ***Complex – Li_2MnO_3-LiNxMnyCozO$_2$**
- **Spinel – $LiMn_2O_4$**
- ***High Voltage Spinel – $LiMn_{1.5}Ni_{0.5}O_4$**
- ***Silicates, Olivines – Li_2MSiO_4, $LiFePO_4$**
- **Requirements**
  - **– Cost, safety, stability, conductivity**

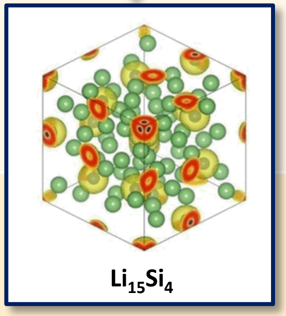


Anode (-)

- Carbon – LiC_6
- *Silicon Composites and Alloys

Electrolyte

- $LiPF_6$ in Organic Carbonate Solvent
- *Higher Voltage Stable
- Electrode Protective



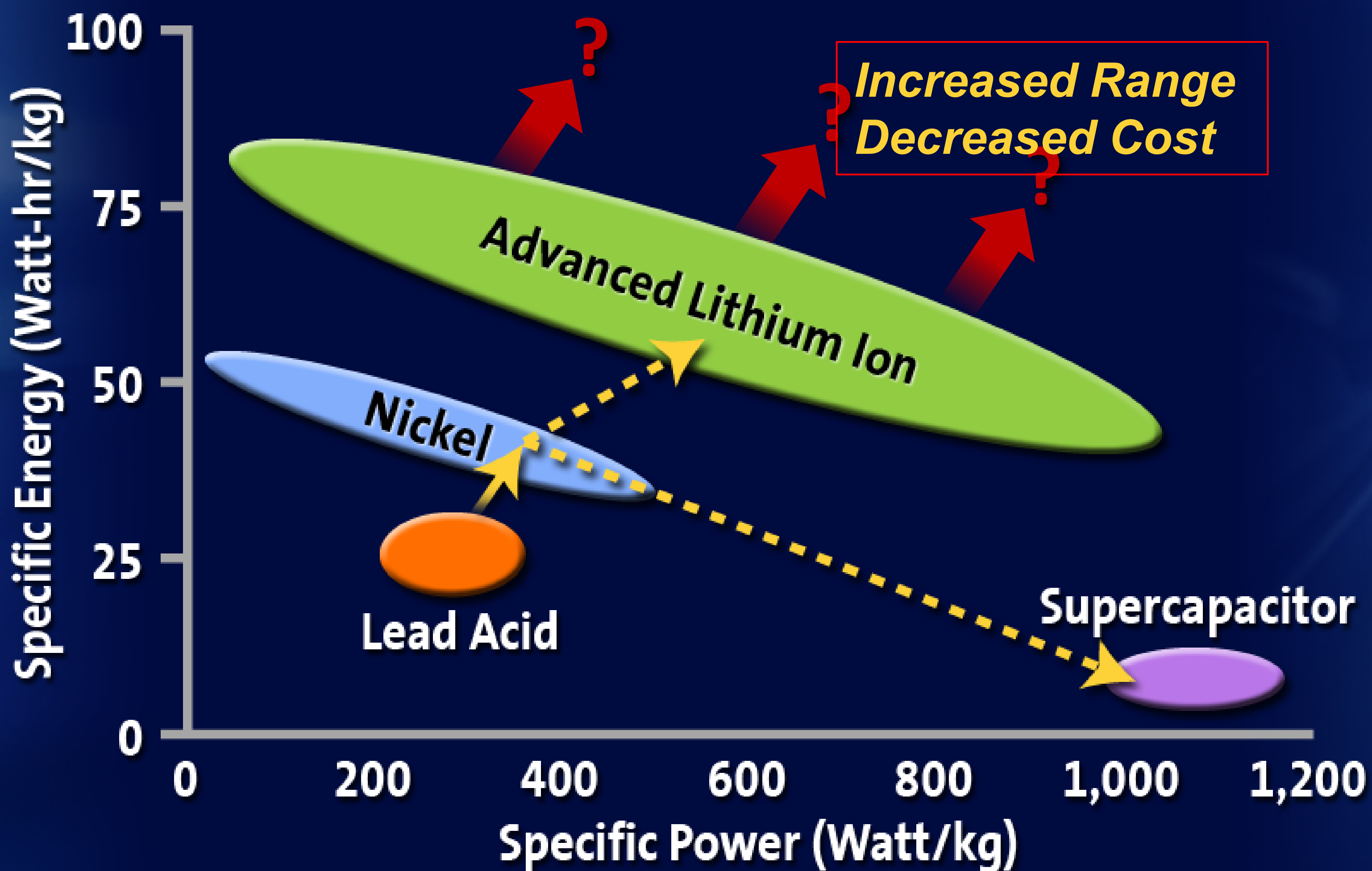
Separator

- Ceramic-Coated Polymer
- *Chemically Functionalized Polymer

*Advanced Materials

- Significant majority of the battery cost/volume/mass is in the cell materials
- Developments are needed in all four of the lithium-ion cell subcomponents

BATTERY TECHNOLOGY IMPROVEMENTS



Overcoming RANGE Anxiety

25-50 miles
BATTERY
Electric Driving

+

HUNDREDS of miles
EXTENDED RANGE
Driving

OPPORTUNITIES FOR ADVANCED APU's!!

