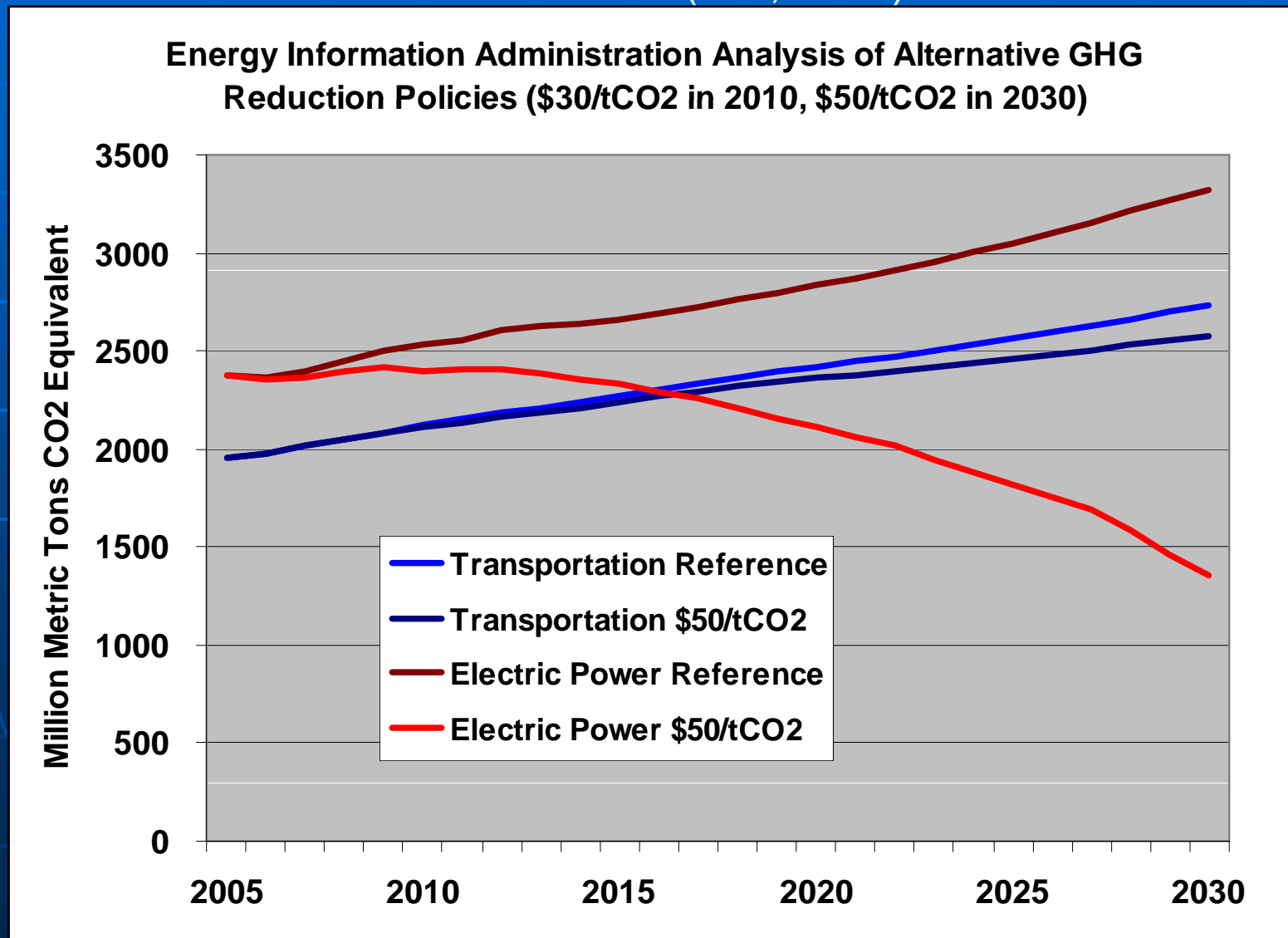


Beyond CAFE: Vehicles

Dr. David L. Greene
Oak Ridge National Laboratory

Environmental and Energy Study Institute Briefing
Russell Senate Office Building
Washington, DC
January 17, 2008

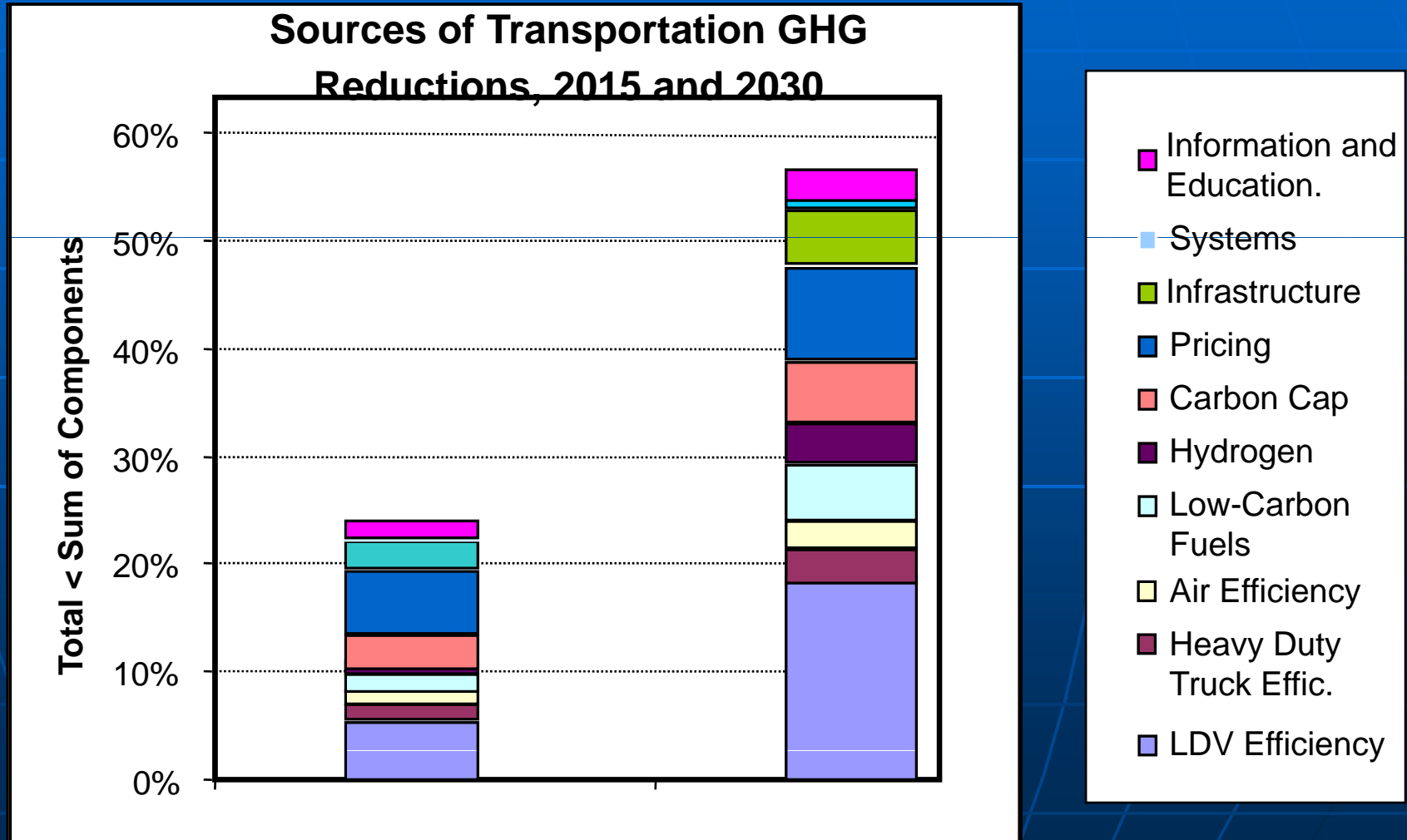
The BAD NEWS: Pricing Carbon is no panacea for transportation: A C-price that would cut utilities C emissions in half by 2030 would have little impact on transportation emissions. (EIA, 2006).



No single policy will do the job for transportation.

1. Major government role in decision making.

2. Energy efficiency “market failure”.



Source: Greene and Schafer, Pew Center on Global Climate Change, May 2003.

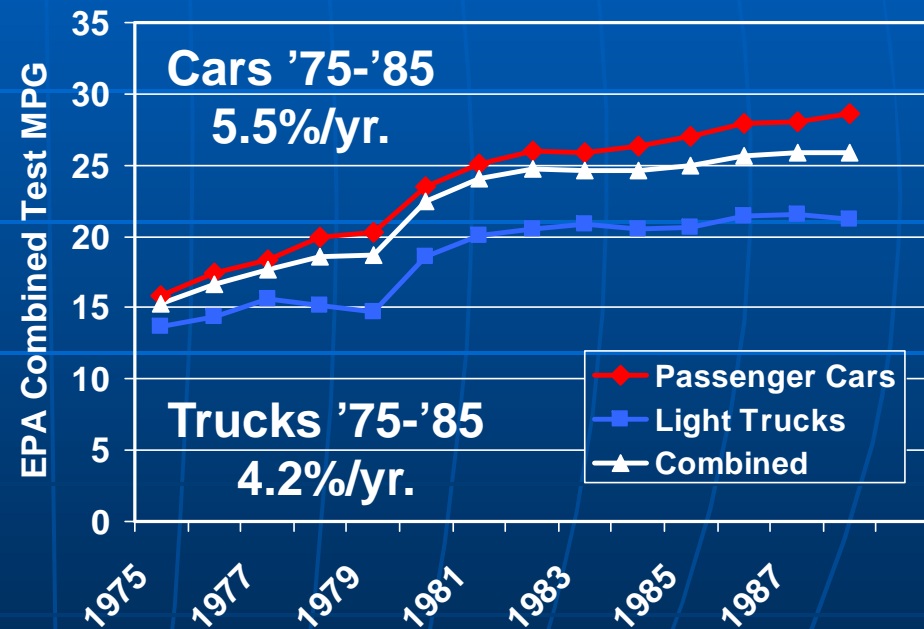
Meeting the Lieberman-Warner goals will require continuing progress in vehicle technology.

- What will the new EISA fuel economy standards get us?
- Where can/should we go with energy efficiency after 2020?
- What must we give up to get energy efficiency?
- What policies will be needed and why?

EISA calls for a 40% increase in light-duty vehicle fuel economy to 35 mpg by 2020.

- Consistent with NAS 2002 cost-efficient criteria at current gasoline prices.
- Two years' lead time plus 10 years to apply technology to all vehicles.
- Rate of about 3.5%/yr. is slower than 1975-85 rate of 5%/yr.

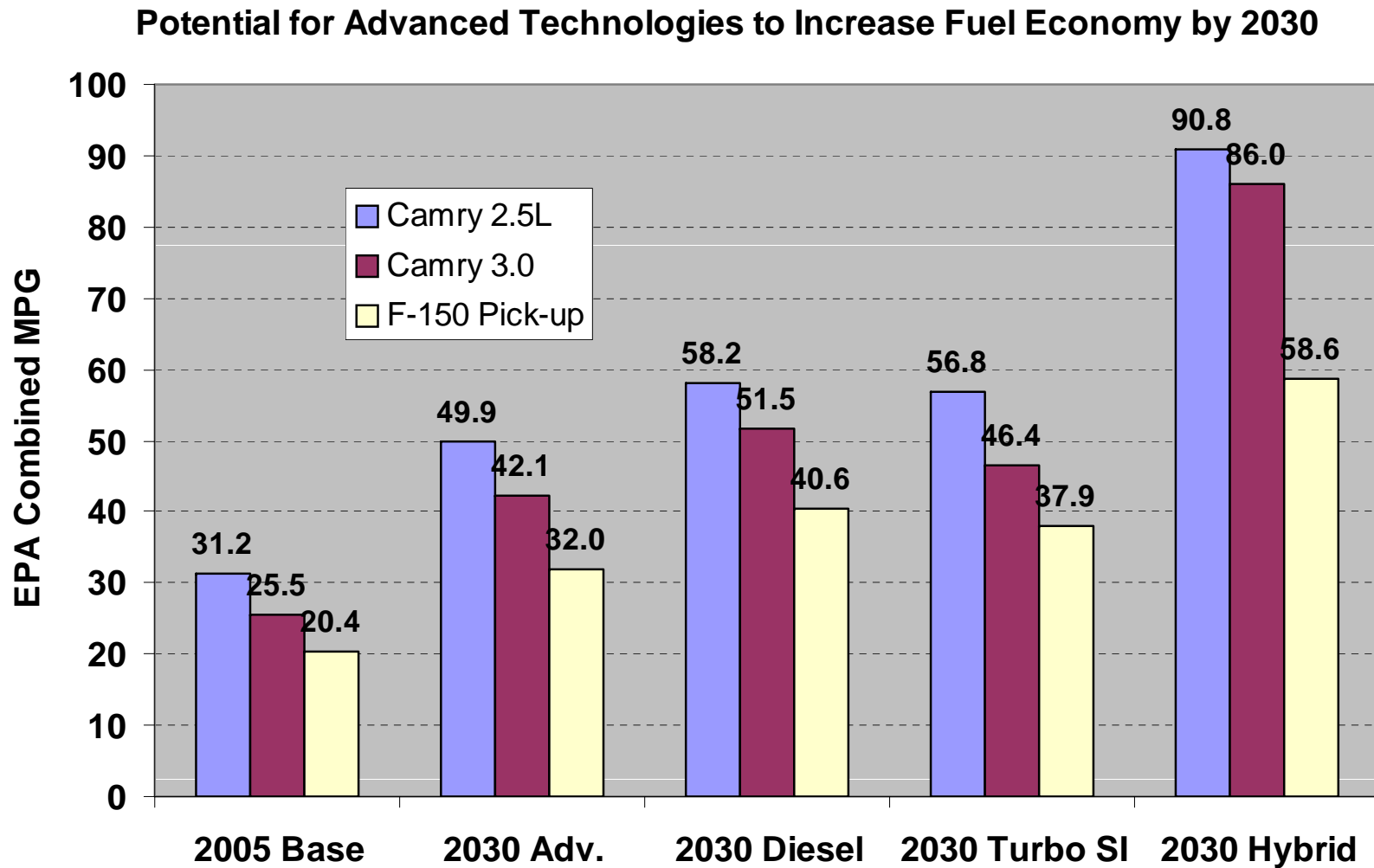
New Light-Duty Vehicle Fuel Economy, 1975-1988



Where next?

