Alternative Energy Vehicles

Challenges and Opportunities

Chris Gearhart
APS March Meeting
Energy Research Opportunities Workshop
March 2, 2014

Historical Perspective on Energy

"We are like tenant farmers, chopping down the fence around our house for fuel, when we should be using nature's inexhaustible sources of energy – sun, wind and tide. . . . I'd put my money on the sun and solar energy. What a source of power! I hope we don't have to wait till oil and coal run out before we tackle that."

Thomas Edison

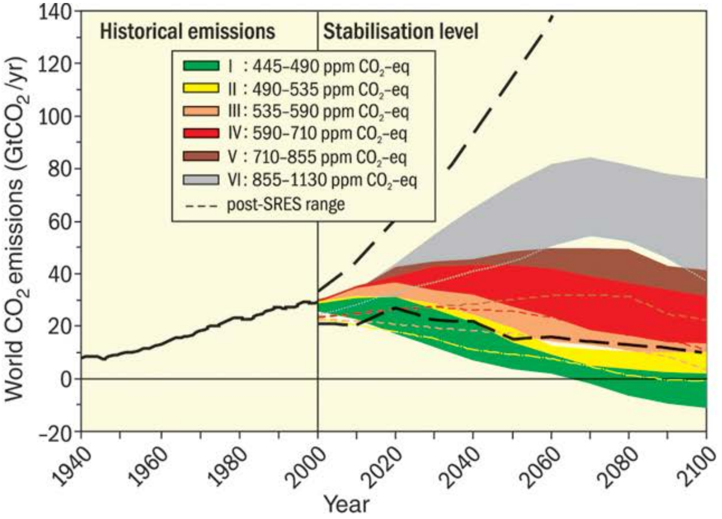
Speaking with Henry Ford and Harvey Firestone, 1931

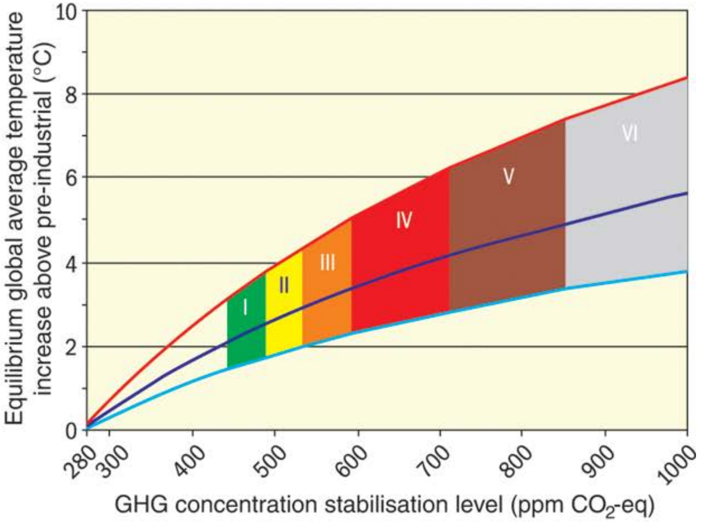
Source: Uncommon Friends: Life with Thomas Edison, Henry Ford, Harvey Firestone, Alexis Carrel & Charles Lindbergh, James Newton, 1987, pg. 31

Thomas Edison and electric car. *Photo: Courtesy of National Museum of American History, Smithsonian Institution*

Climate Change Mitigation

Category	CO_2 concentration at stabilisation (2005 = 379 ppm)[b]	CO_2-equivalent concentration at stabilisation including GHGs and aerosols (2005=375 ppm)[b]	Peaking year for CO_2 emissions[a,c]	Change in global CO_2 emissions in 2050 (percent of 2000 emissions)[a,c]	Global average temperature increase above pre-industrial at equilibrium, using 'best estimate' climate sensitivity[d,e]	Global average sea level rise above pre-industrial at equilibrium from thermal expansion only[f]	Number of assessed scenarios
	ppm	ppm	year	percent	°C	metres	
I	350 – 400	445 – 490	2000 – 2015	-85 to -50	2.0 – 2.4	0.4 – 1.4	6
II	400 – 440	490 – 535	2000 – 2020	-60 to -30	2.4 – 2.8	0.5 – 1.7	18
III	440 – 485	535 – 590	2010 – 2030	-30 to +5	2.8 – 3.2	0.6 – 1.9	21
IV	485 – 570	590 – 710	2020 – 2060	+10 to +60	3.2 – 4.0	0.6 – 2.4	118
V	570 – 660	710 – 855	2050 – 2080	+25 to +85	4.0 – 4.9	0.8 – 2.9	9
VI	660 – 790	855 – 1130	2060 – 2090	+90 to +140	4.9 – 6.1	1.0 – 3.7	5

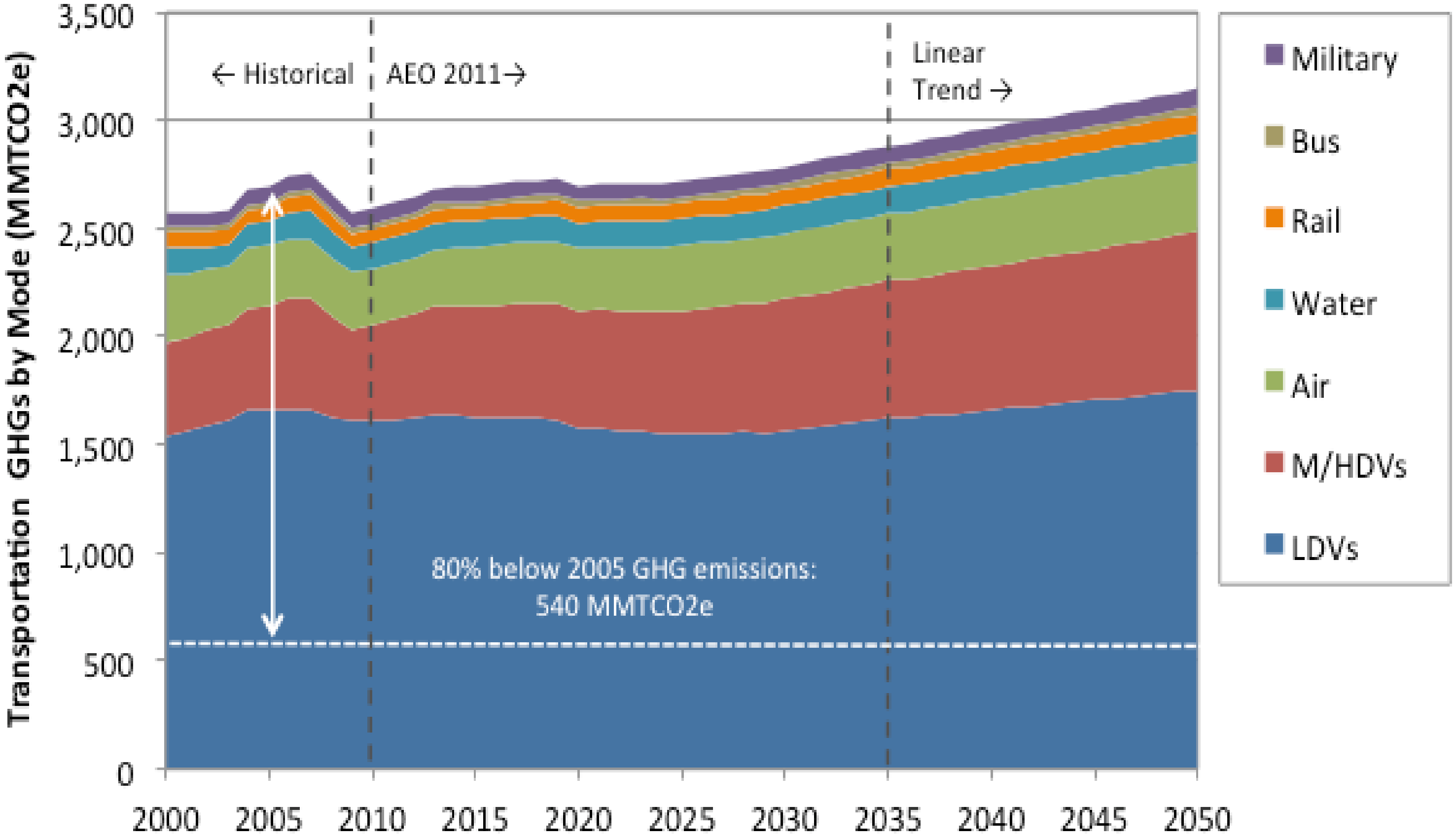




Source: *Intergovernmental Panel on Climate Change Fourth Assessment Report*, Climate Change 2007 (Synthesis Report)

U.S. GHG Emissions Reduction Target

GHG Projections by Transportation Market Segment



Source: Melaina, M.W.; Heath, G.; Sandor, D.; Steward, D.; Vimmerstedt, L.; Warner, E.; Webster, K.W. (2013). *Alternative Fuel Infrastructure Expansion: Costs, Resources, Production Capacity, and Retail Availability for Low-Carbon Scenarios.* Transportation Energy Futures Series.

Implications for Vehicles

Divide the problem into three pieces:

1. **Energy consumption of the vehicles**
2. **Carbon intensity of the energy source**
3. **Distance driven**

$$\left(\frac{\text{Energy}}{\text{Distance}}\right)\left(\frac{CO_2}{\text{Energy}}\right)\text{Distance} < CO_2\ \text{Target}$$

$$\left(\frac{\text{Energy}}{\text{Distance}}\right)\left(\frac{CO_2}{\text{Energy}}\right) < \frac{CO_2\ \text{Target}}{\text{Distance}}$$

Emission Reduction Targets

CO_2 Emission Target

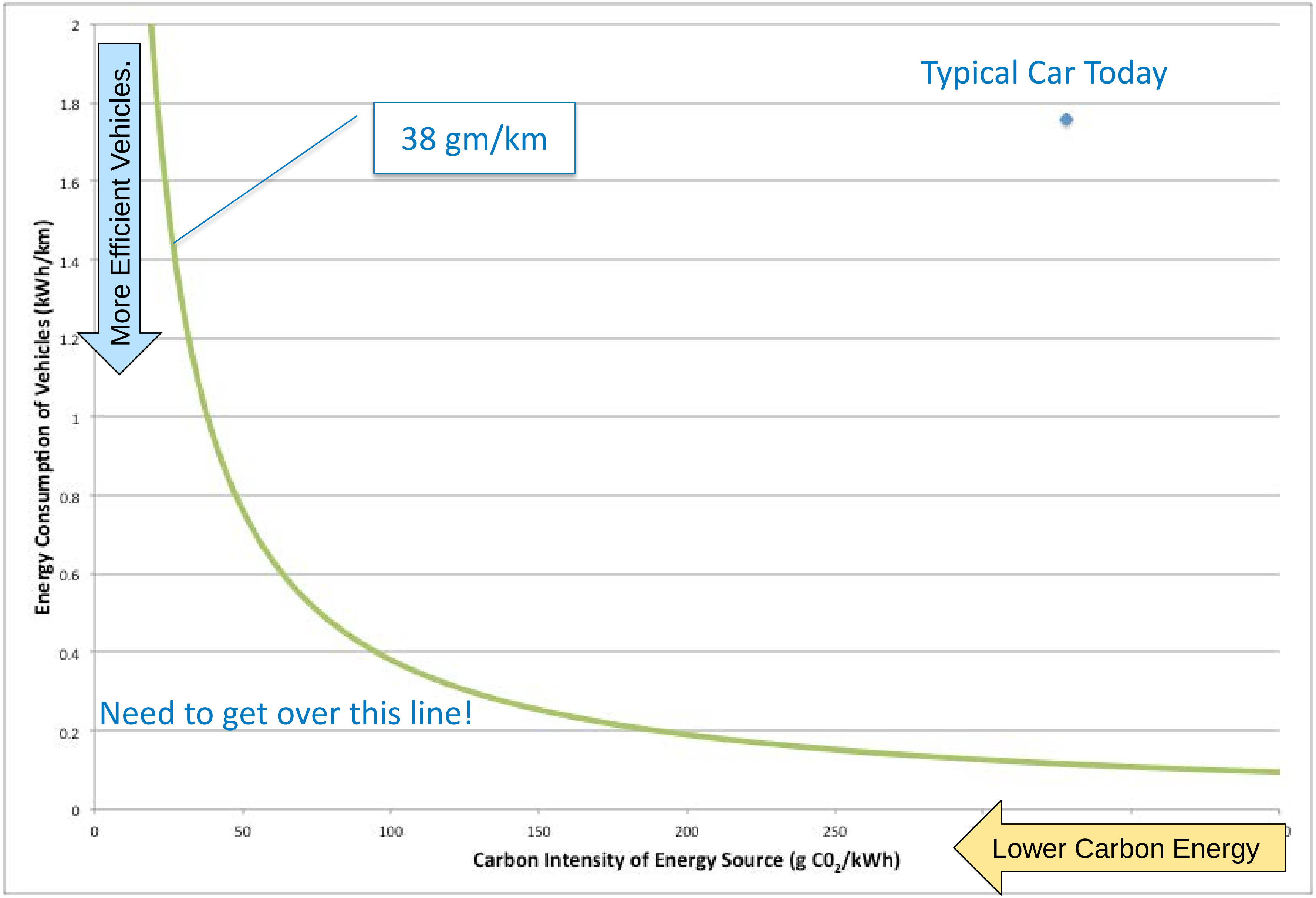
- 540 million metric tons for entire transportation sector
- Assume light-duty vehicles (LDVs) get same percentage of budget in 2050 as in 2005 (~57%)
- 308 million metric tons (3.08 x10^{14} g).