VOLT

PROJECT DRIVEWAY

35-50 MILES
GAS-FREE

2,400,000
MILES LOGGED

ENERGY CARRIER PROPERTIES: ONBOARD STORAGE

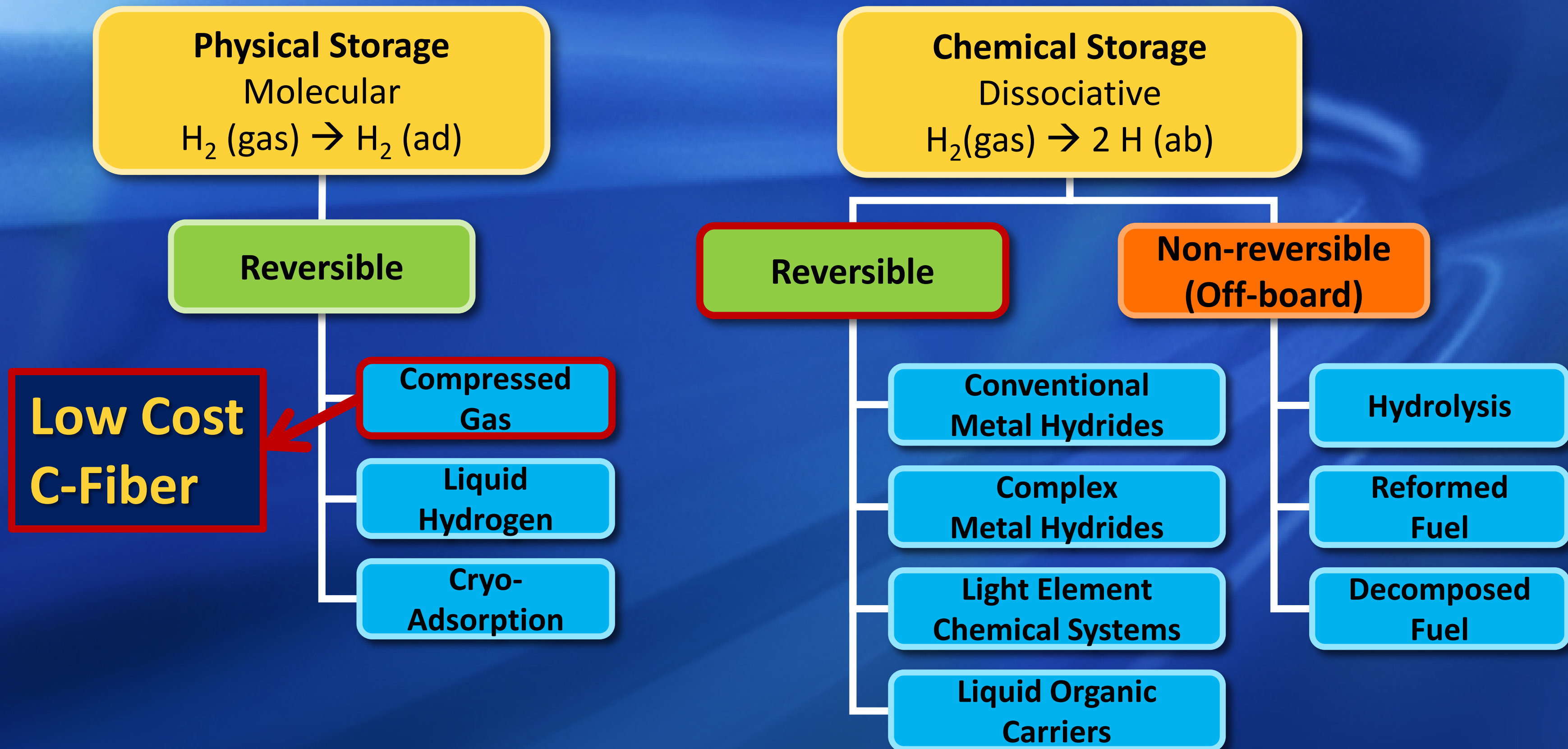
WHY IS PETROLEUM THE DOMINANT TRANSPORTATION FUEL?

Weight & Volume of Energy Storage System for 500 km Range

	Diesel	Compressed Hydrogen 700 Bar 6 kg hydrogen = 200 kWh chemical energy	Lithium-Ion Battery 100 kWh electrical energy
	System / Fuel	System / Fuel	System / Cell
Weight (System)	43 kg	125 kg	830 kg
Weight (Fuel / Cell)	33 kg	6 kg	540 kg
Volume (System)	46 L	260 L	670 L
Volume (Fuel / Cell)	37 L	170 L	360 L

EXPLORING VARIETY OF HYDROGEN STORAGE OPTIONS

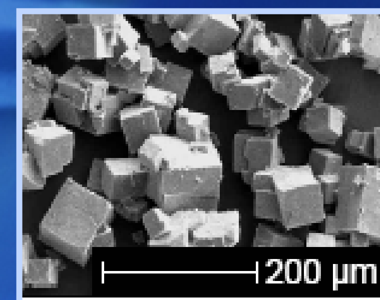
- Liquid and compressed gas storage are closest to feasibility
- No clear winner yet that meets all system targets, particularly cost



CRYO-ADSORPTION AND NANOTECHNOLOGY: MOFS

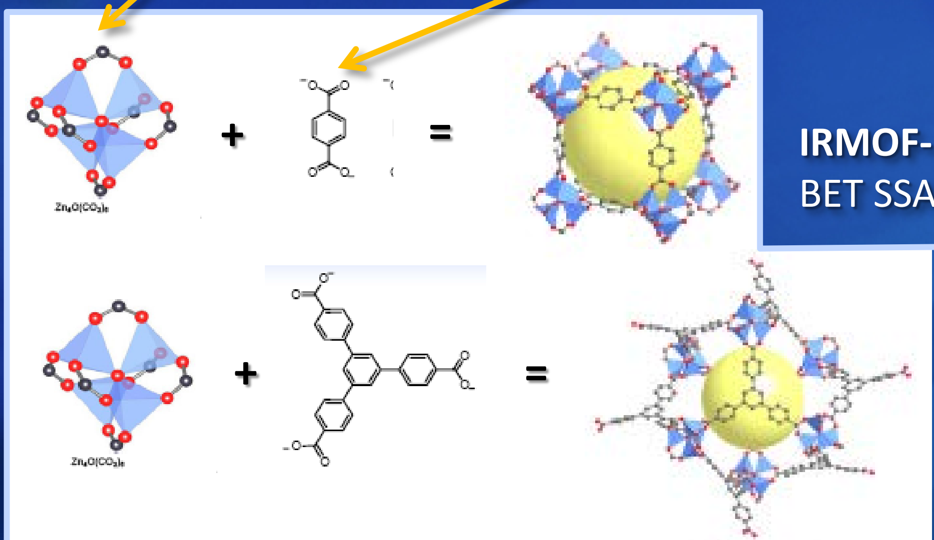
- Metal-Organic Frameworks
  - High surface area for adsorption
  - “Designer” pores

- H_2 molecules physisorbed onto a high surface area substrate
  - H_2 binding energy <10 kJ/mole H_2
  - Cryogenic temperatures required



“Secondary Building Unit” (SBU) e.g., zinc acetate

“Linker” e.g., organic carboxylate



IRMOF-1 (or MOF-5)
BET SSA (N_2) = 3100 m^2/g

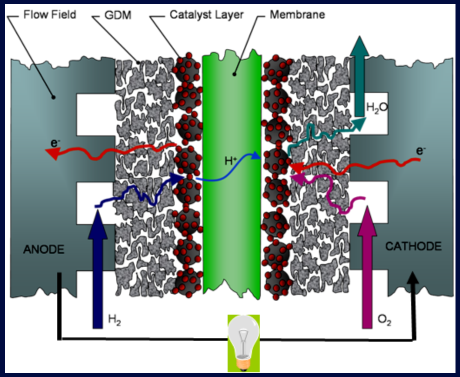
MOF-177
BET SSA (N_2) = 4310 m^2/g

E. Poirier, A. Dailly; J. Phy. Chem. C; **112**, 13047 (2008)

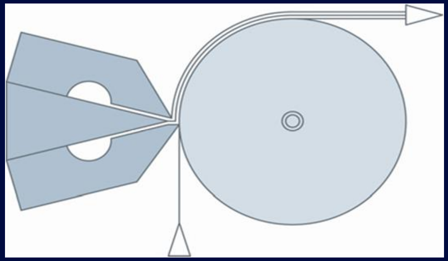
FUEL CELL MATERIAL CHALLENGES

Material/Processing Cost

Membrane Electrode Assembly Cost



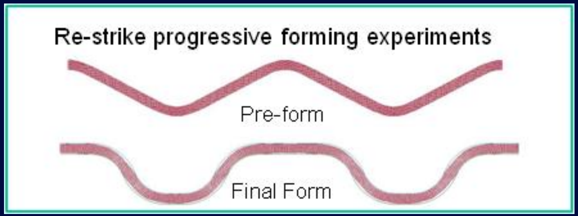
- Platinum reduction – 30 → <10gm/vehicle
- **Low-cost lower-relative-humidity membrane**
- Diffusion media (carbon fiber) cost



