Vehicle Technology: How Far and How Fast?

John German, Program Director, ICCT

An ACEEE 30th Anniversary Symposium: Transportation Efficiency in the 21st Century

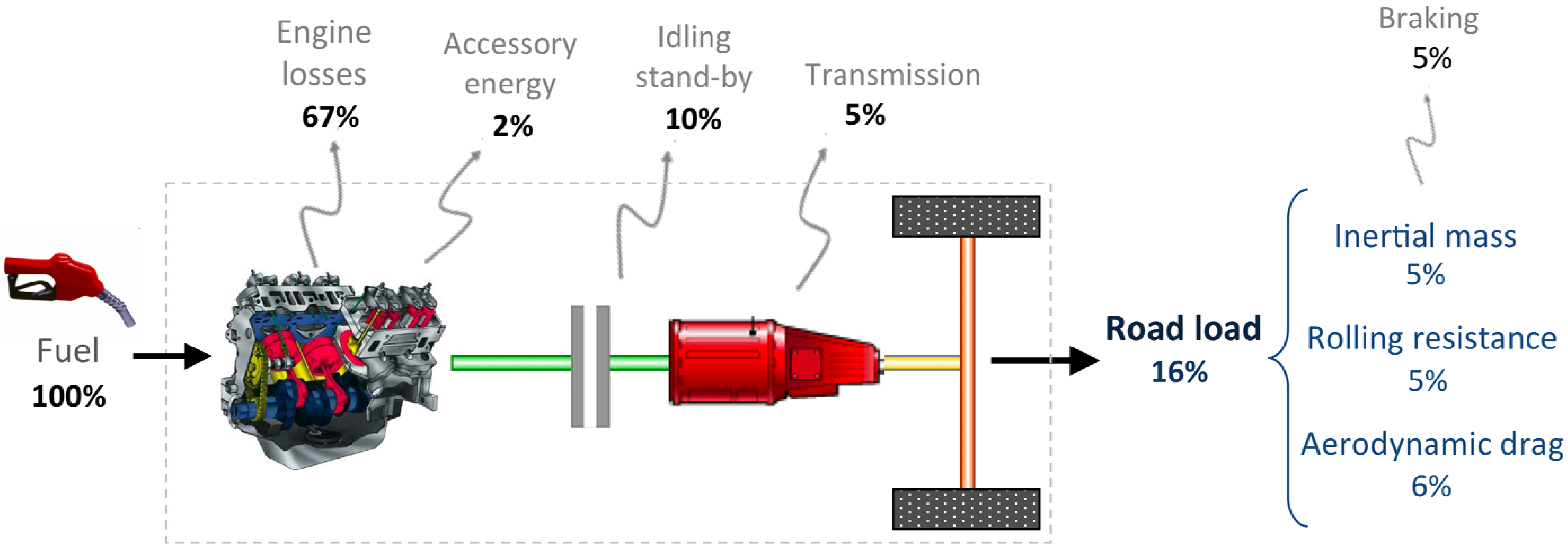
November 12, 2010

THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION

Conventional Technology Development

Where Does the Energy Go?

- **Modern vehicles are generally 15-20% efficient with potential for improvement**



Engine losses
67%

Accessory energy
2%

Idling stand-by
10%

Transmission
5%

Braking
5%

Fuel
100%

Road load
16%

Inertial mass
5%

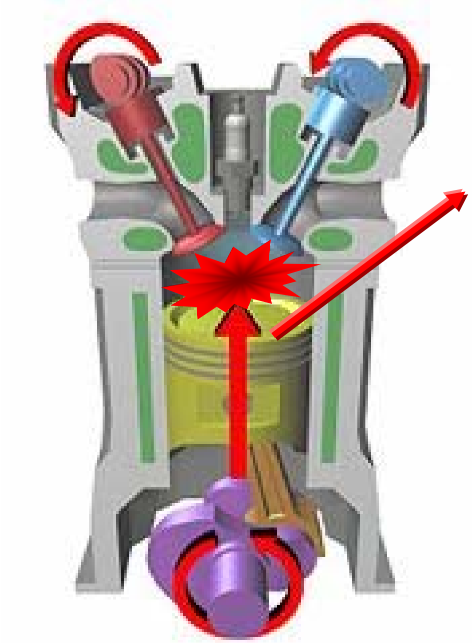
Rolling resistance
5%

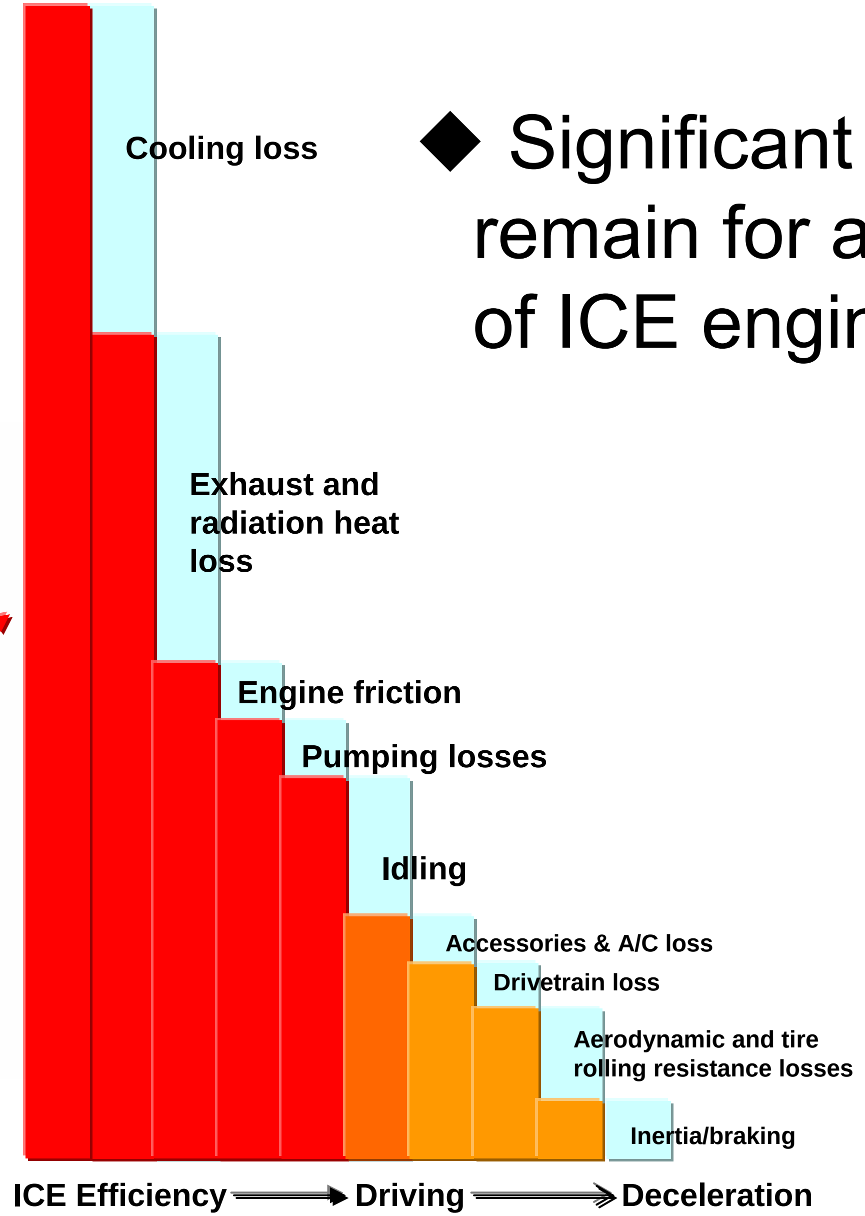
Aerodynamic drag
6%

Percents are approximate, based on energy losses for vehicles on the combined U.S. city and highway drive cycles.
Sources: Kromer and Heywood, 2007 and U.S. EPA, 2010 http://www.fueleconomy.gov/feg/atv.shtml

IC Engine Efficiency

◆ Significant opportunities remain for advancement of ICE engine efficiency

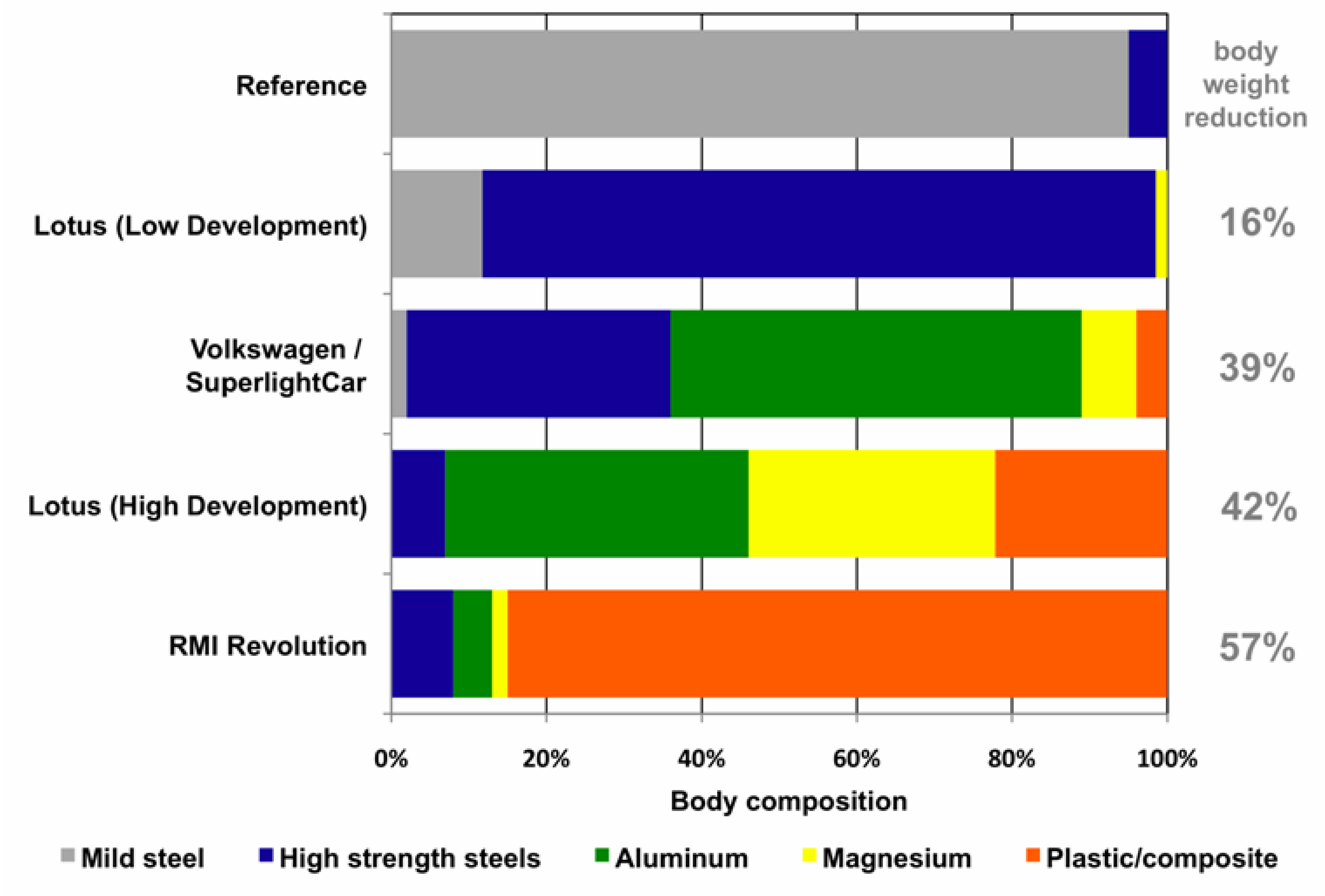




Note – Losses vary widely depending on vehicle, technology, and operating conditions