Vehicle Miles Traveled (VMT)

- Business-as-usual (BAU) VMT continues to increase.
- Estimate about 8 x 10^{12} kilometers by 2050.

Emissions per Kilometer — 38 g/km.

What Does the Solution Look Like?



More Efficient Vehicles.

38 gm/km

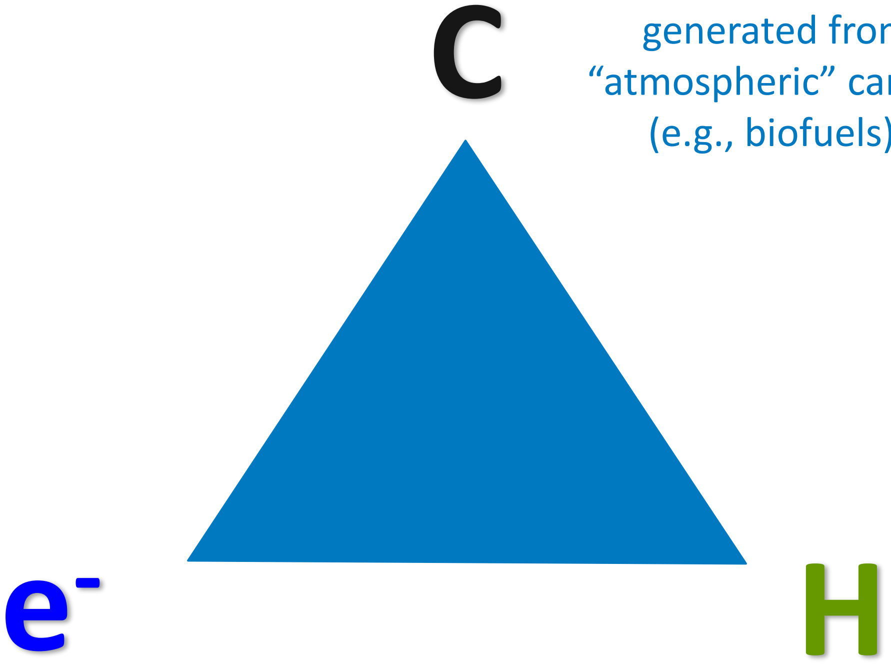
Typical Car Today

Need to get over this line!

Lower Carbon Energy

Low-Carbon Energy Carriers

Only Three Options

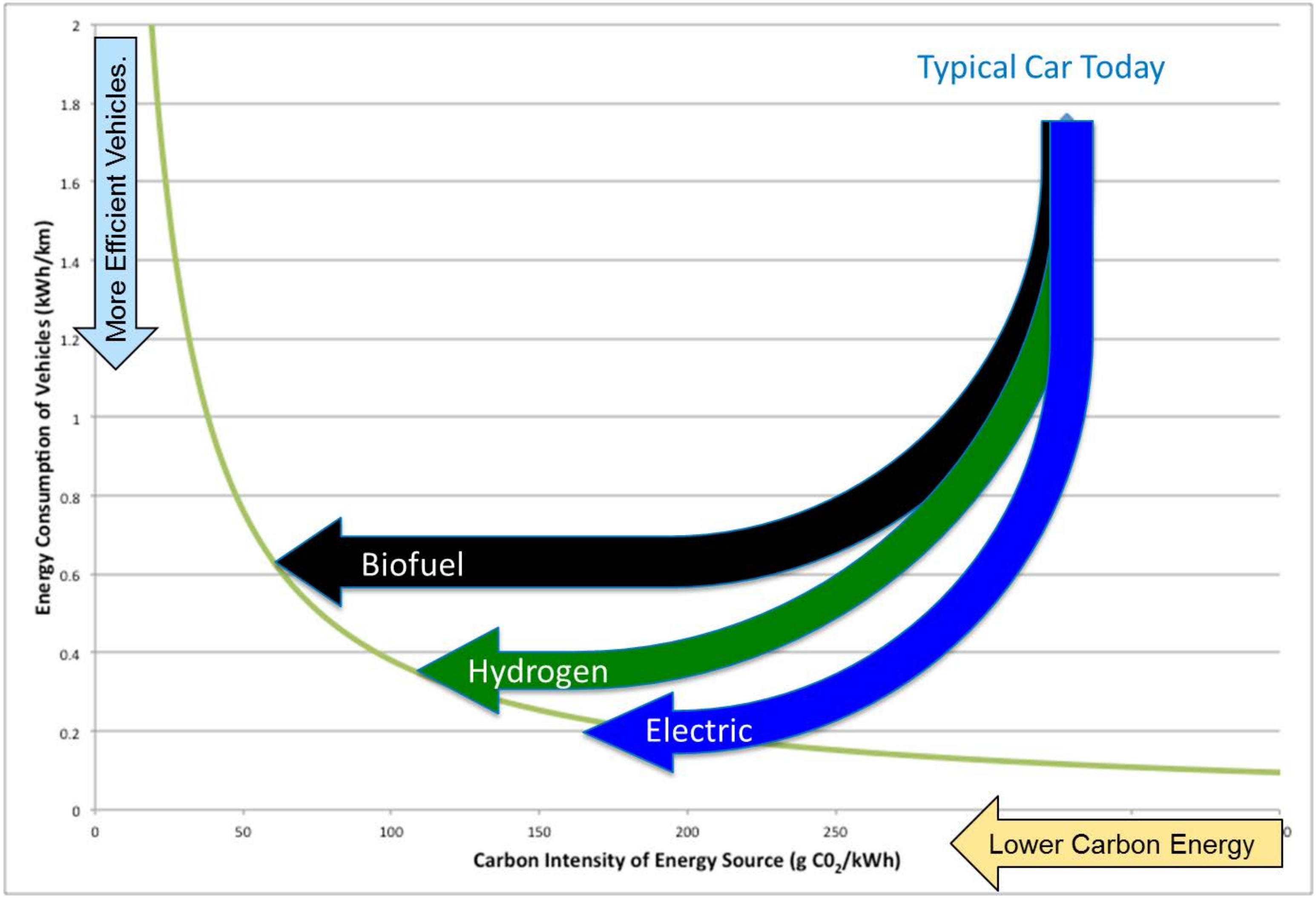


Hydrocarbons
generated from
“atmospheric” carbon
(e.g., biofuels).

Batteries to store
electricity generated
from renewable
sources, or fossil
sources combined with
carbon sequestration.

Hydrogen generated
from renewable
sources, or fossil
sources combined with
carbon sequestration.

Three Pathways



- Figure shows rough estimates of energy consumption potential of each pathway
- Does not show the carbon intensity of each pathway.

How Long Will it Take to Replace the U.S. LDV Fleet?

Photo: Warren Gretz/NREL

How Long Will it Take to Replace the U.S. LDV Fleet?

240 Million LDVs

16 Million Sales/Year

15 Years to Replace LDV Fleet

2050 GHG target is really a 2035 technology target.

Photos (left to right): Ken Kelly/NREL, Willie B. Thomas/iStock, Dennis Schroeder/NREL

Strategies

Reduce VMT

- **Mass transit, rideshare, telecommute, walk, bike.**

Improve Vehicles

- **More efficient vehicles**
  - Aerodynamics
  - More efficient transmission
  - Electrify auxiliaries (A/C, steering, water/oil pumps)
- **Reduce vehicle mass**
- **Very efficient internal-combustion engines (ICEs)**
- **Conventional powertrain to hybrid electric vehicle (HEV) to plug-in-hybrid electric vehicle (PHEV) to fully electric vehicle (EV).**

Shift to Renewable Energy

- **Biofuels**
- **Renewable hydrogen**
- **Renewable electricity.**

Vehicle-Level Research Opportunities

- **Hydrogen fuel cell electric vehicles**
- **Battery electric vehicles**
- **Biofuel combustion/ICE efficiency improvement**
- **General vehicle energy consumption reduction**
- **Transportation system efficiency gains**

Hydrogen Fuel Cell Electric Vehicles

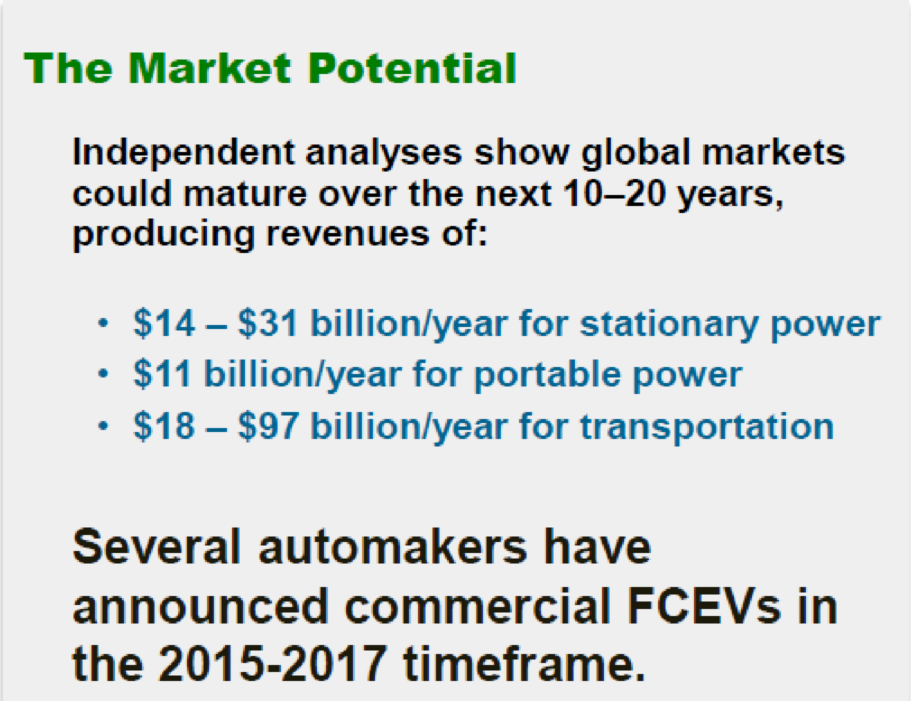
Fuel Cell Market Overview

Market Growth

Fuel cell markets continue to grow

48% increase in global MWs shipped

62% increase in North American systems shipped in the last year



The Market Potential

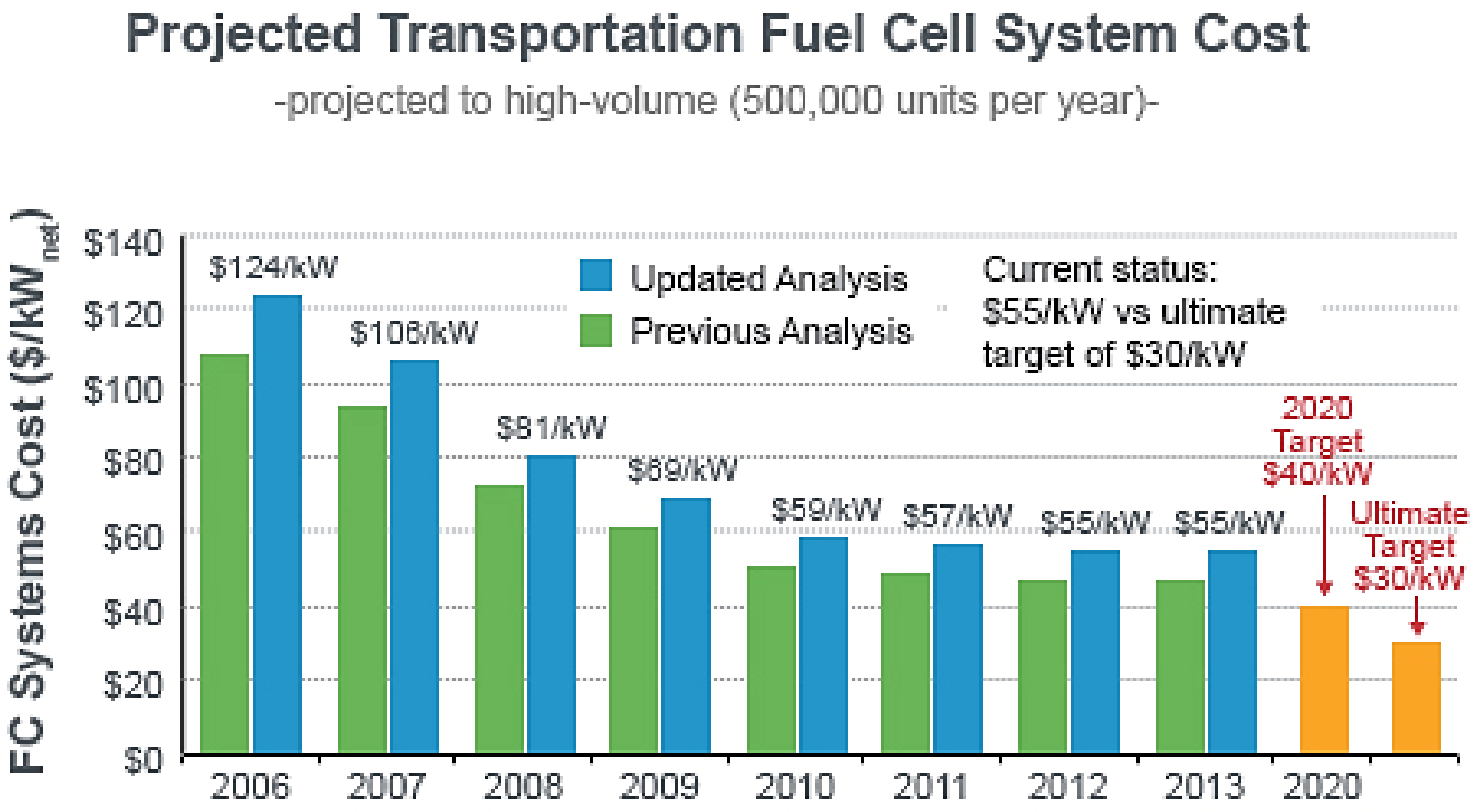
Independent analyses show global markets could mature over the next 10–20 years, producing revenues of:

- $14 – $31 billion/year for stationary power
- $11 billion/year for portable power
- $18 – $97 billion/year for transportation

Several automakers have announced commercial FCEVs in the 2015-2017 timeframe.