- Mulit-layer MEA processing

Bipolar Plate Materials Cost

- Conductive coating cost – Au→ Carbon

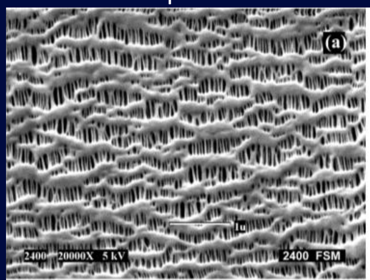


- Stainless Steel Cost
  - Eliminate nickel (austenitic→ferritic)
  - May require two-hit stamping

POLYMER SEPARATORS HAVE COMMON FUNCTIONS/CHALLENGES

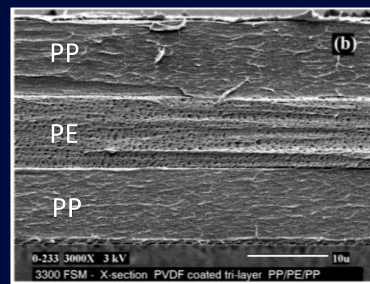
Lithium-Ion Batteries
(Polymer Separator/Liquid Electrolyte)

Top down



~1 micron openings

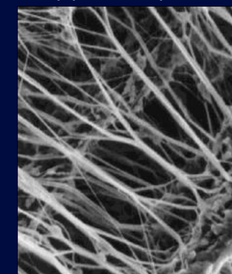
Cross-Section



~25 micron, 3 layers

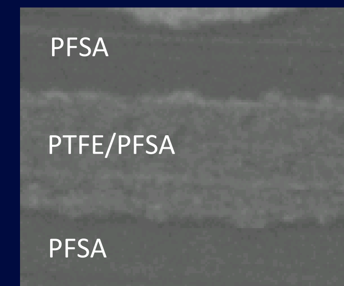
Polymer Electrolyte Fuel Cells
(Polymer Separator/Polymer Electrolyte)

Support Top down



~1 micron openings

Membrane Cross-Section



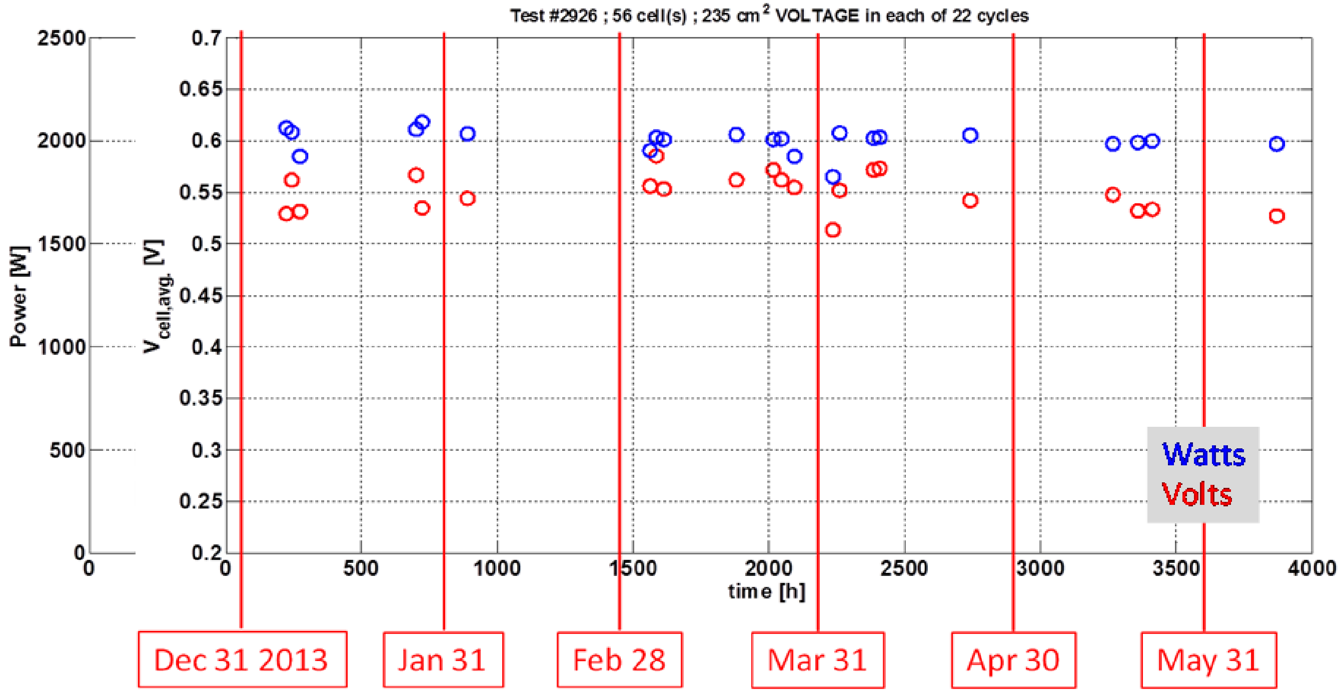
~25 micron, 3 layers

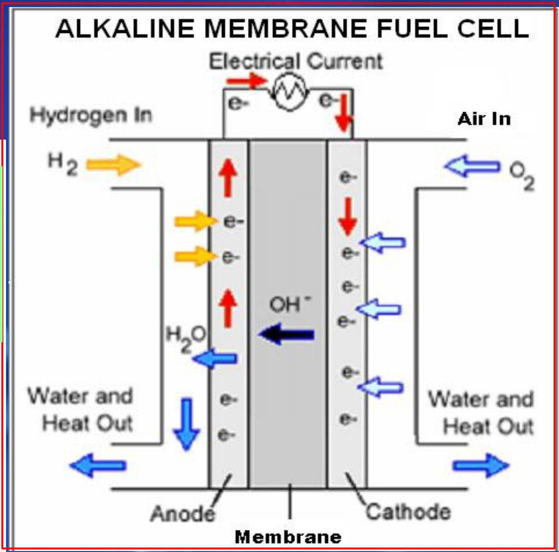
	Lithium-Ion Batteries	Fuel Cells
Current Technology		
Support Material	Polyethylene (PE), Polypropylene (PP)	Polytetrafluroethylene (PTFE)
Electrolyte	Methyl Carbonates (liquid)	Poly[Perfluorosulfonic Acid] (solid) (PFSA)
Transporting Ions	Li^+, PF_6^-	H^+
Total Thickness	~25 micron	~25 micron
Area in Application (100 kW)	~250 m^2	~10 m^2
Challenges		
Improved ionic conductance	Thinner, more porous, less tortuous	
Mechanical robustness	Higher puncture resistance, higher thermal stability	
Chemical robustness	Inert at high voltage (5V vs. Li/Li^+)	Inert to peroxide radicals
Cost	<$1/$m^2$	<$5/$m^2$ (including ionomer)

Recent Progress in Alkaline Fuel Cells Offers Further Cost Reductions

2kW AMFC H_2/Air Stack (56 cells):
Testing in Back-Up Power Mode* over total time of
4000 hours (22 start-up/shut down cycles) **

