Technology Options in Transportation

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by
Dr. George C. Eads
Senior Consultant, CRA Charles River Associates Inc.
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Sources for presentation

- This presentation is based primarily on the following sources:
  - The final report of the National Research Council's Committee on Transitions to Alternative Vehicles and Fuels (NRC2013)
  - The US Energy Information Agency's *Annual Energy Outlook – 2014* (AEO2014)
  - The EPA's *Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends Through 2013* (Trends2013)
  - The Oak Ridge National Laboratory's *Transportation Energy Data Book Edition 33* (2014) (TEDB2014)
  - International Energy Agency, *World Energy Outlook 2013* (AEO2013)
  - Society of Automotive Engineers, *Automotive Industry,* various recent issues (AE)
  - *Automotive News,* various recent issues (AN)

Charge to NRC Committee on Transitions to Alternative Vehicles and Fuels

- "The NRC will appoint an ad hoc study committee to conduct a comprehensive analysis of energy use within the light-duty transportation sector, and use the analysis to conduct an integrated study of the technology and fuel options (including electricity) that could reduce petroleum consumption and greenhouse gas emissions….Scenarios will consider technology as well as policy options and consider the likelihood of achieving 50 percent reduction in petroleum consumption by 2030 as well as 80 percent reduction in petroleum consumption and greenhouse gas emissions by 2050. In addition to technology, potential reduction in vehicle miles traveled (VMT) will be considered."

NRC2013, Appendix A

Transportation is a major energy user and accounts for a large share of GHG emissions, not only in the US, but also worldwide

- In 2012, transportation accounted for 28% of US energy consumption;
- In that same year, emissions by transportation vehicles accounted for 25% of US energy-related CO_2 emissions.
- Emissions generated in the production of transportation fuels accounted for approximately another 5%.
- Worldwide figures are more difficult to interpret, but according to the IEA, in 2010 "transport" accounted for 34% of World final energy demand; in 2011 it accounted for 22% of World CO2 emissions by sector.

AEO2014, IEA2013

Three transport modes – light-duty vehicles, freight trucks, and air -- account for 88% of US transport energy use

Energy Use by transport mode (2012)			
	Quads	%	cum%
Light-duty vehicles (including passenger cars and 2 axle, four-tire light-duty trucks	15.5	58.0%	58.0%
Freight trucks (including larger commercial light trucks)*	5.5	20.6%	78.6%
Air	2.5	9.4%	88.0%
All other modes**	3.2	12.0%	100.0%
Total	26.7	100.0%	

* Commercial trucks 8501-10,000 pounds gross vehicle weight rating

** Includes bus transportation, rail (passenger and freight, waterborne (domestic and international), recreational boats, military use, lubricants, and pipeline fuel

Source: AEO2014, Table A7, additional calculations by speaker

In what different ways can "technology" help reduce transport energy use and GHG emissions?

- Energy use and GHG emissions of any transport mode is the product of three factors:
  - Energy use per unit of travel (e.g., gallons/100 miles)
  - Number of travel units experienced by the mode (e.g., vehicle miles traveled -- vmt)
  - GHG emissions of fuel used for each unit of travel (e.g., g/mile)
- Obviously, "technology" can impact the energy use per vehicle mile traveled. But it also can impact the number of vehicle miles traveled as well as the ability of a given mode to use fuels having different GHG emissions per unit of energy use.

First Factor: Energy Use per Vehicle Mile Traveled

- Relevant measure is energy use (e.g., gallons/100mi), not “fuel economy” (miles per gallon)
- Is “actual” and not “as tested” results (typically a 20% difference)
- Is the energy consumption of the “average in use vehicle” not the energy consumption of the most energy-efficient new vehicle or even the energy consumption efficiency of the average new vehicle in the vehicle fleet.