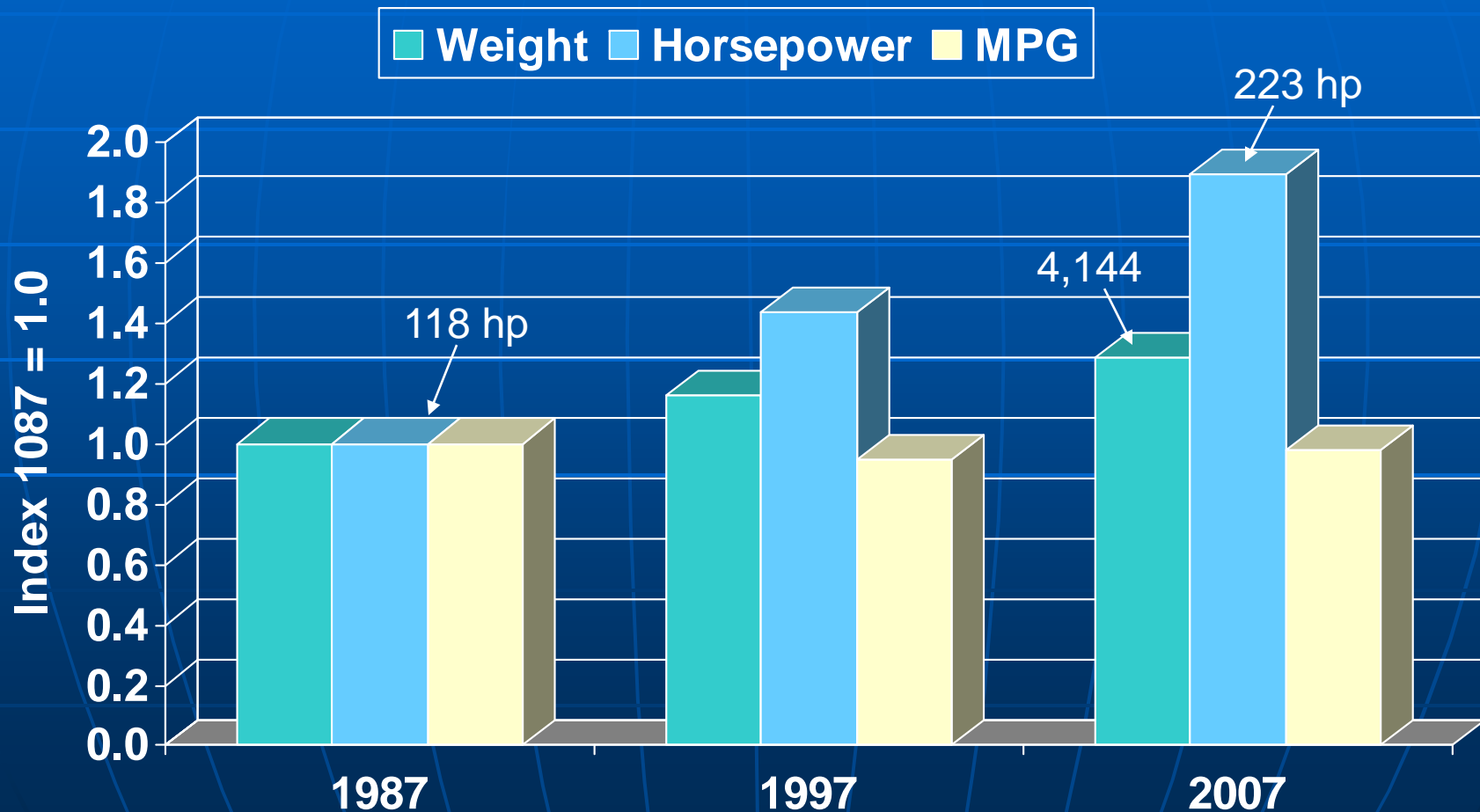
- Continued improvement in fuel economy for conventional gasoline and diesel vehicles.
 - Direct injection, turbo-charging, engine downsizing.
 - Mass reduction via materials substitution.
 - Improved aerodynamics, rolling resistance, accessory efficiency, etc.
- Advanced electric drive vehicles.
 - Advanced motors and controllers (DOE/FCVT)
 - Advanced batteries (\$250/kWh PHEV, \$750/kWh HEV)
 - Advanced fuel cells (\$50/kW FC, \$15/kWh storage)

A 2007 MIT study predicts MPG gains of 80-85% for model year 2030 vehicles via continuous improvement of conventional technology at a rate of 2-2.5%/year.



Source: Kasseris & Heywood, SAE Technical Paper 2007-01-1605, April, 2007.

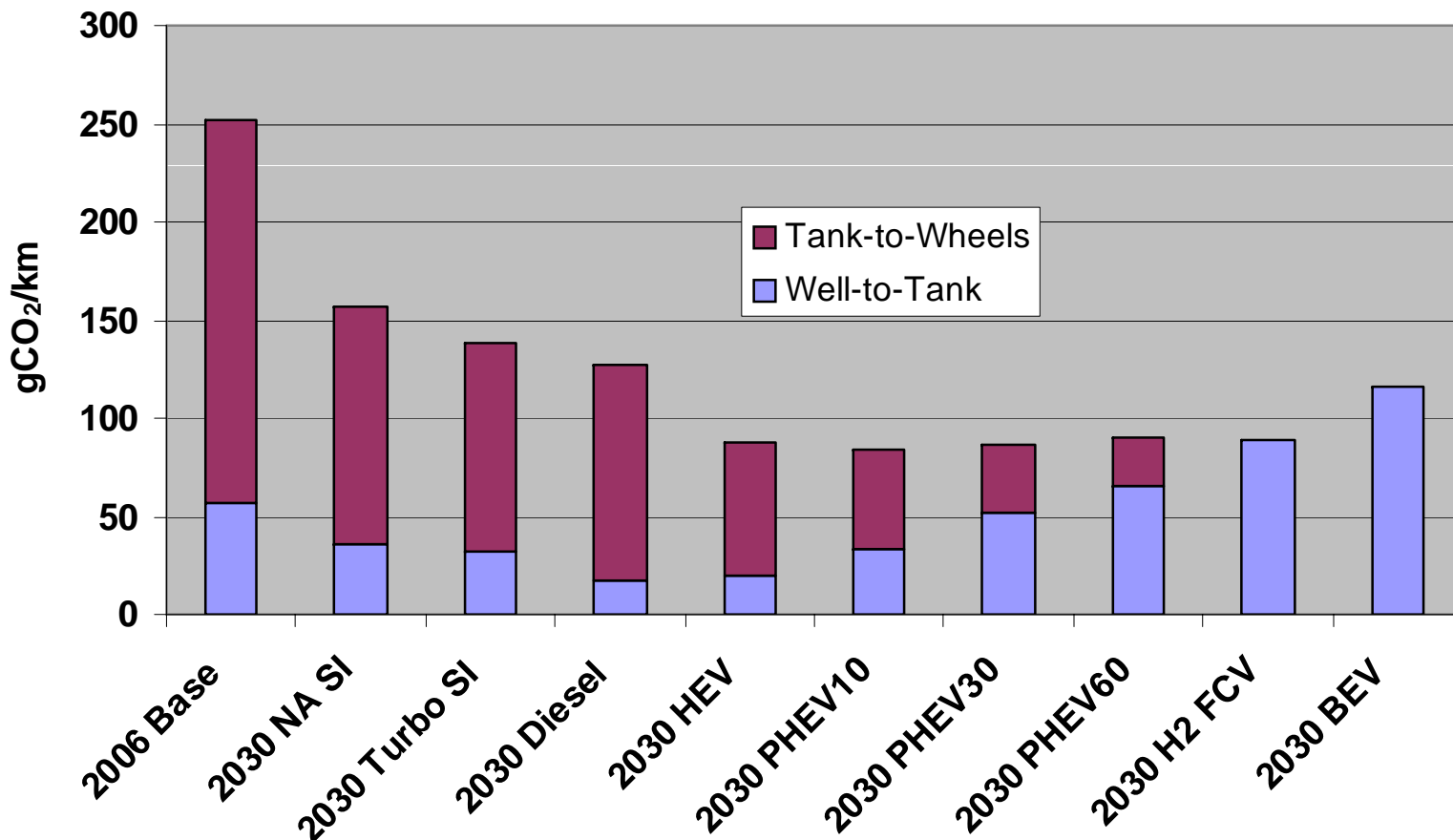
What must we give up? The horsepower & weight race.



Source: U.S. EPA, Light-Duty Automotive Technology and Fuel Economy Trends: 1975-2007, p. ii.

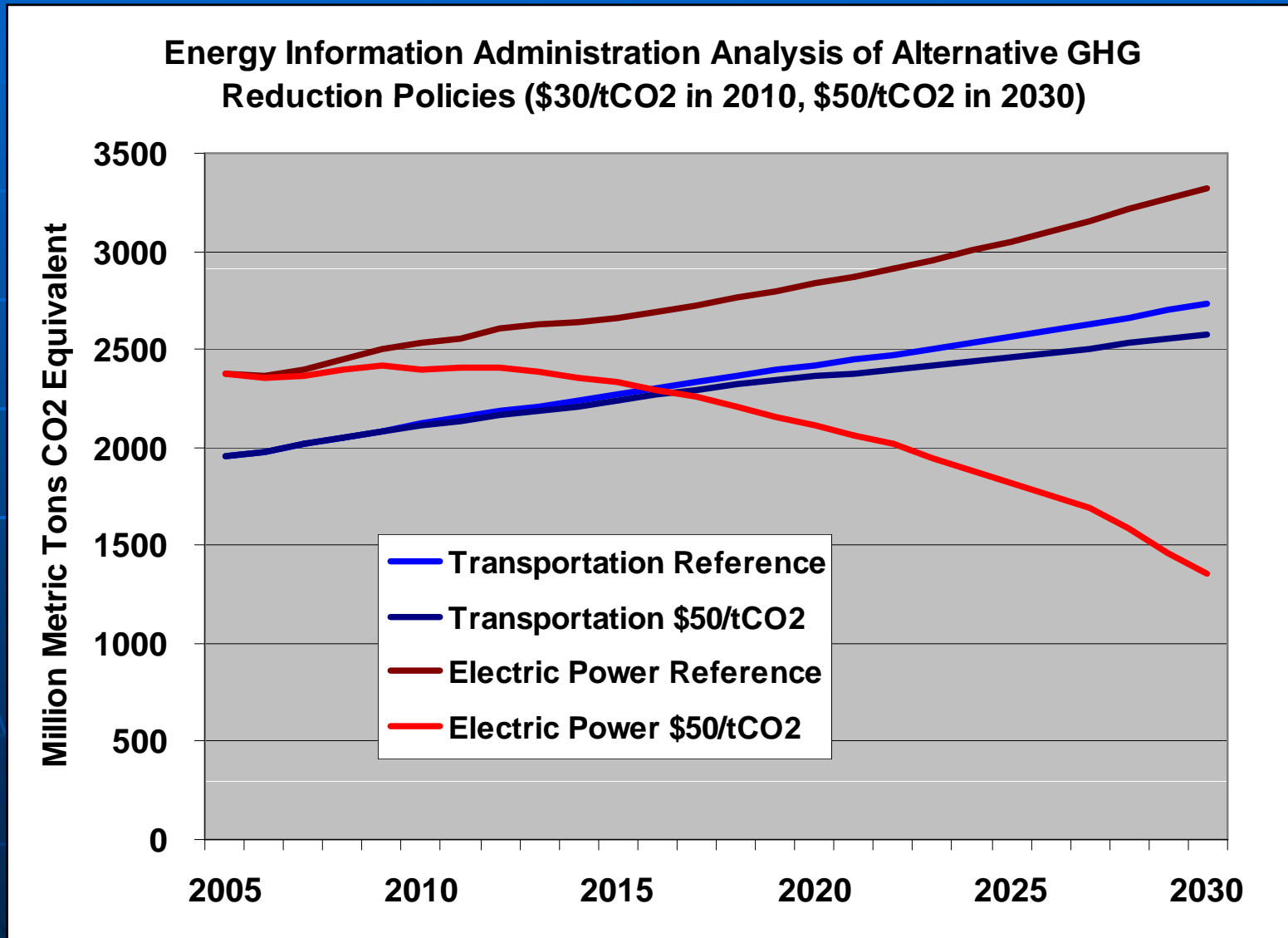
The greater energy efficiency of electric drive technologies can cut well-to-wheel GHG emissions in half and more.