* Operation in continuous ON mode for 1,000 hours repeated in several stacks

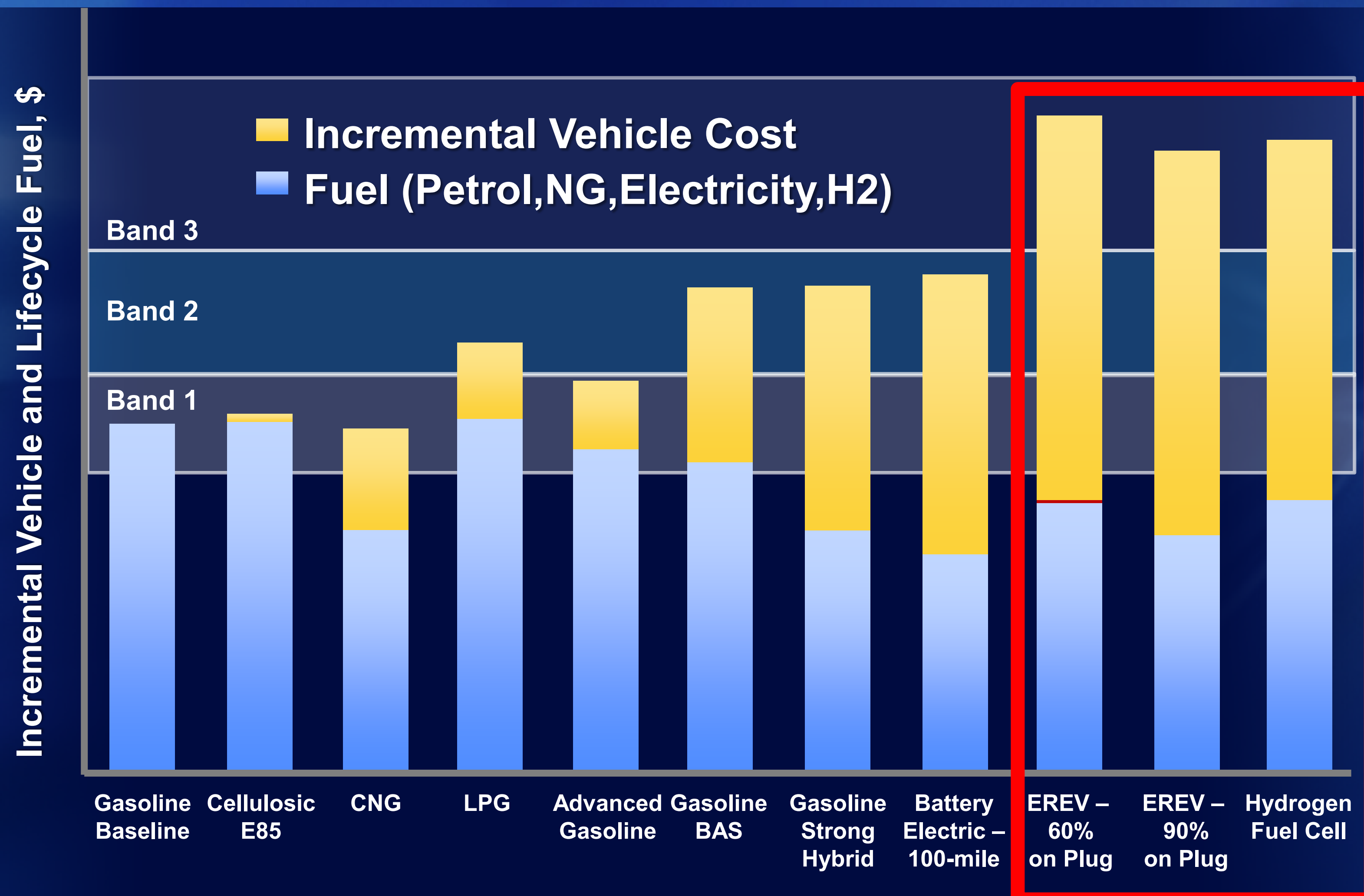




** Achieved by strongly lowering losses during Off time and Restart/Shut down cycles

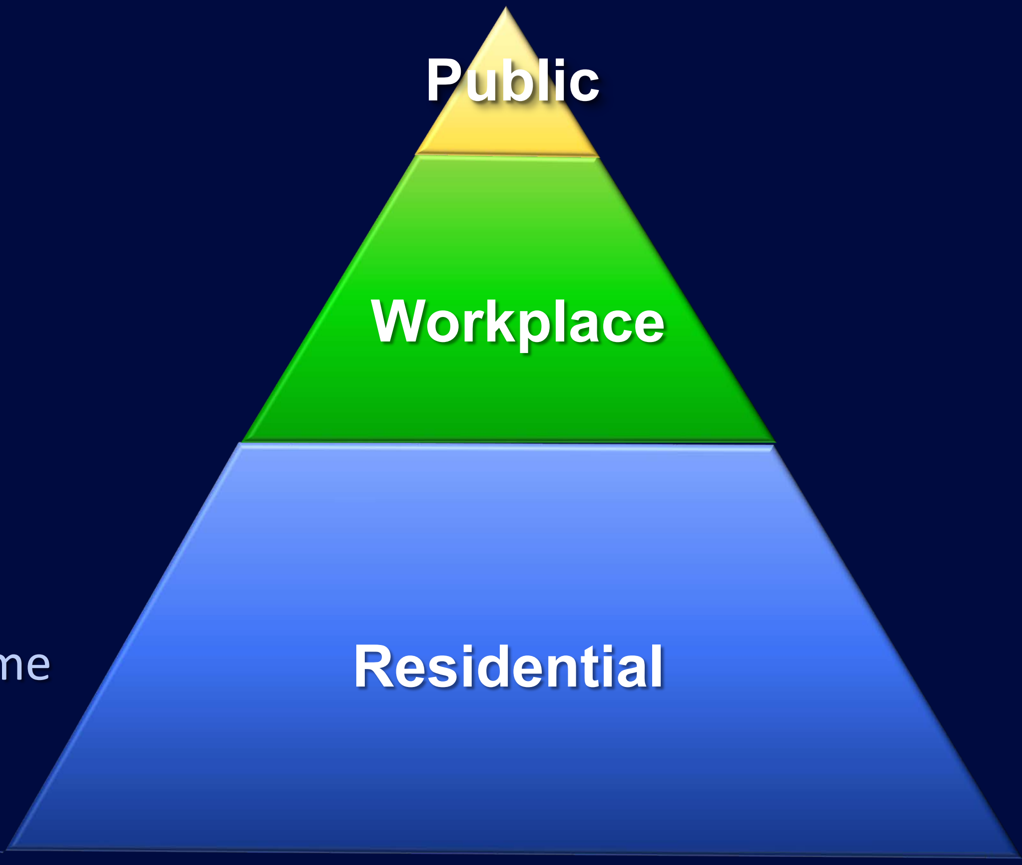
Courtesy CellEra

INCREMENTAL VEHICLE AND 10-YEAR FUEL COST – EXAMPLE ANALYSIS



CHARGING INFRASTRUCTURE

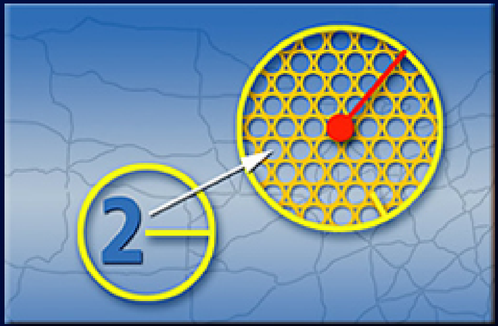
- Public charging
  - High visibility
  - Commercial/Retail
  - Public education and outreach
- Workplace
  - Corporate, municipal parking lots
- Residential (majority)
  - Satisfying consumer-driven home installation process
  - Permits, electricians, inspections, meters, rates