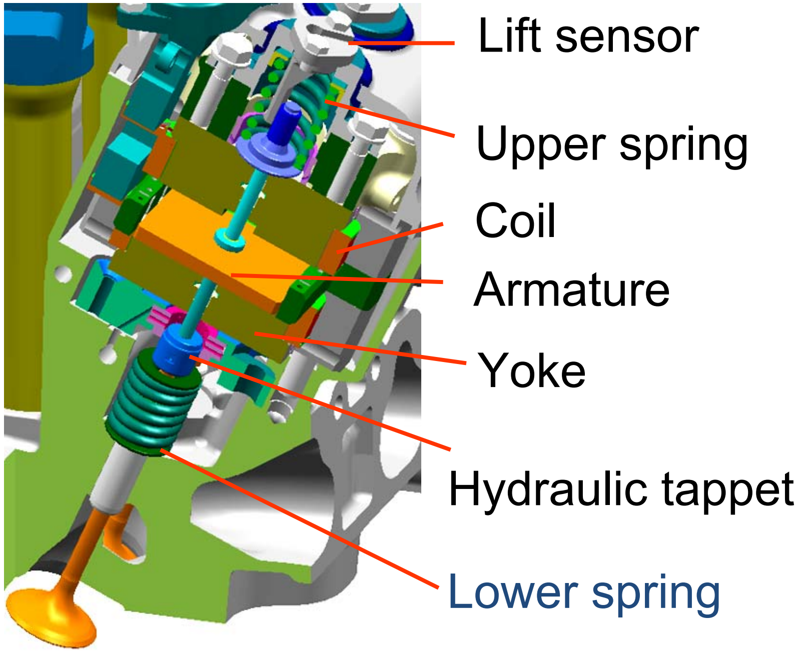
Lightweight materials offer great potential

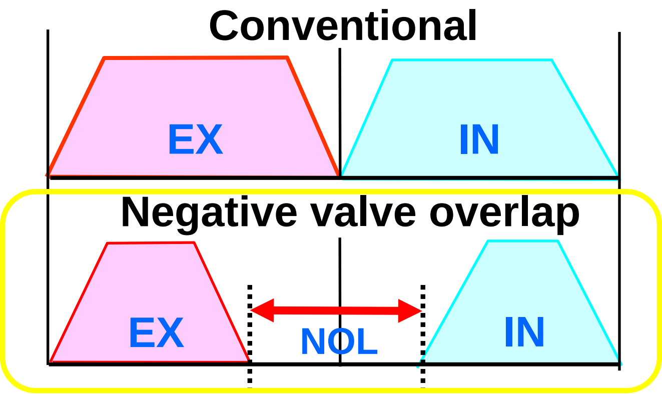
Material composition of lightweight vehicle body designs:



Next-generation Gasoline Engines

Camless Valve Actuation

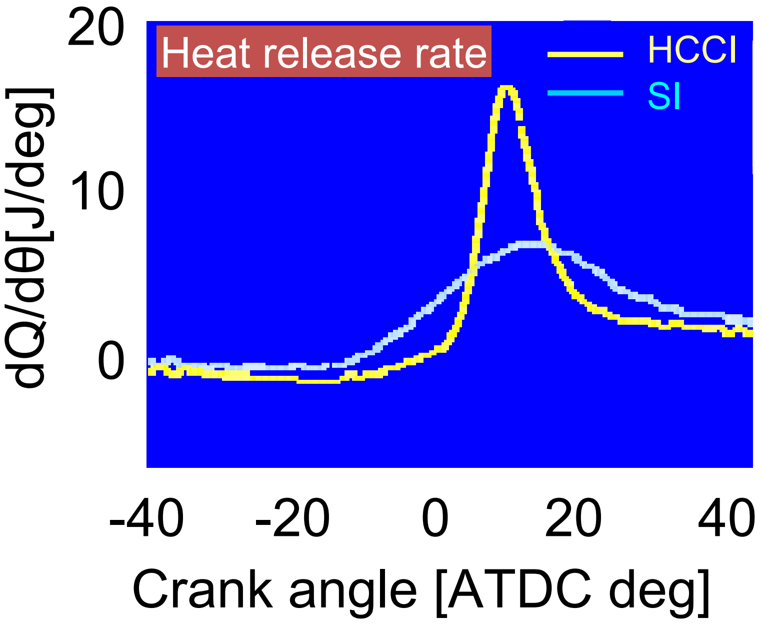




HCCI Engine

Improement in fuel economy: 30%

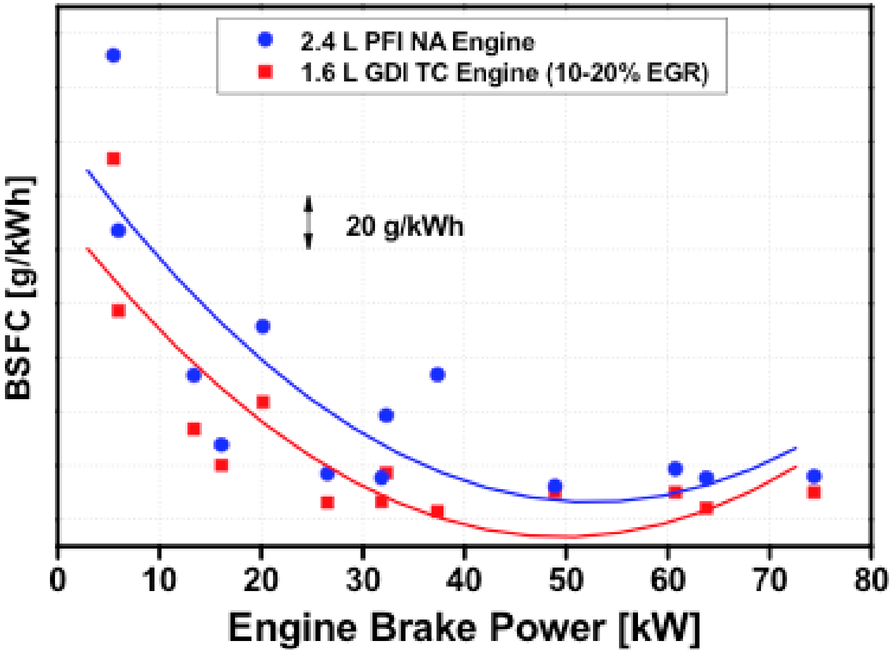
Honda Prototype Engine Base (Electro-magnetic valve)

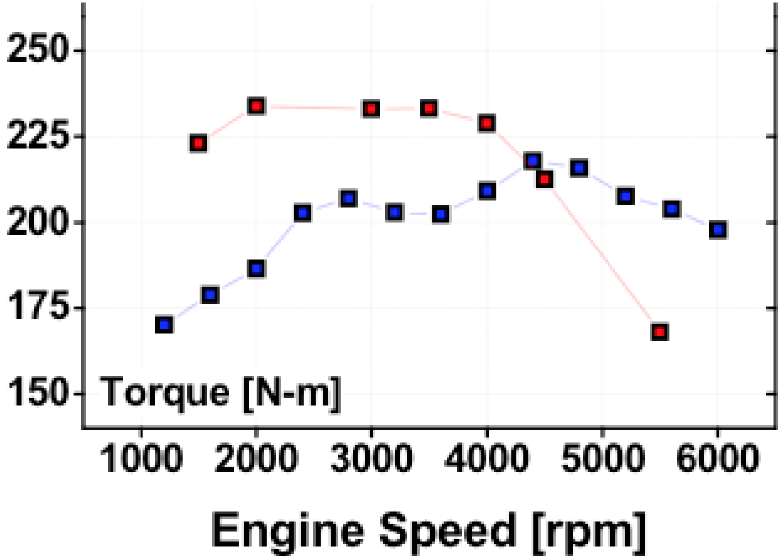


Requires increasing the self-ignition region

Boosted EGR Engines

- Turbo-boosted EGR for highly dilute operation
- Dilute combustion offers considerable efficiency improvement
- Advanced ignition systems are a key to highly dilute operation





High Efficiency Dilute Gasoline Engines (HEDGE)
Southwest Research Institute

i-DTEC - Super Clean Diesel for US

Improved Combustion

- New Combustion Chamber Design
- High Pressure Piezo Common Rail
- Lower Compression Ratio
- Combustion Pressure Sensor

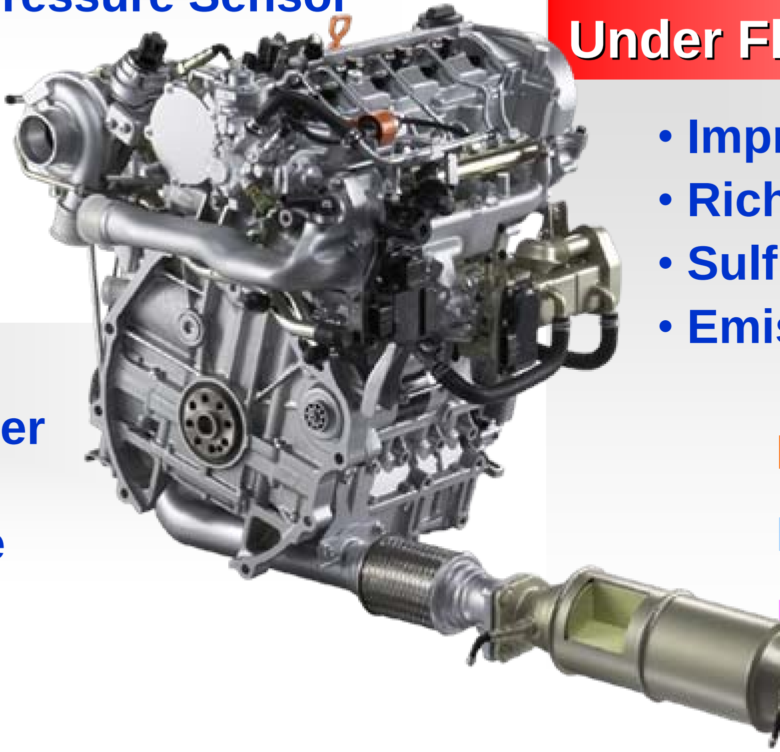
New Software

em

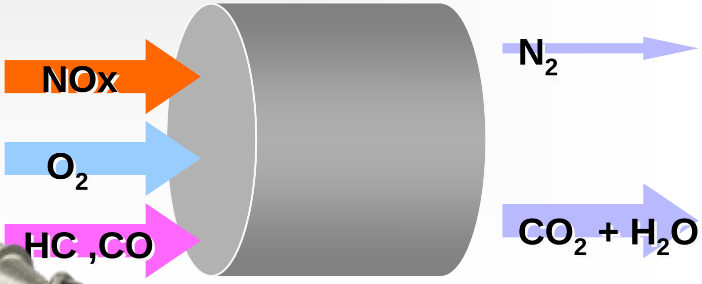
- LNC Control
- Combustion Control
- Cetane Estimation