Well-to-Wheel GHG Emissions of Advanced Vehicle Technologies

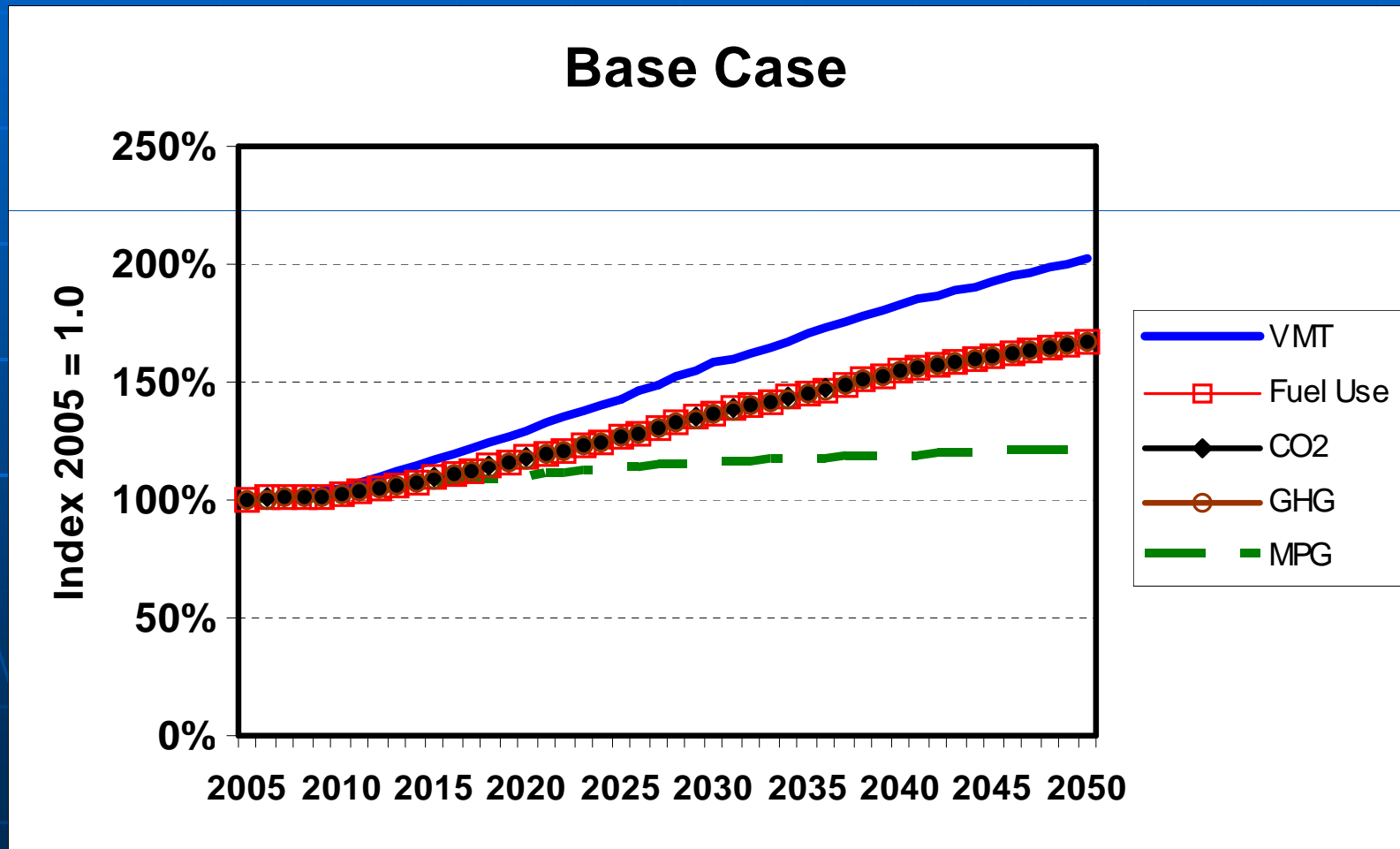


Source: Kromer & Heywood, 2007. Assumes H2 from natural gas, electricity is EIA 2030 mix.

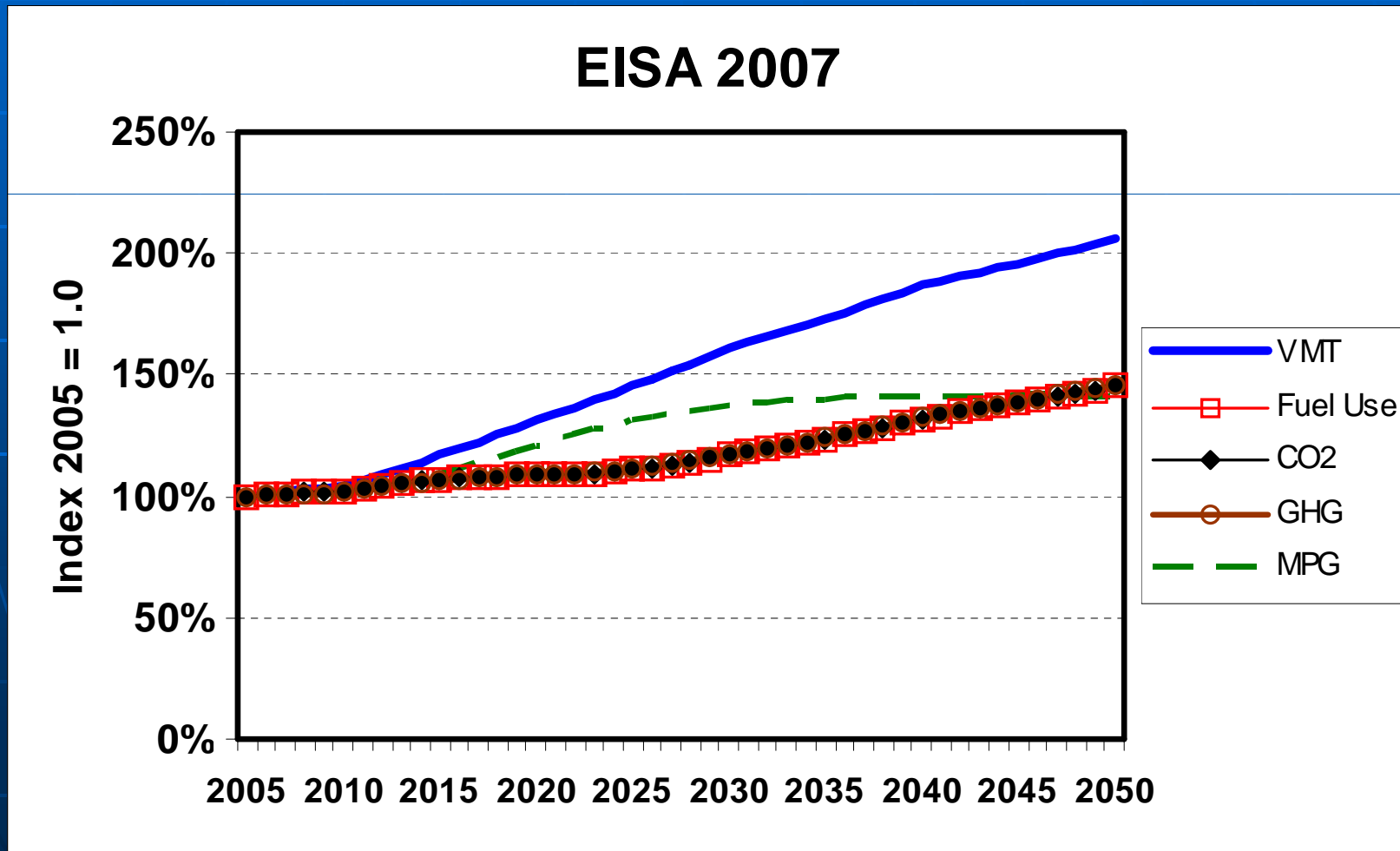
The GOOD NEWS: If there is a meaningful carbon policy, electricity will be a low-carbon source of energy for transportation.



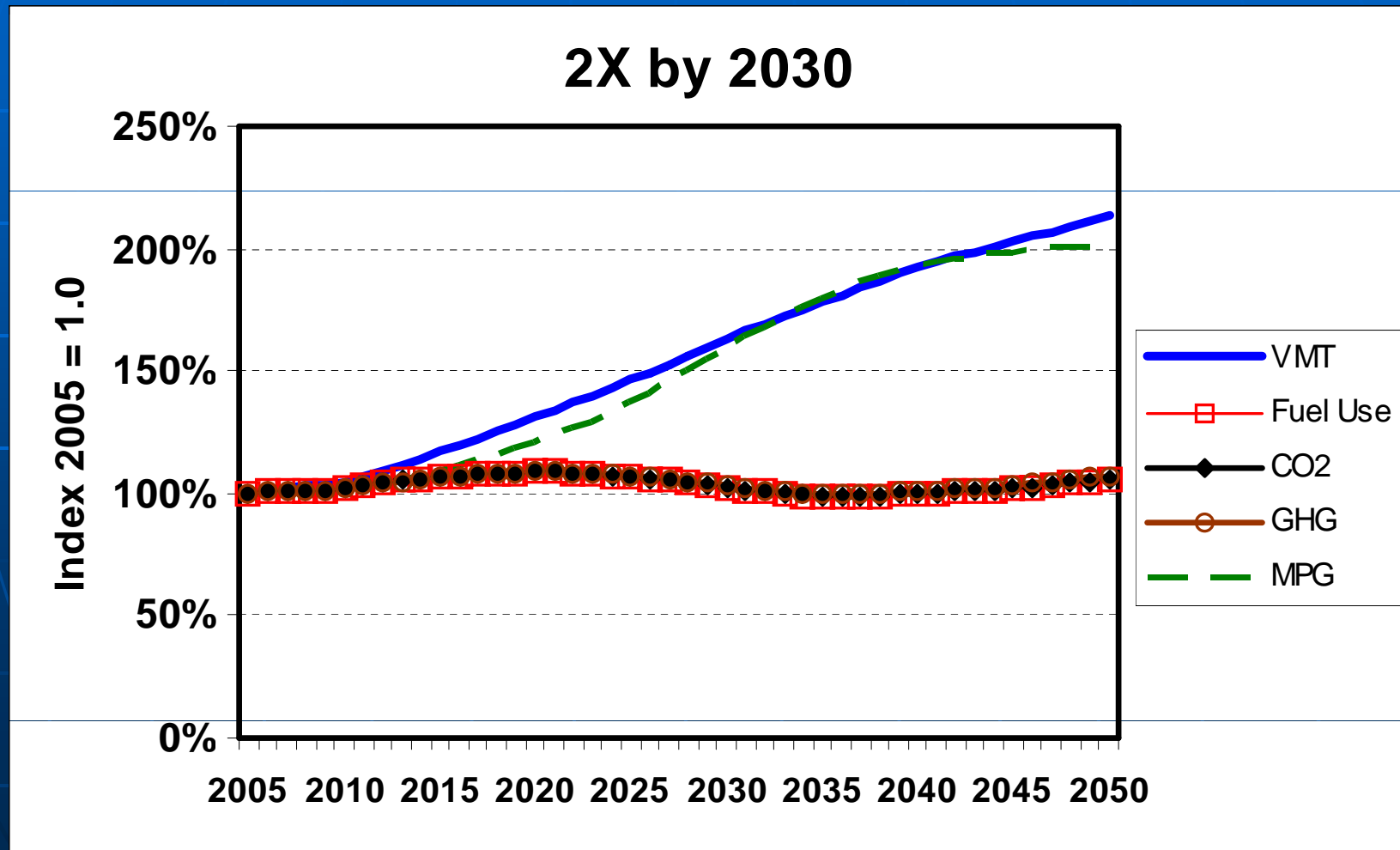
The base case (based on AEO 2007) projects a doubling of vehicle travel by 2050, with fuel use and CO2 emissions increasing by two thirds.