Source: S. Satyapal, 2013 DOE AMR
http://www.hydrogen.energy.gov/pdfs/review12/joint_plenary_satyapal_2012_o.pdf

Fuel Cell Costs Are Dropping



Source: DOE
https://www1.eere.energy.gov/hydrogenandfuelcells/accomplishments.html

Total Cost of Ownership for Future LDVs

Multiple technologies are cost competitive, supporting portfolio approach.

- **Analysis project in collaboration with the Vehicle Technologies Office**
- **Vehicle life cycle costs updated based on stakeholder input received from 2011 RFI**

Common Assumptions

- 15-year ownership
- 10,000 miles per year
- 7% discount for annual fuel costs
- 0 resale value at the end of 15 years

Vehicle Types

2012 Spark ignition (SI): Current gasoline car
Adv SI ICEV: 2035 gasoline car
Adv Compression ignition (CI): 2035 diesel car
Adv NG SI ICEV: 2035 natural gas car
Gasol HEV: 2035 hybrid electric car
SI PHEV10: 2035 gasol PHEV10
SI EREV40: 2035 gasol EREV40
FCEV: 2035 fuel cell hybrid electric car
BEV100, BEV300: 2035 battery electric cars

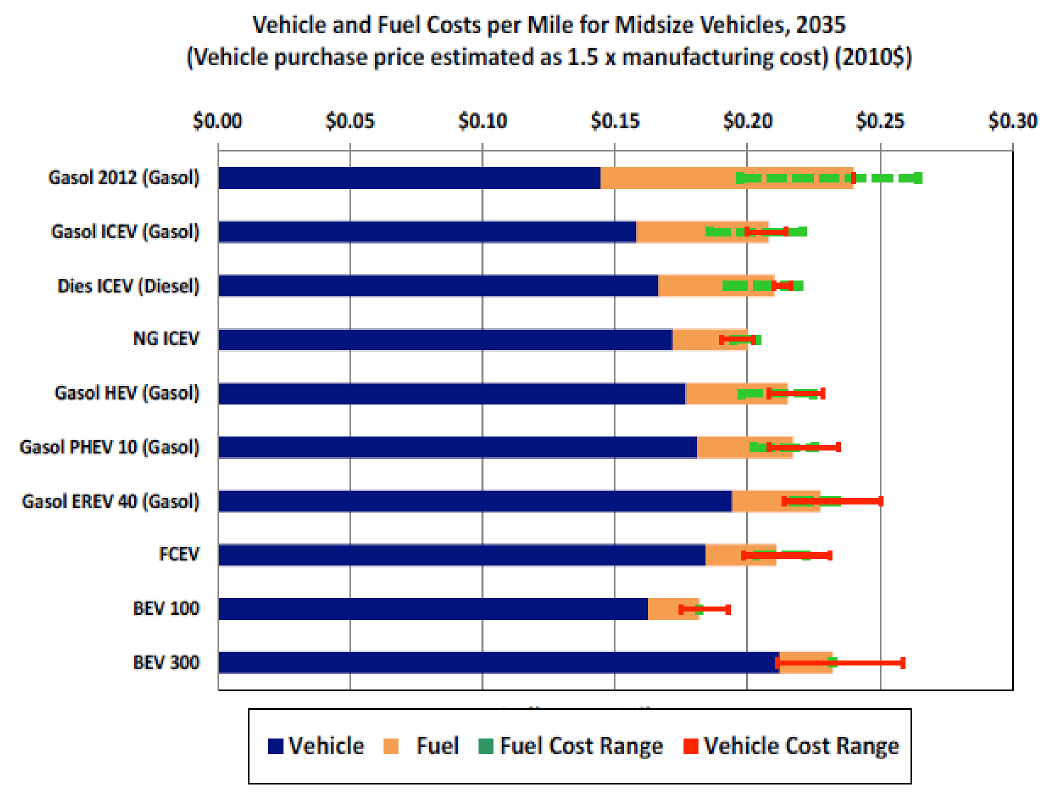
Error Bars

Green: range of assumptions for fuel prices (EIA projections for fuels other than hydrogen; hydrogen range: $2.50 - $5.00 per kg)

Red: range of assumptions for technology success.

See record:
http://hydrogen.energy.gov/pdfs/13006_ldv_life_cycle_costs.pdf

Costs Based on 15-Year Life (Societal Perspective)



	FCEV	BEVs
Battery Cost, $/kWh		$75, $81, $84
Battery Cost, $/kW	$20, $25, $28	
Fuel Cell Cost, $/kW	$32, $35, $38	
Fuel Cost in $/gge (¢/kWh)	$2.50, $3.50, $5.00	$3.94 (11.7¢), $3.98 (11.8¢), $4.01 (11.9¢)

Source: F. Joseck, 2013 DOE AMR
http://www.hydrogen.energy.gov/pdfs/review13/2013_h2_amr_plenary_analysis_joseck.pdf

Barriers to Implementation

Cost

- Mostly due to catalyst activity.

Durability

- Mostly due to catalyst durability.

Hydrogen storage energy density

Cost and durability
are linked.

What improves one
tends to make
the other worse.

Polymer Electrolyte Fuel Cell R&D Needs

Electrocatalysis

- Low platinum (Pt)
- Non-precious.

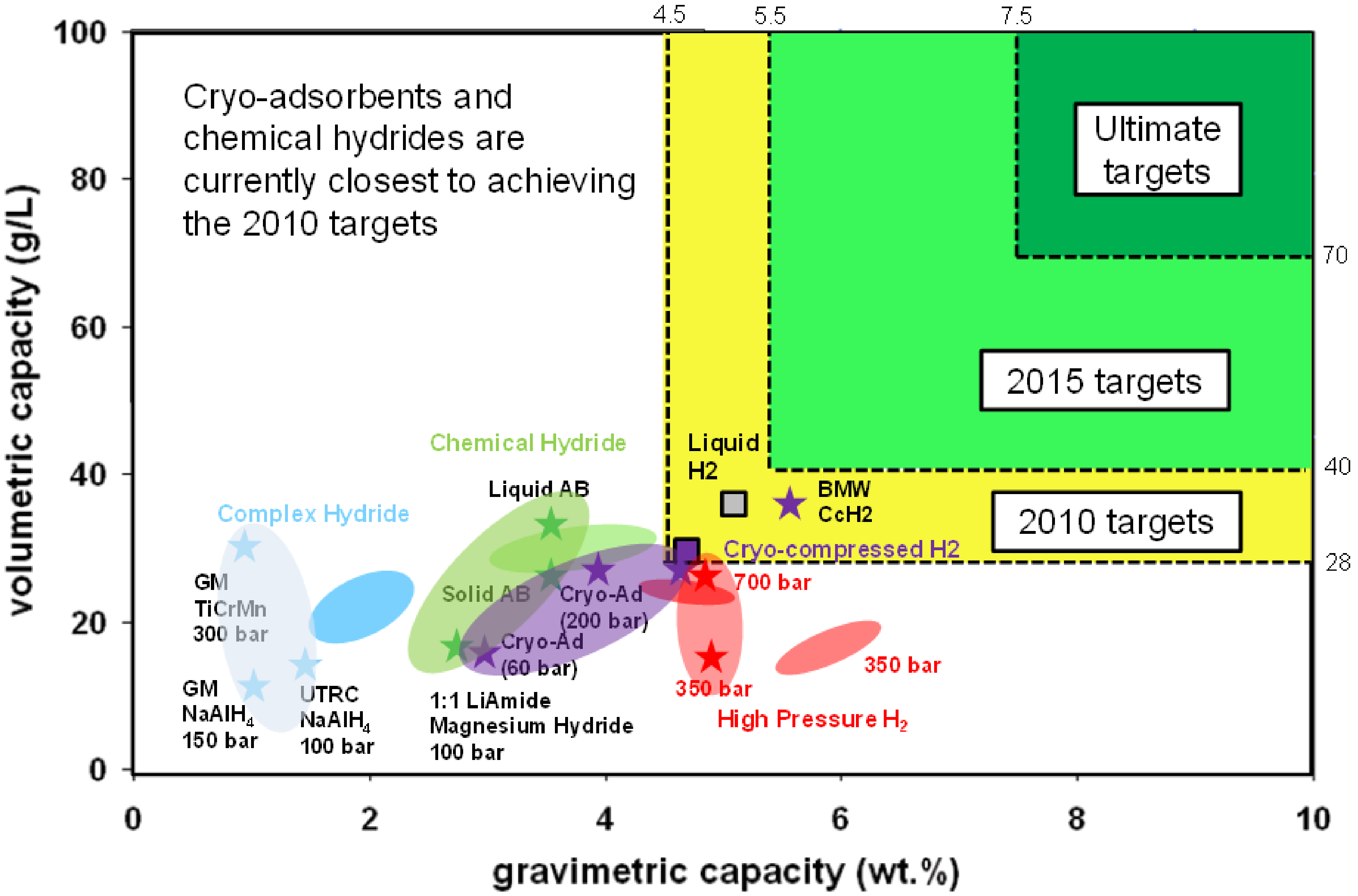
Alkaline Membrane Fuel Cells

Electrodes

Membranes

NREL R&D focus is heavily directed towards critical materials needs and novel materials development, with a specific focus on electrode design and fabrication. The primary goal is to reduce Pt, make systems higher performing and more durable.

Hydrogen Storage System Status



Cryo-adsorbents and chemical hydrides are currently closest to achieving the 2010 targets

Source: *Innovation for Our Energy Future*, NREL

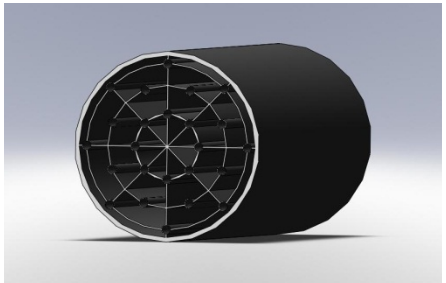
Solid/Condensed State Storage

Physical Storage-Compressed Gas (350-700 bar), Cold Gas, or Liquid

- Known technology and infrastructure
- High-pressure operation
- High material costs for storage vessel
- Low volumetric capacity.

Solid/Condensed State Storage-Metal Hydrides, Chemical Hydrides, and Adsorbents

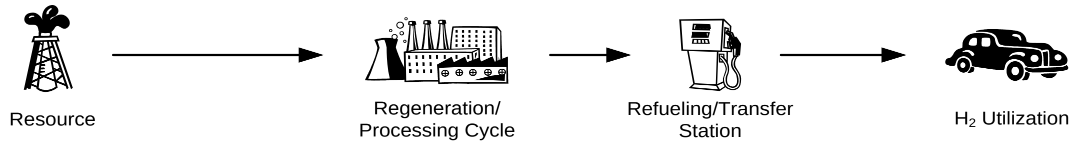
- Low-pressure operation
- Ambient storage temperature
- High hydrogen capacity
- Fluid phase or solid phase
- Flexibility of material space
- Lower cost?