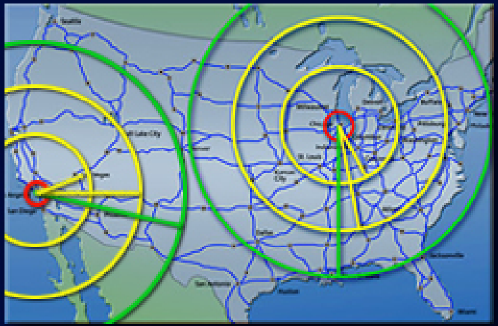
U.S. INFRASTRUCTURE DEVELOPMENT FOR FIRST MILLION FCEVs

- $10-25B investment would establish network of 11,700 stations
  - Top 100 urban areas
  - 130,000 miles of highway

Station always within 2 miles in urban areas



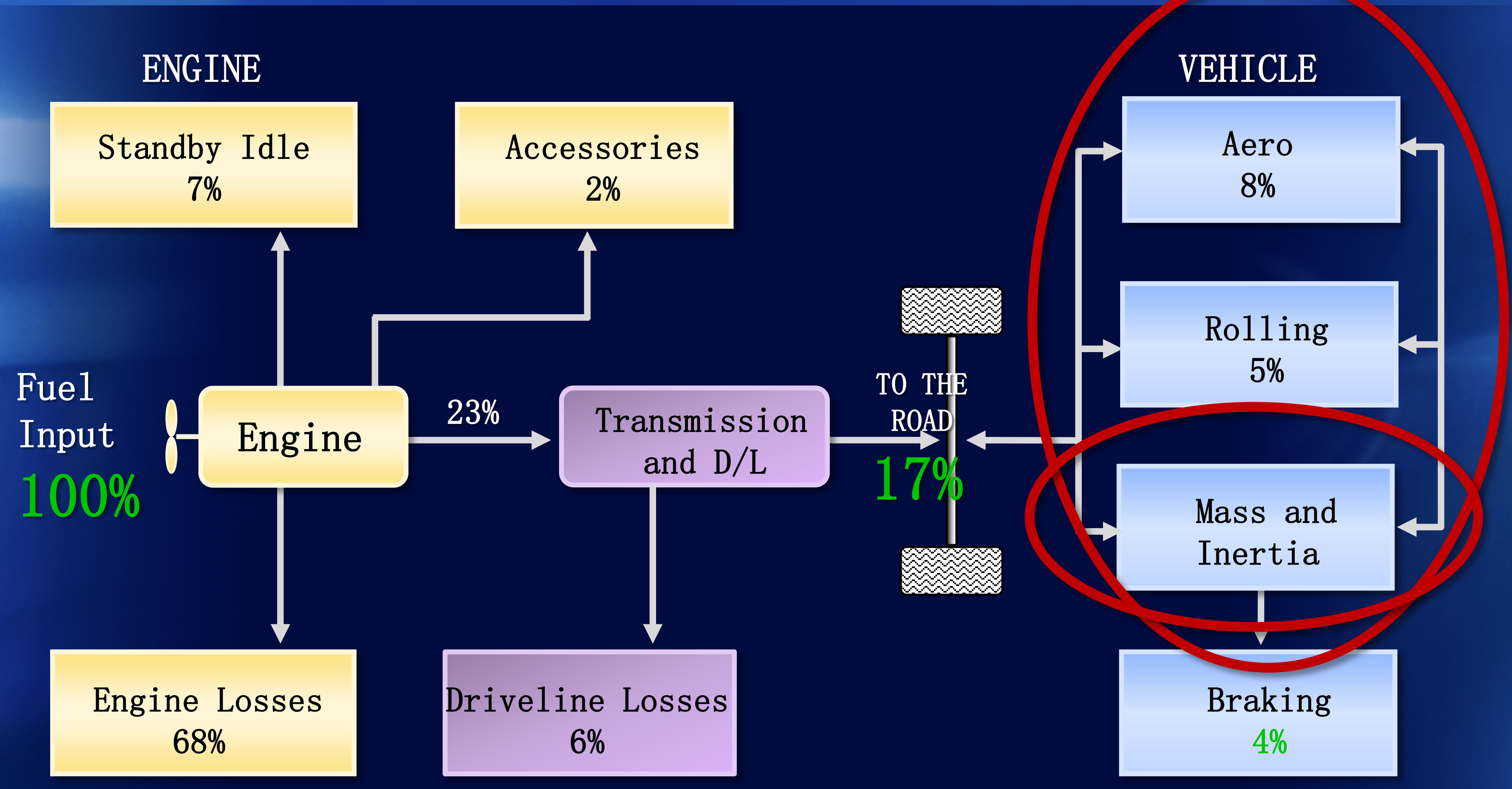
Top 100 U.S. metro areas



1 highway station every 25 miles

TYPICAL VEHICLE-LEVEL ENERGY BREAKDOWN

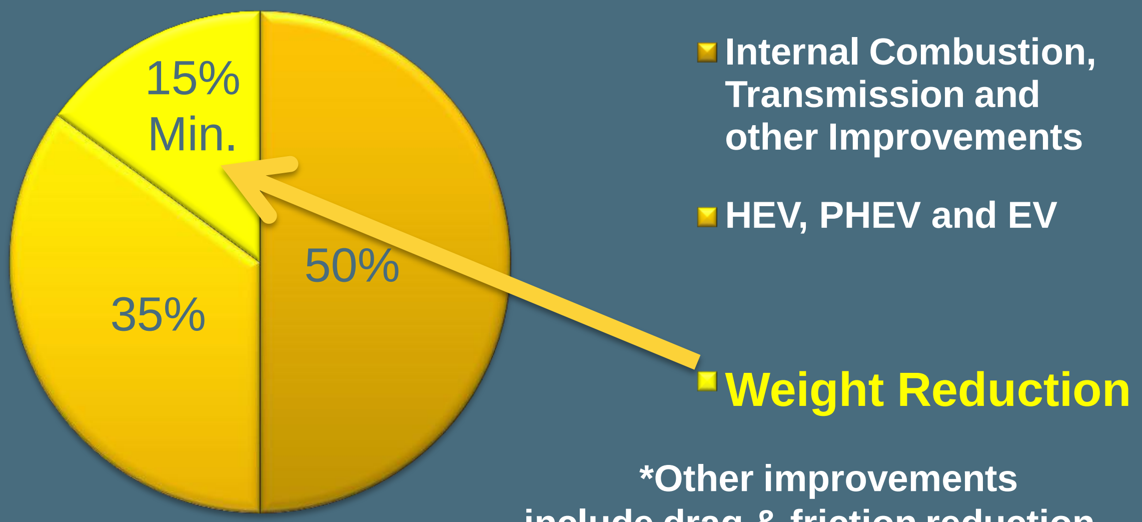
Compact Sedan with Four-cylinder Engine and Automatic Transmission (U.S. Federal Test Procedure, Composite City-Highway Drive Cycle)



Regulatory Impact on Materials

Weight savings is expected to provide 3 to 6 miles per gallon of fuel economy improvement by 2025.

