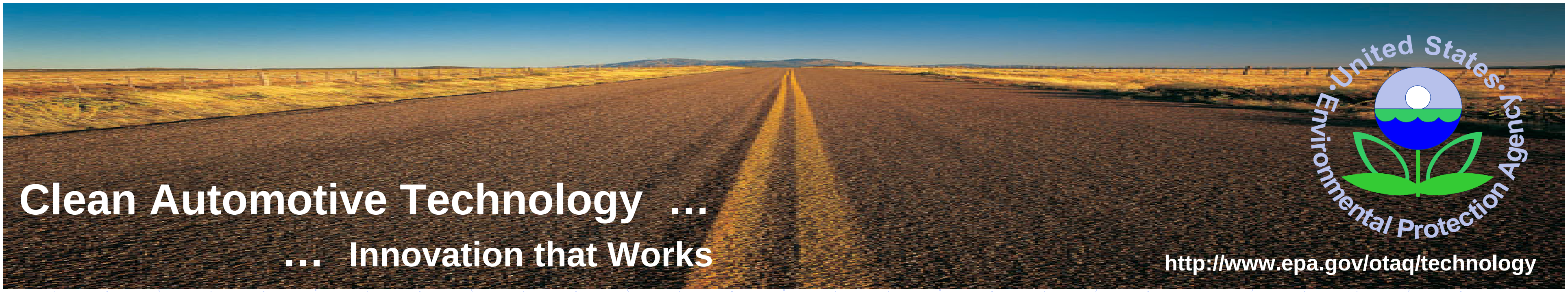


Carbon Constrained/Energy Driven Transitions to 2050

2009 ERC Symposium

10 June, 2009

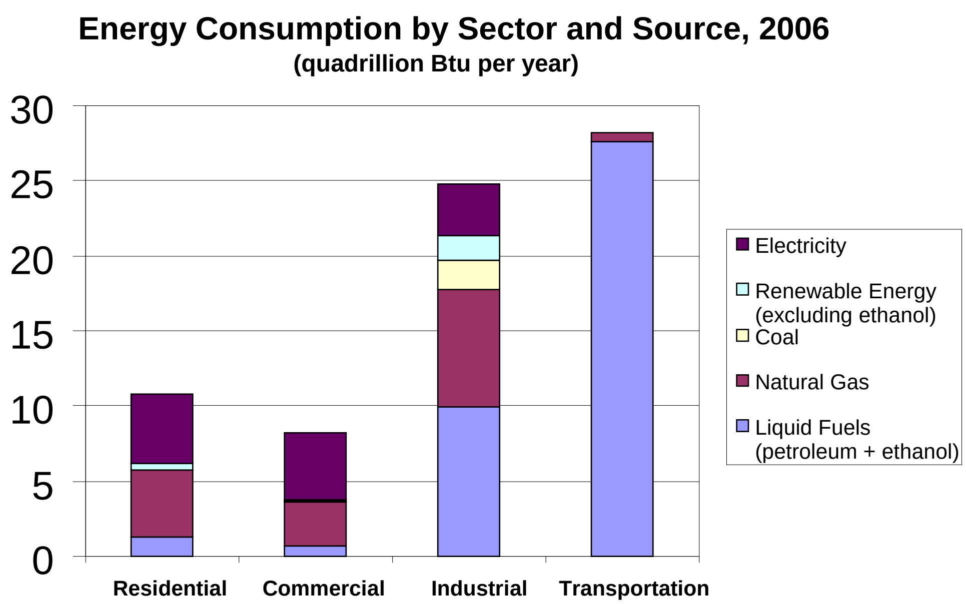
David Haugen
Advanced Technology Division
National Vehicle & Fuel Emissions Laboratory

We are at an inflection point in our response to Transportation's Energy & Environmental Policy

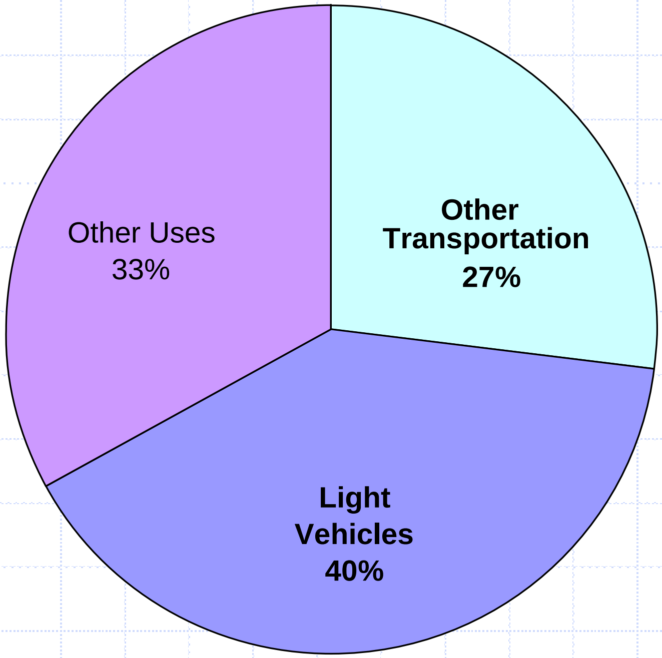
- ENVIRONMENTAL FOCUS
  - Criteria Pollutants (Health of the Population)
  - Climate Change (Health of the Planet)
- TRANSPORTATION ENERGY POLICY
  - Economic Dependence on Oil (Balance of Trade)
  - Geopolitics of Oil Reserves (National Security)
  - Finite Supply w/ Transition Concerns (Cost, Affordable)
- ADDRESSING CLIMATE CHANGE
  - Brought together-carbon emissions & energy efficiency