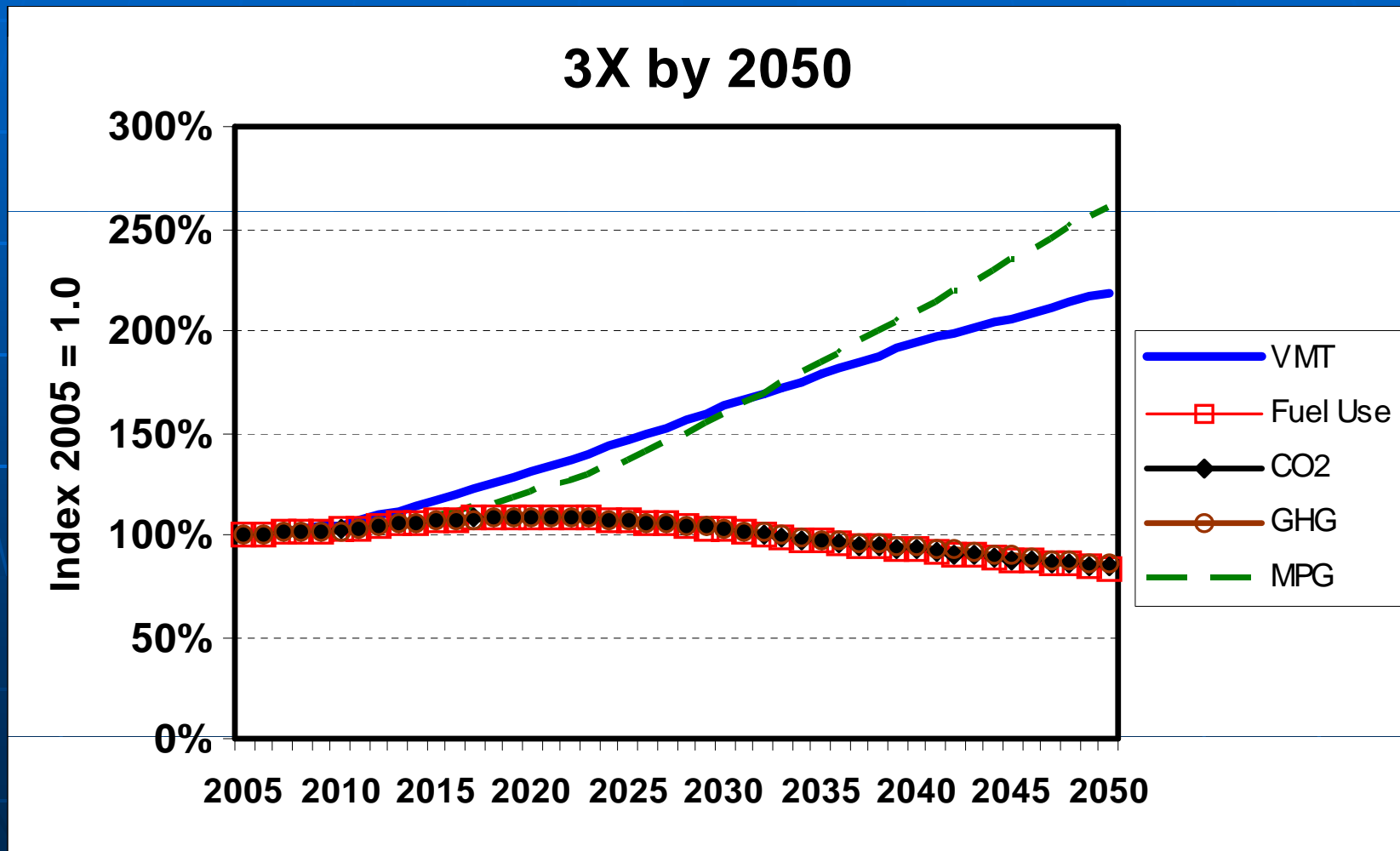
The higher fuel economy standards of the EISA should restrain the growth of fuel use through 2025, saving about 20 billion gallons in 2025 and 25 billion gallons in 2030.



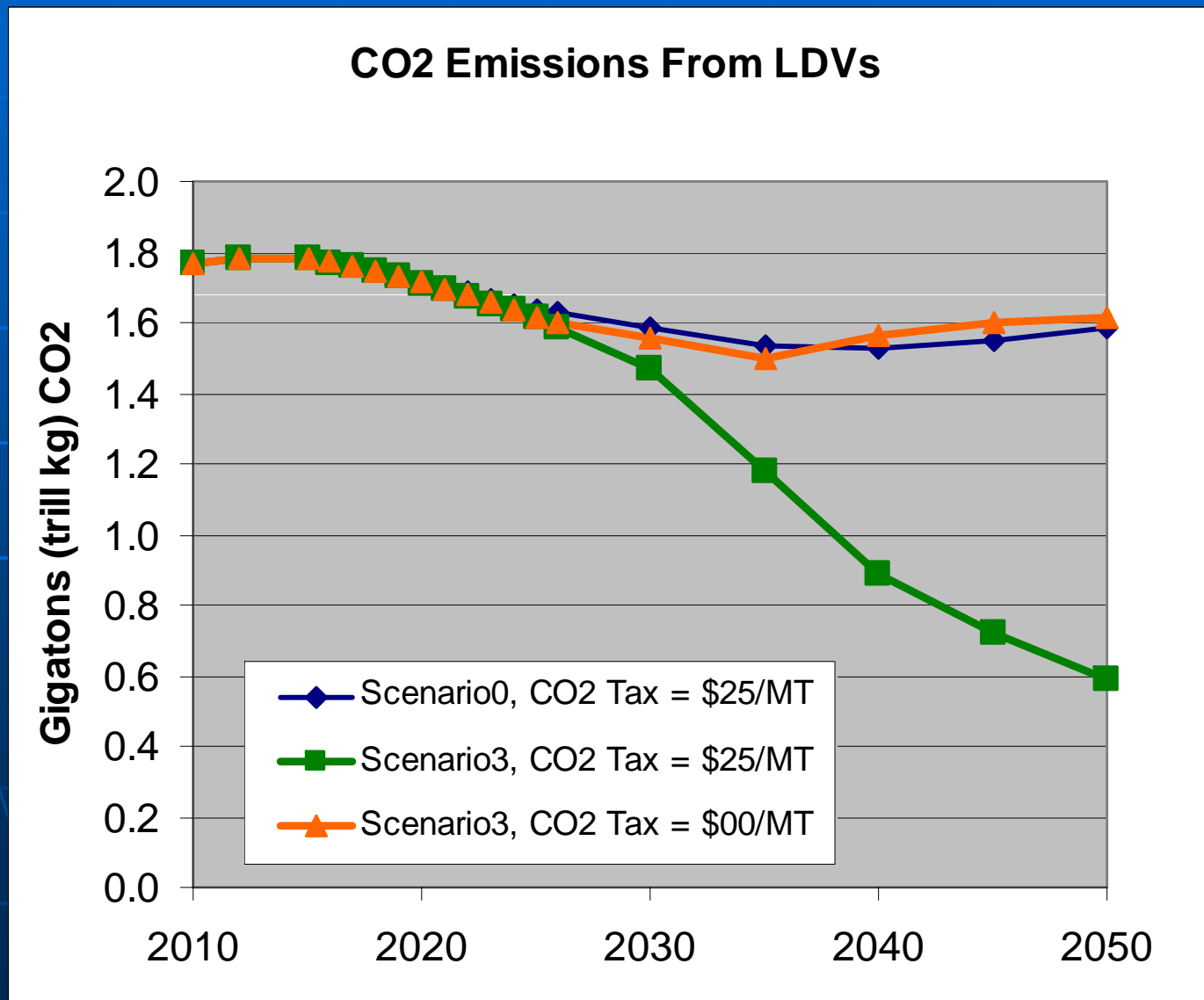
And, if we could double new LDV fuel economy by 2030, that would hold CO2 emissions approximately constant through 2050.



In addition, if we could triple light-duty vehicle fuel economy by 2050 that would reduce CO₂ emissions below their 2005 levels.



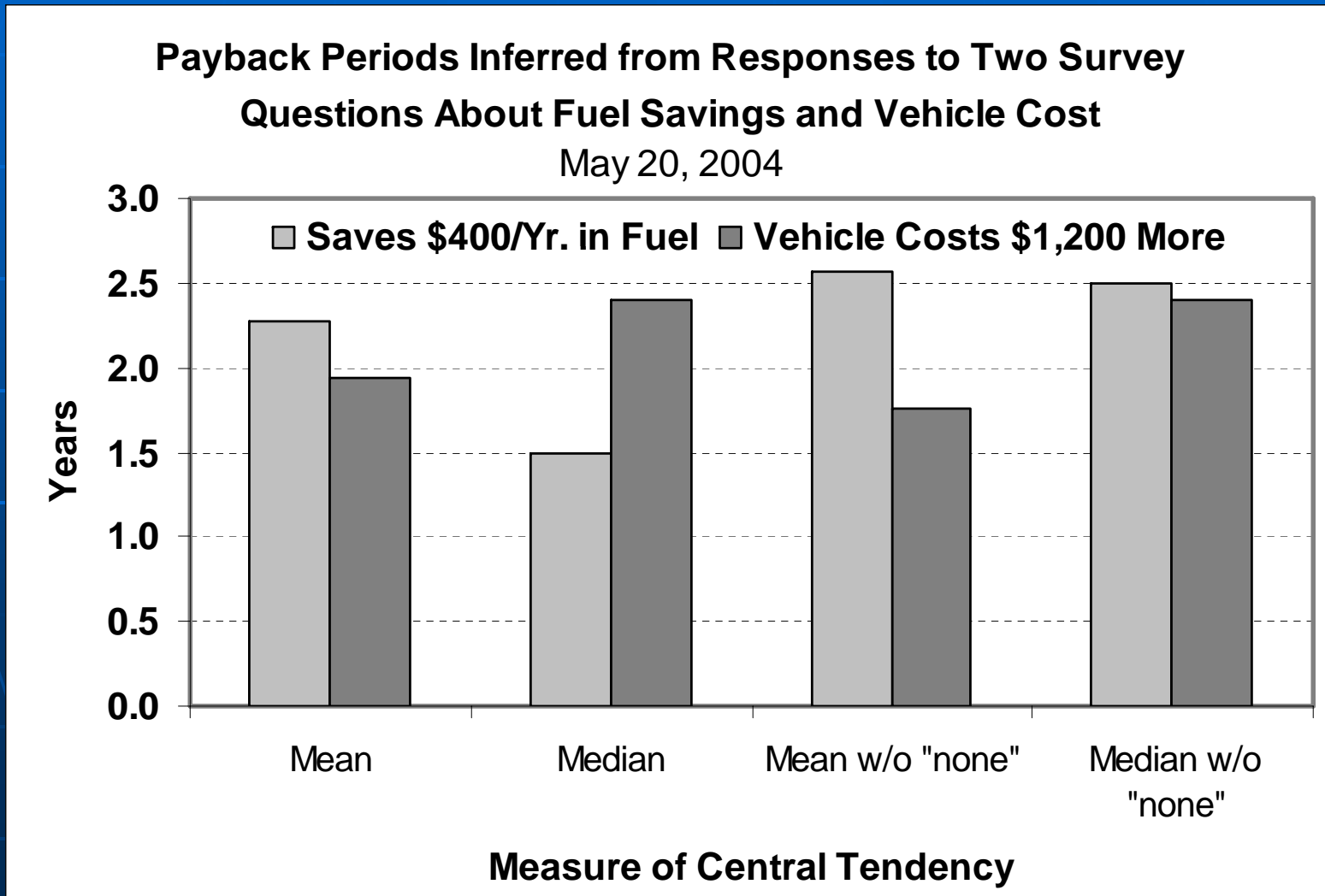
Reducing C emissions to Lieberman-Warner levels will require new sources of energy AND C-constraining policy. (e.g., \$10/tCO₂ in 2010 to \$25/tCO₂ in 2025).



Observations on vehicle policy: What “market failure”?