2025 Sources of Improvement in CO2 Reduction and Real Fuel Economy



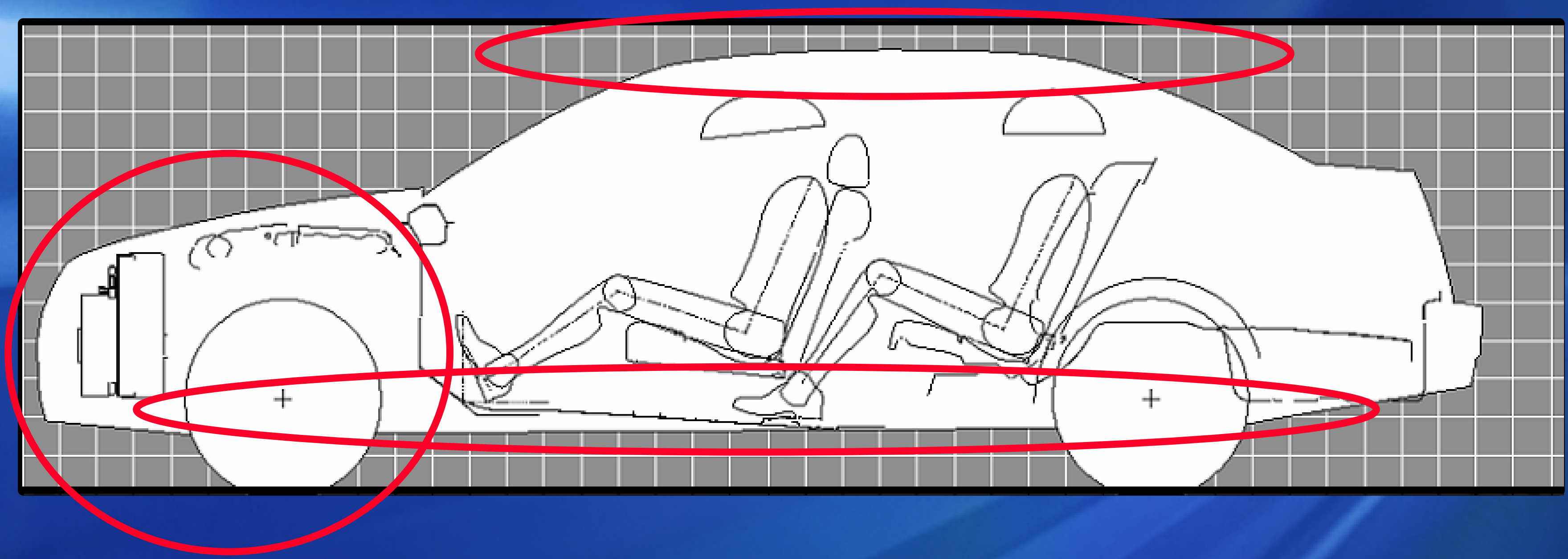
20 more MPG

***Other improvements include drag & friction reduction, Aerodynamics, HVAC optimization**

1250 Maplelawn | Troy | Michigan | 48084
248.644.0086

Rule of thumb for rational design:

10% weight reduction ~ 6% fuel economy



Achieve lower weight by:

- Better design
- Higher specific strength & modulus materials

Rule of thumb for rational design:

10% weight reduction ~ 6% fuel economy

$$\$/\mathrm{lb}_{saved} \approx \$/\mathrm{gal}_{gasoline}$$

* societal impact: 10 years @ 12,000 miles per year; 0% interest

Customers typically want 3 year payback

$$\$/\mathrm{lb}_{saved} \approx 1/3 * \$/\mathrm{gal}_{gasoline}$$

→ Vehicle chief engineer compares with other fuel economy options

$$Historically \sim< \$2/\mathrm{lb}_{saved}$$

ADVANCED MATERIALS FOR LIGHTWEIGHT VEHICLES

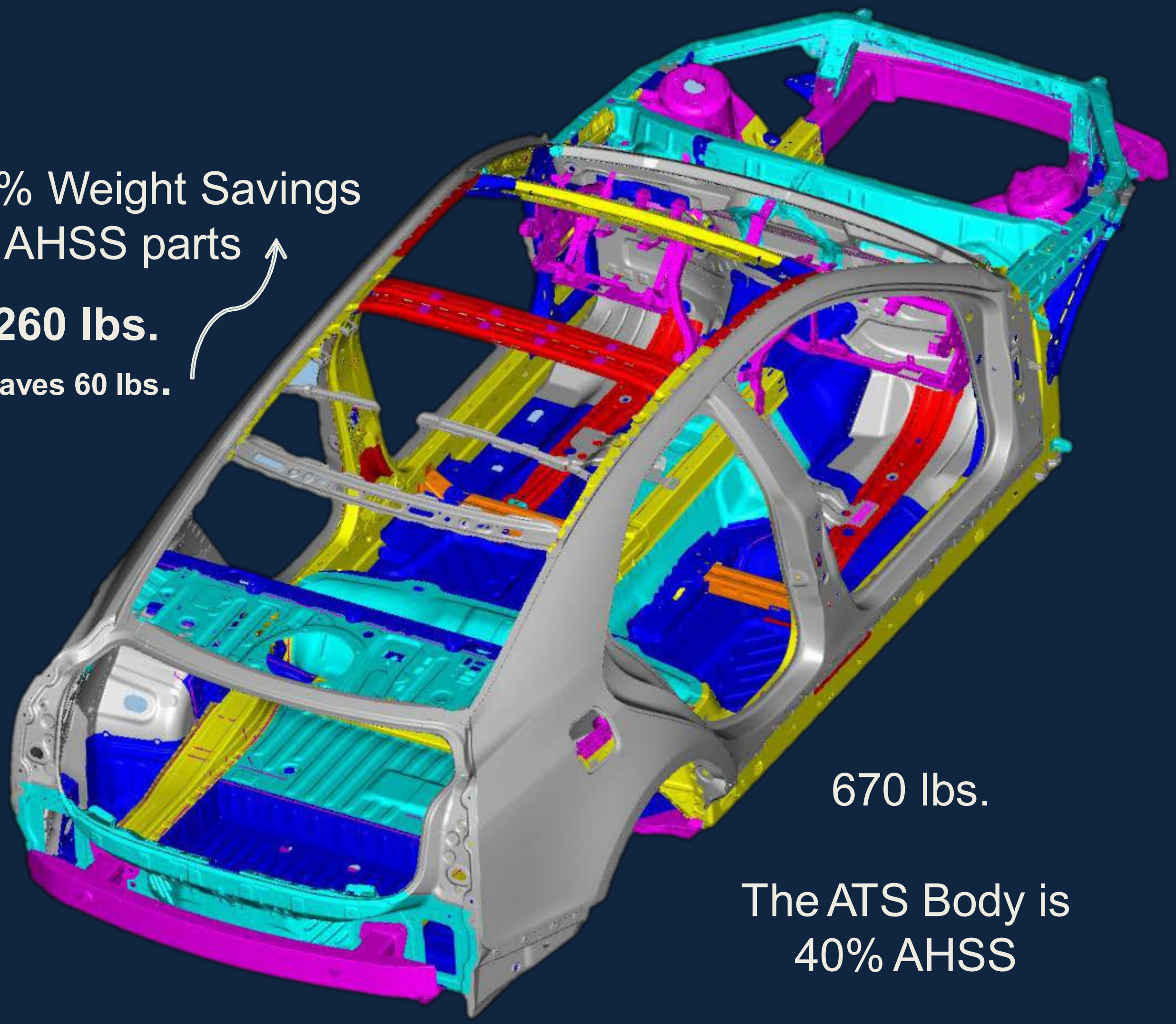
Material	Weight Reduction vs. Low-Carbon Steel
High-strength steel	15-25%
Glass-fiber composite	25-35%
Aluminum	40-50%
Magnesium	55-60%
Carbon-fiber composite	55-60%