U.S. - Transportation and Oil

Transportation is 97% dependent on petroleum

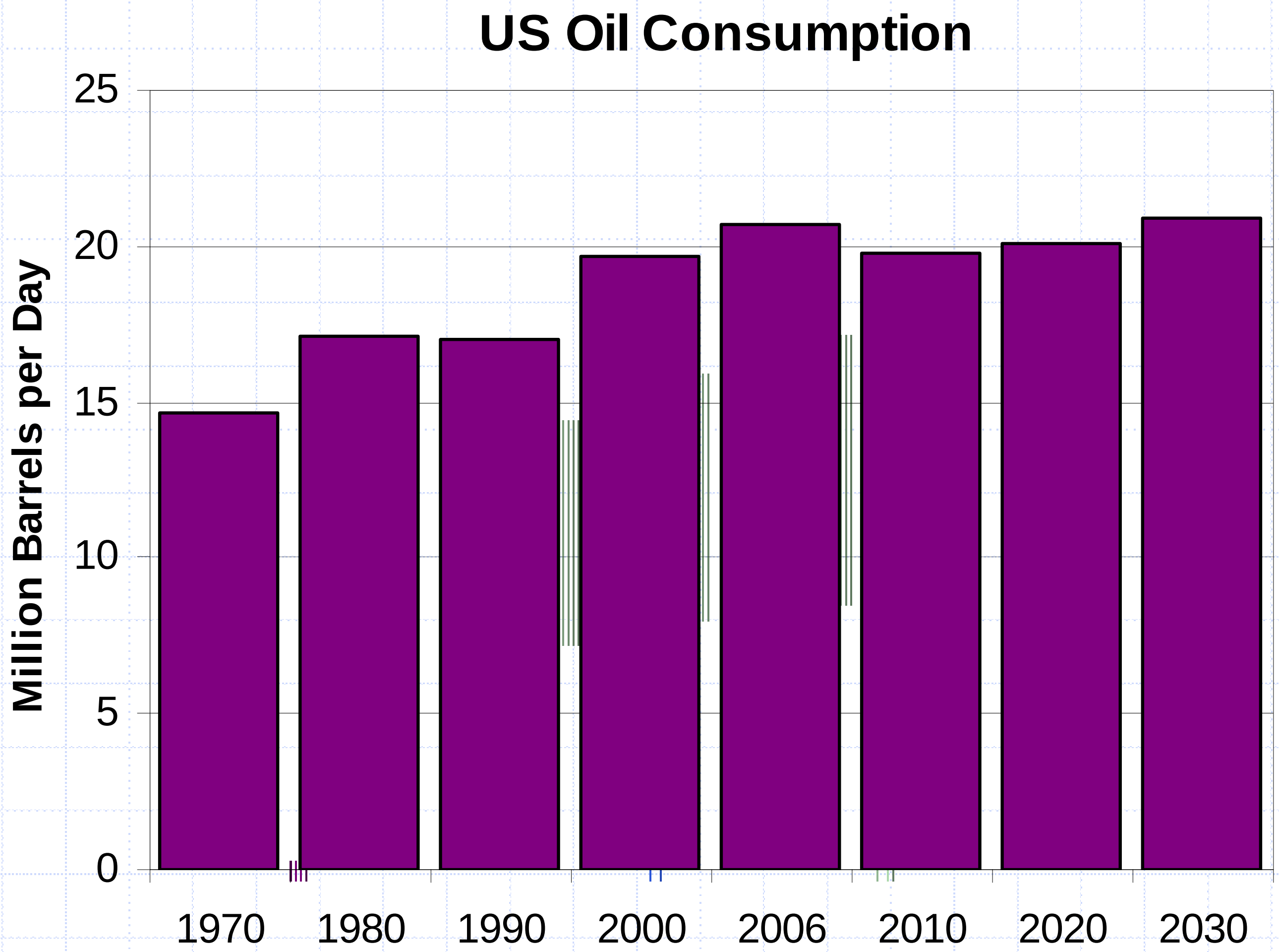


In the U.S., transportation uses 67% of all petroleum



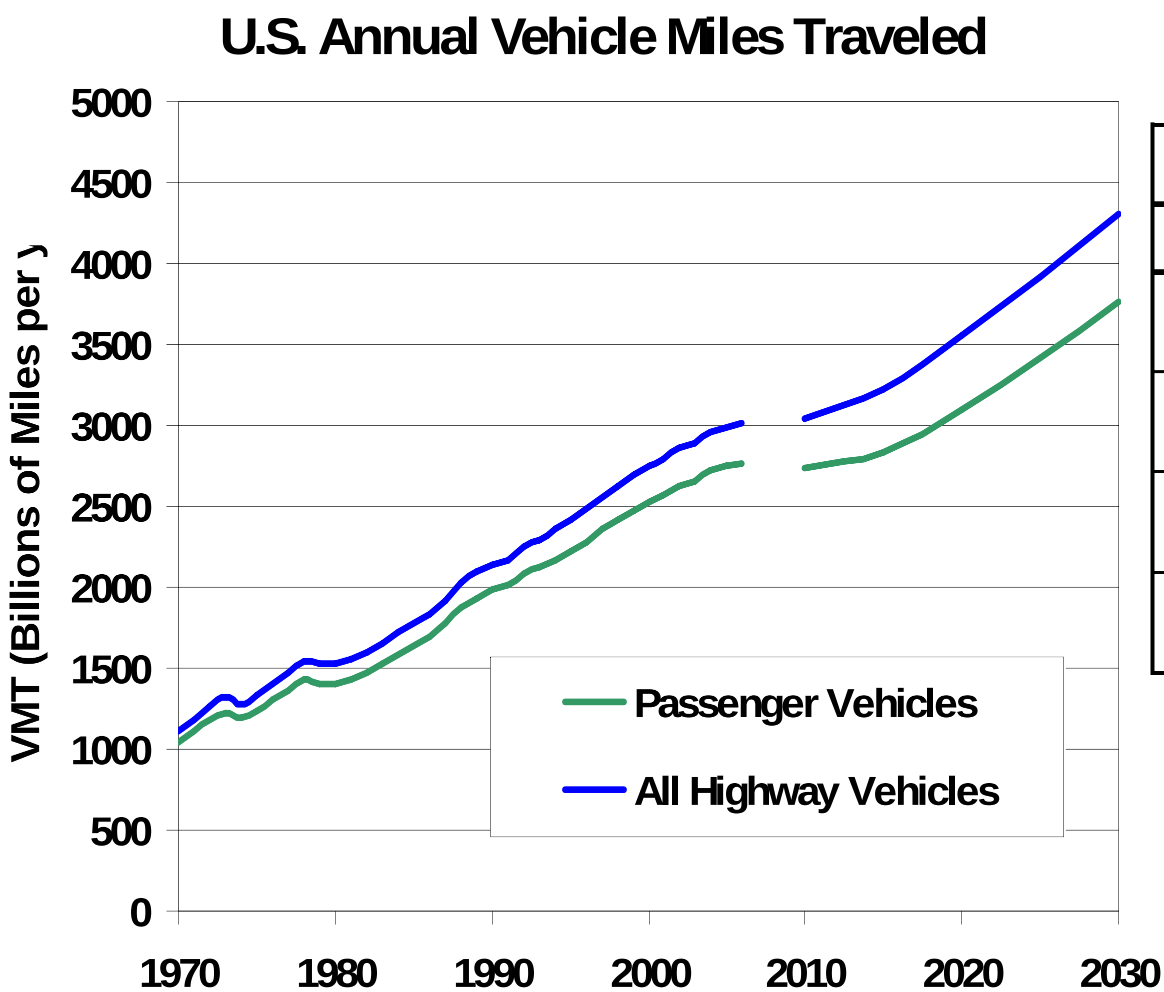
Source: Annual Energy Outlook 2008

Trend of US Oil Consumption Considering EISA2007 & ARRA2009



[-] Annual Energy Review 2006. Table 11.10. Energy Information Administration. Report No. DOE/EIA-0384(2006). June 2007.
[-] Updated Annual Energy Outlook 2009, Reflecting ARRA.Table 21. Energy Information Administration. SR/OIAF/2009-03 Apr09

Improved Vehicle Efficiency offset by more cars driving more miles



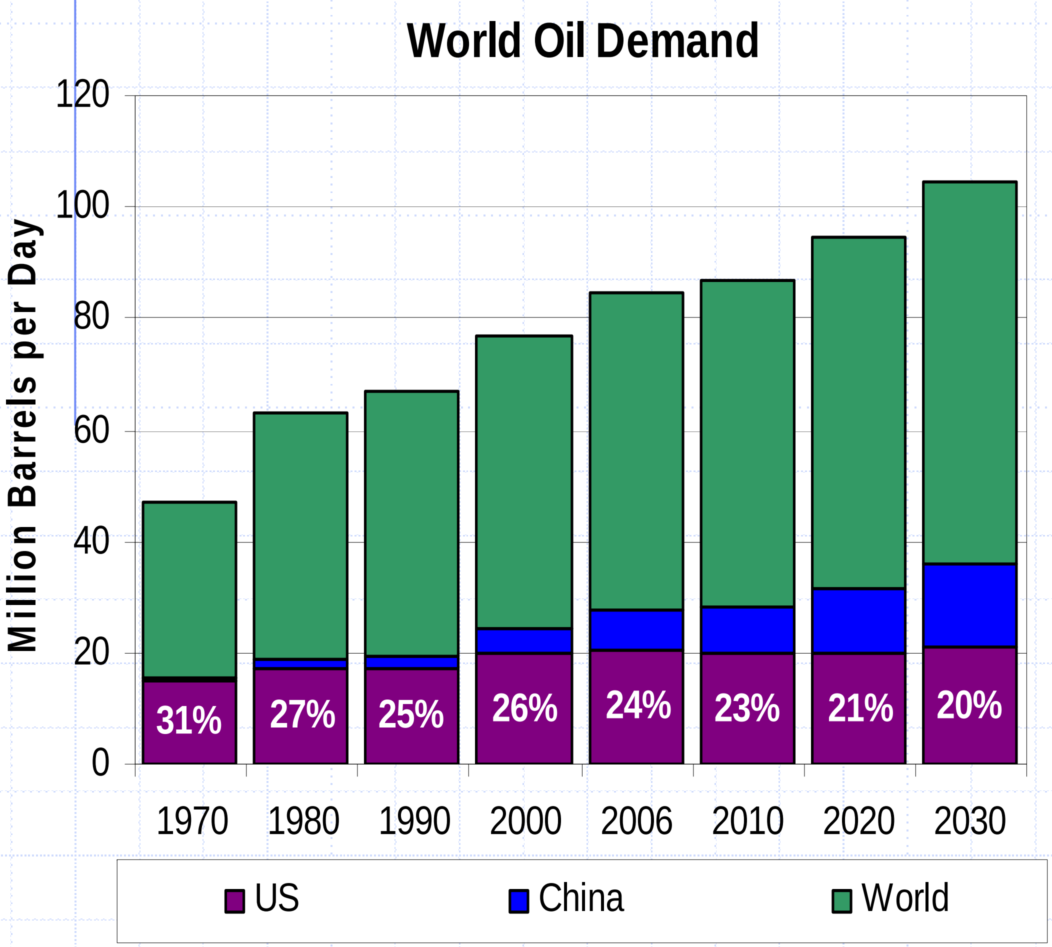
EISA2007 CAFE Proposal Combined LD Car & Truck			
MY	CAFE (mpg)	Real World (mpg)	Tailpipe (CO2 gm/mi)
2009	25.1	20.2	444
2010	25.3	20.4	436
2011	27.8	22.3	398
2012	29.2	23.5	378
2013	30.5	24.6	362
2014	31.0	25.0	356
2015	31.6	25.5	349
2016	32.3	26.0	342
2017	32.9	26.5	336
2018	33.6	27.0	329
2019	34.3	27.6	322
2020	35.0	28.2	315