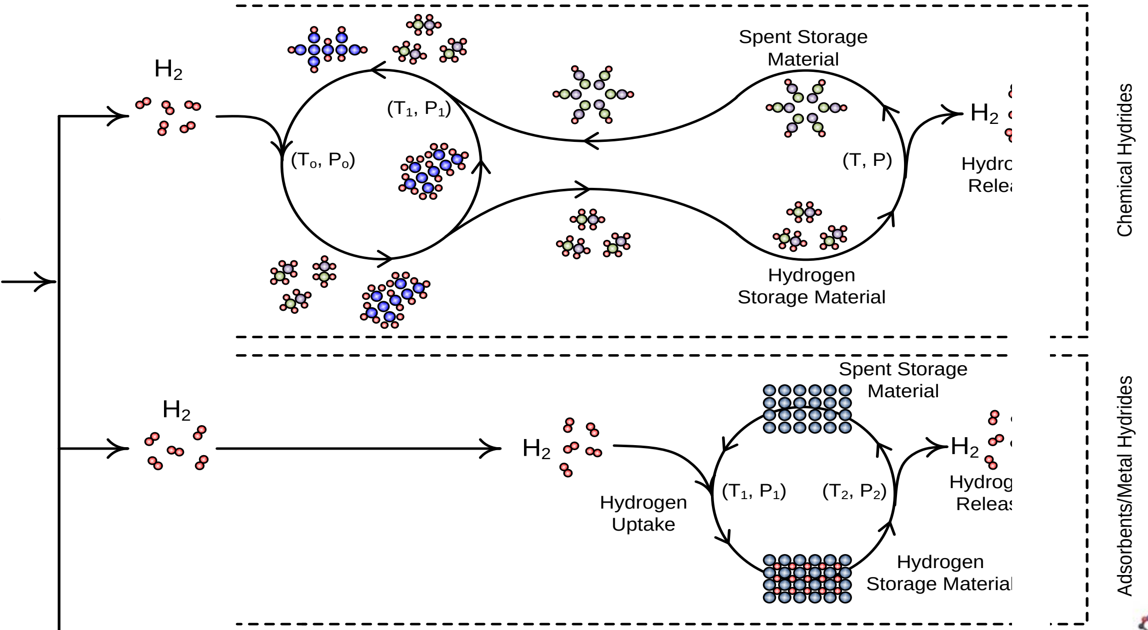


Source: *Innovation for Our Energy Future,* NREL

Solid/Condensed State Storage

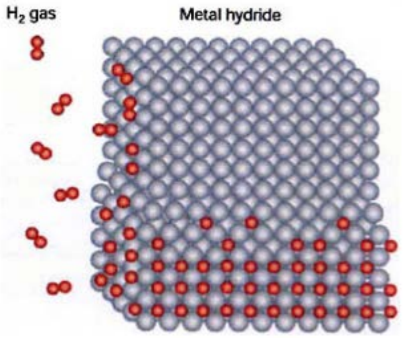
Three Material Classes: Chemical Hydrides, Metal Hydrides, and Adsorbents

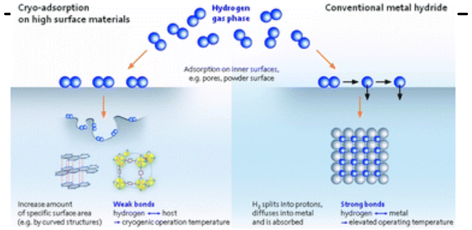




Chemical Hydrides,

Metal Hydrides and Adsorbents





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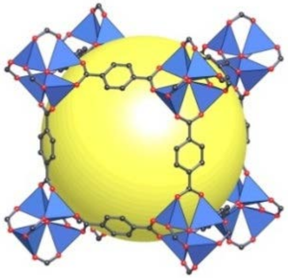
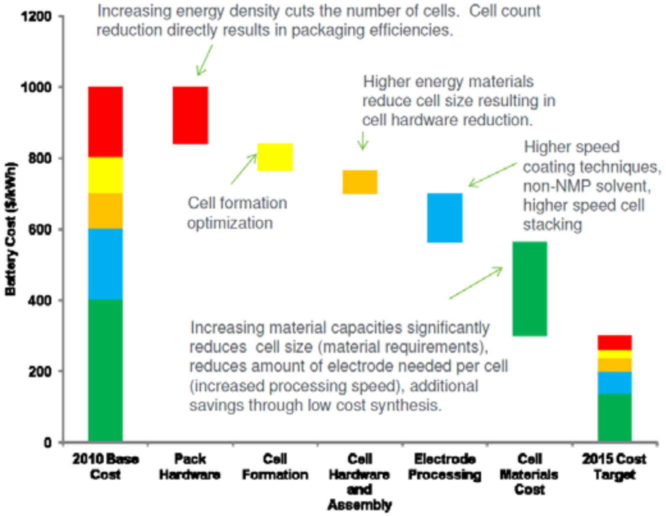


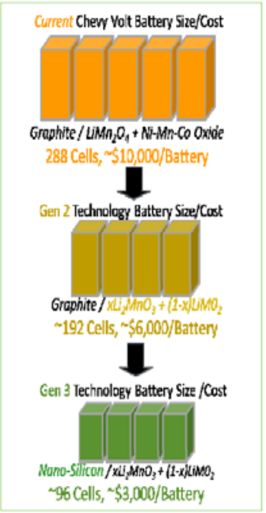
Source: *Innovation for Our Energy Future*, NREL

Battery Electric Vehicles

Barriers to Implementation

EV Battery Development Challenges





- **Cost**
- **Lifetime**
- **Energy density**
- **Power**
- **Infrastructure/charger access**
- **Safety.**

Reducing Battery Size & Cost

EV Battery Choices: Energy and Power

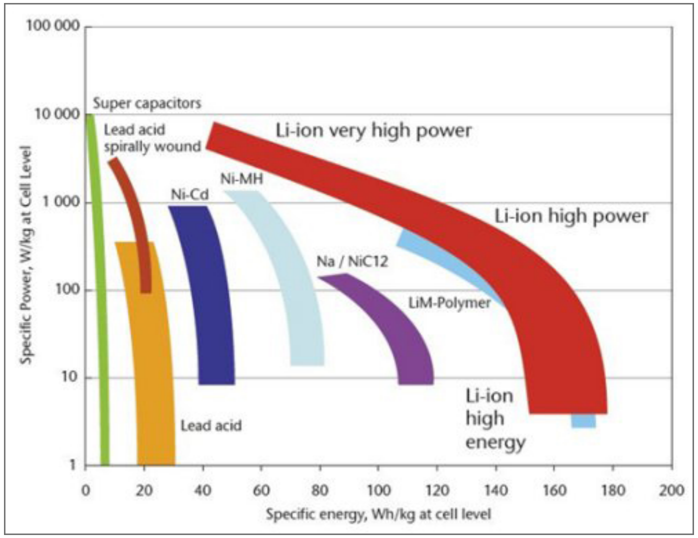


Figure: *DOE*

DOE GOALS:

Reduce Battery Cost from $1,000/kWh to $150/kWh by 2020

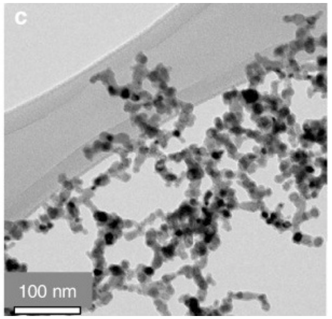
Batteries 1/2 Today's Price in 2015, 1/4 Today's Price in 2020

Progress:

- **35% reduction in HEV/PEV battery cost**
- **50%-100% more energy capacity.**

Battery Materials and Synthesis Process

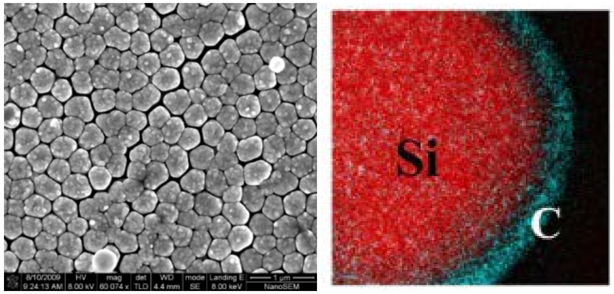
- Improved Li-ion electrode durability with interface modification using atomic layer deposition coatings



ABR Program

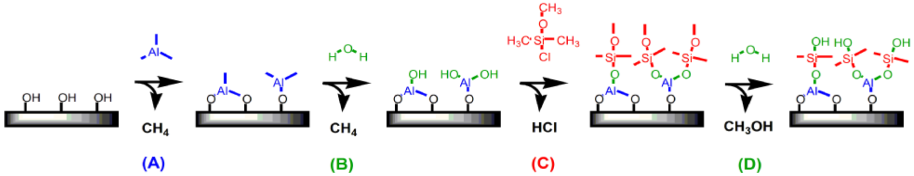
Applied Battery Research for Transportation

- Developing high-capacity silicon anodes stabilized with molecular layer deposition coatings



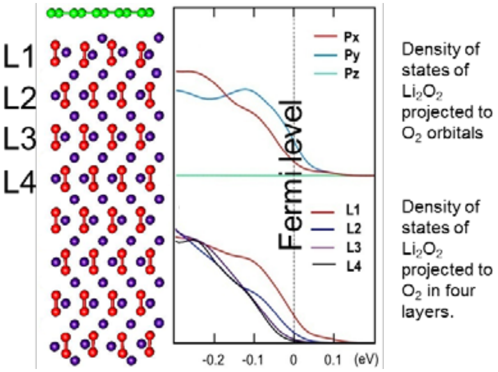
BATT Program

Batteries for Advanced Transportation Technologies



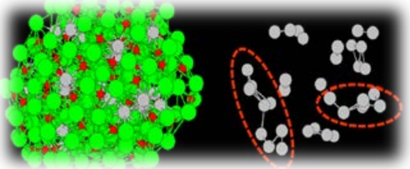
Polysiloxane ALD coating

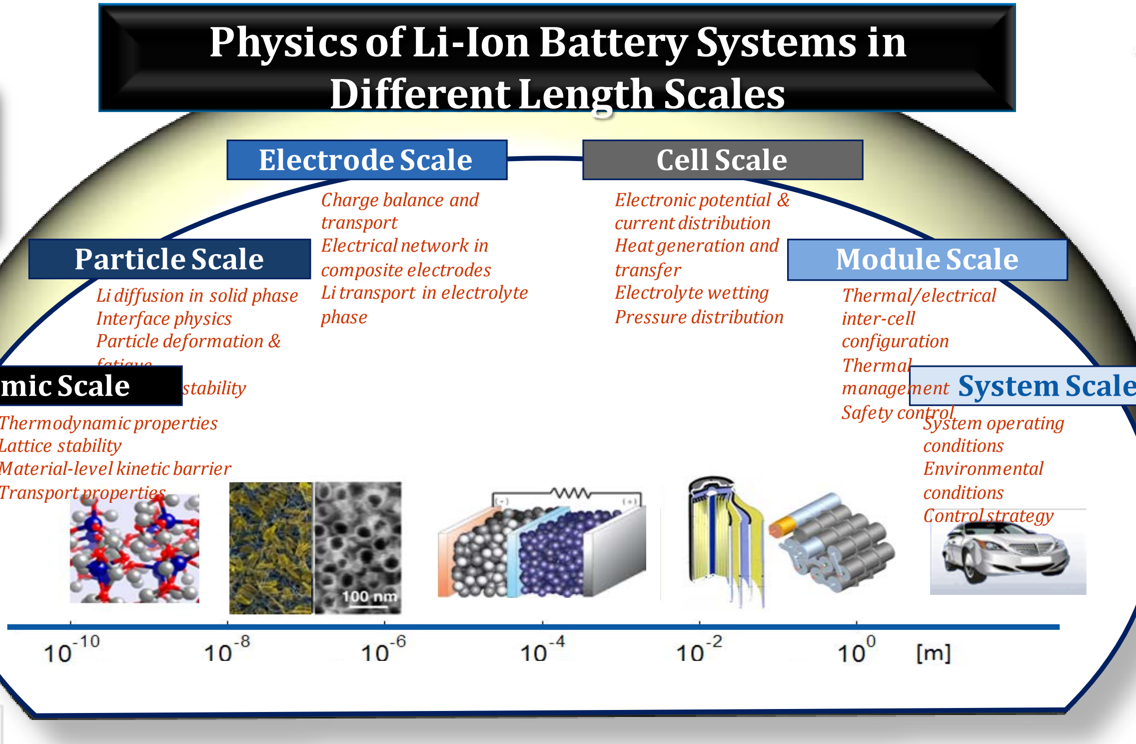
- Demonstrated difficulty in moving electrons across the peroxide barrier in Li-Air batteries; investigating potential modifications to the oxide layers to overcome this issue.



Multi-Physics Battery Modeling

NREL has developed a unique set of multi-physics, multi-scale modeling tools for simulating performance, life, and safety of lithium ion batteries.