Under Floor Lean NOx CAT System

- Improved Lean NOx Catalyser
- Rich Air/Fuel Ratio Spike Control
- Sulfur Regeneration
- Emission Stabilizing System



Closed-coupled Catalytic Converter + Diesel Particulate Filter (DPF)

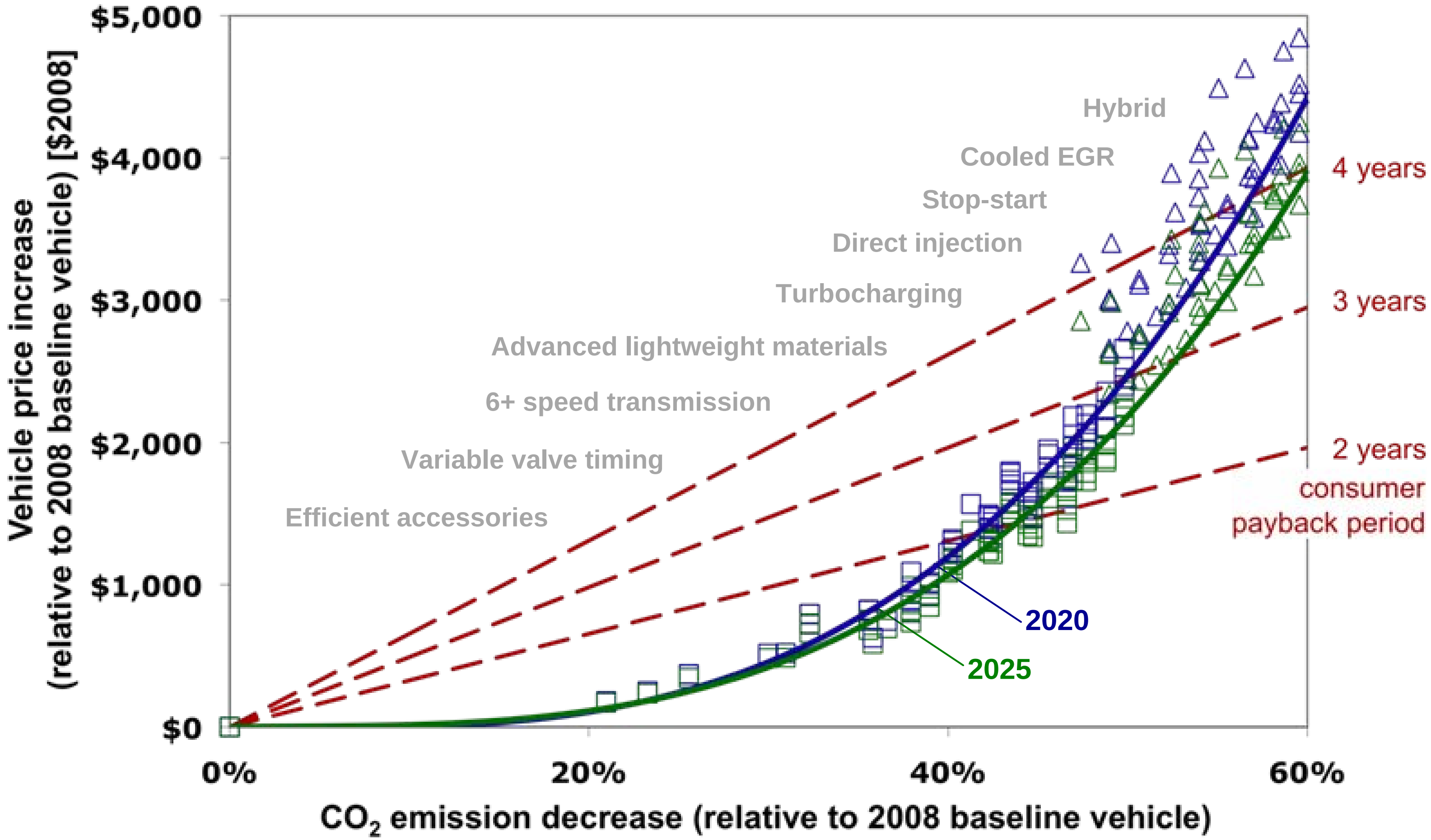


Source: American Honda Motor Co.

Technology cost / benefit estimates

Major incremental efficiency improvement comes at modest cost

US Environmental Protection Agency (EPA) 2017-2025 rulemaking estimates:



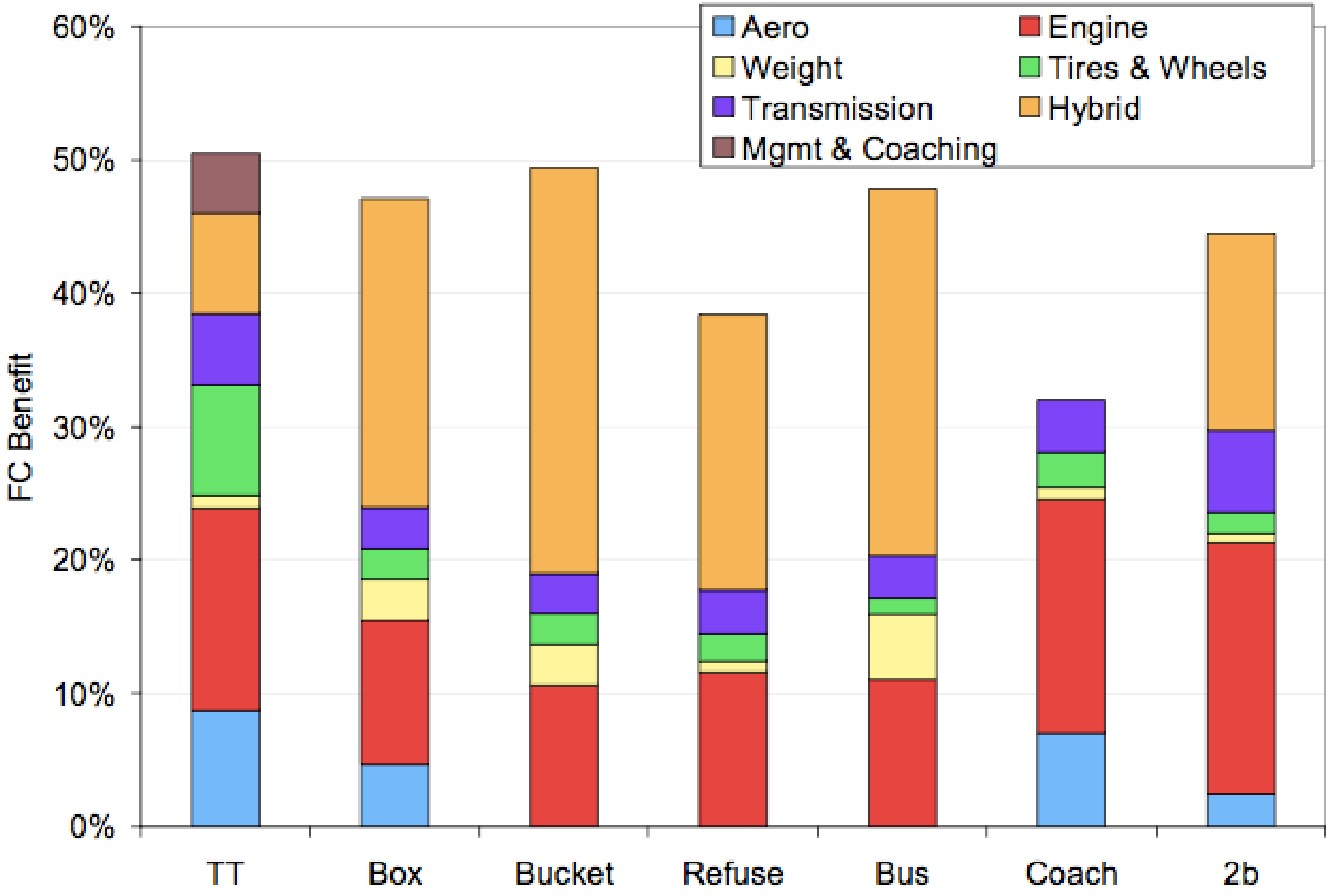
Data source: EPA, NHTSA, CARB Interim Joint Technical Assessment Report: Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards for Model Years 2017-2025

Consumer payback calculation assumptions: Baseline fuel consumption 6 l/100 km, fuel price 1.30 €/l, annual mileage 15,000 km

Significant potential for heavy-duty

National Academy of Sciences study shows close to 50% reduction

Potential fuel savings for new vehicles in 2015-2020:



Source: National Academy of Sciences (NAS), 2010, values compared to MY 2008-2009
TT: tractor-trailer (Class 8); Box: straight box truck (Class 3-6); Bucket: straight truck with utility bucket (Class 3-6); Refuse: refuse hauling truck (Class 8); Bus: transit bus (Class 7-8); Coach: motor coach (Class 7-8); Class 2b: pick-up trucks and vans

Consumers Behavior and Real Fuel Costs

Turrentine & Kurani, 2004

In-depth interviews of 60 California households' vehicle acquisition histories found ***no evidence*** **of economically rational decision-making about fuel economy.**