Sources:

[-] U.S. DOT, Federal Highway Administration, Highway Statistics 2006, Table VM-1 & Table 3.4

[-] Annual Energy Outlook 2009. Table A7. Energy Information Administration. Report No. DOE/EIA-0383(2009). March 2009

Global Trend of Oil Consumption



Country/Region	Vehicles per 1000 people 1996	2006	% annual change
Africa	23.4	25.6	0.9%
Asia, Far East	110.3	154.1	3.4%
Asia, Middle East	57.1	63.3	1.0%
Central & South America	67.8	99.8	3.9%
China	9.3	26.6	11.1%
Europe, East	167.0	254.4	4.3%
Europe, West	495.6	593.7	1.8%
Pacific	459.8	524.7	1.3%
United States	780.4	840.3	0.7%
Canada	560.0	599.6	0.7%

U.S. Population Growth **0.95%/year**

China's Population Growth **0.60%/year**

Global Population Growth **1.14%/year**

[-] Annual Energy Review 2006. Table 11.10. Energy Information Administration. Report No. DOE/EIA-0384(2006). June 2007.
[-] Updated Annual Energy Outlook 2009, Reflecting ARRA.Table 21. Energy Information Administration. SR/OIAF/2009-03 Apr09

Key IPCC Findings on Climate Change Impacts

- Warming of the climate system is unequivocal. The probability that warming is caused by natural climatic processes alone is less than 5%.
- Both past and future anthropogenic carbon dioxide emissions will continue to contribute to warming and sea level rise for more than a millennium.
- *"Impacts due to altered frequencies and intensities of extreme weather, climate, and sea levels are very likely to change."*
- *"Adaptation will be necessary to address impacts resulting from the warming which is already unavoidable due to past emissions."*
- *"Future vulnerability depends not only on climate change but also on development pathway."*
- *"Impacts of climate change will vary regionally but, aggregated and discounted to the present, they are very likely to impose net annual costs which will increase over time."*

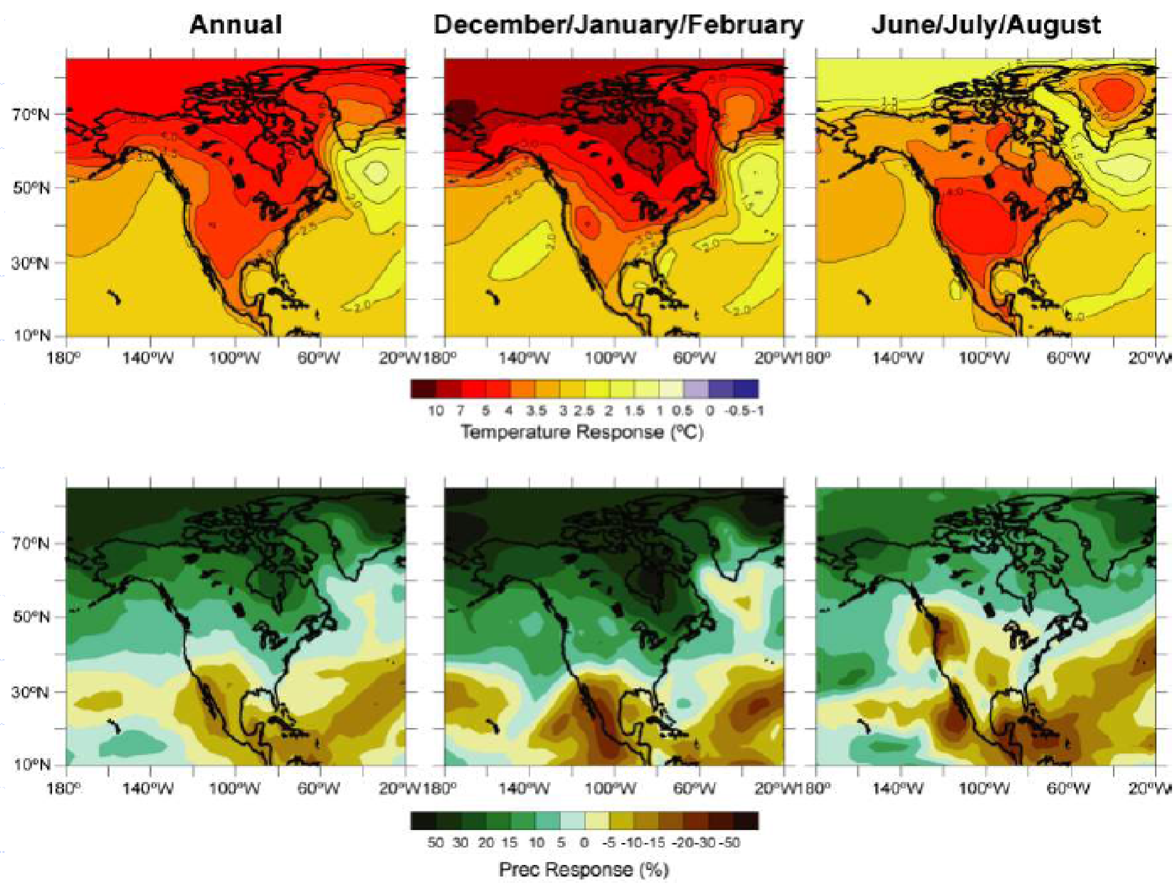
Source: IPCC (2007) Summary for Policymakers of Working Group II.

Climate Change – another policy consideration – Not “just” or even “like” energy\oil & economics

Toward the end of this 21st century, assuming moderate emissions growth, the United States will be much warmer and dryer.

All economic sectors can be expected to participate in GHG reduction strategies.

Figure 6.10: Projected temperature and precipitation changes over North America from the MMD-A1B simulations.



Source: Christensen et al. (2007). Top row: Annual mean, December-January-February, and June-July-August temperature between 1980 to 1999 and 2080 to 2099, averaged over 21 models. Bottom row: same as top, but for fractional change in precipitation.