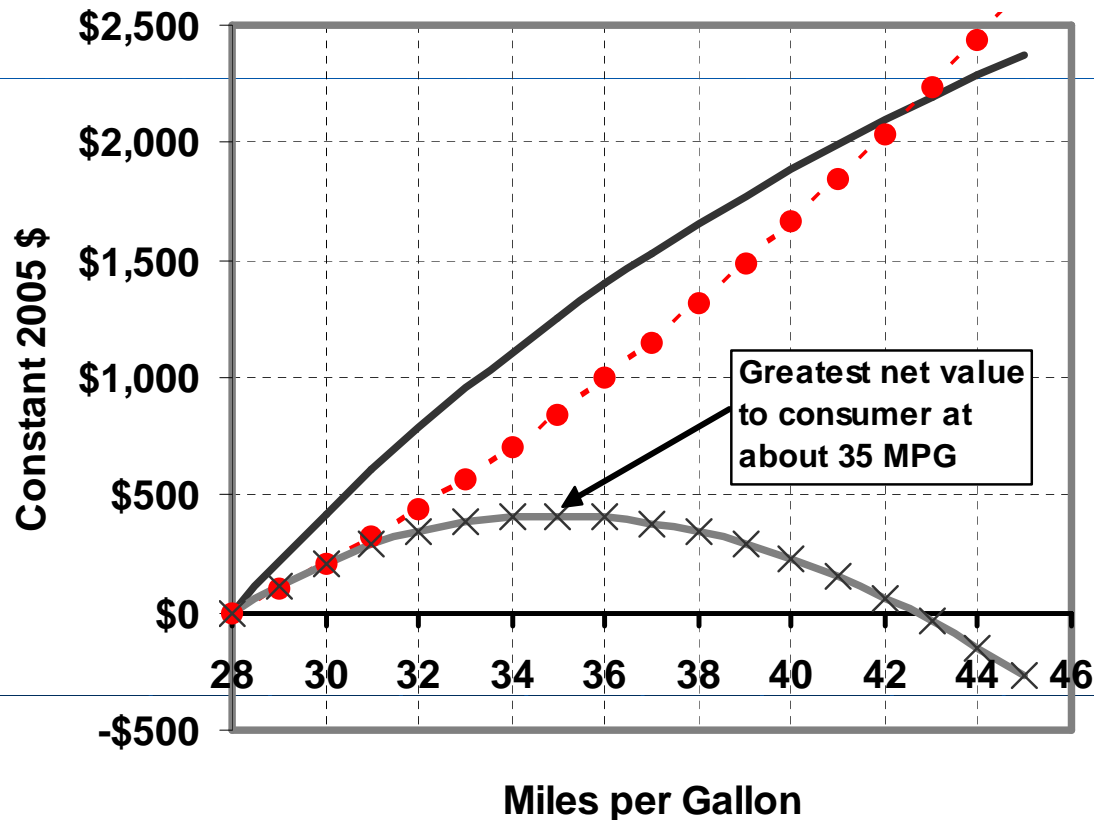
- Consumers do not follow the rational economic model (Turrentine & Kurani, *Energy Policy*, 2007).
- Uncertainty and loss aversion sufficient to account for a significant energy efficiency “market failure”.
- Value of performance and weight may also involve comparative utility and externalities.
- Energy efficiency market failure may extend to all energy using markets to a greater or lesser degree.
- Affects R&D as well as adoption and application of energy efficient technology.

Asked about fuel economy payback, consumers respond with short payback periods. But few actually think about gas mileage in financial terms (Turrentine & Kurani, 2007).



Rational economic model: Assuming certainty and precise preferences, a 25% increase in MPG would be optimal (& cost-efficient). But in reality the payoff is very uncertain.

Price and Value of Increased Fuel Economy to Passenger Car Buyer, Using NRC Average Price Curves



Greatest net value to consumer at about 35 MPG

$$PV = \int_{t=0}^L P_t M_o e^{-\delta t} \left(\frac{1}{E_o} - \frac{1}{E_1} \right) e^{-rt} dt$$

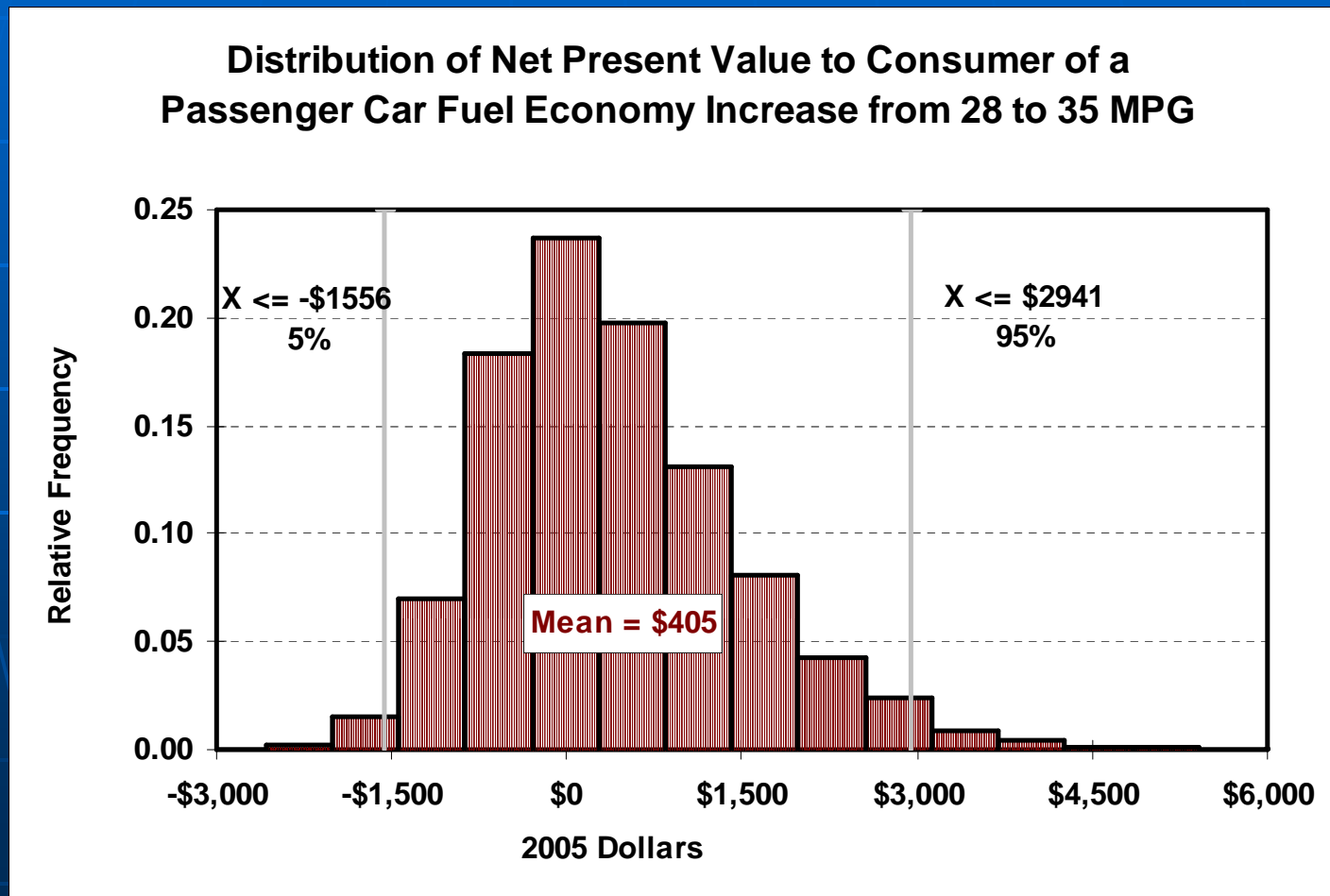
- Fuel Savings
- - - ● Price Increase
- × Net Value

Assumes cars driven 15,600 miles/year when new, decreasing at 4.5%/year, 12% discount rate, 14 year vehicle life, \$2.00/gallon gasoline, 15% shortfall between EPA test and on-road fuel economy.

Uncertainty about key factors makes higher fuel economy a *risky bet*.

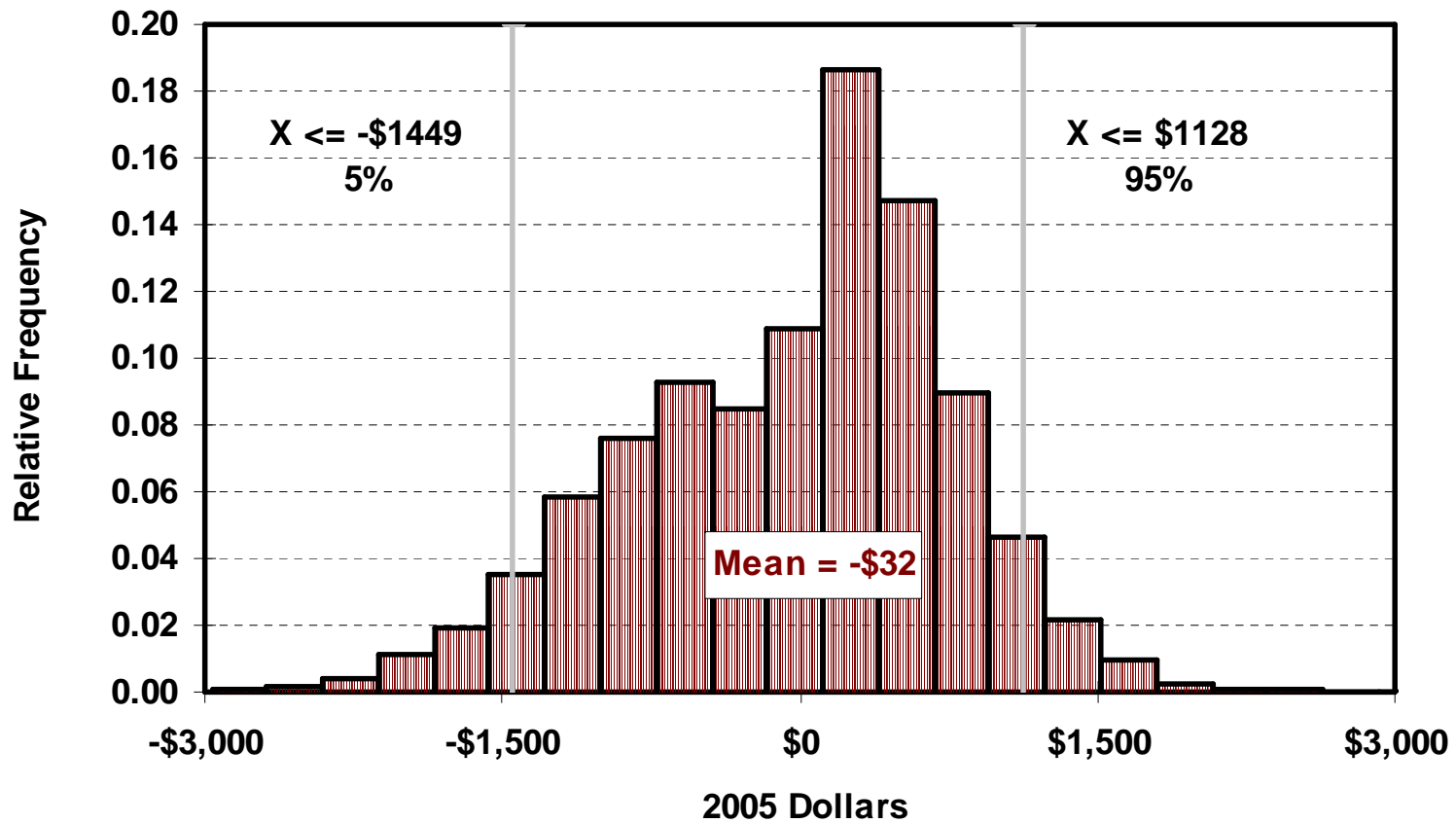
- Sure, there's a fuel economy label but what MPG will I get?
- What will gasoline cost?
- How much driving will I do?
- How long will my car last?
- (How long will I last?)
- What will I have to give up to get better fuel economy? (How much will it cost?)

A simulation reflecting these uncertain factors indicates that the fuel economy bet has an ***expected present value*** of \$405.