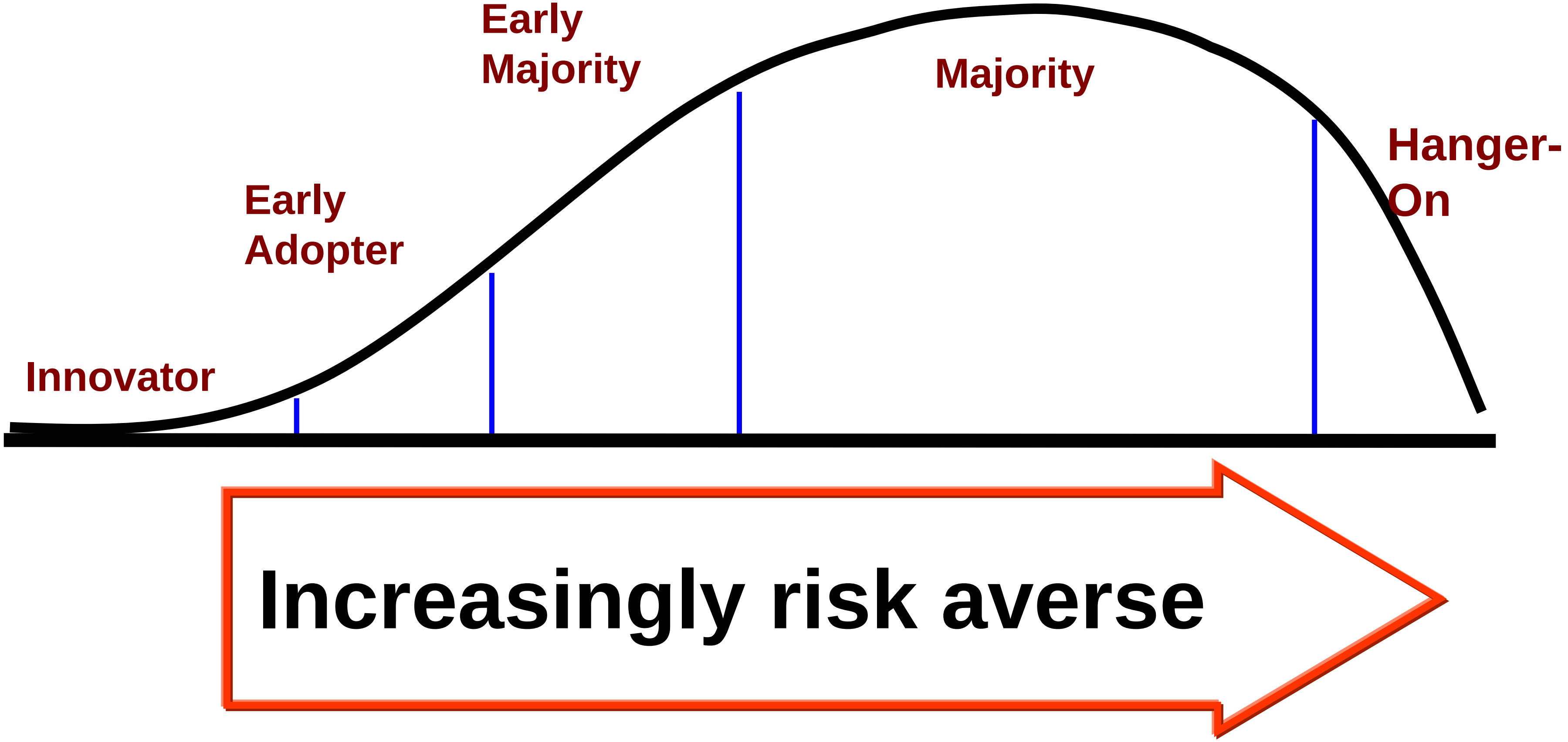
- Out of 60 households (125 vehicle transactions) 9 stated that they compared the fuel economy of vehicles in making their choice.
- 4 households knew their annual fuel costs.
- None had made any kind of quantitative assessment of the value of fuel savings.

Consumers are, as a general rule, LOSS AVERSE

- Uncertainty about future fuel savings makes paying for more technology **a risky bet**
  - What MPG will I get (your mileage may vary)?
  - How long will my car last?
  - How much driving will I do?
  - **What will gasoline cost?**
  - What will I give up or pay to get better MPG?

Causes the market to produce less fuel economy than is economically efficient

New Customer Profile



Innovator

Early Adopter

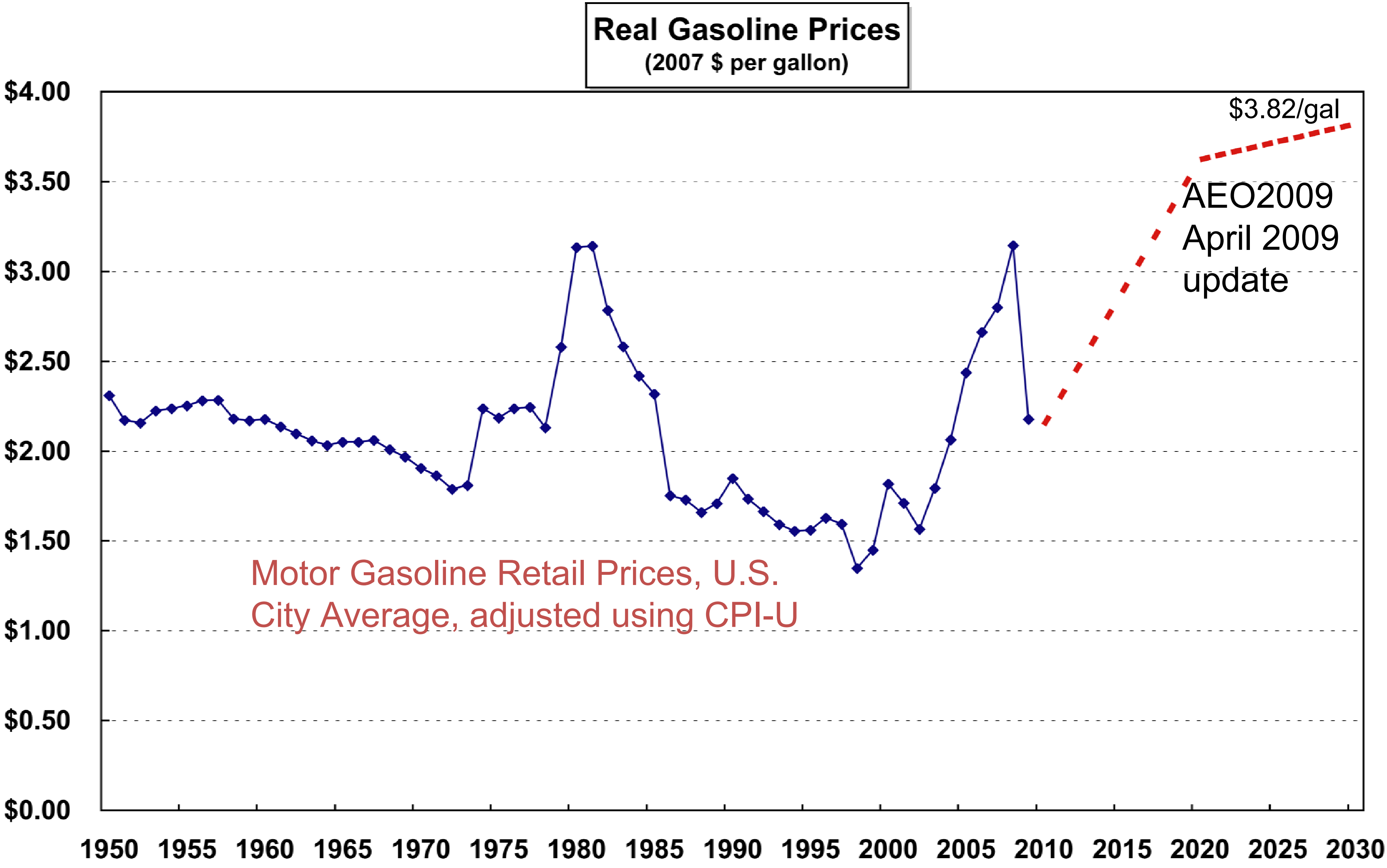
Early Majority

Majority

Hanger-On

Increasingly risk averse

Real Gasoline Price



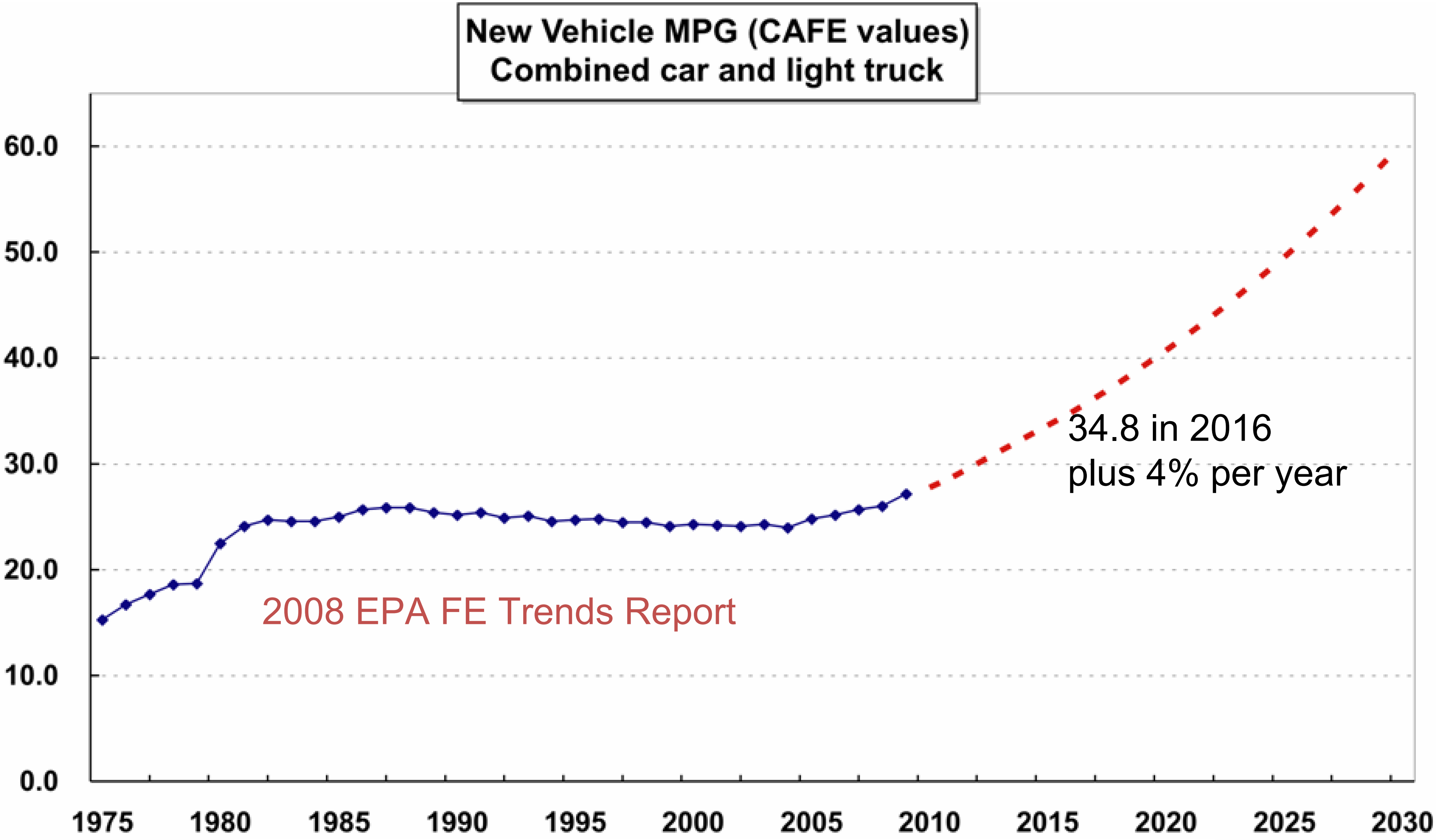
Real Gasoline Prices
(2007 $ per gallon)