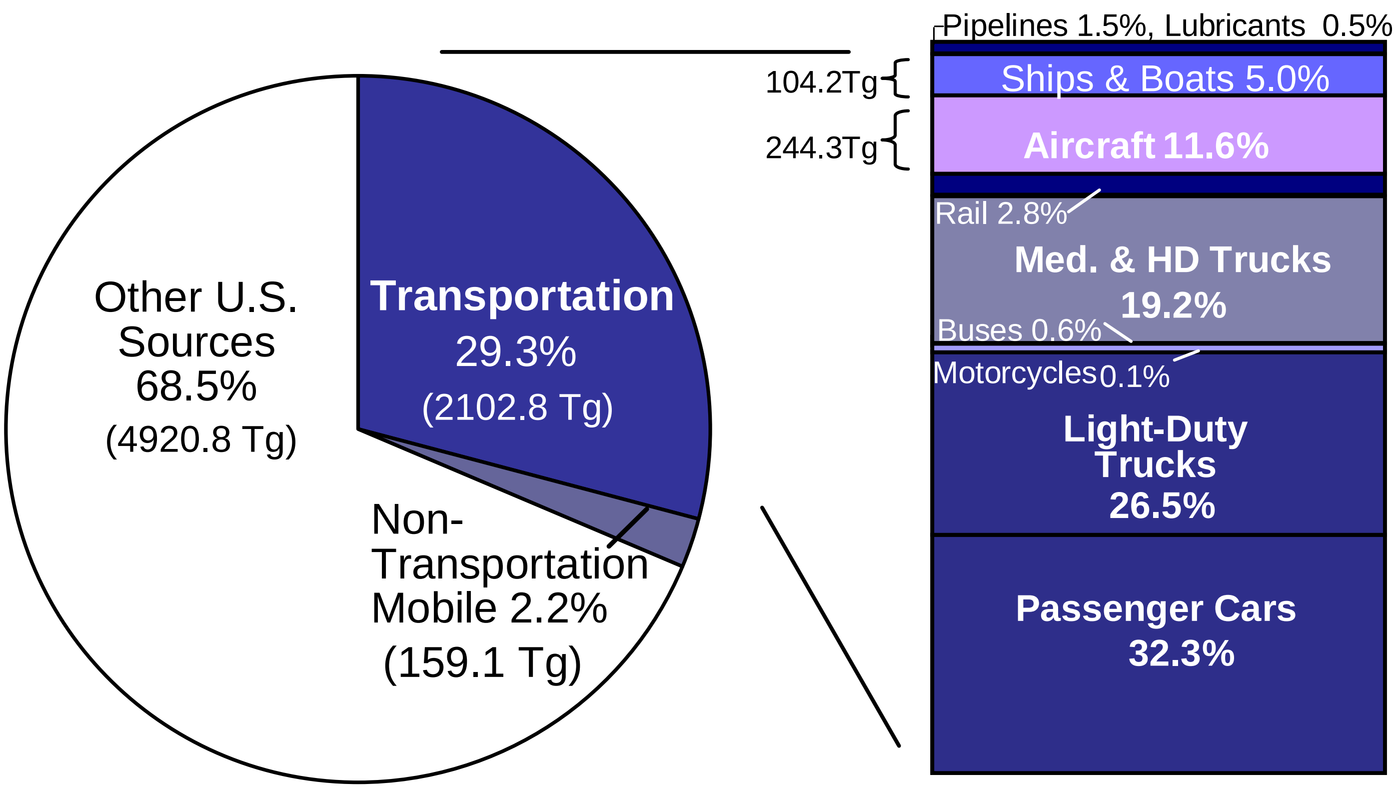
SOURCE: 2008 Draft Technical Support Document on Climate Change (EPAHQOAR-2008-0318-0082)

Carbon Constrained

- On April 17, 2009, EPA's Administrator Jackson signed a proposal that finds six key greenhouse gases – CO_2, CH_4, N_2O, HFCs, PFCs & SF_6 – threaten the public health and welfare of current and future generations.
- In response to the 2007 US Supreme Court order regarding Mass. v. EPA, EPA is proposing to regulate these GHG emissions from new motor vehicles and motor vehicle engines under 202(a) of the Clean Air Act.
  - Longer term, this suggests that GHG might be addressed in the manner EPA has regulated NOx, CO, HCs, & PM
  - Looking at transportation within the context of section 202(a) of the CAA, it is not unreasonable to expect that any light-duty auto standards could be followed by heavy-duty on and off-road, small engines, and marine
- Opportunity to comment closes June 23, 2009

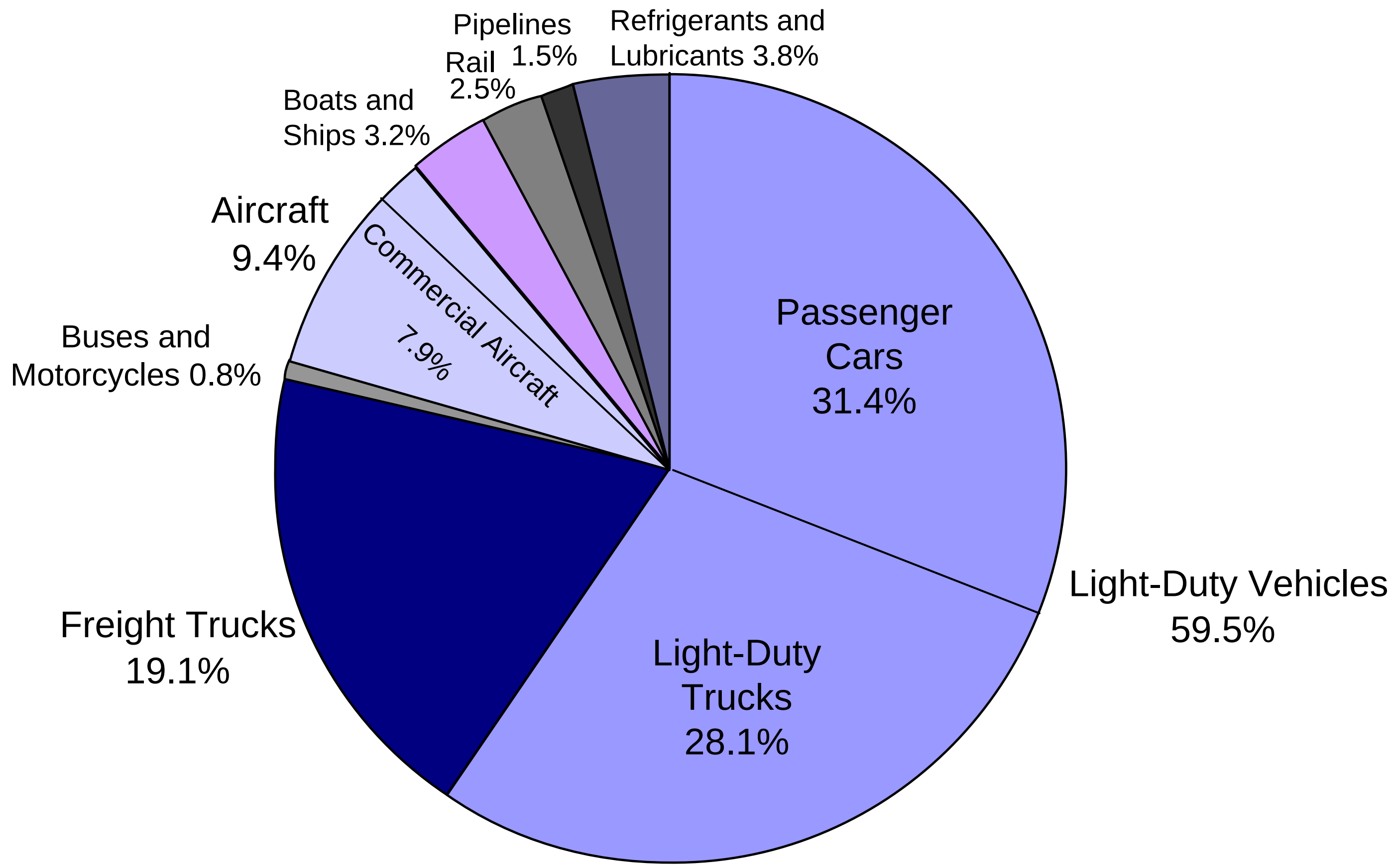
Mobile Sources have been a Large and Growing Share of the Nation's GHGs - 31.5% of all US sources

2006 U.S. GHG Emissions



Transportation is the fastest-growing source of GHGs in the U.S., accounting for 47 percent of the net increase in total U.S. emissions from 1990-2006.