2013 Cadillac ATS Body, Bumpers and IP
"Every Gram, Every Day"

16% Mild Steel
17% Bake Hard
22% HSLA
29% Dual-Phase/Multi Phase
5% Martensitic
5% Press Hardened Steel
6 % Aluminum Saves 30 lbs.
Aluminum Hood and Cradle
(not shown) also saves 30 lbs.

260 lbs.
Saves 60 lbs.

20% Weight Savings
for AHSS parts



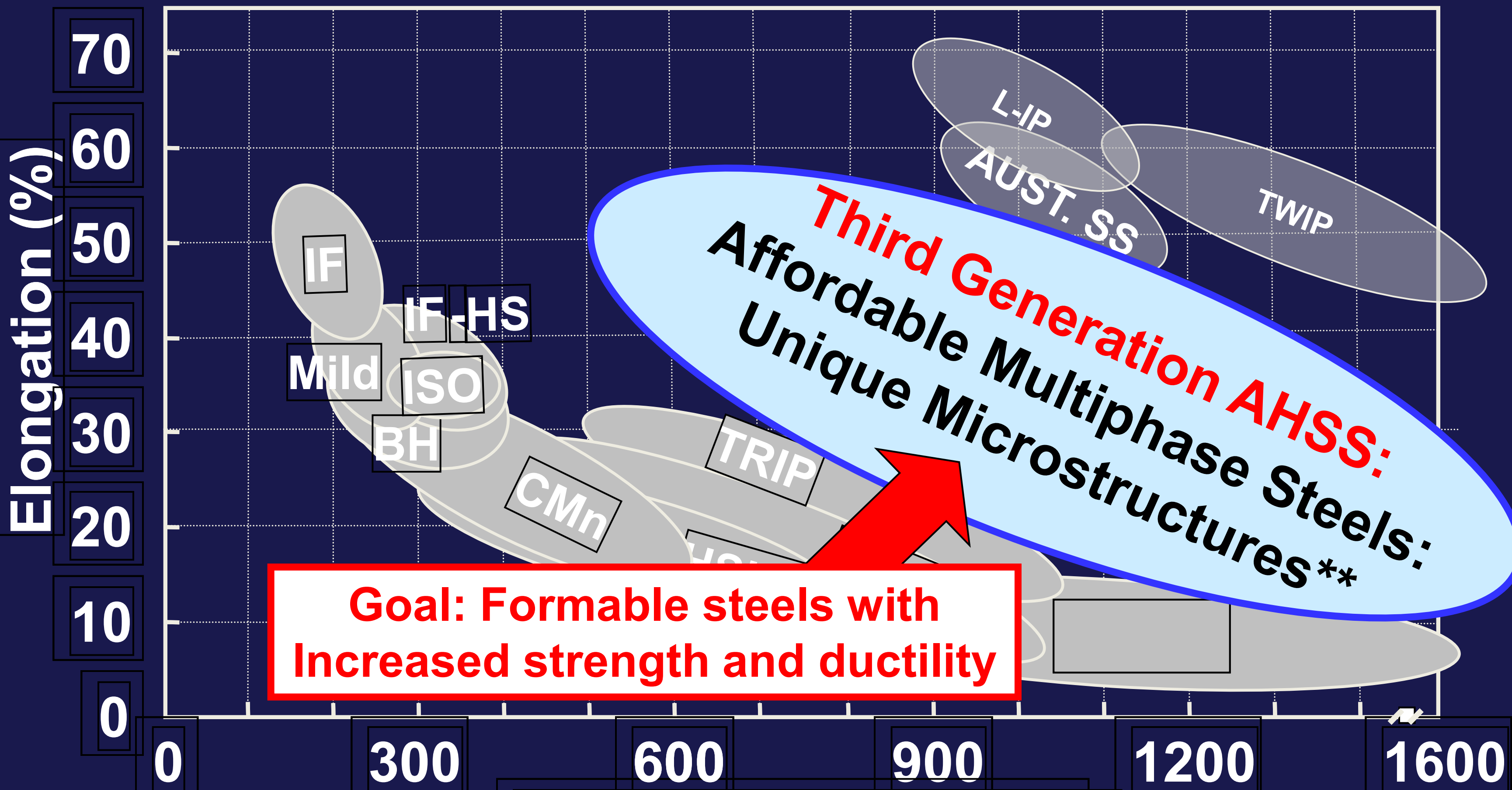
670 lbs.

The ATS Body is
40% AHSS

Future Opportunities for AHSS

**Predicted to contain:

- High strength constituent
- Retained austenite with controlled stability



D. Matlock 06/18/2013

AISI: www.steel.org (2006)

ADVANCED MATERIALS FOR LIGHTWEIGHT VEHICLES

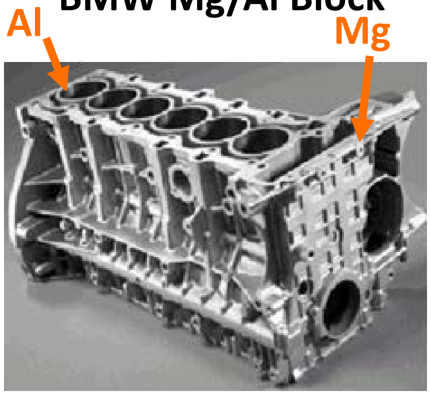
Material	Weight Reduction vs. Low-Carbon Steel
High-strength steel	15-25%
Glass-fiber composite	25-35%
Aluminum	40-50%
Magnesium	55-60%
Carbon-fiber composite	55-60%

ENGINE BLOCK

Cast Iron Block
(~68 kg)

GM Die Cast Al Block
(~26 kg)

BMW Mg/Al Block



GM Lost Foam Cast
Al Block

USCAR Mg Block

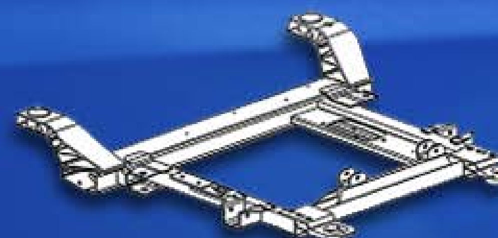
1950 1990 Al ~50% weight reduction 2000 Mg ~25% weight reduction 2010

Future is towards Linerless

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

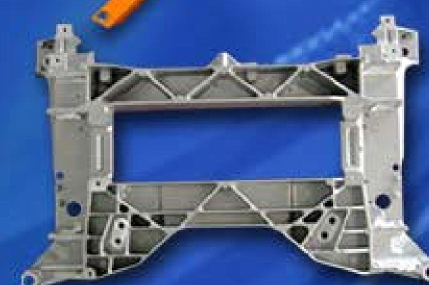
FRONT CRADLE

Steel Sheet
Construction
(46 parts/28 kg)



Wrought Al
Welded
(17 parts/18 kg)

Al Casting-Intensive
(6 parts/16 kg)



Mg Casting
(1 part/10 kg)

1950 1990 2000 2010

EARLY ALUMINUM CLOSURES

1909 Ford Model T Touring Car

Aluminum Hood,
1915 Model T

Photos courtesy of Model T Ford Club of America

"The lack of interest in the use of aluminum for motor cars and motor cycles is chiefly economic (the higher cost of aluminum sheet as compared to steel) and partly technical – in particular the difficulty in joining body panels together..."