$3.82/gal

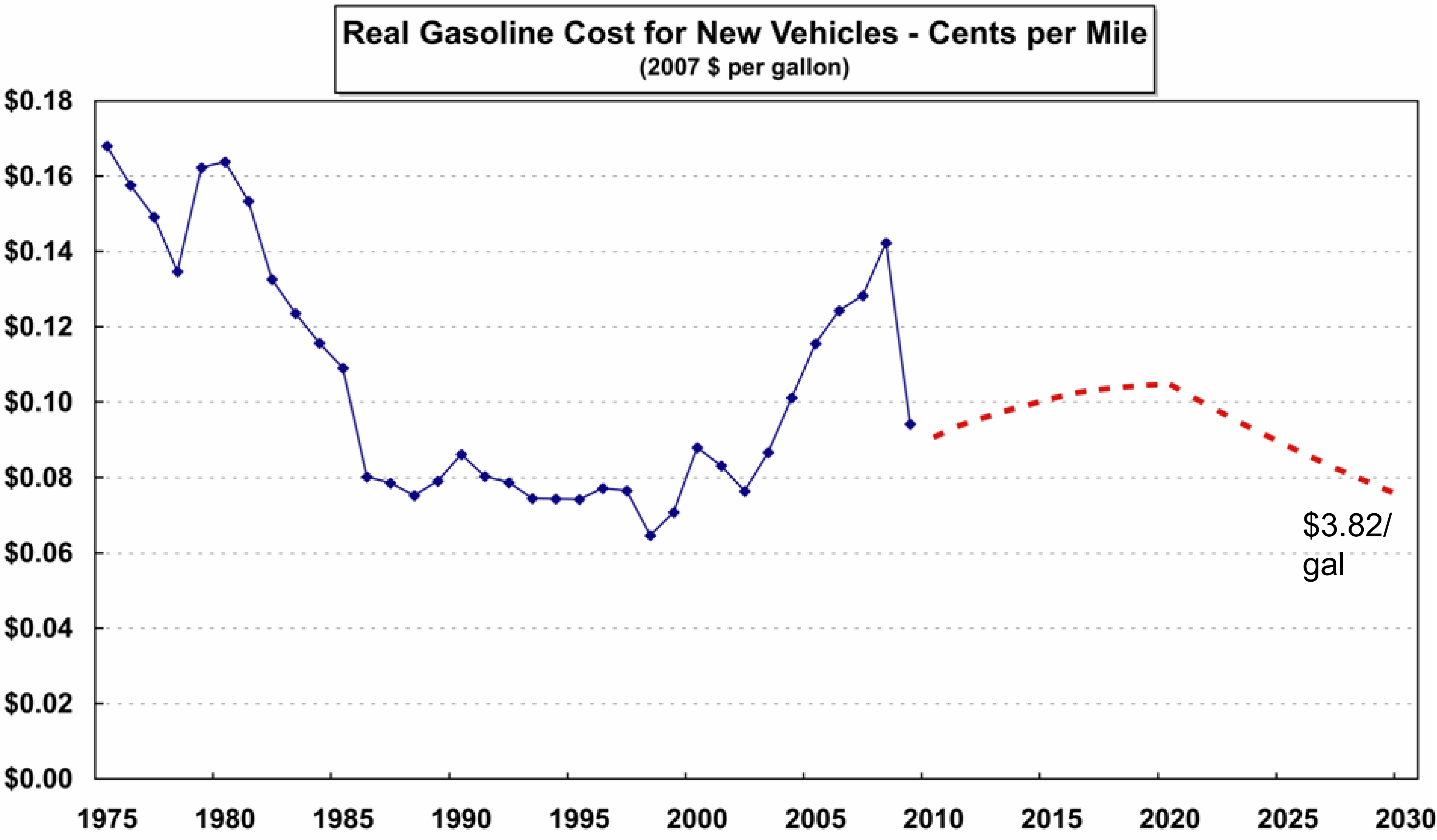
AEO2009
April 2009
update

Motor Gasoline Retail Prices, U.S.
City Average, adjusted using CPI-U

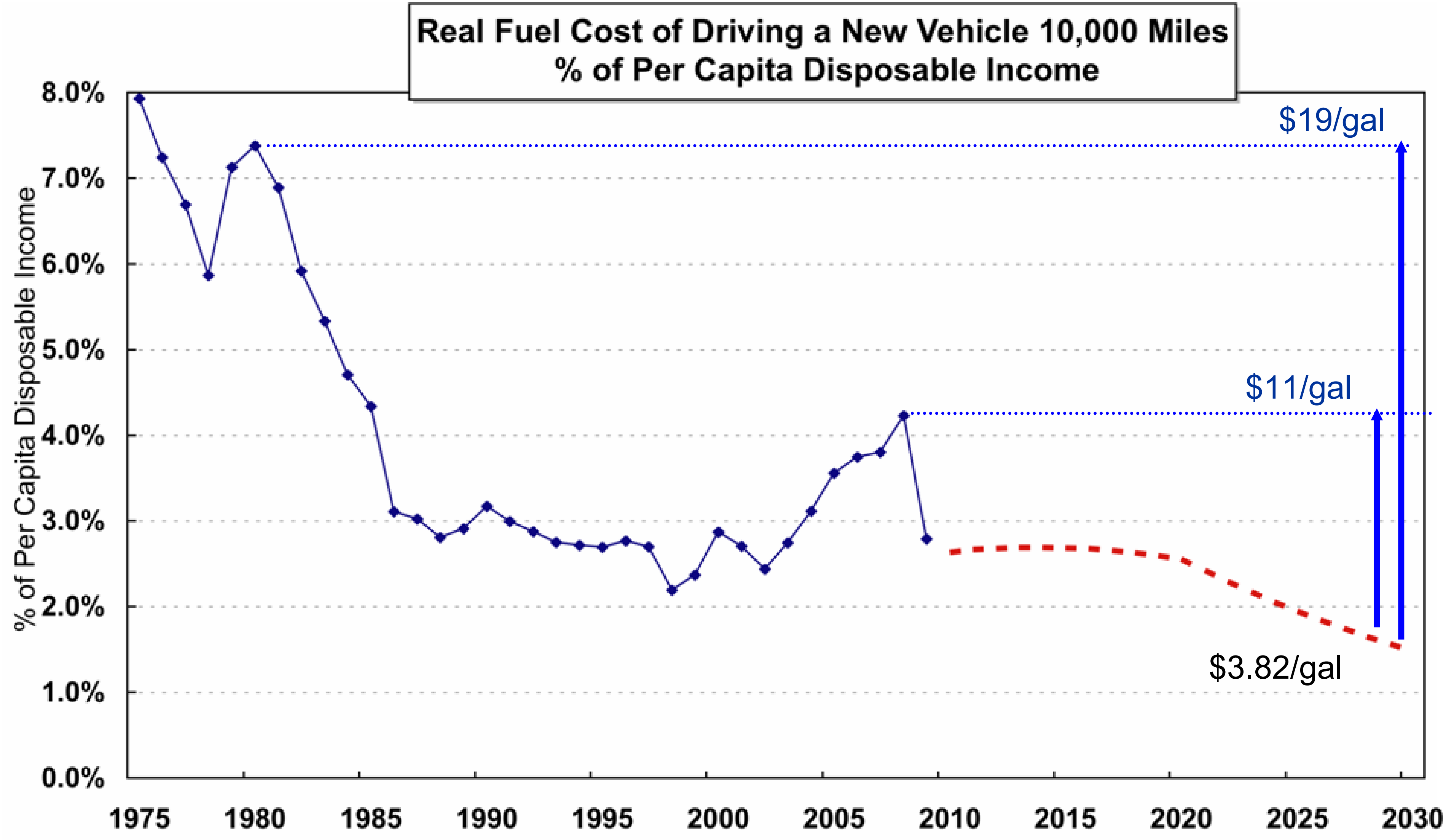
New Vehicle Fuel Economy



New Vehicle Gasoline Cost per Mile



Real Fuel Cost - % of Disposable Income



Forecasted Per Capita Disposable Income from AEO2009 April 2009 update

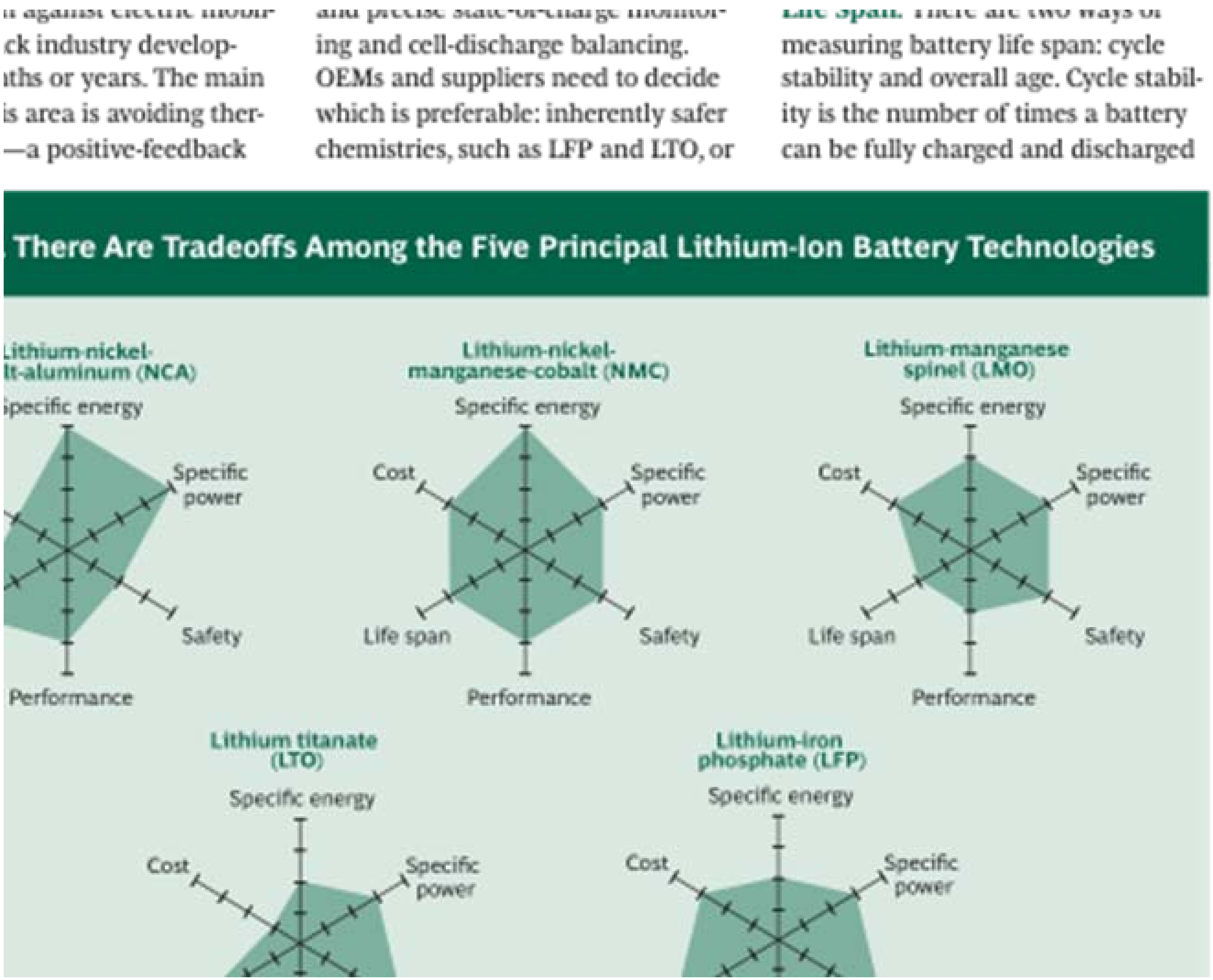
Batteries, Hybrids, and Electric Vehicles