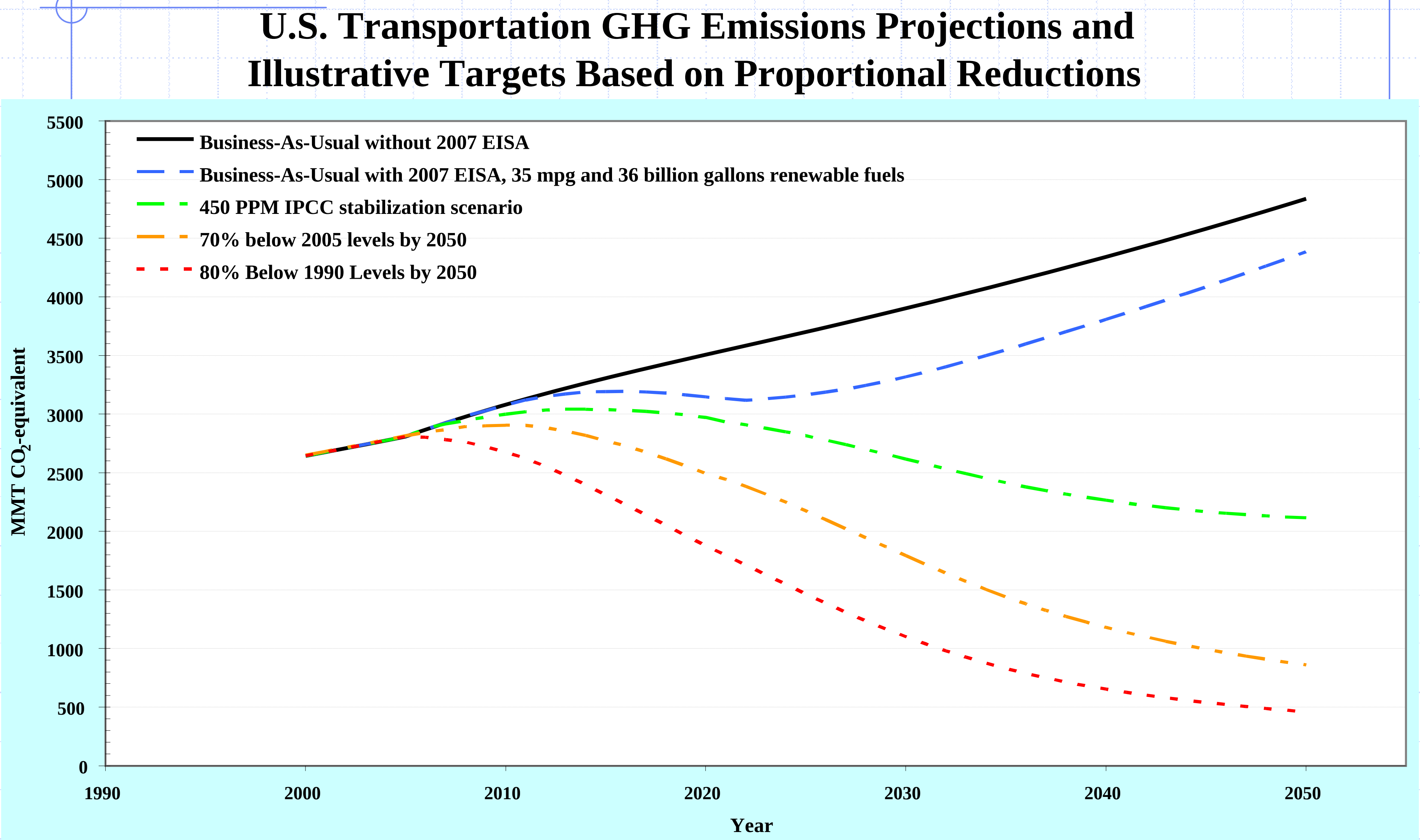
U.S. Transportation Sector GHG Emissions, 2005



Emissions weighted based on global warming potential of greenhouse gases (CO_2, CH_4, N_2O and HFCs).
Official transportation sector estimates do not include emissions from international bunkers, which are reported in the Inventory but not included in the national total.
Emissions from agricultural and construction equipment are classified as "non-transportation mobile" sources and are reflected in industrial sector totals.

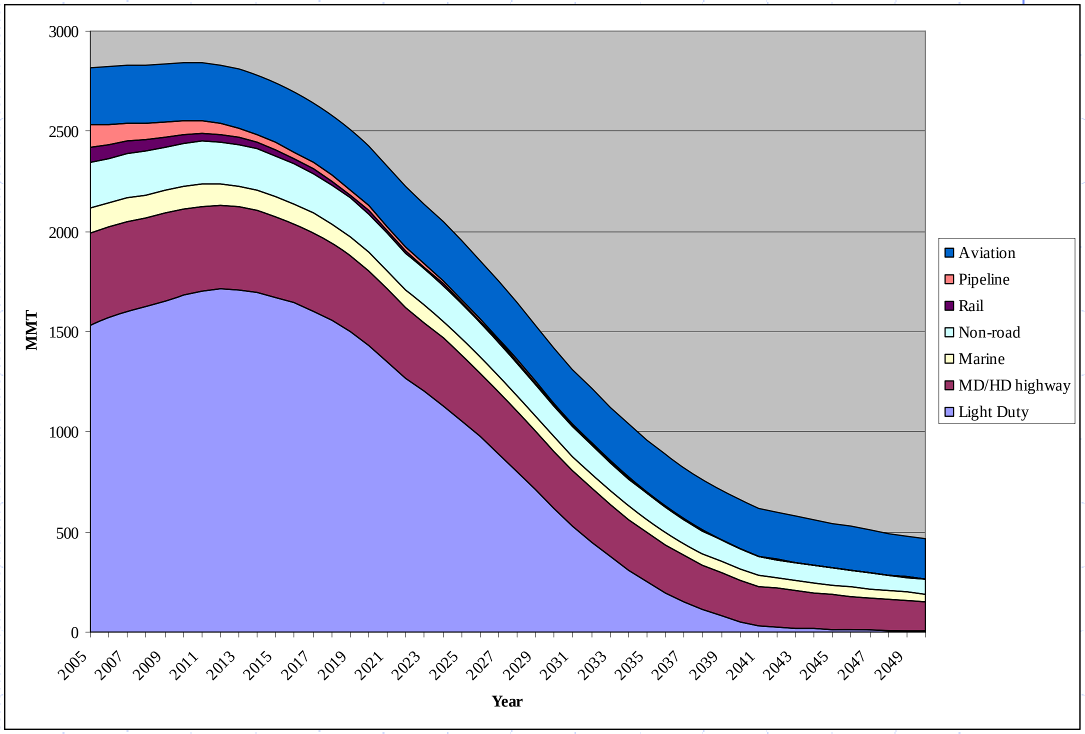
Source: Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2005

Transportation has a direct and compelling part to play in Climate\Energy solutions