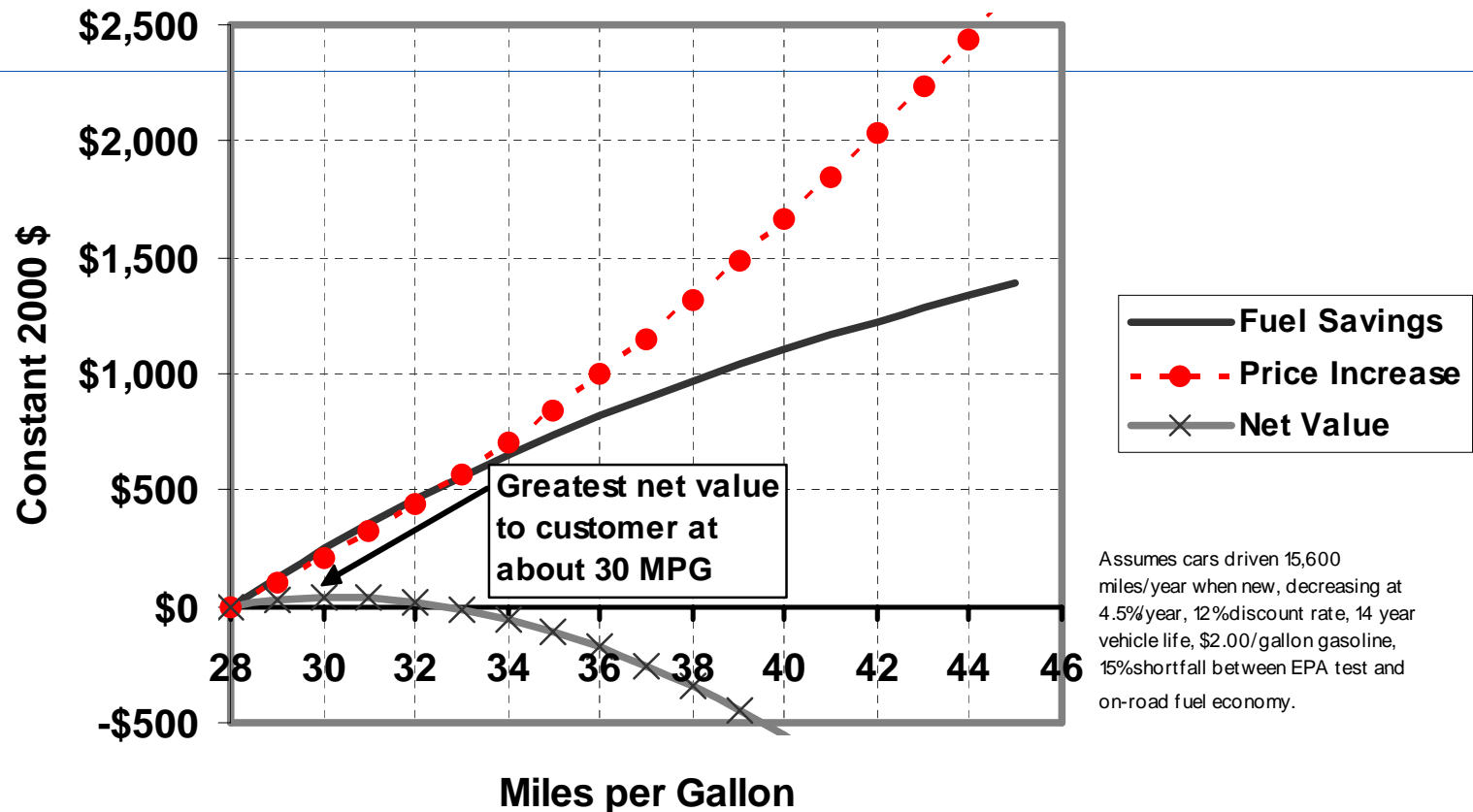
Applying Kahneman and Tversky's typical consumer **loss aversion** function changes the value of the fuel economy bet to **-\$32**.

Net Present Value Distribution of Loss Averse Consumer



The practical effect of a 3-year payback vs. loss aversion & uncertainty are essentially the same.

Price and Value of Increased Fuel Economy to Passenger Car Buyer, Using NRC Average Price Curves



Effective vehicle policies must get around the uncertainty+loss aversion market failure.

- Regulatory standards – EU, US, Japan, China, et al., have them.
- Feebates – “road not taken”
 - Market-based policy
 - Provides continuing incentive
- Research, Development & Demonstration
- All of the above?

THANK YOU.

How do we know?

- Engineering-Economic analysis of what can be achieved by proven technologies.
- Proven: in-use in some mass-produced vehicle (market ready).
- No change in vehicle size or acceleration performance.
- Cost efficient: marginal cost to consumer = expected marginal present value of fuel savings to consumer.

Technology/Cost analysis produces a list of technologies, ranked by cost-effectiveness and accounting for synergies. (EEA 2006).

TECHNOLOGY TYPE	Short Term (2006-2012)		Medium Term (2013-2018)		Long Term (2019-2025)	
	Cumulative GHG Benefit (%)	Cumulative RPE (US\$)	Cumulative GHG Benefit (%)	Cumulative RPE (US\$)	Cumulative GHG Benefit (%)	Cumulative RPE (US\$)
Early Torque Converter Lockup	0.50	5	0.50	5	0.50	5
Rolling Resistance Reduction by 10%	1.99	25	1.99	25	1.99	25
Drag Reduction by 10%	3.95	53	3.95	53	3.95	53
Rolling Resistance Reduction by 20%	3.95	53	5.30	85	5.30	85
Drag Reduction by 20%	3.95	53	7.00	127	7.00	127
Aggressive Shift Logic	4.17	58	7.21	152	7.21	152
Improved Lube Oil						
Engine Friction Reduction by 8% I4						
Stoichiometric GDI I4						
Weight Reduction by 5%						
Engine Friction Reduction by 15% I4						
DOHC VVT (Intake) I4						
VVT (Intake plus Exhaust) DOHC I4						
Engine Friction Reduction by 8% V6						
Alternator Improvements						
VVL Discrete OHV-2v V6						
Stoichiometric GDI V6						
VVL Discrete OHC-4v I4						
Engine Friction Reduction by 8% V8						
Engine Friction Reduction by 15% V6						
VVT Intake Continuous DOHC I4						
Engine Off at Idle (Manual Transmission)						
VVL Discrete OHV-2v V8						
Engine Friction Reduction by 15% V8						
Electric Power Steering						
Five Speed Automatic Transmissions						
Six Speed Automatic Transmissions						
Seven Speed Automatic Transmissions						
Continuously Variable Transmissions (Engines < 4.5 Valves I4)						
Camless Valve Actuation I4						
Stoichiometric GDI V6						
Weight Reduction by 10%						
Turbocharging & GDI with Engine Downsize V6						
DOHC VVT (Intake) V6						
DOHC VVT (Intake) V8						
VVT (Intake plus Exhaust) DOHC V6						
VVT (Intake plus Exhaust) DOHC V8						
VVL Discrete OHC-4v V6						
VVL Intake Continuous DOHC V6						
Continuously Variable Transmissions (Engines > 4.5 Valves V6)						
Turbocharging & GDI with Engine Downsize V8						
VVL Discrete OHC-4v V8						
VVL Intake Continuous DOHC V8						
Cylinder Deactivation V6 with Noise Cancellation						
Cylinder Deactivation V8 & Cont. VVLT						
Camless Valve Actuation V6 Incl. Cyl Deact.						
Camless Valve Actuation V8 Incl. Cyl Deact.	20.10	1104	21.42	232	21.04	2390
Engine Off at Idle (Auto. Transmission & AC)	20.10	1104	40.11	2901	40.31	2939
Weight Reduction by 15%	20.10	1104	40.11	2901	41.92	3596
Electric Water Pump	20.10	1104	40.41	2951	42.21	3646
Homogeneous Combustion Compression Ignition (HCCI) I4	20.10	1104	40.41	2951	42.21	3646
Homogeneous Combustion Compression Ignition (HCCI) V6	20.10	1104	40.41	2951	42.30	3772

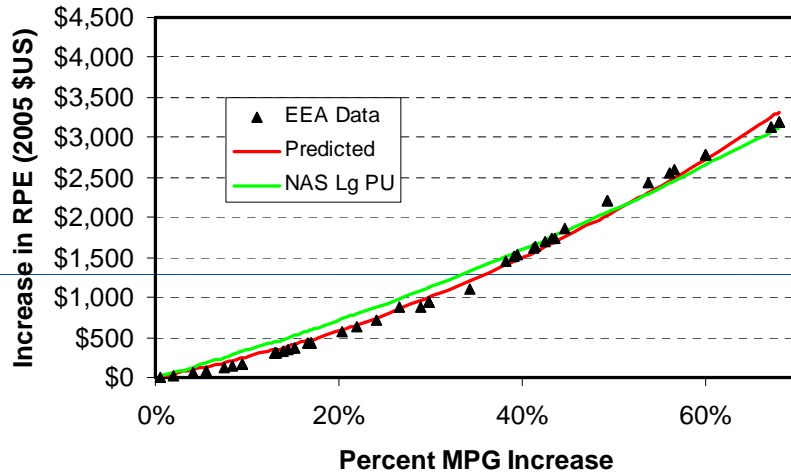
Technology

- Early Torque Converter Lock-up
- Rolling Resistance Reduction by 10%
- Drag Reduction by 10%
- Rolling Resistance Reduction by 20%
- Drag Reduction by 20%
- Aggressive Shift Logic
- Improved Lube Oil
- Engine Friction Reduction by 8% I4
- Stoichiometric GDI I4
- Weight Reduction by 5%
- Engine Friction Reduction by 15% I4
- DOHC VVT (Intake) I4
- VVT (Intake plus Exhaust) DOHC I4
- Engine Friction Reduction by 8% V6
- Alternator Improvements
- VVL Discrete OHV-2v V6
- Stoichiometric GDI V6
- VVL Discrete OHC-4v I4
- Engine Friction Reduction by 8% V8
- Engine Friction Reduction by 15% V6
- VVT Intake Continuous DOHC I4
- Engine Off at Idle (Manual Transmission)
- VVL Discrete OHV-2v V8
- Engine Friction Reduction by 15% V8
- Electric Power Steering
- Five Speed Automatic Transmissions
- Six Speed Automatic Transmissions
- Seven Speed Automatic Transmissions
- Continuously Variable Transmissions (Engines < 4.5 Valves I4)
- Camless Valve Actuation I4
- Stoichiometric GDI V6
- Weight Reduction by 10%
- Turbocharging & GDI with Engine Downsize V6
- DOHC VVT (Intake) V6
- DOHC VVT (Intake) V8
- VVT (Intake plus Exhaust) DOHC V6
- VVT (Intake plus Exhaust) DOHC V8
- VVL Discrete OHC-4v V6
- VVL Intake Continuous DOHC V6
- Continuously Variable Transmissions (Engines > 4.5 Valves V6)
- Turbocharging & GDI with Engine Downsize V8
- VVL Discrete OHC-4v V8
- VVL Intake Continuous DOHC V8
- Cylinder Deactivation V6 with Noise Cancellation
- Cylinder Deactivation V8 & Cont. VVLT
- Camless Valve Actuation V6 Incl. Cyl Deact.

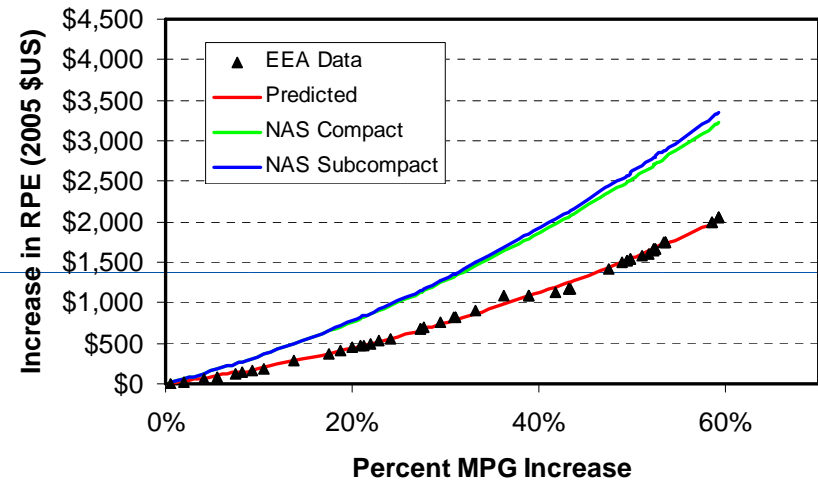
Medium Term Potential % FC Red.	Potential Cumulative Cost	Potential Cumulative % FE Incr.
0.50%	\$5	0.503%
1.99%	\$25	2.030%
3.95%	\$53	4.112%
5.30%	\$85	5.597%
7.00%	\$127	7.527%
7.58%	\$139	8.202%
8.50%	\$159	9.290%
9.52%	\$189	10.522%
12.13%	\$278	13.804%
14.85%	\$369	17.440%
15.79%	\$409	18.751%
16.70%	\$447	20.048%
17.25%	\$467	20.846%
17.55%	\$479	21.286%
17.96%	\$496	21.892%
18.63%	\$528	22.895%
19.39%	\$565	24.054%
21.42%	\$676	27.259%

Not all technologies are applicable to all vehicle types. (Compare 2006 study by EEA with 2002 NAS results)