Physics of Li-Ion Battery Systems in Different Length Scales

Atomic Scale

- *Thermodynamic properties*
- *Lattice stability*
- *Material-level kinetic barrier*
- *Transport properties*

Particle Scale

- *Li diffusion in solid phase*
- *Interface physics*
- *Particle deformation & fatigue*
- *stability*

Electrode Scale

- *Charge balance and transport*
- *Electrical network in composite electrodes*
- *Li transport in electrolyte phase*

Cell Scale

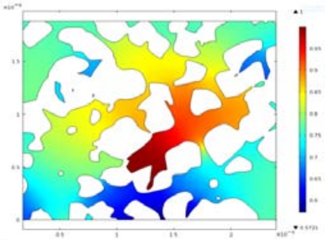
- *Electronic potential & current distribution*
- *Heat generation and transfer*
- *Electrolyte wetting*
- *Pressure distribution*

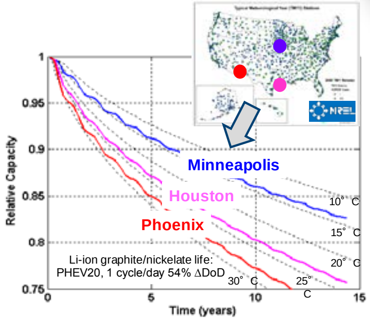
Module Scale

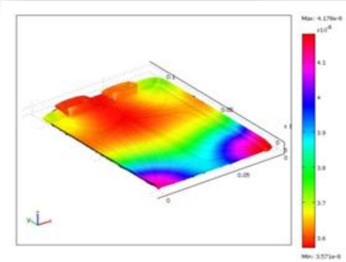
- *Thermal/electrical inter-cell configuration*
- *Thermal management*
- *Safety control*

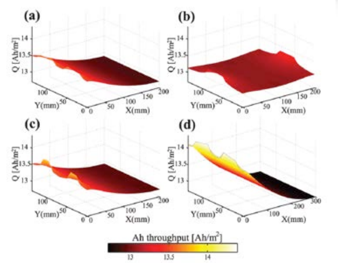
System Scale

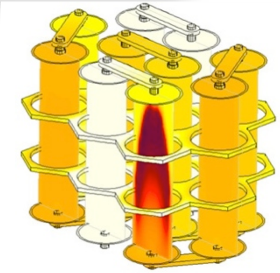
- *System operating conditions*
- *Environmental conditions*
- *Control strategy*

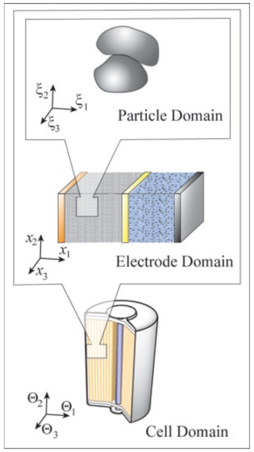










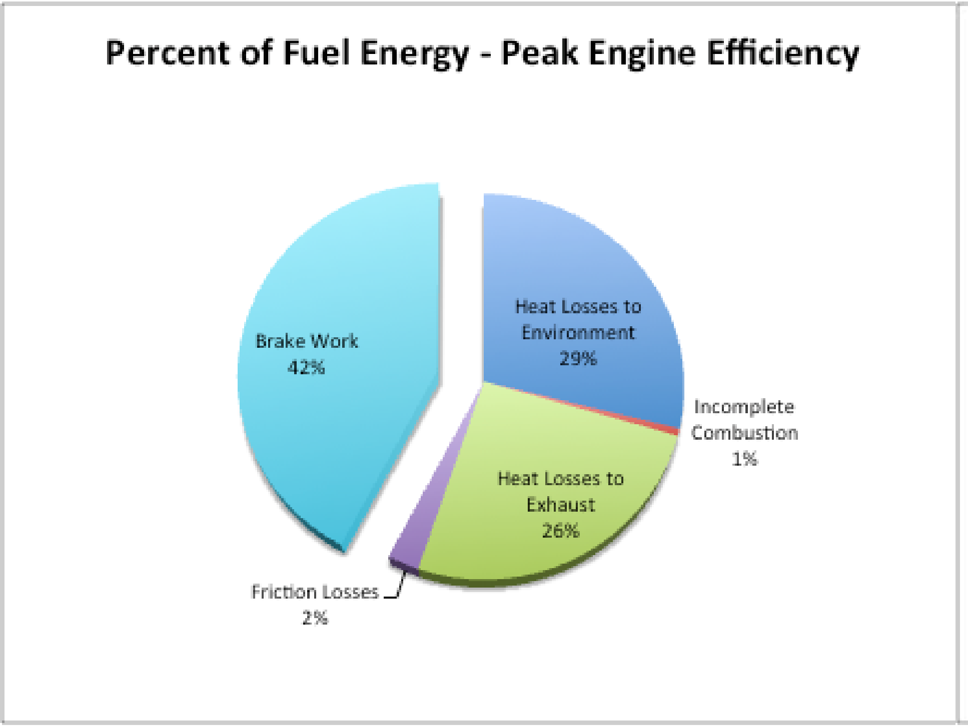


NREL
NATIONAL RENEWABLE ENERGY LABORATORY

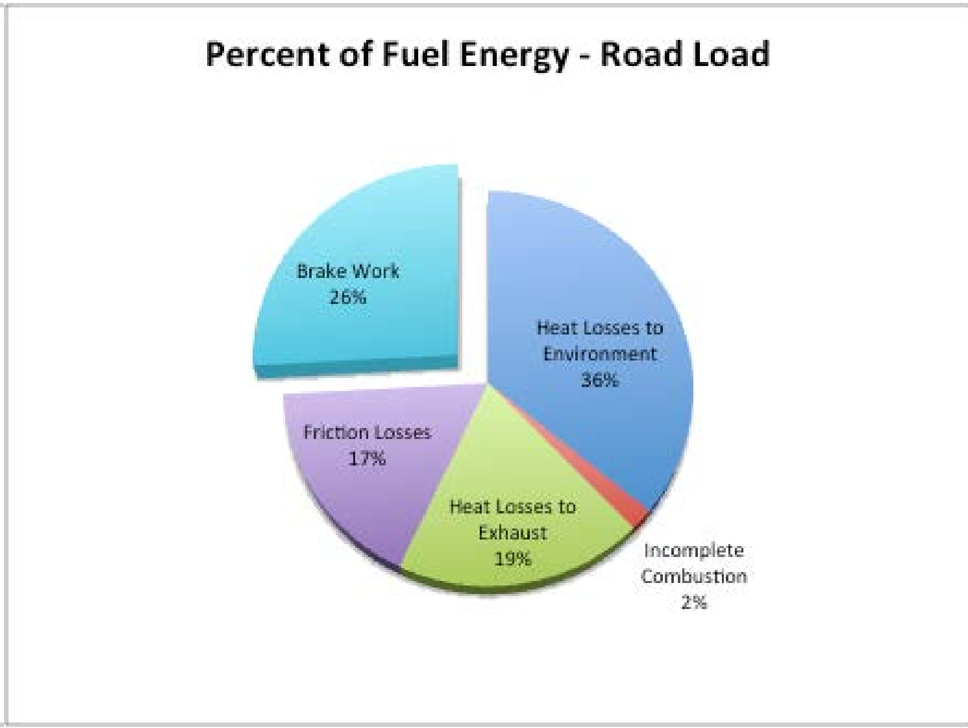
Biofuel ICE Vehicles

Barriers to Implementation

- **Suitable biofuels**
- **Very efficient internal combustion engines.**



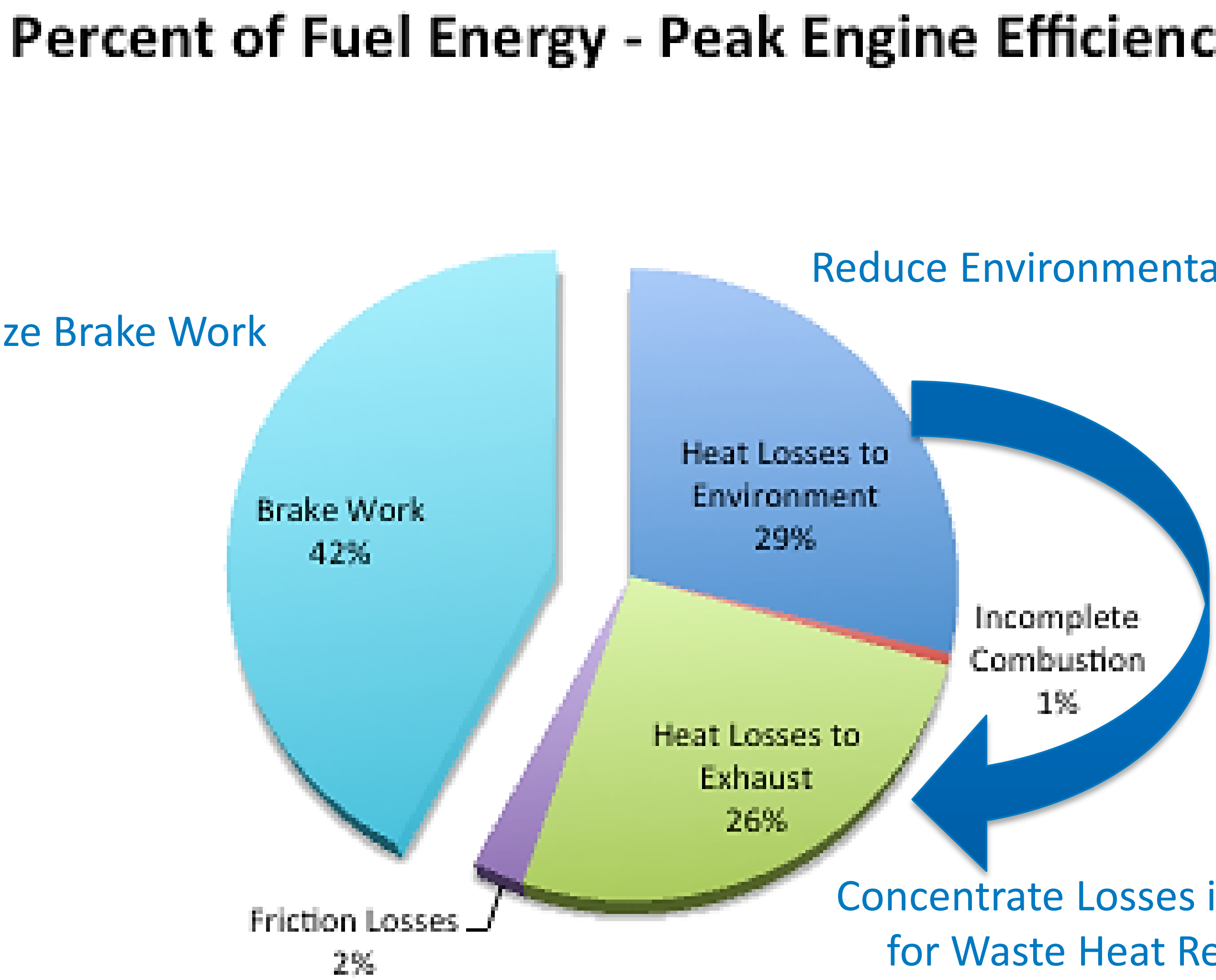
Percent of Fuel Energy - Peak Engine Efficiency



Percent of Fuel Energy - Road Load

Source: NREL/DOE

Strategies for Increasing ICE Efficiency



Maximize Brake Work

Reduce Environmental Losses

Concentrate Losses in Exhaust for Waste Heat Recovery

Source: NREL/DOE

Maximize Brake Work

$$W=\Delta(PV)/(1-\gamma)$$

- **Increase work by**
  - Increasing change in pressure and volume
  - Increasing gamma
- **Increase compression ratio**
- **Over-expanded cycle (Atkinson cycle)**
- **Turbocharging**
- **Fuel selection to provide high gamma**

Research Opportunities

- **Advanced materials that can withstand high temperatures**
  - Reduces the amount of heat that has to be extracted through coolant.
- **Advanced combustion techniques**
- **Exhaust energy recovery**
  - Efficient turbo machinery
  - Thermo-electrics

Research challenges for internal combustion engines

- Efficiency can be increased with high pressure, low temperature combustion, using high compression ratios, boost, lean mixtures, and dilution…
  - But these make ignition control difficult, so technologies such as plasma ignition may be required
  - Other strategies rely on controlled autoignition through chemical kinetics