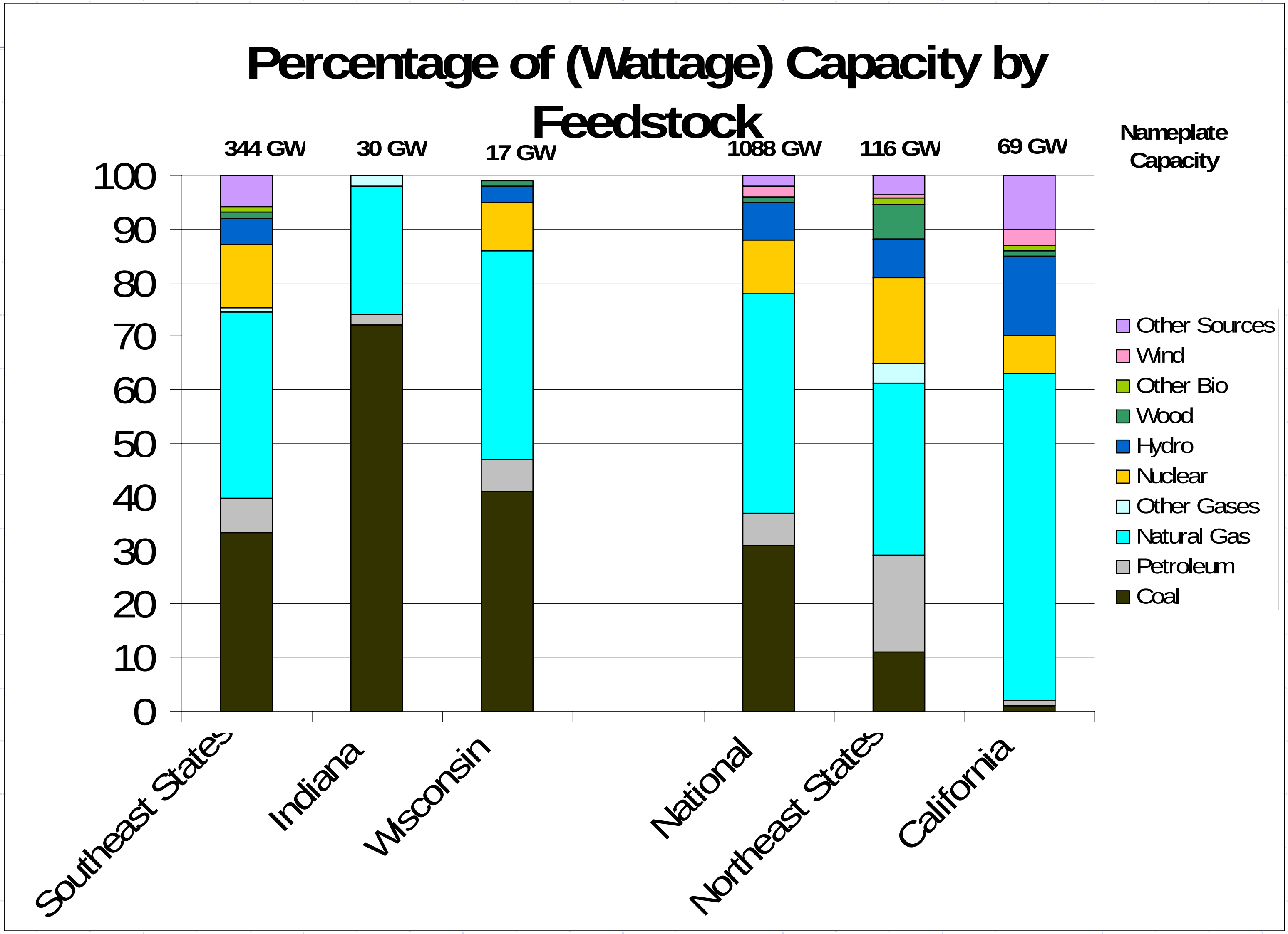


What might an ~80% GHG reduction by 2050 look like?

- One example pathway — do all of the following:
  - Light Duty
    - 100% electric vehicles in fleet (running on zero-GHG electricity)
    - NO liquid fuels
  - Heavy Duty
    - Fuel economy—equivalent to today's LDVs (20 mpg onroad)—PLUS
    - 20% reduction in VMT
  - Rail and Pipelines
    - Full electrification (running on zero-GHG electricity)
  - Air
    - 50% reduction in energy demand (combination of efficiency & VMT)
  - Marine
    - 66% reduction in energy demand (combination of efficiency and VMT)
  - Nonroad
    - 70% reduction in energy demand (combination of efficiency and VMT)
  - Fuels
    - 40 billion gallons of cellulosic ethanol used across the sector in gas and diesel engines



Today's Electric Energy Feedstocks



Source-to-Sink Comparison: Today's Fossil Sources

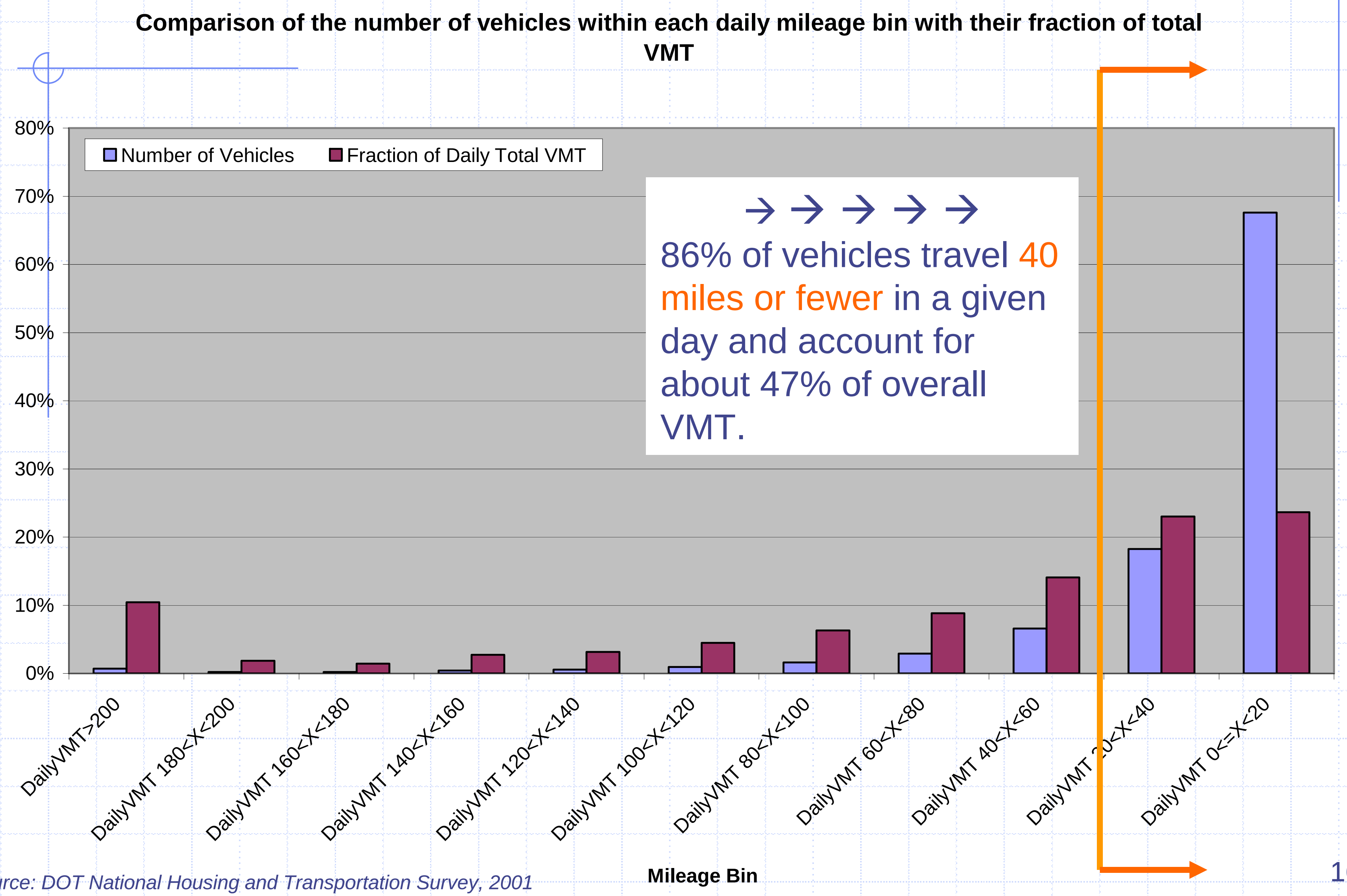
	Crude Oil			Coal Electric	National Electric
FUEL	Gasoline	Gasoline	Gasoline	Coal-fired Electric (today)	National Electric Mix (today)
Vehicle Type & Vehicle Cost	**Compact Sedan** convention powertrain **~$18k**	**Compact Sedan** Advanced Gas-Hybrid **~$21-24k**	**Compact Sedan with PHEV - Extended Range EV type $30k+** "Never Plugged In" |	"All Electric" fuelled	
	Resource Used, Energy Consumed for 300 miles of driving				
Fuel Cost	**$26** $3/gal, 8.8 gal	**$19** $3/gal, 6.2 gal	**$20** $3/gal, 6.7 gal	**$11** 12c/kWh, <30 mi / trip	**$11** 12c/kWh, <30 mi / trip
Feedstock Consumed	0.24-.29 barrel oil	0.16-.21 barrel oil	0.17-.22 barrel oil	35-41 kg coal	~~~~~
Feedstock-Energy Used	~1.4 GJ	~0.9 GJ	~1.0 GJ	~1.0GJ	~~~~~
Feedstock-Energy Rate	~1.3 kW-hr/mi	~0.8 kW-hr/mi	~0.9 kW-hr/mi	~0.9 kW-hr/mi	~0.9 kW-hr/mi
Vehicle Energy Used (measured at tank or plug)	1.1 kW-h/mi 34 mi/gal	0.7 kW-h/mi 49 mi/gal	0.8 kW-h/mi 45 mi/gal	~0.3 kW-h/mi	~0.3 kW-h/mi
	GHG Emissions for 300 miles of driving				
Carbon Emitted - LifeCycle	~106 kg CO_2 in Air	~75 kg CO_2 in Air	~81 kg CO_2 in Air	~130 kg CO_2 in Air	~93 kg CO_2 in Air
CO2 in Air gm/mile	320-360 gmCO_2/mi	230-270 gmCO_2/mi	240-275 gmCO_2/mi	390-435** gmCO_2/mi	280-320** gmCO_2/mi