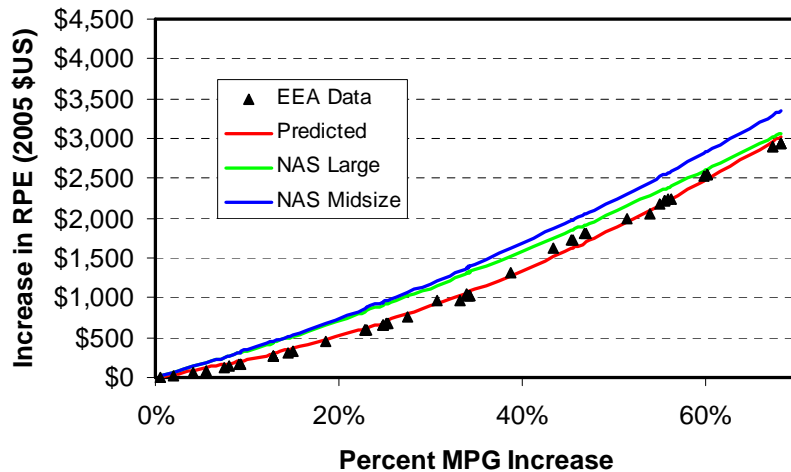
**Fuel Economy Increase Cost Curve
Large Domestic Pick-UP (EEA, 2006)**



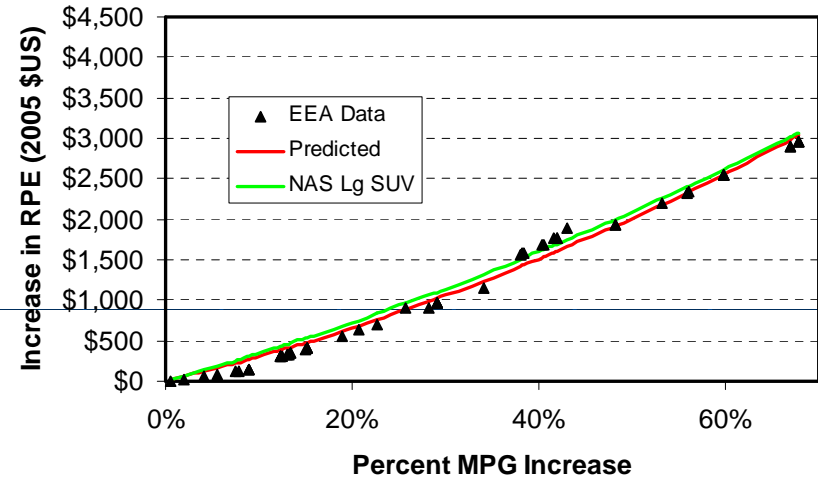
**Fuel Economy Increase Cost Curve
Small Car Domestic Standard (EEA, 2006)**



**Fuel Economy Increase Cost Curve
Large Domestic Car (EEA, 2006)**

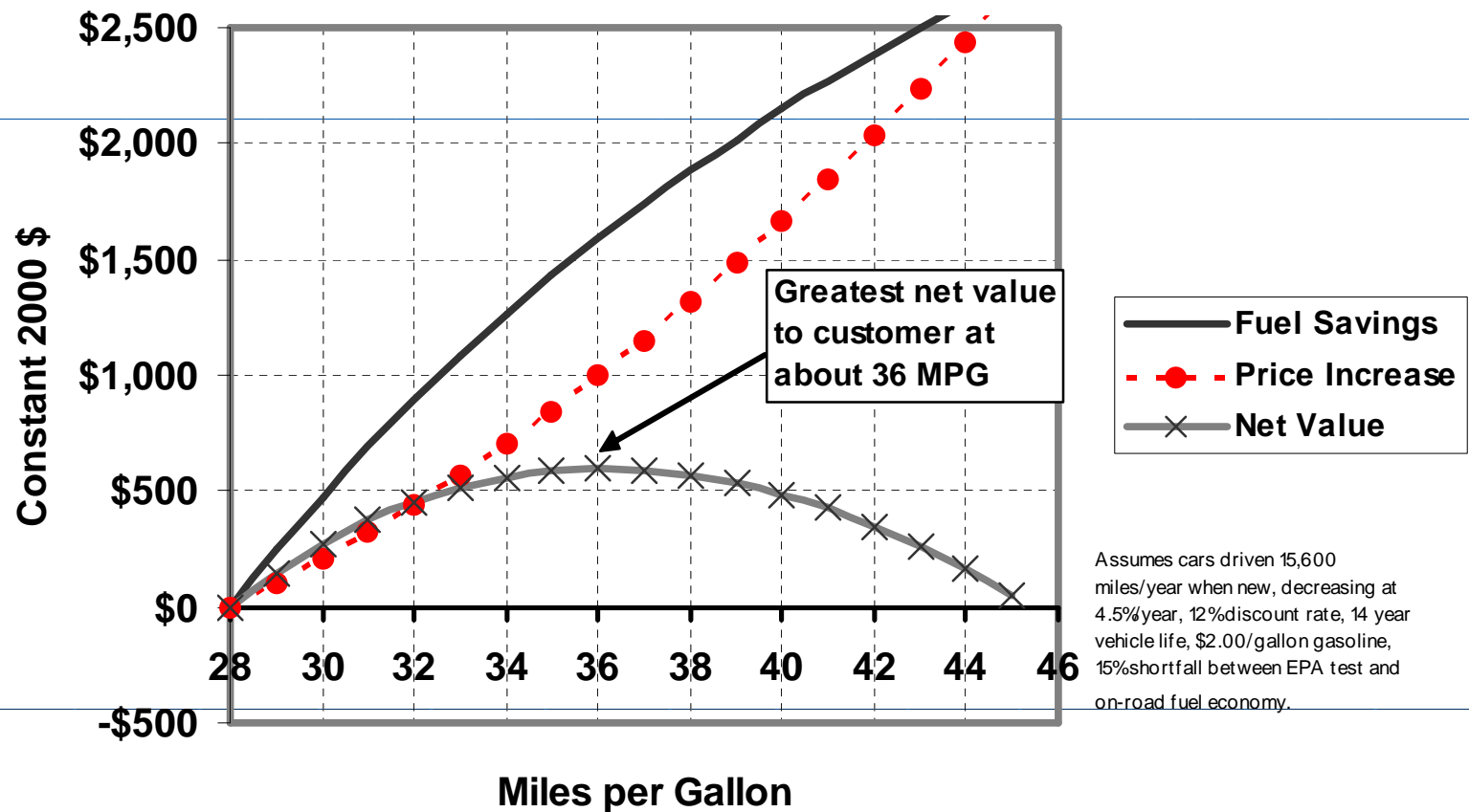


**Fuel Economy Increase Cost Curve
Large Domestic SUV (EEA, 2006)**



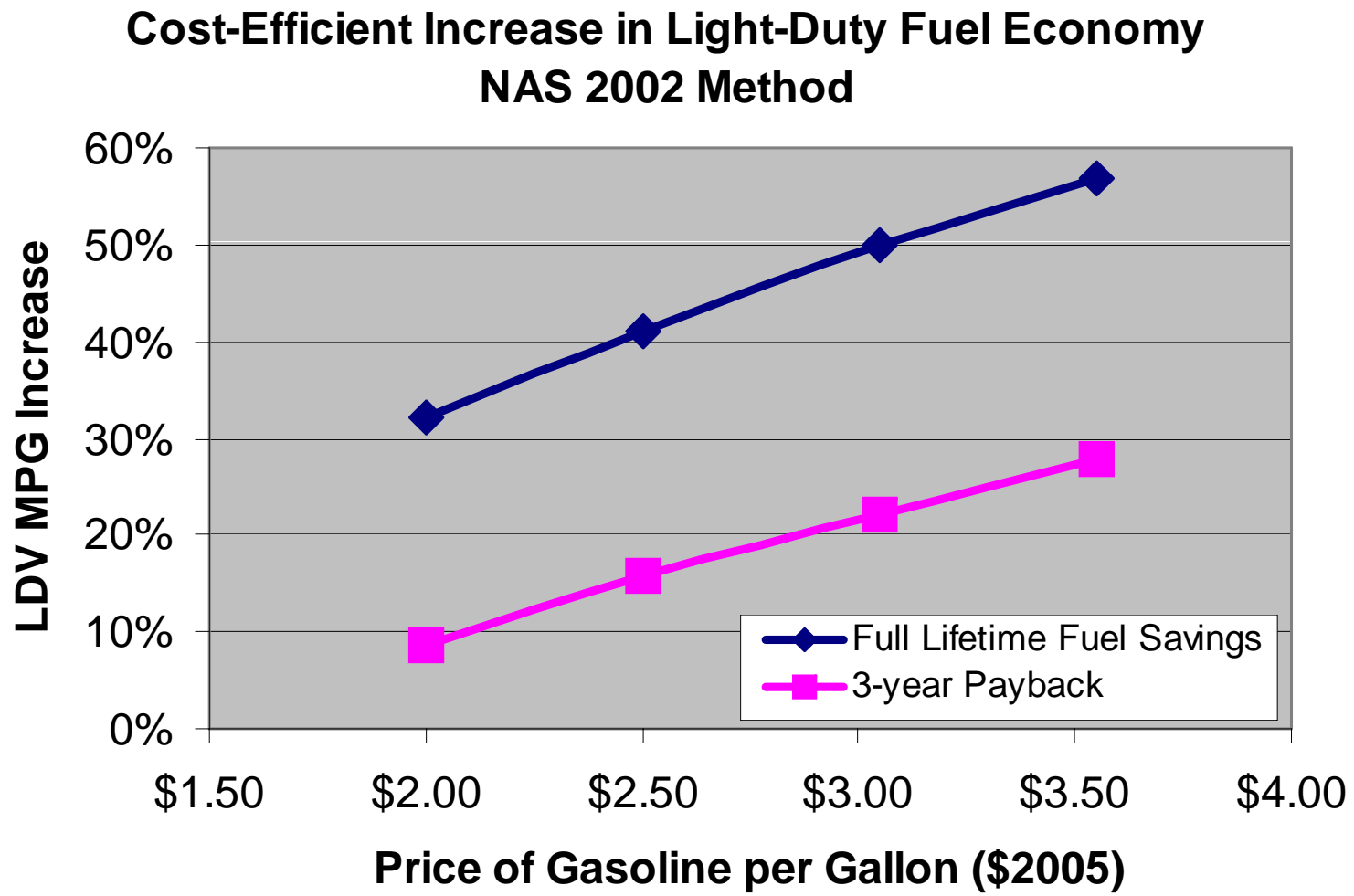
The NAS “cost-efficient” method sets $MC = MV$, maximizing expected net value to the car buyer. Net value varies only a little around the optimum.

Price and Value of Increased Fuel Economy to Passenger Car Buyer, Using NRC Average Price Curves



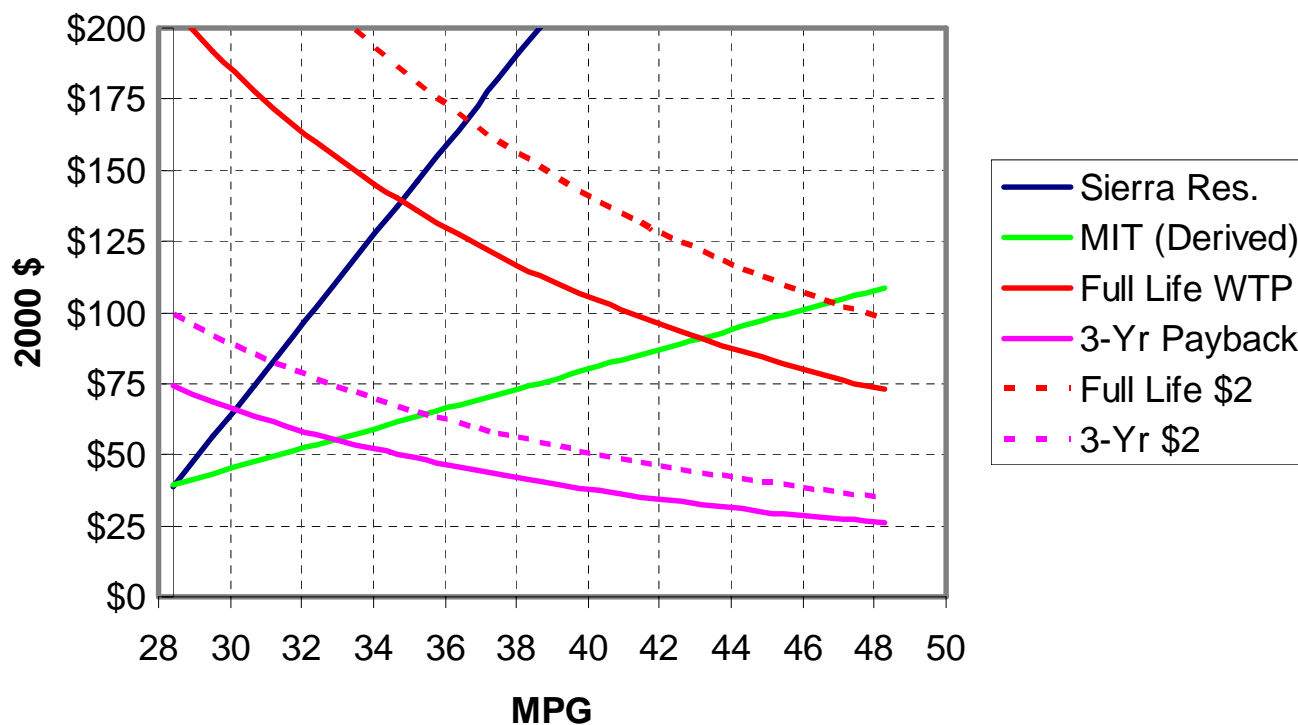
Source: Calculated from data in NAS, 2002.