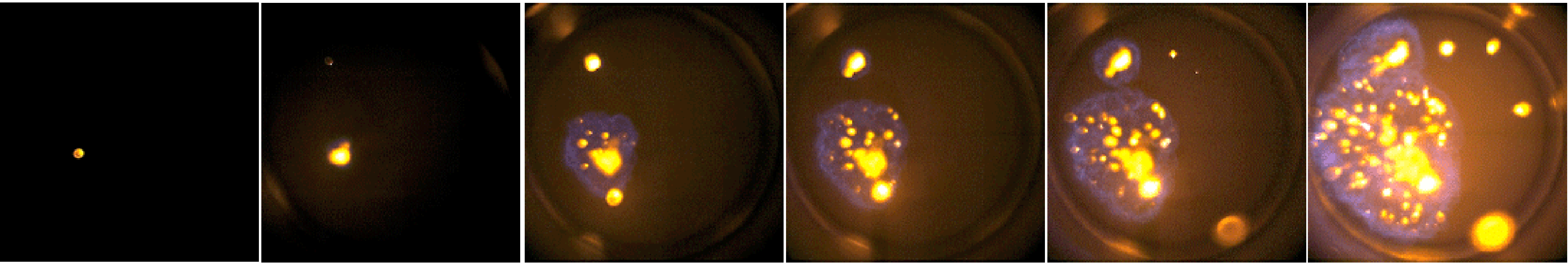
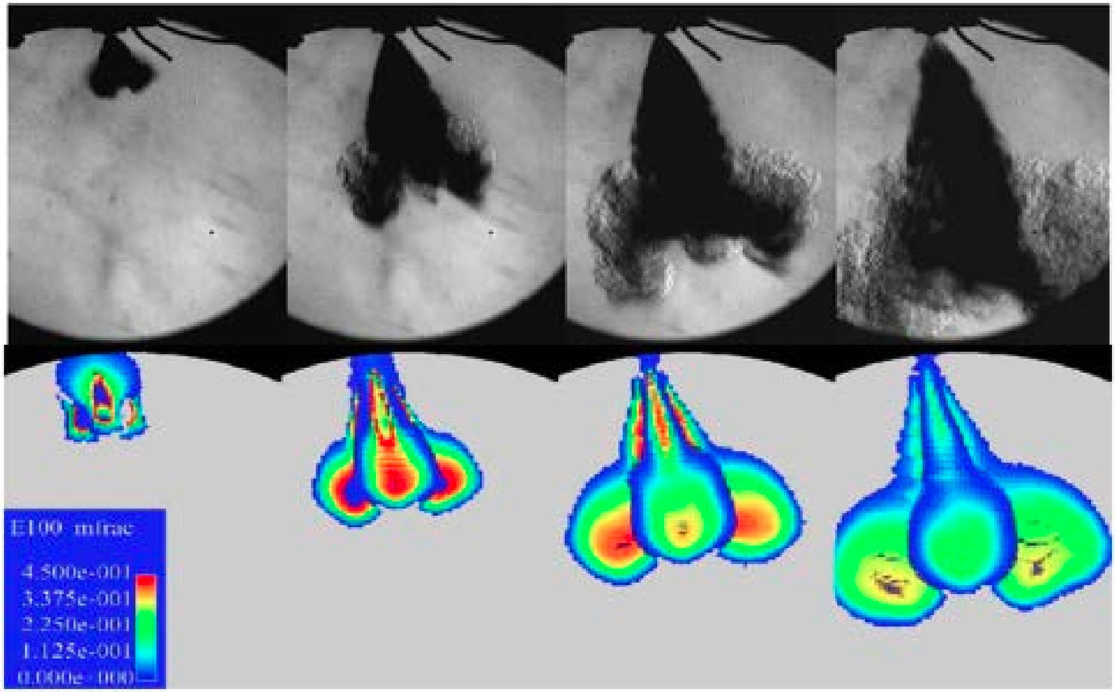


Image sequence from U. Michigan, M.S. Wooldridge research group, http://www-personal.umich.edu/~mswool/researchimagelibrary.htm

Research challenges for internal combustion engines

- Computational models must be improved to simultaneously study reacting flows with fluid dynamics and chemical kinetics
  - Fuel spray dynamics
  - Fundamental understanding of flame structure



Matsumoto, et al., Spray Characterization of Ethanol Gasoline Blends and Comparison to a CFD Model for a Gasoline Direct Injector
SAE 2010-01-0601

Research challenges for internal combustion engines

Two key combustion challenges at the atomic or molecular level:

- Ignition / control of the combustion system
- Minimizing harmful emissions (NOx, soot, HCs)

Understanding the chemical kinetic mechanisms for thousands of fuel molecular compounds is a massive challenge

Photos by Dennis Schroeder, NREL

Vehicle Efficiency

Vehicle Efficiency: Where Are the Losses?

Power Required to Move the Vehicle

- Inertia – reduce vehicle mass
- Overcome aerodynamic drag – reduce drag coefficient of frontal area
  - Front, back, sides, mirrors, wipers, underbody
- Lower tire rolling resistance
  - Need to turn and stop

Engine Losses

- Improve combustion efficiency, reduce pumping losses and friction
- Operate only at higher efficiencies
  - Downsize engine
  - Deactivate cylinder
  - Reduce transients through load leveling – hybridizing

Other Loads

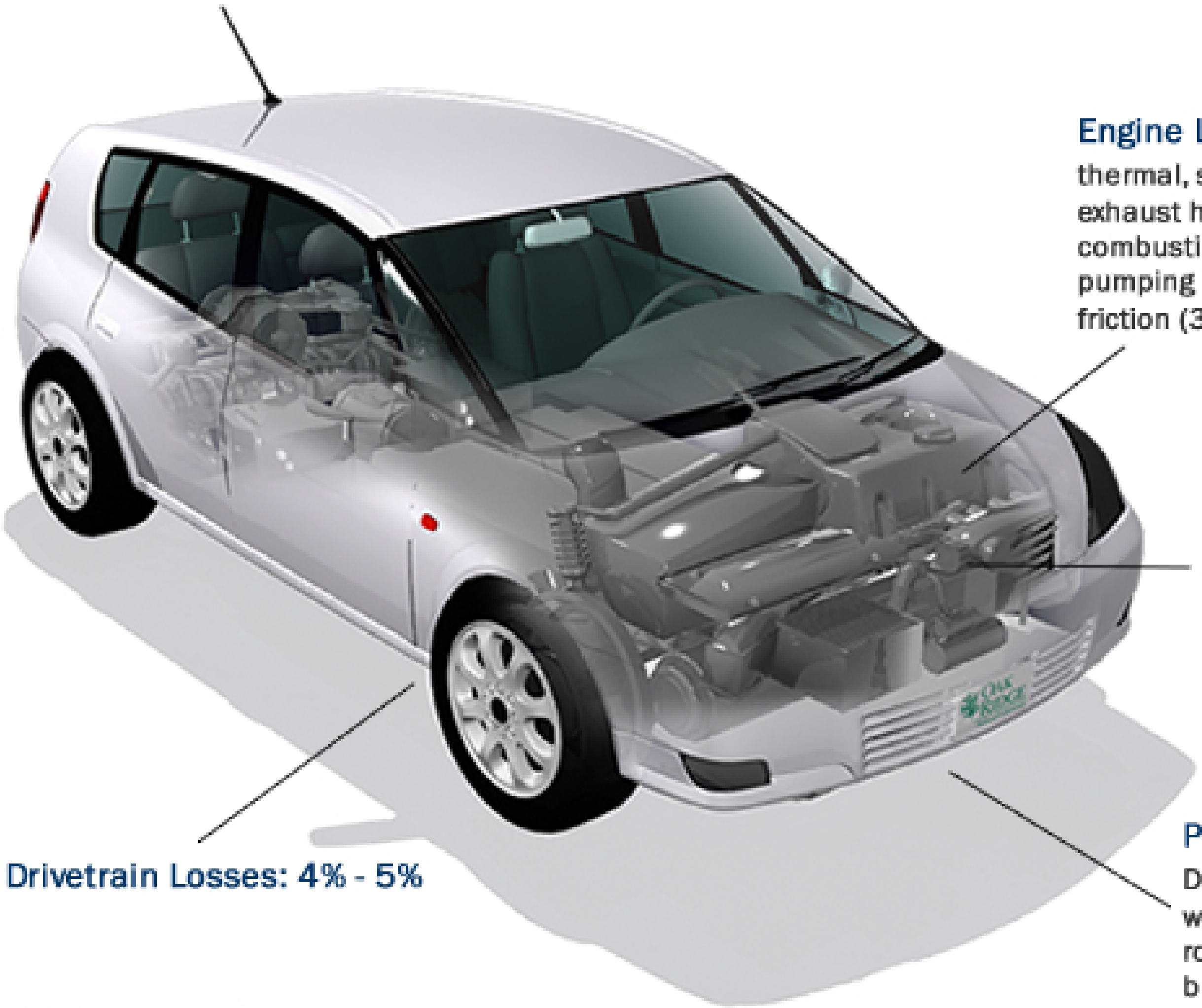
- Reduce auxiliary loads (climate control/defrost, informatics, entertainment, wipers, lights, steering, etc.)
- Improve efficiency of ancillary equipment (oil/water pumps, radiator fans, alternator)

Reclaiming Lost Energy

- Use regenerative braking to reclaim kinetic energy lost as heat through braking
- Recover heat – exhaust gases or engine coolant
- Use turbochargers – recover pressure in exhaust stream.

Vehicle Losses: City Driving

Energy Requirements for City (Stop and Go) Driving



Engine Losses: 74% - 75%
thermal, such as radiator,
exhaust heat, etc. (63% - 64%)
combustion (3%)
pumping (5%)
friction (3%)

Parasitic Losses: 6% - 7%
(e.g., water pump,
alternator, etc.)

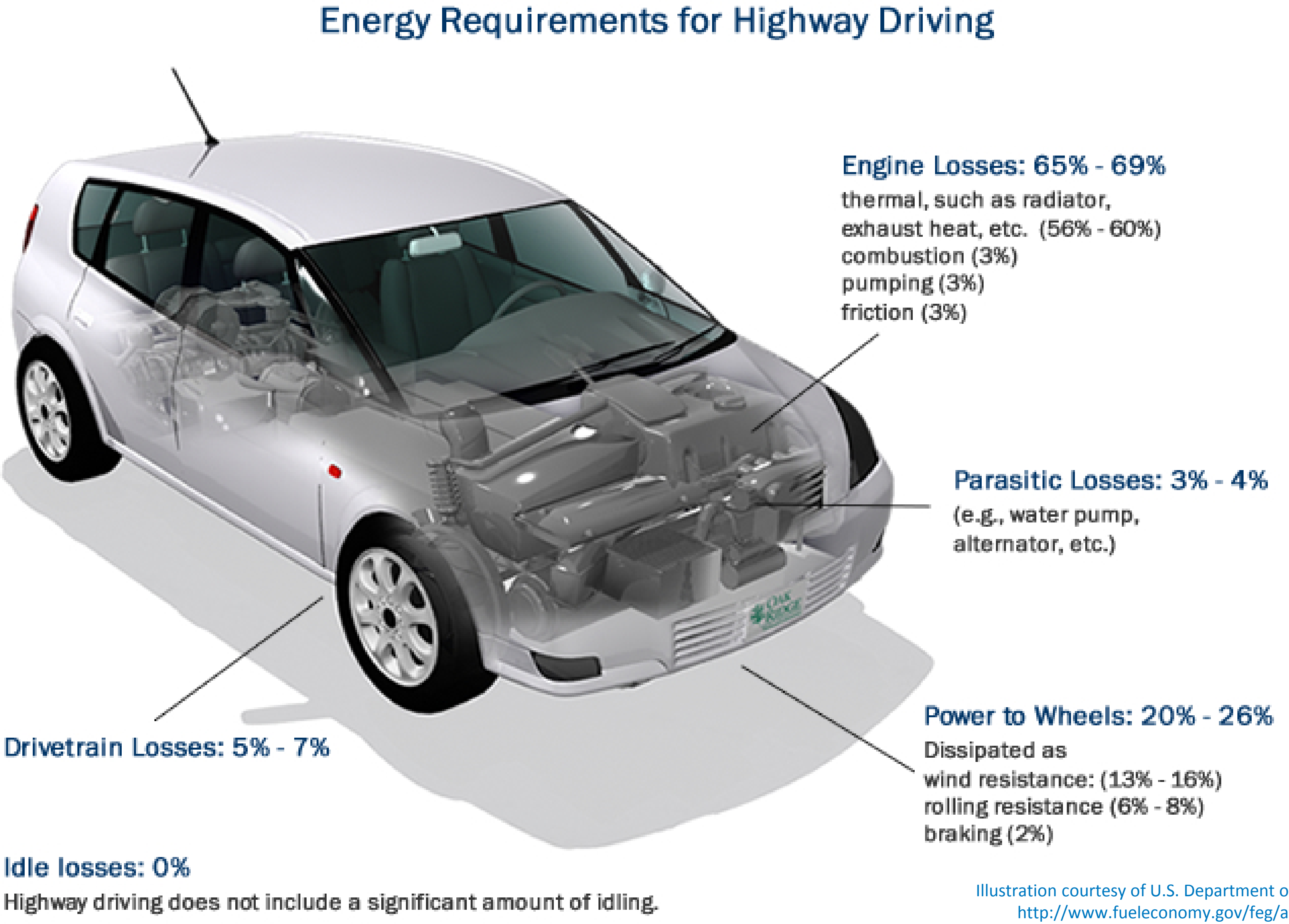
Power to Wheels: 14% - 16%
Dissipated as
wind resistance: (4%)
rolling resistance (4% - 5%)
braking (6% - 7%)

Drivetrain Losses: 4% - 5%

Idle Losses: 6%
In this figure, they are accounted for as part of the engine and parasitic losses.

Illustration courtesy of U.S. Department of Energy
http://www.fueleconomy.gov/feg/atv.shtml

Vehicle Losses: Highway Driving



Energy Requirements for Highway Driving

Engine Losses: 65% - 69%
thermal, such as radiator,
exhaust heat, etc. (56% - 60%)
combustion (3%)
pumping (3%)
friction (3%)

Parasitic Losses: 3% - 4%
(e.g., water pump,
alternator, etc.)