"gal-ge" is a gallon of fuel with gasoline energy equivalency

* All vehicles are comparable size and utility (1,400 kg - Toyota Prius or GM "Delta" platform)

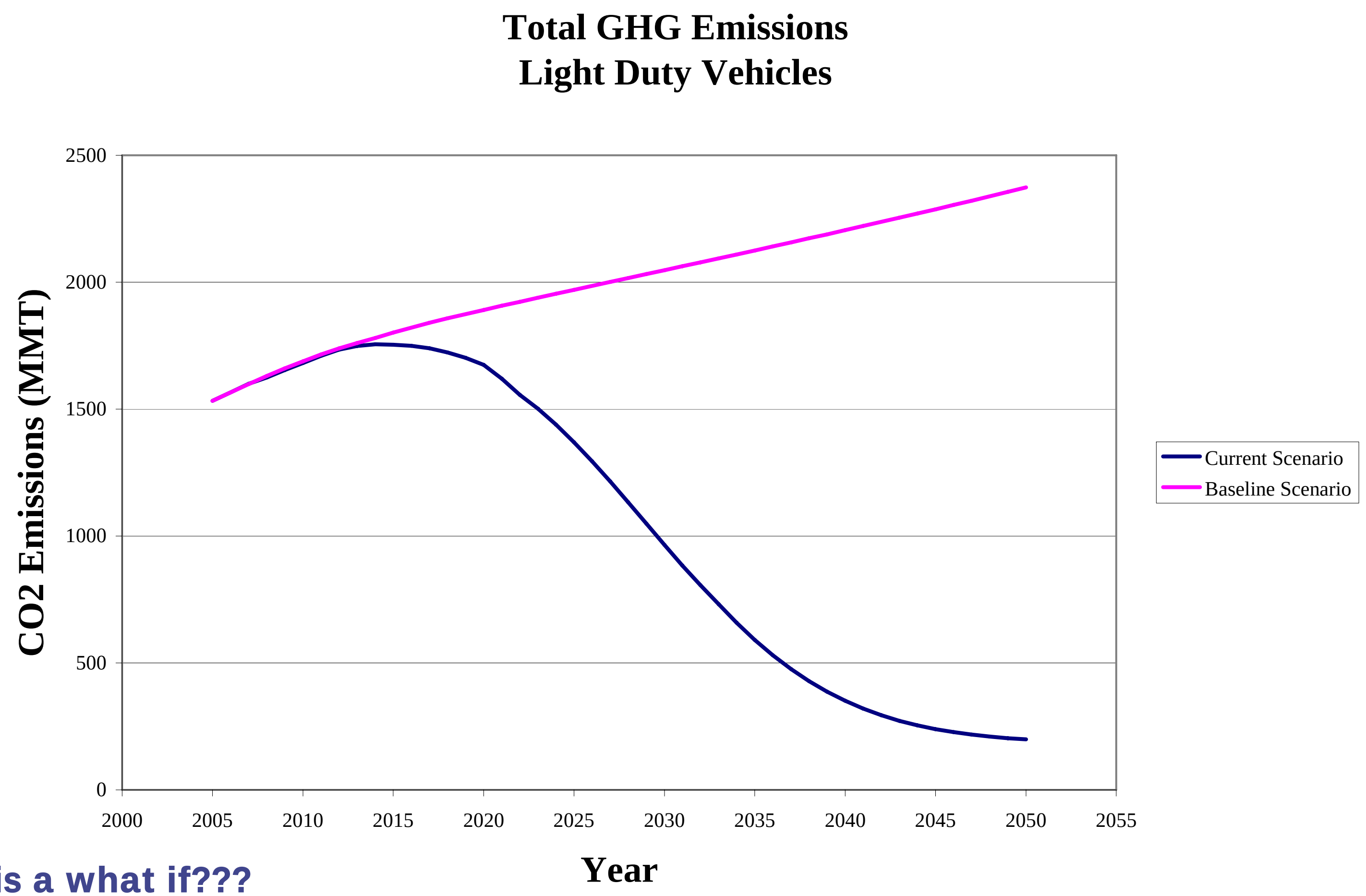
** Assumes best "GHG case" operating cycle for PHEVs - not more than 30 miles per charge (i.e., used like a short range BEV)

Typical Daily Vehicle Mileage



Source: DOT National Housing and Transportation Survey, 2001

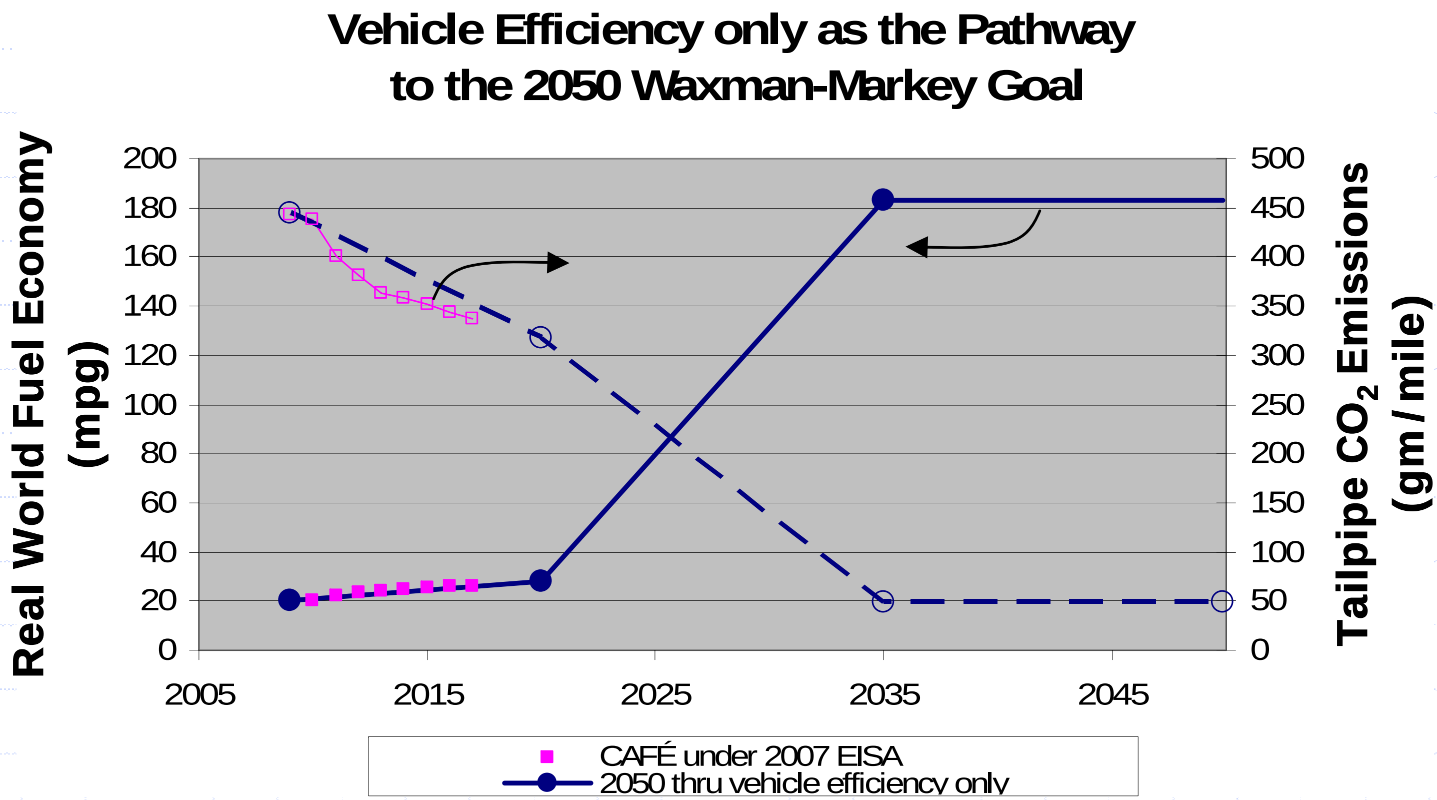
WHAT IF?... we tried to reach 2050 GHG thru vehicle efficiency improvements only



This is a what if???