Challenges: Liquid Fuel Advantage

ENERGY FUTURE: Think Efficiency
American Physical Society, Sept. 2008, Chapter 2, Table 1

	Energy density per volume		Energy density per weight	
	kWh/liter	vs gasoline	KWh/kg	vs gasoline
Gasoline	9.7		13.2	
Diesel fuel	10.7	110%	12.7	96%
Ethanol	6.4	66%	7.9	60%
Hydrogen at 10,000 psi	1.3	13%	39	295%
Liquid hydrogen	2.6	27%	39	295%
NiMH battery	0.1-0.3	2.1%	0.1	0.8%
Lithium-ion battery (present time)	0.2	2.1%	0.14	1.1%
Lithium-ion battery (future)			0.28 ?	2.1%

Li-ion Chemistry Tradeoffs



n against electric mobil-
ck industry develop-
nths or years. The main
is area is avoiding ther-
—a positive-feedback

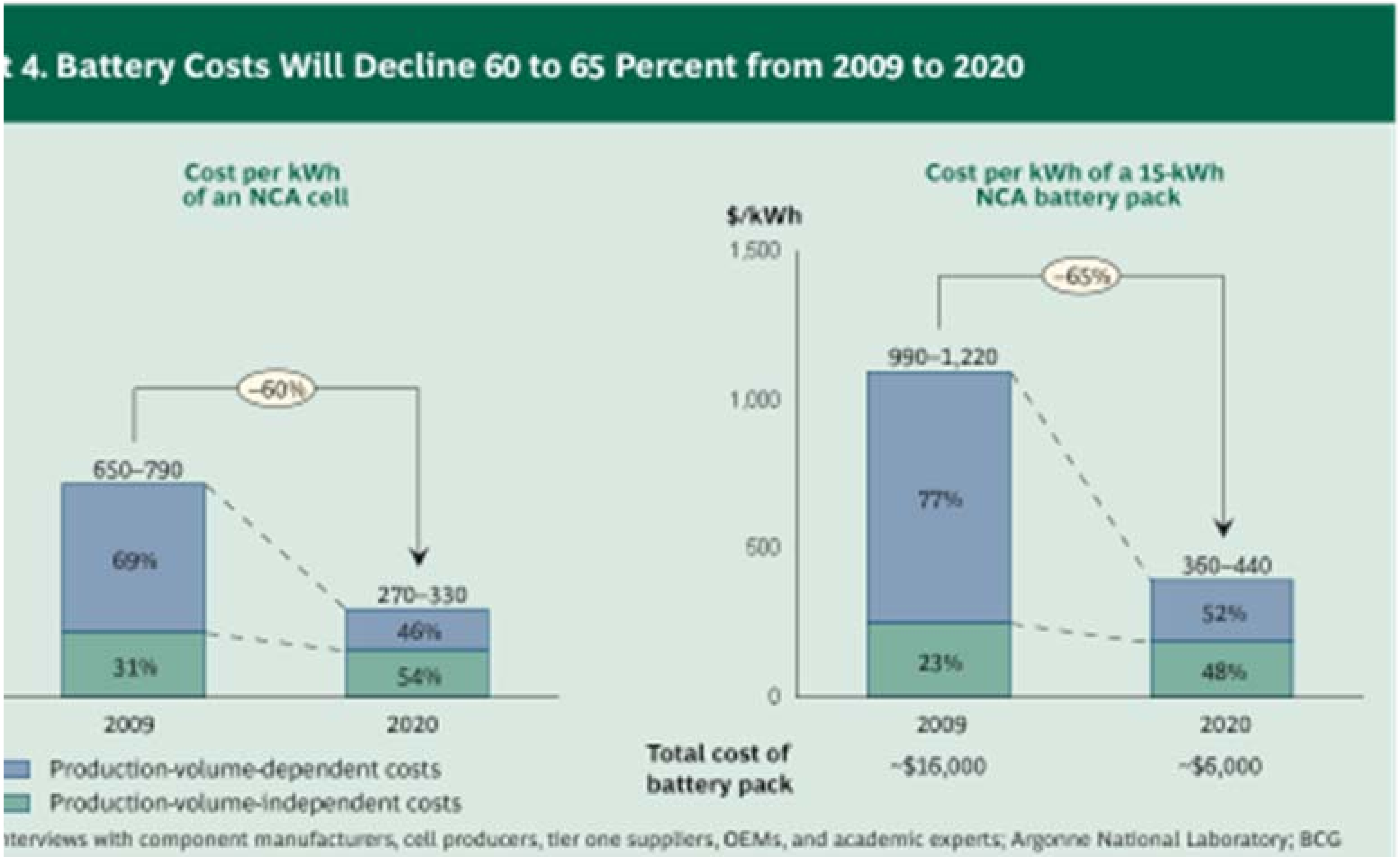
and precise state-of-charge monitoring and cell-discharge balancing. OEMs and suppliers need to decide which is preferable: inherently safer chemistries, such as LFP and LTO, or

Life span. There are two ways of measuring battery life span: cycle stability and overall age. Cycle stability is the number of times a battery can be fully charged and discharged

There Are Tradeoffs Among the Five Principal Lithium-Ion Battery Technologies

The Boston Consulting Group – Batteries for Electric Cars: Challenges, Opportunities, and the Outlook to 2020

Future Li-ion Cost

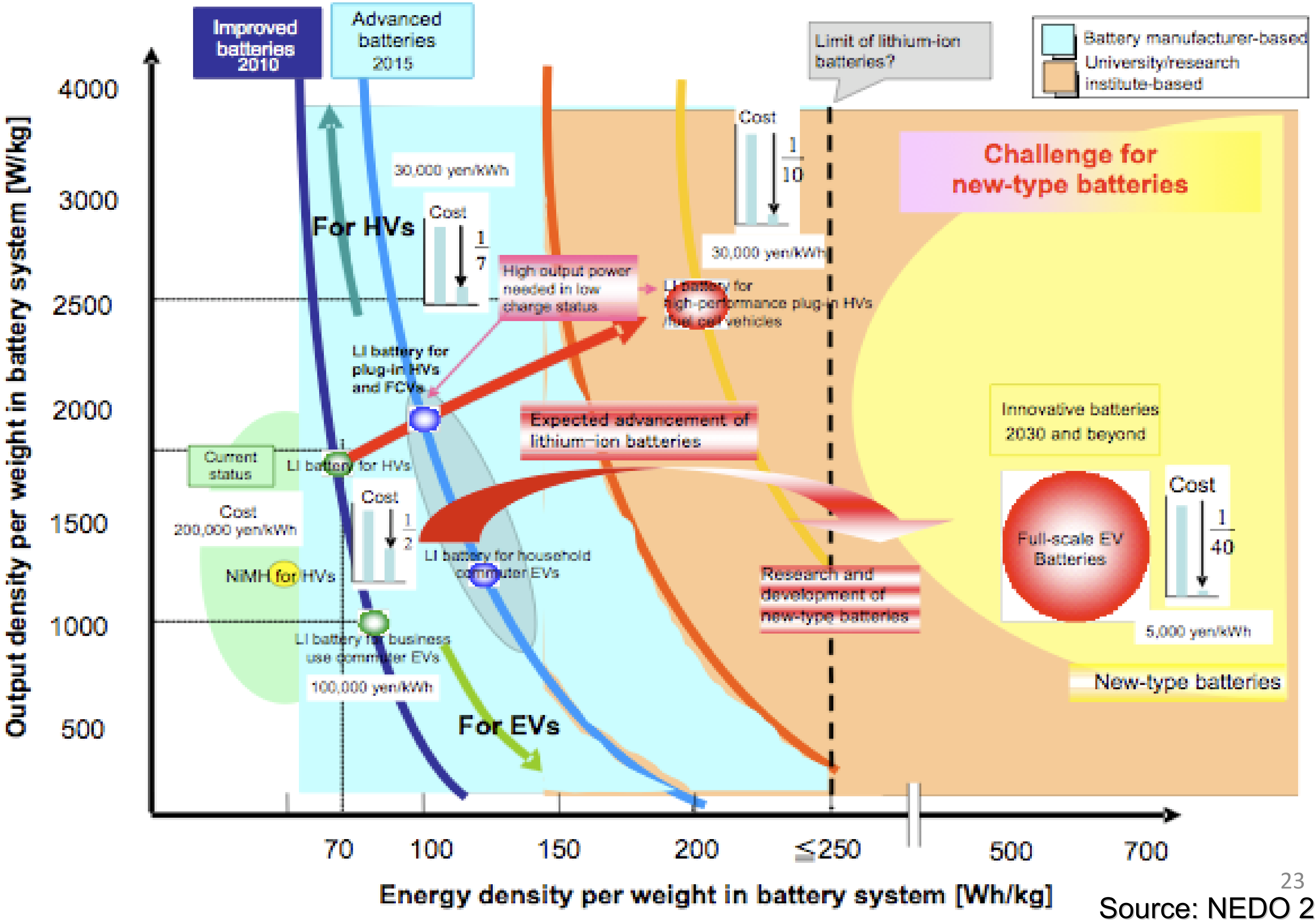


4. Battery Costs Will Decline 60 to 65 Percent from 2009 to 2020

nterviews with component manufacturers, cell producers, tier one suppliers, OEMs, and academic experts; Argonne National Laboratory; BCG

The Boston Consulting Group – Batteries for Electric Cars: Challenges, Opportunities, and the Outlook to 2020