Depending on the price of fuel, increasing LDV fuel economy by 30% to 50% would be “cost efficient” at gasoline prices from \$2 to \$3 per gallon.

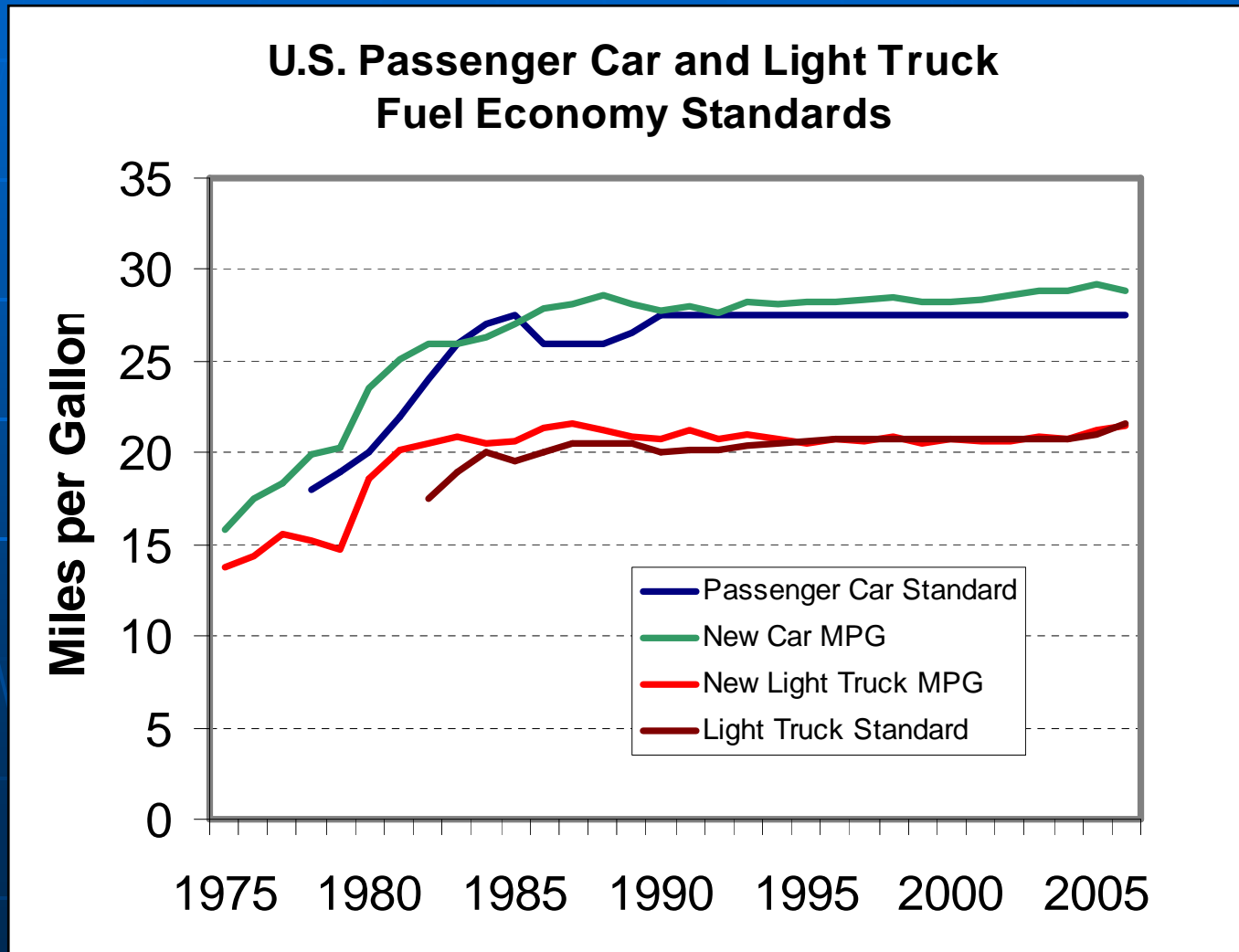


The marginal value of fuel savings is the consumer's demand curve for increased MPG. The derivative of the quadratic cost curve is the manufacturer's supply curve.

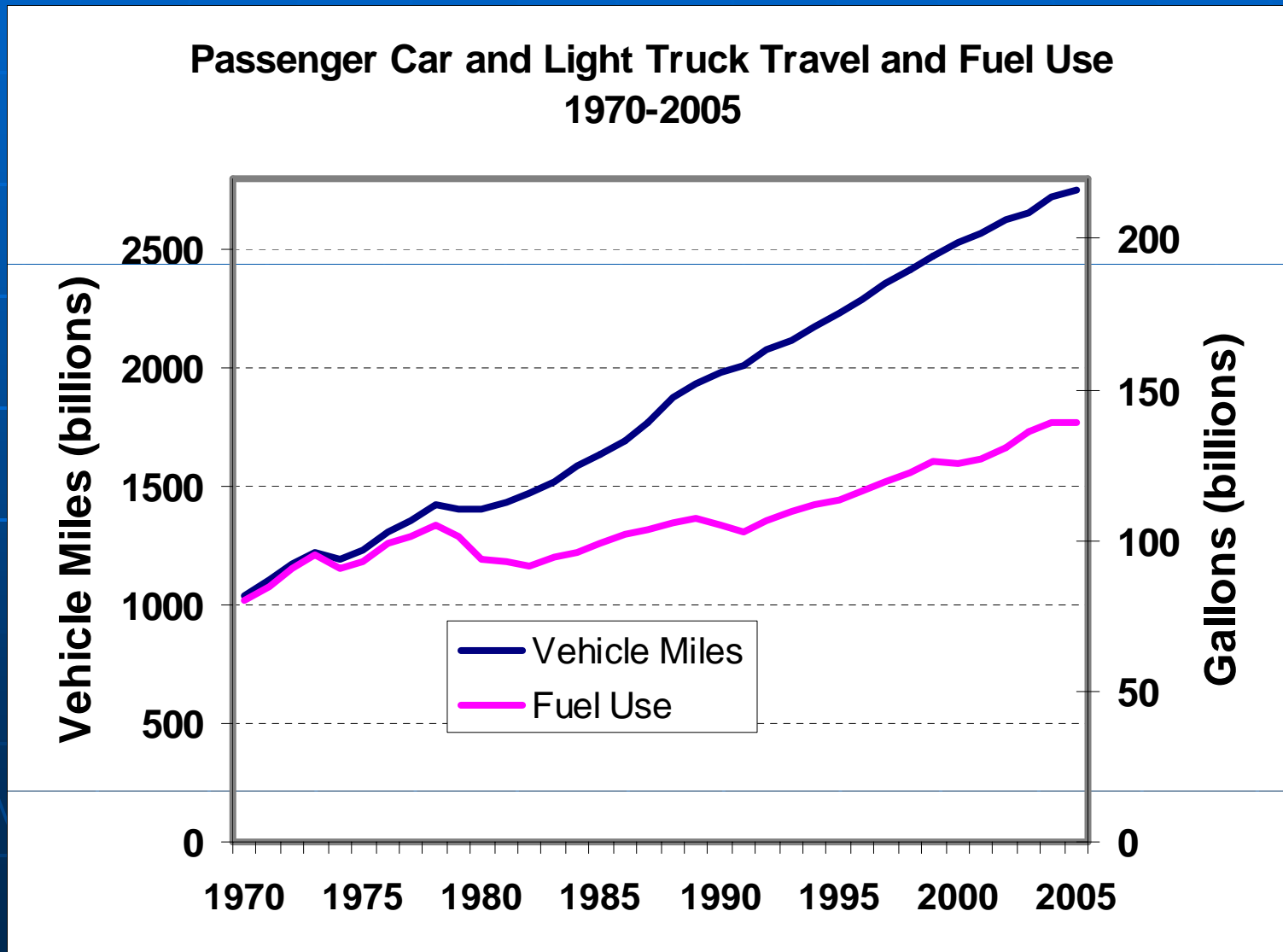
Effect of Technology and Consumer Rationality on Supply and Demand for Fuel Economy



Historical fuel economy increases track the standards closely.

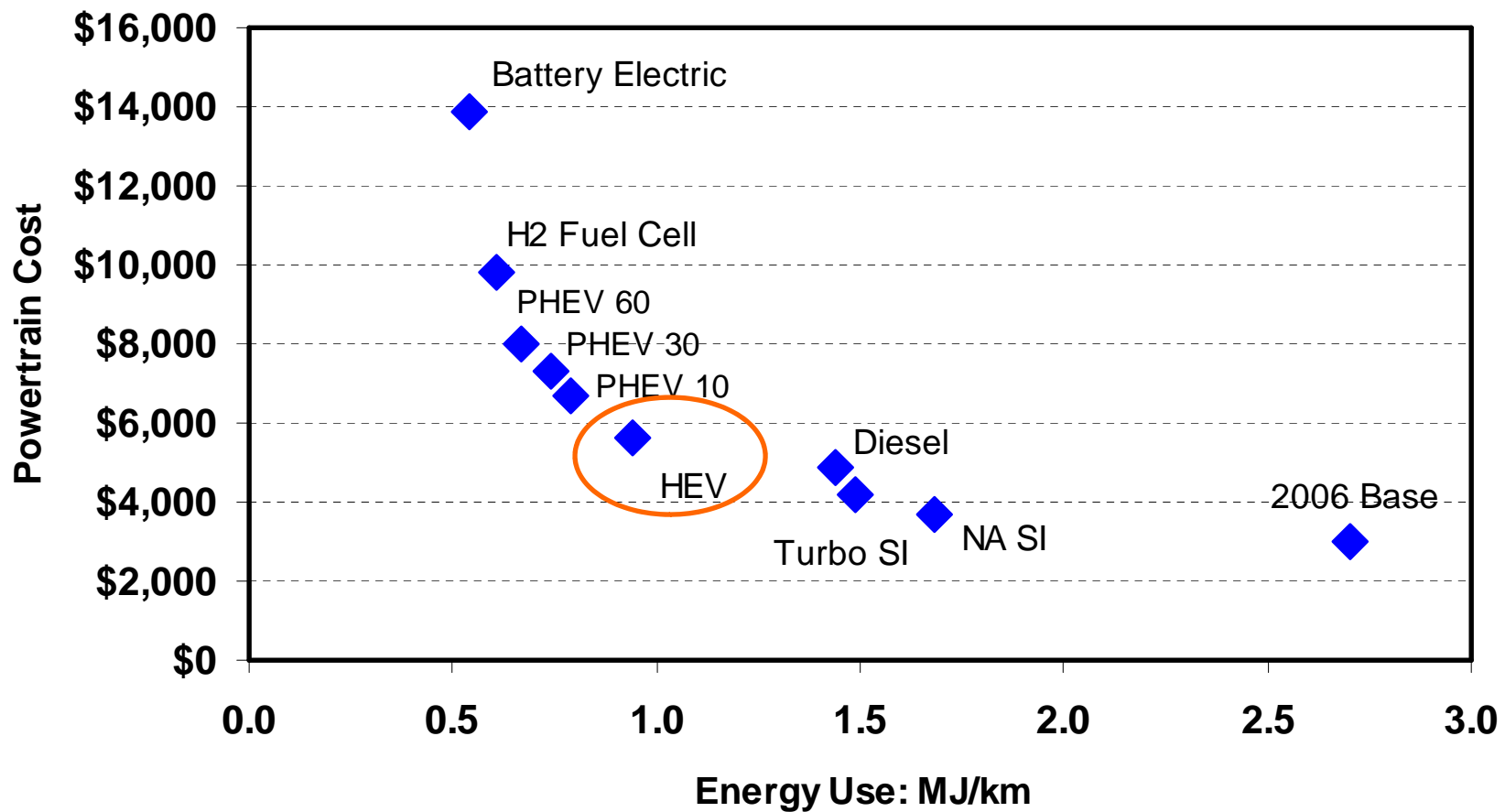


Fuel economy standards have worked well, and today save motorists about 70 billion gallons per year.



MIT also analyzed the technical potential & cost for electric drive to raise energy efficiency by 2030.

Cost v. Energy Efficiency of Future Electric Powertrain Technologies



Source: Kromer & Heywood, LFEE 2007-02 RP, May, 2007.