-How much would LD vehicle energy\fuel efficiency need to improve if LD vehicles met "their fair share" contribution to the fleet reduction of an 83% reduction in GHG by 2050, if vehicle efficiency alone was used (no fuels carbon reduction)

WHAT IF?... we tried to reach 2050 GHG thru vehicle efficiency improvements only



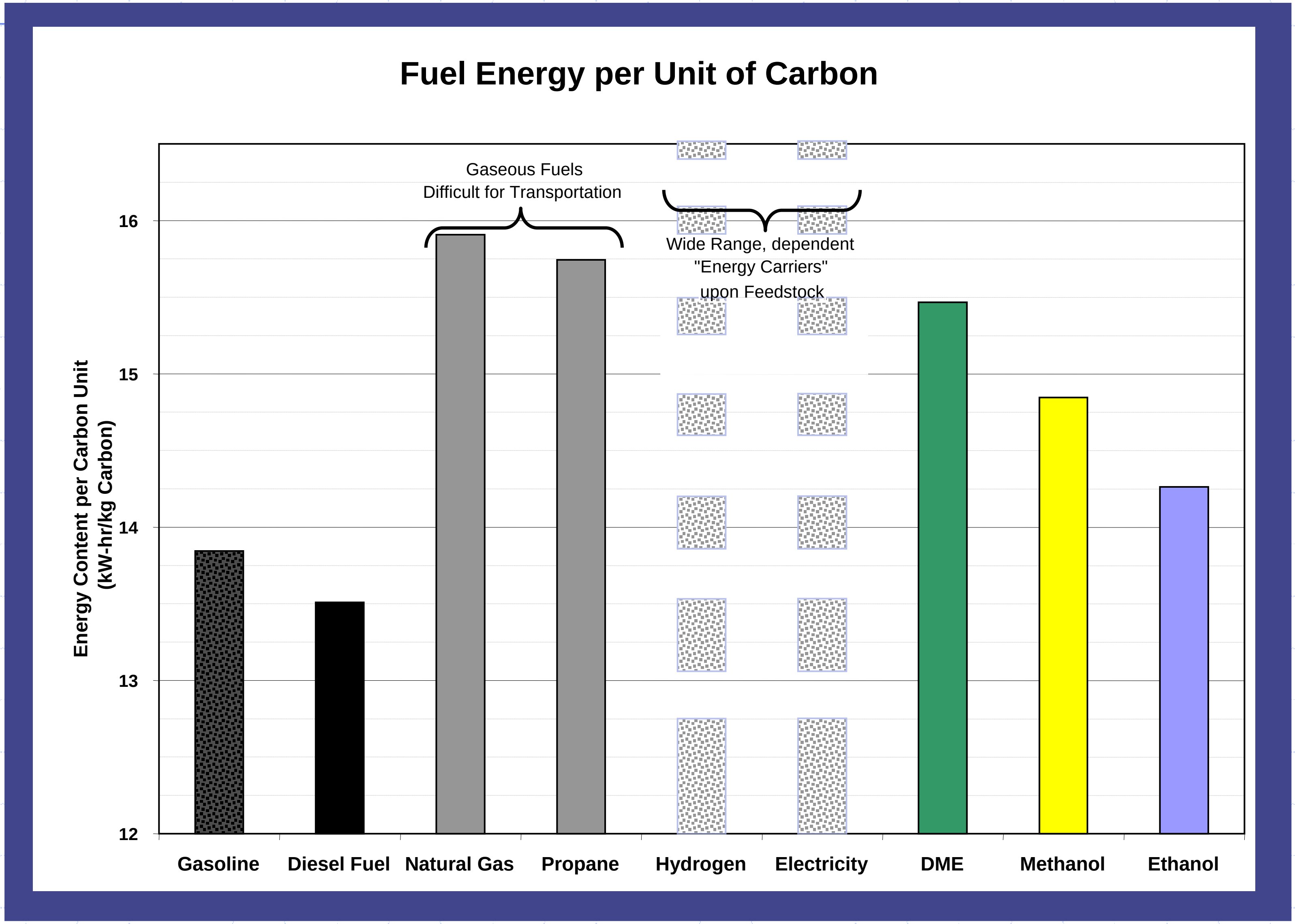
	What if???			
MY	Real World (mpg)	CAFE\Lab (mpg)	Tailpipe (CO2 gm/mi)	Fleet Ave. (CO2 gm/mi)
2009	20	26	444	444
2020	28	35	317	
2035	183	229	49	
2049.86	183	229	49	57

Source-to-Sink Comparison: 2020-2030 Options

	Best Fossil (Future)	Nuclear	Biomass Gasification	Biomass Gasification w/CCS
FUEL	Coal-fired Electric Plant (future w/ CCS)	Electric Plant (nuclear)	Cellulose>Synthetic\ Alcohol Fuel	Cellulose>Synthetic\ Alcohol Fuel (w/ CCS)
Vehicle Type & Vehicle Cost	**Compact Sedan** PHEV-ER EV $30+k**	**Compact Sedan** PHEV-ER EV $30+k**	**Compact Sedan** Advanced IC Engine + Hybrid **$21-24k**	**Compact Sedan** Advanced IC Engine + Hybrid **$21-24k**
	Resource Used, Energy Consumed for 300 miles of driving			
Fuel Cost	**$13** 15.6c/kWh, 10x30 mi trips	**$11** 12c/kWh, 10x30 mi trips	**$??** $?/gal, 6.1 gal	**??** $?/gal, 6.1 gal
Feedstock Consumed	39-44 kg coal		70-78 kg biomass	78-87 kg biomass
Feedstock-Energy Used	~1.1GJ		~410 kW-hr	~450 kW-hr
Feedstock-Energy Used	~1.02kW-hr/mi		~1.37 kW-h/mi	~1.50 kW-h/mi
Vehicle Energy Used (measured at tank or plug)	0.28 kW-h/mi 120 mi/gal-gas equivalent	0.28 kW-h/mi 120 mi/gal-gas equivalent	0.70 kW-h/mi 50 mi/gal	0.70 kW-h/mi 50 mi/gal
	GHG Emissions for 300 miles of driving			
Carbon Emitted - in AIR & GND	~21 kg CO_2 in Air ~82 kg CO_2 in Gnd	~2 kg CO_2 in Air 0 kg CO_2 in Gnd	~7 kg CO_2 in Air ~0 kg CO_2 in Gnd	~(-30) kg CO_2 in Air ~32 kg CO_2 in Gnd
Net CO2 in Air gm/mile	60-85** gmCO_2/mi	5-10** gmGHG/mi	20-30 gmCO_2/mi	-(70-90) gmCO_2/mi

Transportation Fuel's Carbon Content

(Not including fuel conversion efficiency of ICE\FCV\BEV or Source-to-Tank Carbon emissions)



Focusing IC Engine Research on Low-GHG liquid Future Fuels

Alcohols & DME (Dimethyl Ether) fuels for engines:

- Enable high compression ratio engines, for high efficiency
- Tolerant of high boost and exhaust gas recirculation (EGR) for
  - Unthrottled operation, for high efficiency
  - Advanced combustion phasing, for best efficiency
  - Lower NOx and PM formation
  - Alcohols: high EGR rates/high CR reduces enrichment requirements for TWCs

- **Methanol** (M85) and **Ethanol** (E85) are well suited to low cost Spark-Ignition, Port Fuel Injection, with conventional exhaust aftertreatment

- **DME** fits within the traditional heavy-duty Direct Fuel Injection architecture

The Future Vehicle Fleet

- A policy response to Climate Change will truly be a paradigm shift in how fleet efficiency issues are dealt with in the Transportation Sector
- The degree of vehicle efficiency improvements to meet GHG goals will need to be fleet transformative, not incremental
- Decarbonizing the fuel should be a major thrust of the technical development, but vehicle efficiency will also be paramount if we are to retain the affordability of personal mobility
- During the next 20+ years we can be hopeful - but not depend - on finding a single breakthrough technology that enables the transportation fleet to reach these GHG levels; advancements in many areas (fuels, batteries, fuel cells, hybrids, vehicles, engines, clean electricity) will be required
- Further development of low carbon fuel & their engines, particularly for the heavy-duty and non-road fleet (where electrification will be even more challenged) is an opportunity for all engine researchers