From *"Aluminum for Automobiles"* by E.G. West, *Journal of the Institution of Automobile Engineers*, January 1946

Al-Intensive Ford F150
Is this the industry tipping point?

What is beyond lightweight metals?

Material	Weight Reduction vs. Low-Carbon Steel
High-strength steel	15-25%
Glass-fiber composite	25-35%
Aluminum	40-50%
Magnesium	55-60%
Carbon-fiber composite	55-60%

Will the automobile follow the aircraft industry with bodies made from carbon-fiber composites?

CARBON FIBER-REINFORCED COMPOSITE PARTS IN CHEVROLET CORVETTE ZR1

Image Source: Plasan Carbon Composites

FIBERGLASS FABRIC-REINFORCED COMPOSITE UNDERBODY PROTOTYPE

GM-TEIJIN CO-DEVELOPMENT AGREEMENT

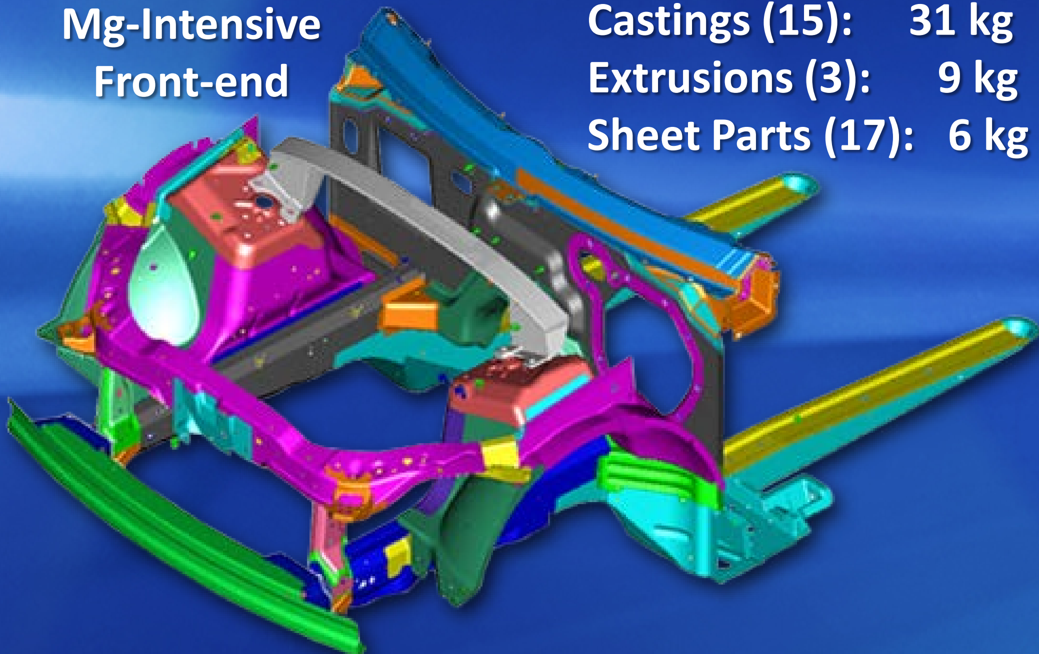
BMW I-Car

Ford, Dow to explore carbon fiber use in vehicles

DETROIT, April 12 (Reuters) - Ford Motor Co and Dow Chemical Co will work to develop cost-effective ways of using carbon fiber in high-volume cars and trucks

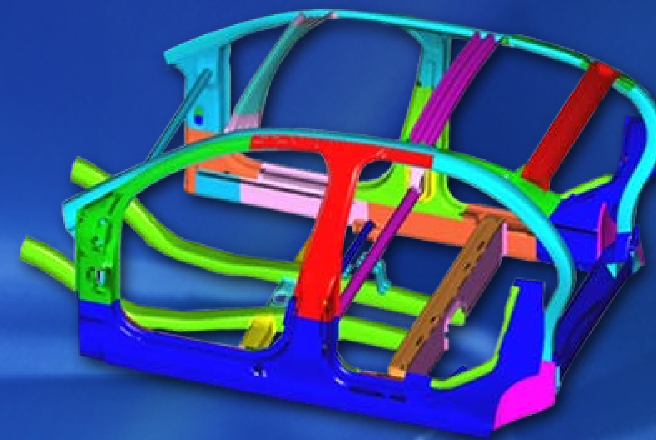
MULTI-MATERIAL BODY – THE FUTURE

Mg-Intensive
Front-end

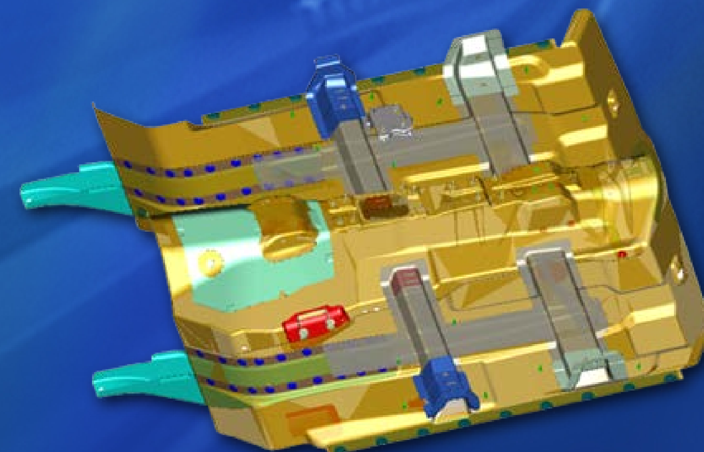


Castings (15): 31 kg
Extrusions (3): 9 kg
Sheet Parts (17): 6 kg

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



AHSS Passenger Compartment



Composite Floor Pan

PETROLEUM SUPPLIES…

35%
OF WORLD'S ENERGY

96%
OF TRANSPORTATION ENERGY

THE TIME TO ADDRESS THESE CHALLENGES IS NOW!!

TYPICAL VEHICLE-LEVEL ENERGY BREAKDOWN

Compact Sedan with Four-cylinder Engine and Automatic Transmission
(U.S. Federal Test Procedure, Composite City-Highway Drive Cycle)

Fuel Input
100%

TO THE ROAD
17%