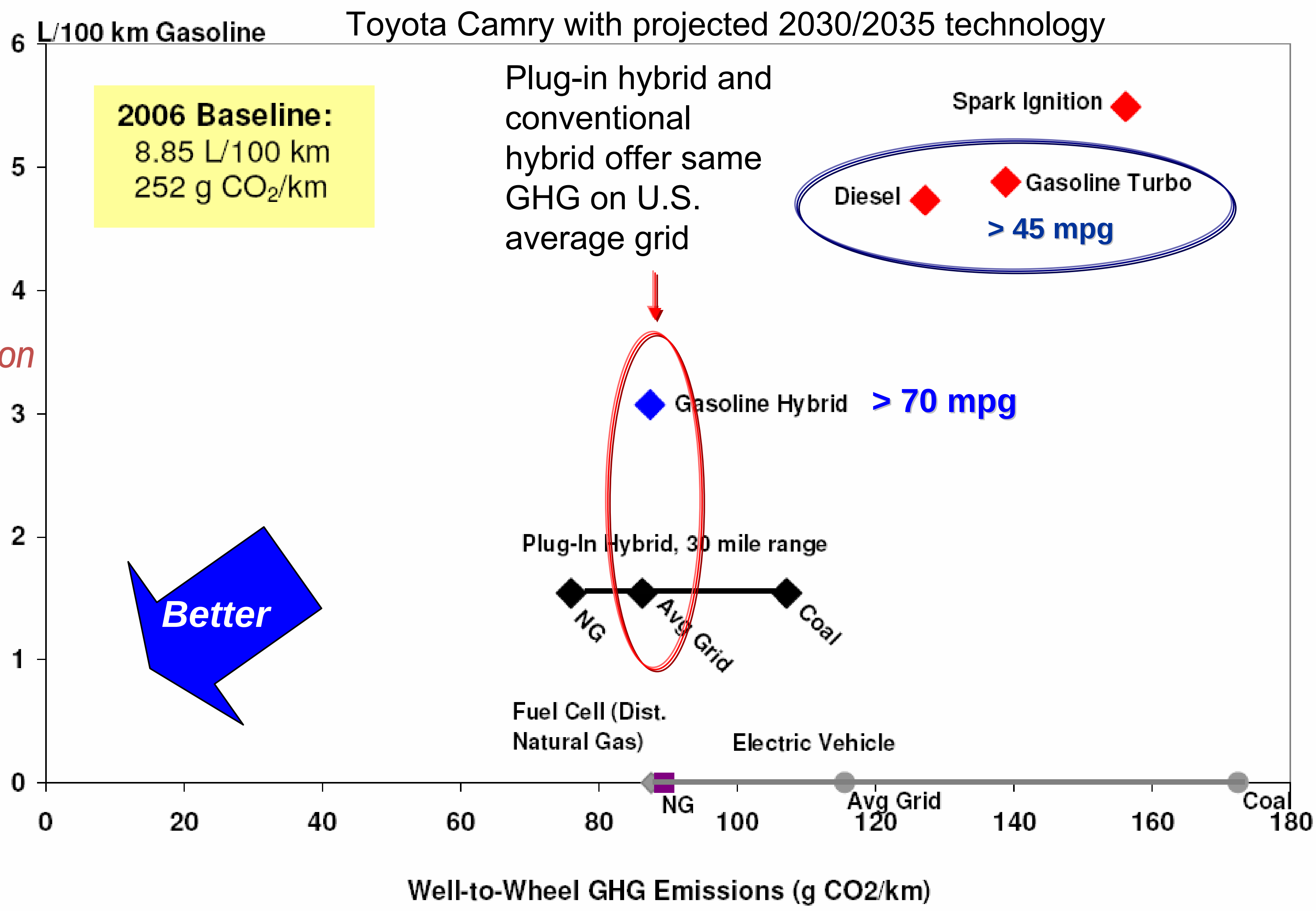
Future Battery Development



Source: NEDO 2006

2030/2035 Technology Comparison

Petroleum Consumption



Toyota Camry with projected 2030/2035 technology

2006 Baseline:
8.85 L/100 km
252 g CO_2/km

Plug-in hybrid and conventional hybrid offer same GHG on U.S. average grid

> 45 mpg

> 70 mpg

GHG

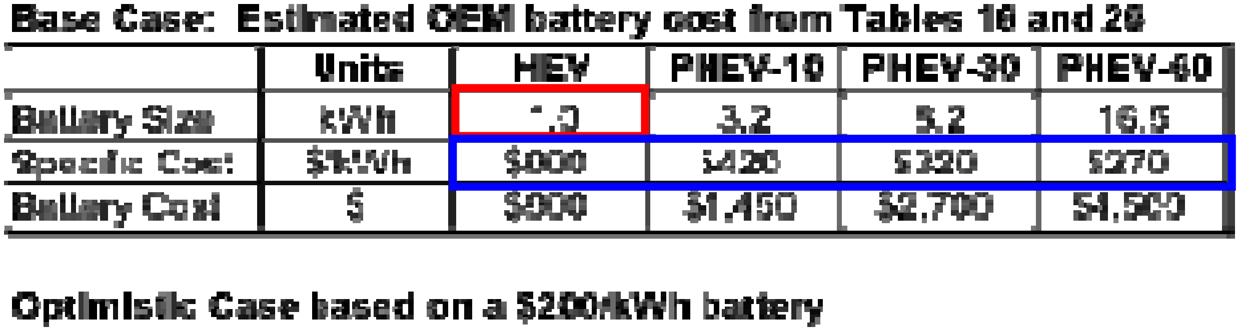
Source: 2007 MIT Study

Future Hybrid Potential

- Hybrid costs are coming down
  - **2-clutch parallel hybrids** – New designs from Nissan, Hyundai, VW, BMW, and Mercedes deliver 90-95% of the benefit at much lower cost
  - **Learning** - Each generation of motor, controller, and battery pack is better integrated and more efficient
  - **Economics of scale** improve as sales increase and more suppliers enter the market
  - **High power Li-ion batteries** coming soon are perfect for parallel hybrids and will reduce size and cost
- Synergies are being developed to increase hybrid efficiency and add consumer features

Cost-Effectiveness Comparison

All compared to 2030 NA-SI baseline



Base Case: Estimated OEM battery cost from Tables 16 and 26

	Units	HEV	PHEV-10	PHEV-30	PHEV-60
Battery Size	kWh	1.0	3.2	5.2	16.5
Specific Cost	$/kWh	$900	$420	$320	$270
Battery Cost	$	$900	$1,450	$2,700	$4,500

Optimistic Case based on a $200/kWh battery

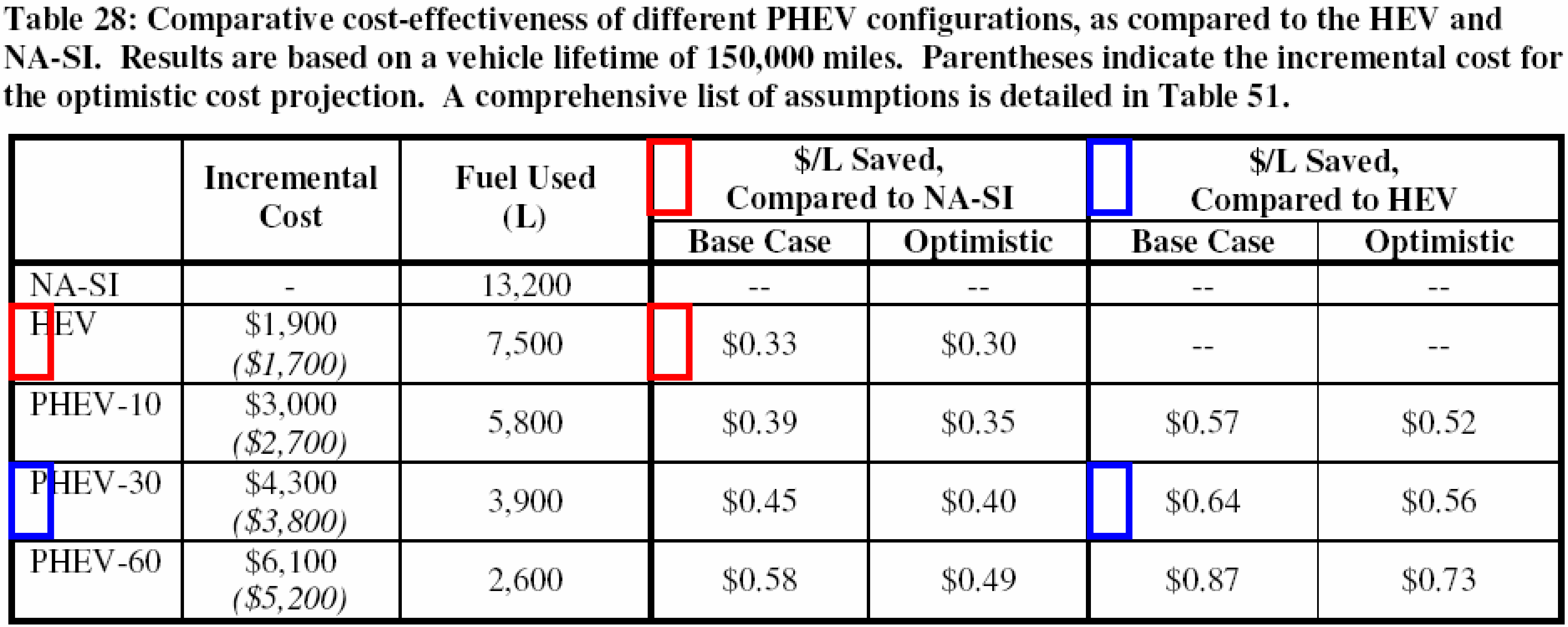


Table 28: Comparative cost-effectiveness of different PHEV configurations, as compared to the HEV and NA-SI. Results are based on a vehicle lifetime of 150,000 miles. Parentheses indicate the incremental cost for the optimistic cost projection. A comprehensive list of assumptions is detailed in Table 51.

	Incremental Cost	Fuel Used (L)	$/L Saved, Compared to NA-SI		$/L Saved, Compared to HEV	
			Base Case	Optimistic	Base Case	Optimistic
NA-SI	-	13,200	--	--	--	--
HEV	$1,900 *($1,700)*	7,500	$0.33	$0.30	--	--
PHEV-10	$3,000 *($2,700)*	5,800	$0.39	$0.35	$0.57	$0.52
PHEV-30	$4,300 *($3,800)*	3,900	$0.45	$0.40	$0.64	$0.56
PHEV-60	$6,100 *($5,200)*	2,600	$0.58	$0.49	$0.87	$0.73

Source: 2007 MIT Study

Uncertainties Larger Barrier for PHEVs

- How much am I going to save on fuel?
- How much will I pay for electricity?
- How often do I need to plug in?
- How much hassle will it be to plug in?
- Can I be electrocuted in the rain or if I work on my vehicle?
- What will it cost to install recharging equipment?
- How long will the battery last?
  - And how much will it cost to replace it?
- How reliable will the vehicle be?
- What will the resale value be?
  - Especially since the next owner also has to install recharging equipment
- What kind of PHEV is best for me?
  - Would a blended strategy be better than electric-only operation?
  - What amount of AER would be best for my driving?
  - What if I move or change jobs?