Power to Wheels: 20% - 26%
Dissipated as
wind resistance: (13% - 16%)
rolling resistance (6% - 8%)
braking (2%)

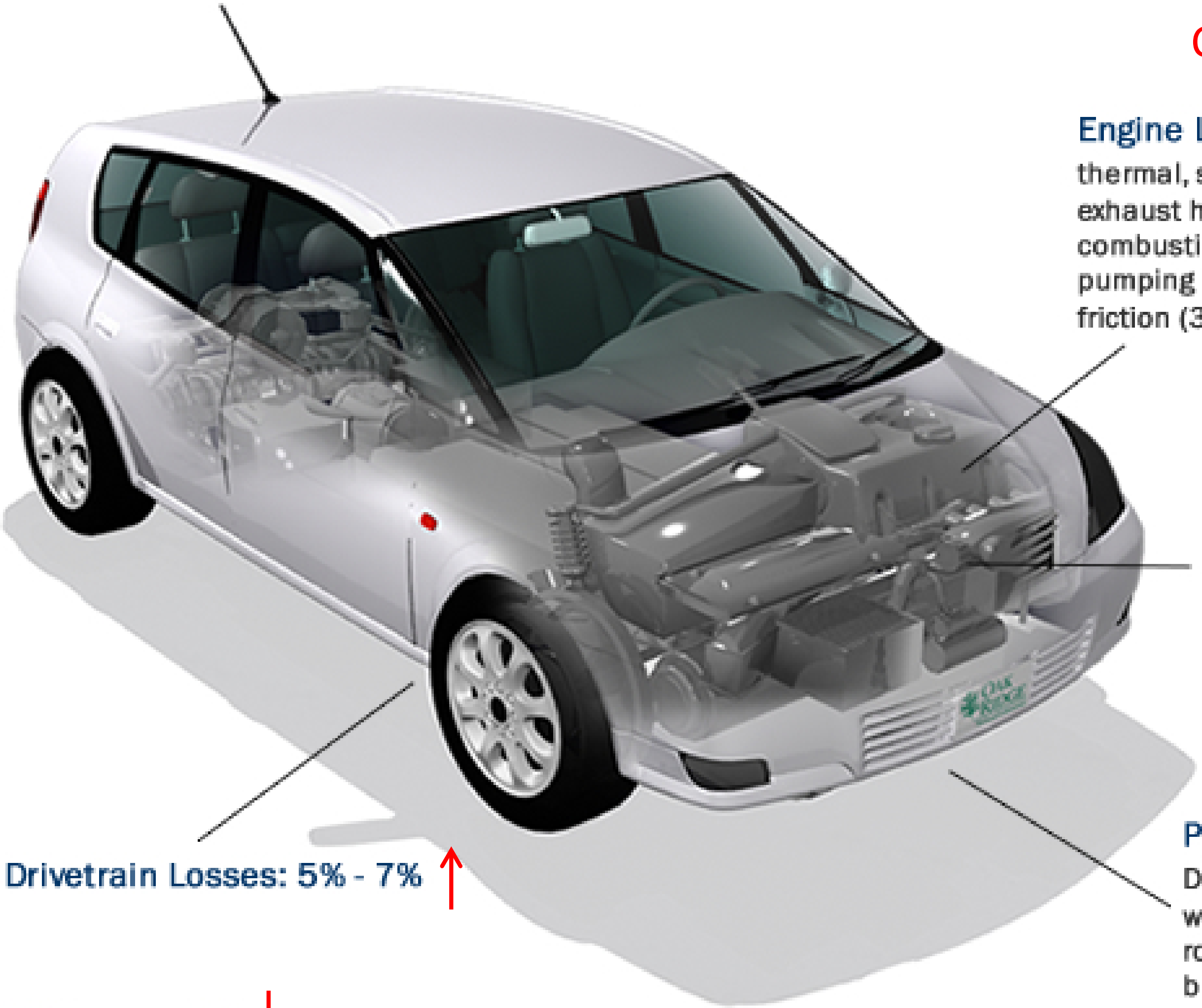
Drivetrain Losses: 5% - 7%

Idle losses: 0%
Highway driving does not include a significant amount of idling.

Illustration courtesy of U.S. Department of Energy
http://www.fueleconomy.gov/feg/atv.shtml

Vehicle Losses: Comparison

Energy Requirements for Highway Driving



Compared with City Driving

Engine Losses: 65% - 69% ↓
thermal, such as radiator, exhaust heat, etc. (56% - 60%)
combustion (3%)
pumping (3%)
friction (3%)

Parasitic Losses: 3% - 4% ↓
(e.g., water pump, alternator, etc.)

Power to Wheels: 20% - 26% ↑
Dissipated as
wind resistance: (13% - 16%)
rolling resistance (6% - 8%)
braking (2%)

Drivetrain Losses: 5% - 7% ↑

Idle losses: 0% ↓
Highway driving does not include a significant amount of idling.

Illustration courtesy of U.S. Department of Energy
http://www.fueleconomy.gov/feg/atv.shtml

Vehicle Losses: Opportunities

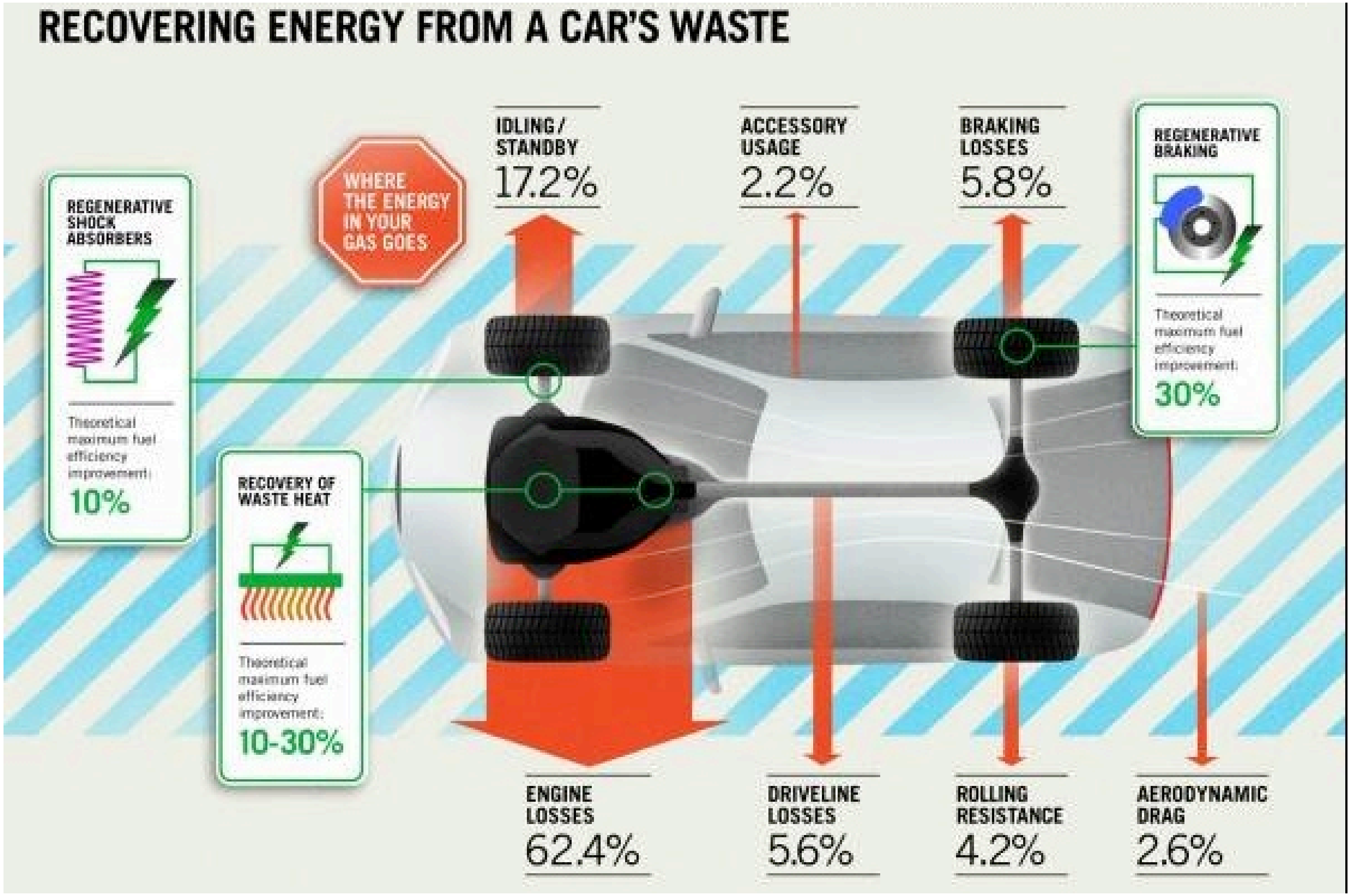
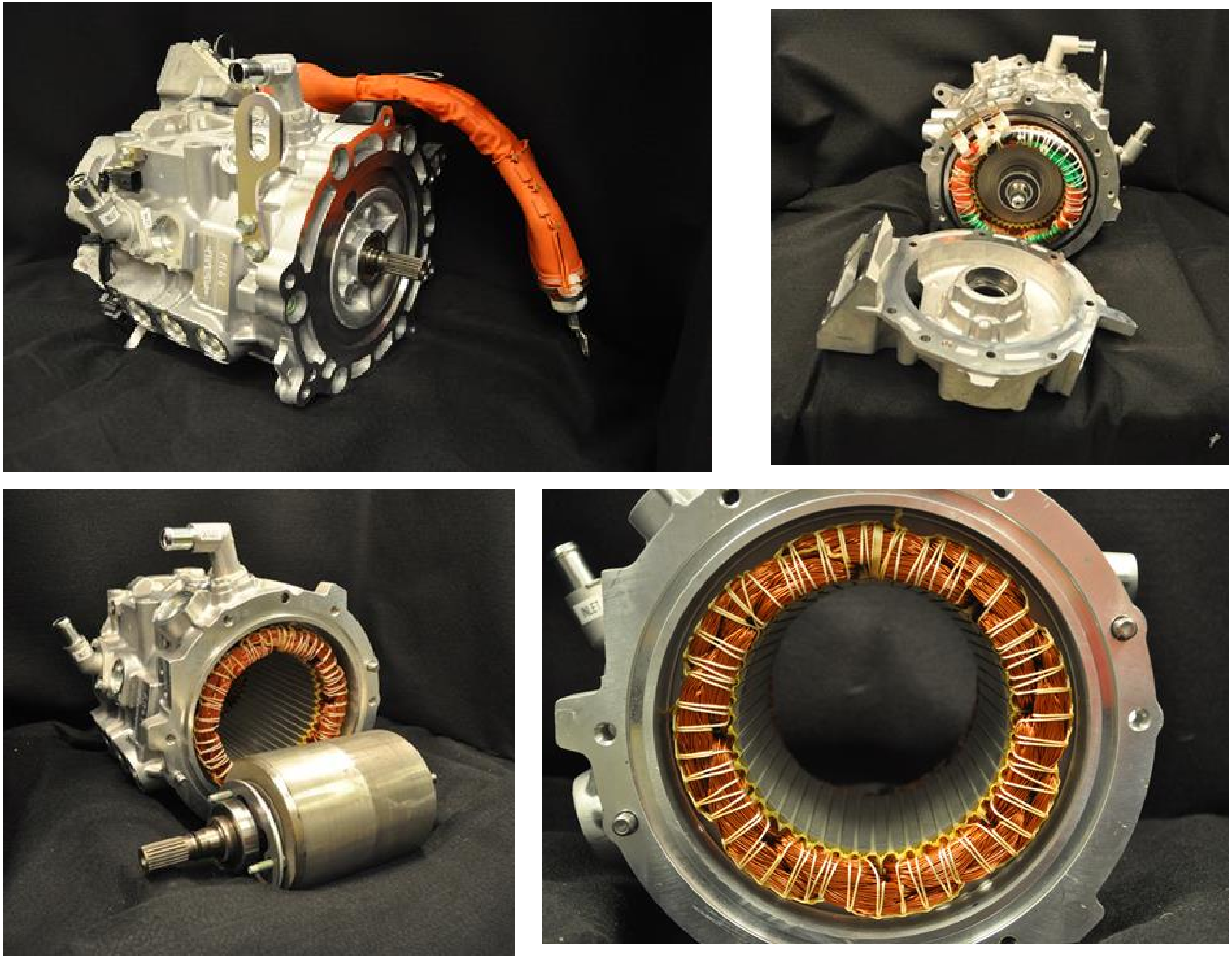