It's bad enough to spend $300 on a Betamax - but $30,000+ ?

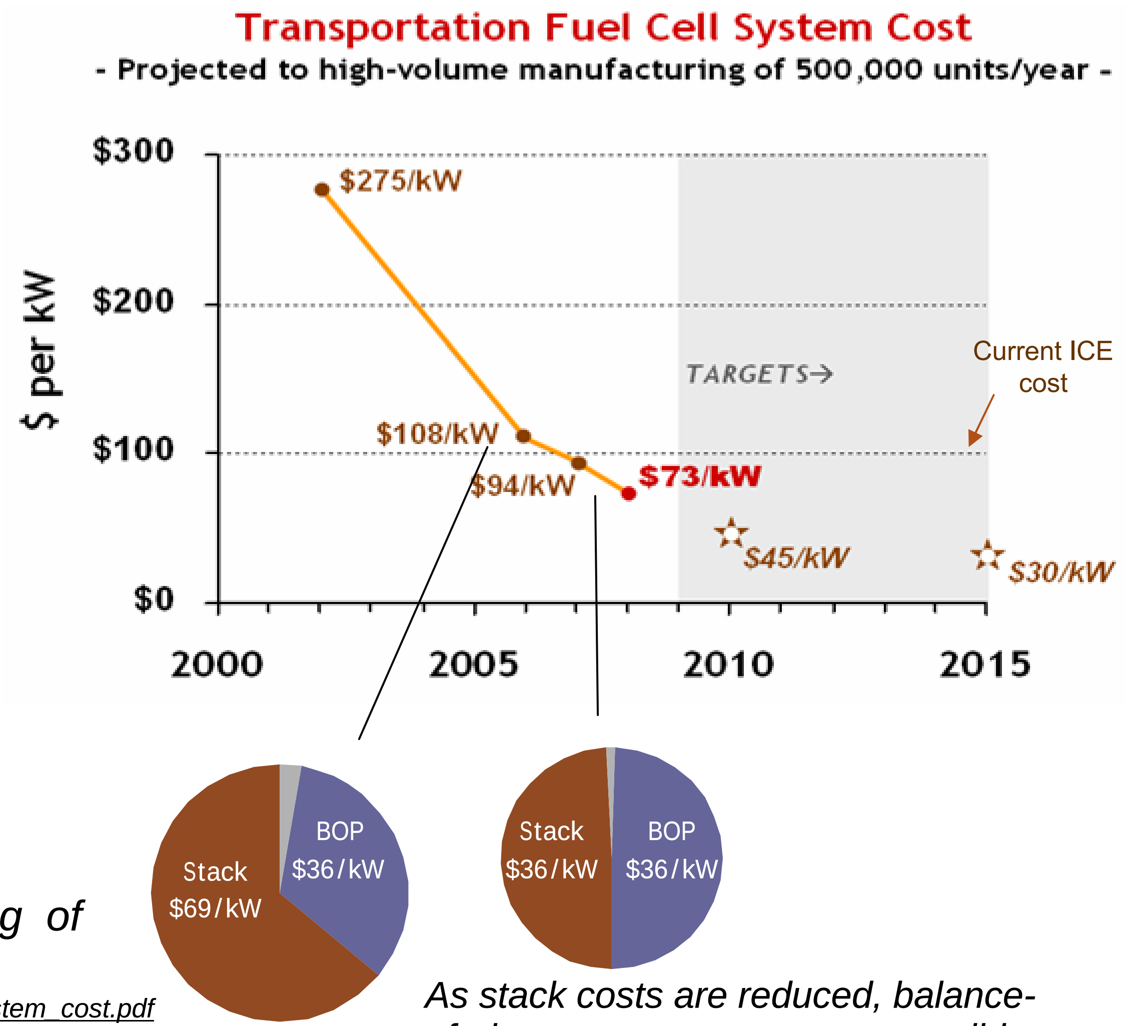
Cost of Full-Function BEV Battery

In-use propulsion energy	250 W-hr/mile	2008 EPRI/NRDC report, "Environmental Assessment of Plug-In Hybrid Electric Vehicles" for 2030 cars (280 Wh for 2006 cars and more for light trucks)
Range	**300 miles**	Minimum requirement for gasoline vehicles
Useable energy	75 kW-hr	Useable energy from battery pack
Depth of discharge	75% (50% currently)	Useable energy is less than nominal battery pack size due to deterioration and durability constraints
Nominal energy	100 kW-hr	Useable energy divided by depth of discharge
Battery pack cost	**$40,000**	$400/kW-hr for 2020 Li-ion battery pack cost from Boston Consulting Group
	$20,000	Long-term, optimistic estimate of $200/kW-hr
Battery pack weight	**880 pounds**	200 W-hr/kg (currently about 90 W-hr/kg)

Fuel Cells Status

The DOE Fuel Cell Program has reduced the cost of fuel cells to $73/kW*

- *Cost projection validated by independent panel***
- *More than 20% reduction in one year*
- *Nearly 75% reduction since 2002*



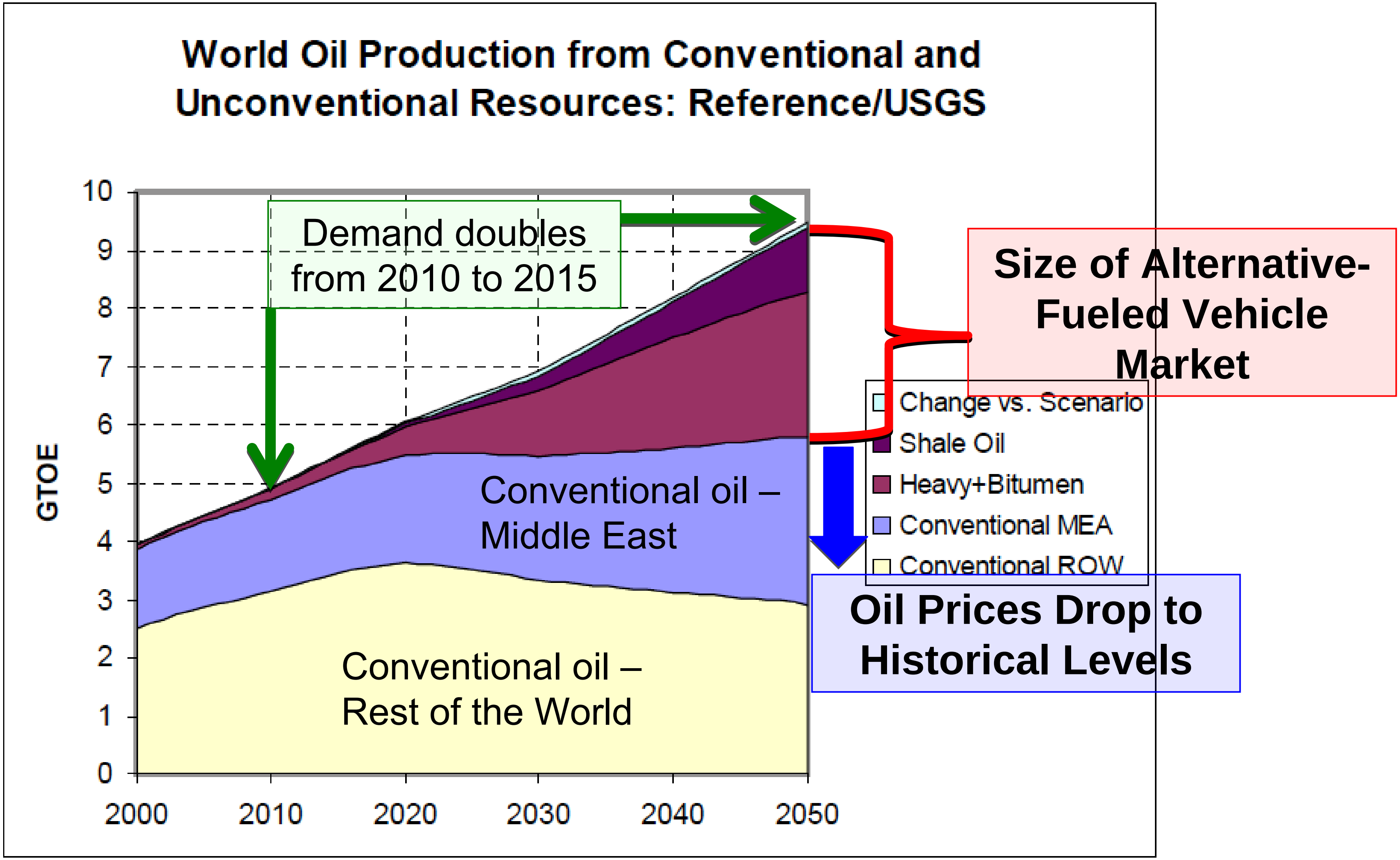
As stack costs are reduced, balance-of-plant components are responsible for a larger % of costs

**Based on high-volume manufacturing of 500,000 units/year*
Source: www.hydrogen.energy.gov/pdfs/8019_fuel_cell_system_cost.pdf

***Panel found $60 – $80/kW to be a "valid estimate"*
Source: http://hydrogendoedev.nrel.gov/peer_reviews.html

Future Petroleum Demand and Prices

Petroleum Demand and Price



Demand doubles from 2010 to 2015

Conventional oil – Middle East

Conventional oil – Rest of the World

Size of Alternative-Fueled Vehicle Market

Oil Prices Drop to Historical Levels

Green, D., Hopson, J., and Li, J., “Running Out of and Into Oil: Analyzing Global Oil Depletion and Transition through 2050”. October 2003

Summary

Future Directions

- Energy and GHG so immense we must do everything
  - No silver bullet – avoid trap of single solutions
  - Alternative fuels need long leadtimes – start soon

- Hybrid costs are dropping and synergies are developing
  - Mass market acceptance likely within 15 years

- Improved gasoline engines and hybrids coming
  - **Fast reductions in fuel consumption and CO2**
  - **But will raise bar for other technologies**

- Low fuel cost challenges:
  - Customers will continue to demand performance, features, and utility, not fuel economy
  - More difficult to implement advanced technology

Transition to Advanced Technologies

- Must eventually move away from internal combustion
  - Long-range climate goals
  - Declining oil production and likely limited supplies of biofuels
- Long lead times - must start early
  - Batteries and fuel cells require cost reduction
  - Industry is extremely capitol intensive
  - Infrastructure development
  - Long time before mainstream consumers feel “secure” with new technology
    - Hybrid sales only reached 2.5 % of the U.S. market after 10 years
- Transition must be facilitated by high petroleum prices
  - Transition must be fast enough to ensure availability of energy, but not too fast to avoid collapse in petroleum prices

Thank You

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