Illustration courtesy of U.S. Environmental Protection Agency

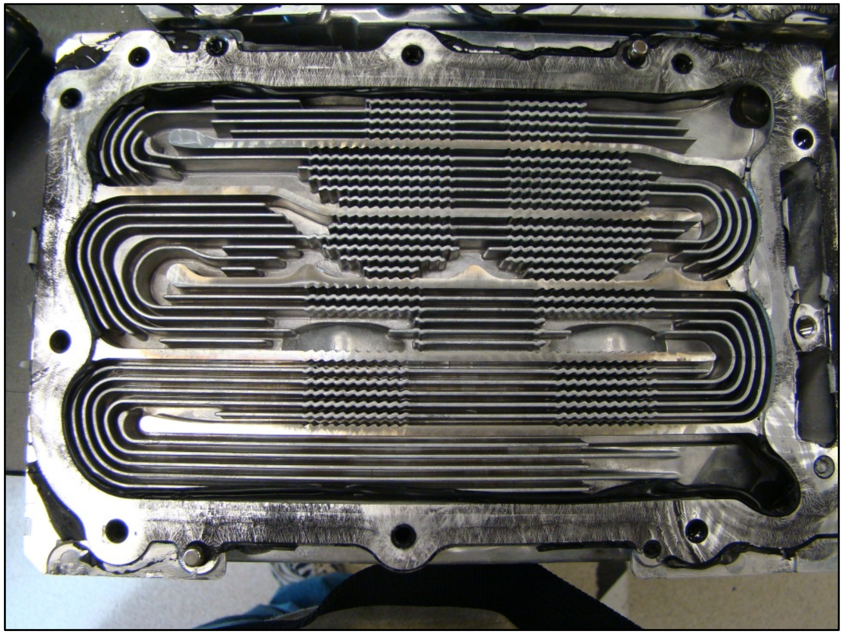
Nissan Leaf Motor: Cooling Challenges



Photos by NREL

Typical Channel Flow Cooling for an Inverter

2007 Toyota Camry



Photos by NREL

Jet Impingement in a Plastic Heat Exchanger

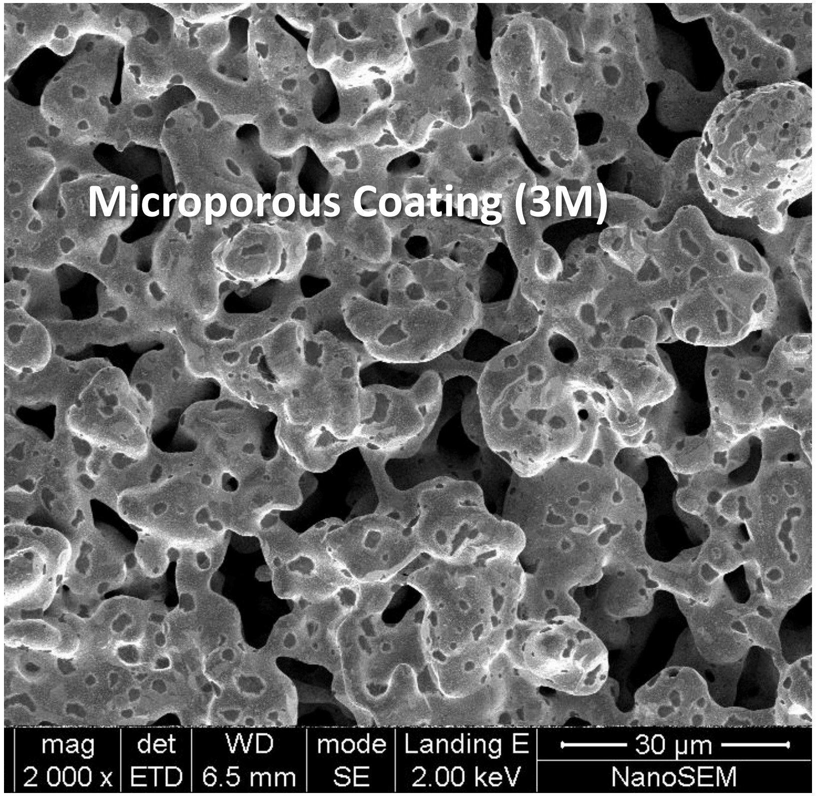
Prototype inverter-scale heat exchanger

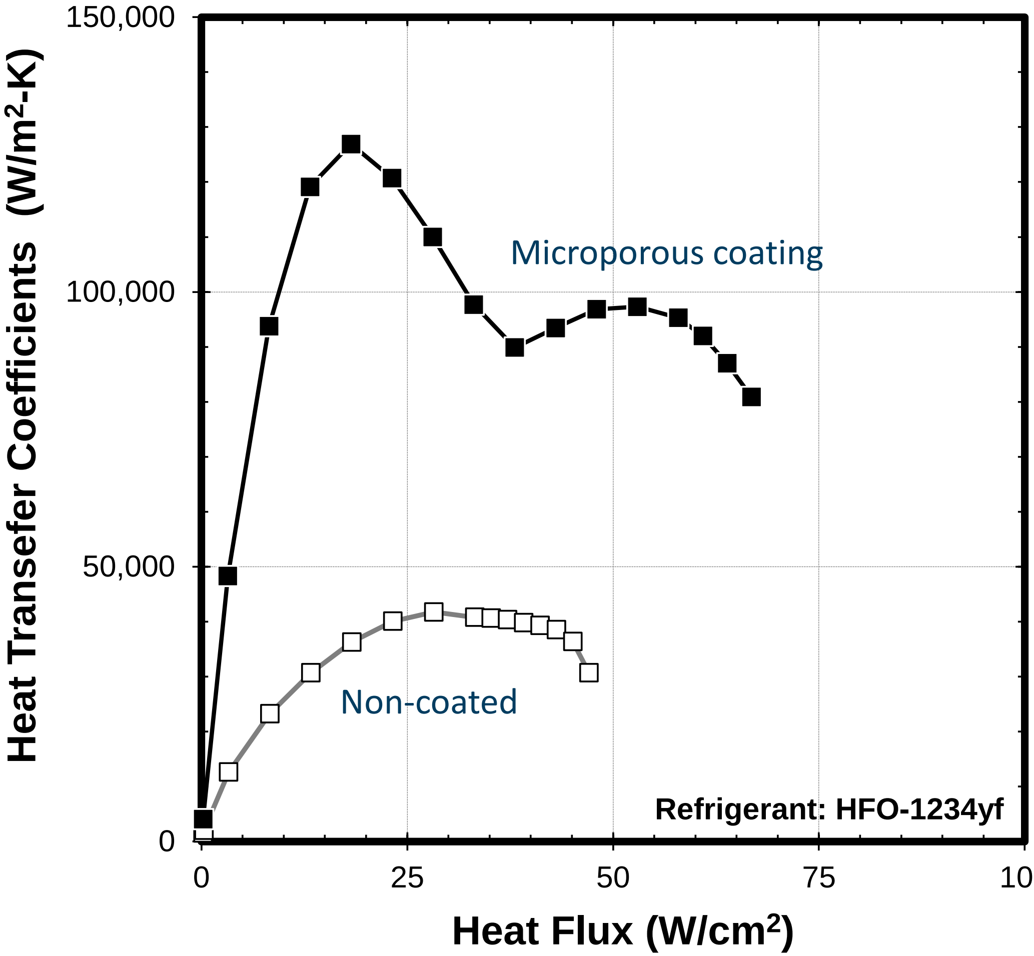
- Reduced thermal resistance ~20% for same pumping power
- Increased coefficient of performance
- 50% weight reduction of the heat exchanger.

Photos by NREL

Two-Phase Heat Transfer Surface Enhancement

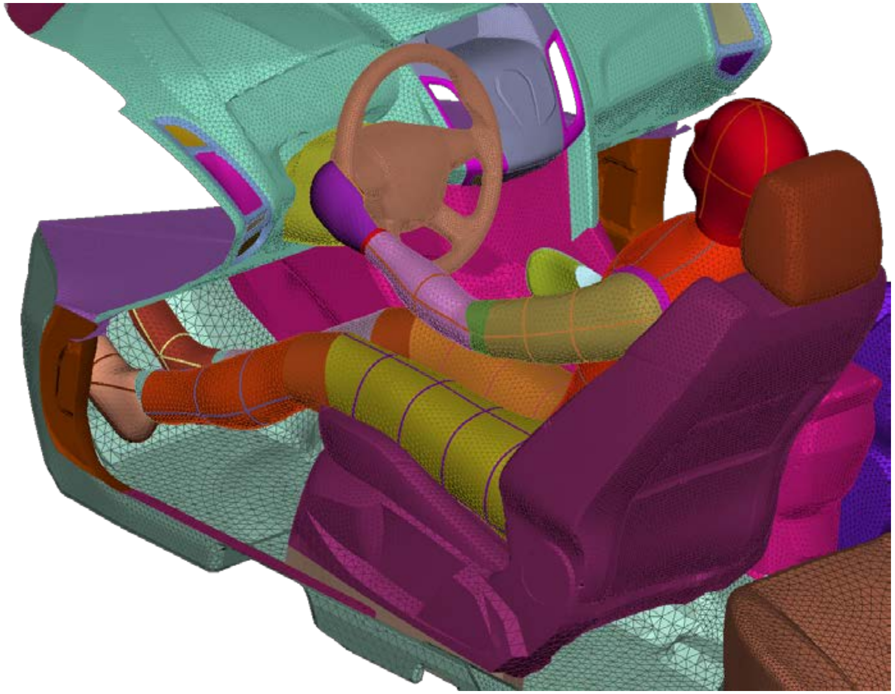
- Passive boiling increases heat transfer coefficient up to 350%
- Simple means to increase power density of electronic devices.





Pool boiling heat transfer coefficients for microporous coated and non-coated surfaces

Reducing Electric-Drive Vehicle Climate Control Loads

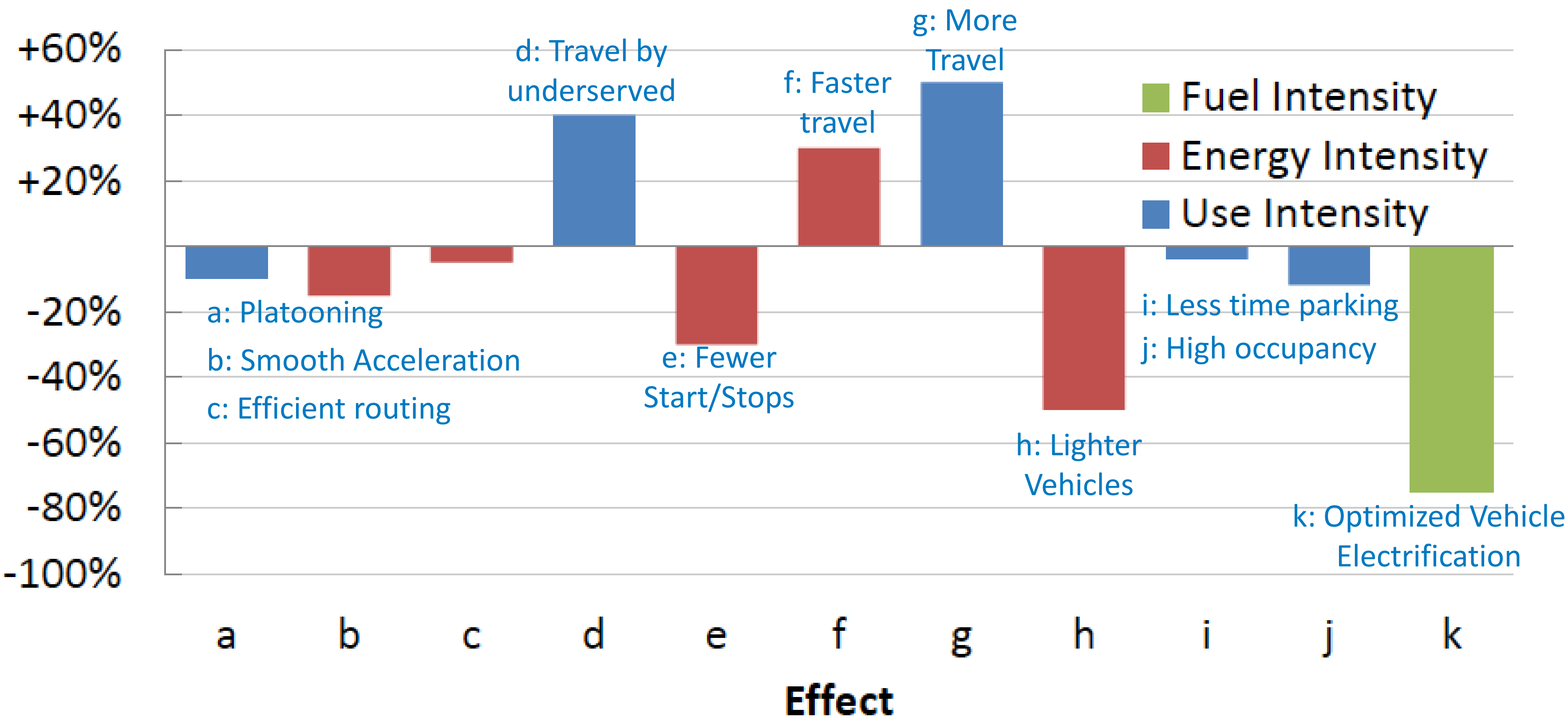


R&D Solutions Leading to 54.5 MPG

- **Degree of electrification (power electronics and energy storage)**
- **Start/stop**
- **Regenerative braking**
- **Low rolling resistance tires**
- **Electric powered steering**
- **Electric infrastructure**
- **Light weighting**
- **Batteries and cooling systems**
- **Turbo-charging, direct fuel injection, advanced combustion, 8-speed transmissions**
- **Variable cylinder management**
- **Improved aerodynamics**
- **Diesel, alternative fuels, hydrogen, etc.**

Transportation System Efficiency

Potential Energy Impact of Autonomous Vehicles



- **Better (cheaper/smaller) sensors**
- **Wireless power transfer.**

Other Options: Transit Modes, Etc.

Photo: Dennis Schroeder/NREL

Multi-mode
Mass transit
Bicycle
Walkable communities
Mode Shifting &
Telecommuting

Photos (top to bottom): Santa Barbara Metro Transit, Dennis Schroeder/NREL, AeroVironment

Photo: Steve Allen

Thank You

Questions ?

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Learn more at
www.nrel.gov/vehiclesandfuels
www.nrel.gov/hydrogen