MY2013 LDV Energy Use (gal/100mi) and Fuel Economy (mpg)

	gal/100 mi	mpg
Vehicle with lowest energy use (Toyota Prius)	1.4	71
Average "as tested" new vehicle	3.3	30
Average "actual" new vehicle	4.1	24
Light-duty stock	4.7	21

*MY2013 data are preliminary; light-duty stock figure is for 2012

Sources: Trends2013, AEO2014

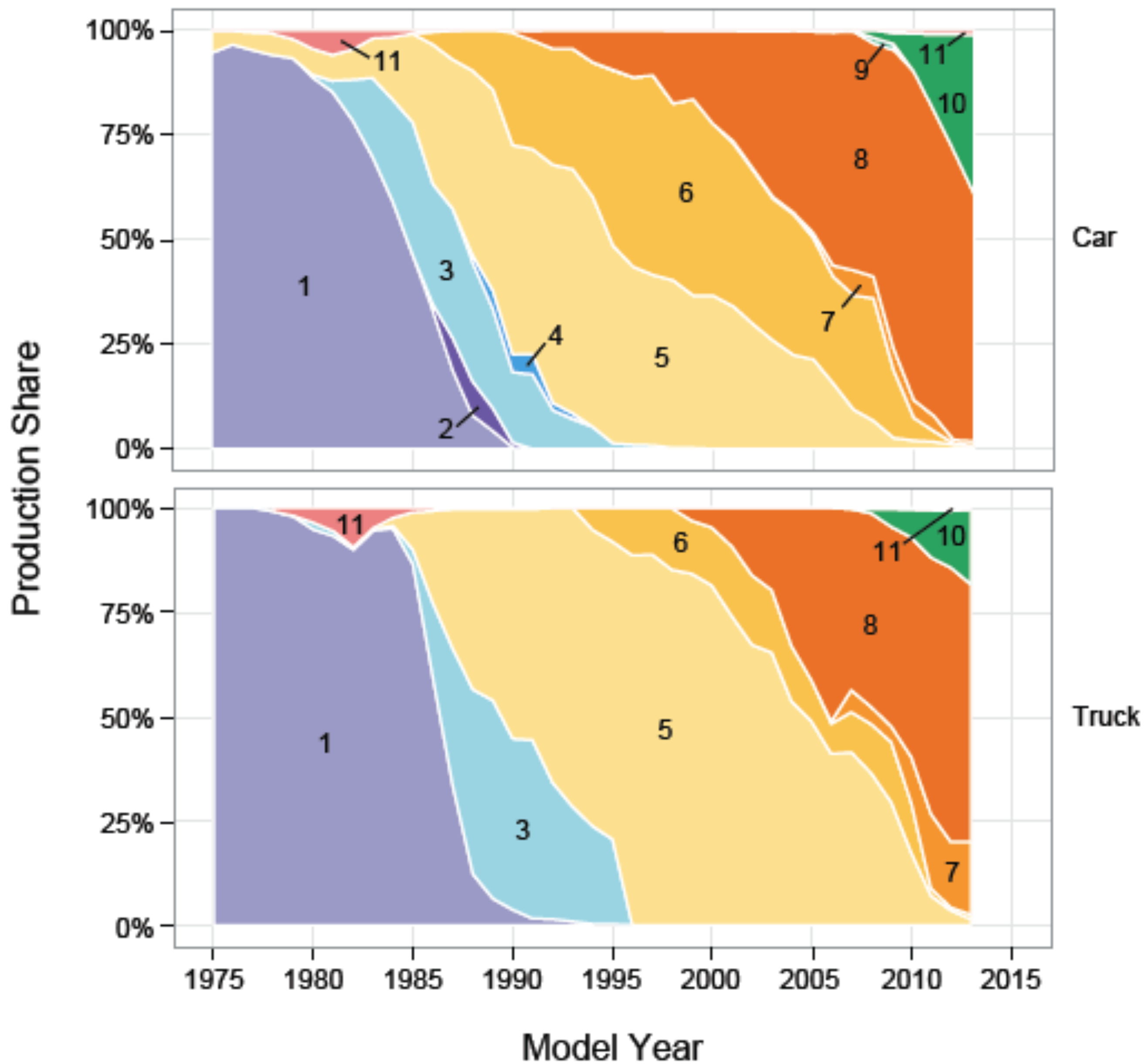
Drivetrain opportunities to reduce vehicle energy use and emissions

- Internal combustion engines and transmissions
- “Conventional” Hybrids
- Plug-in hybrids
- Battery electric vehicles
- Fuel Cell Electric Vehicles

Internal combustion engines

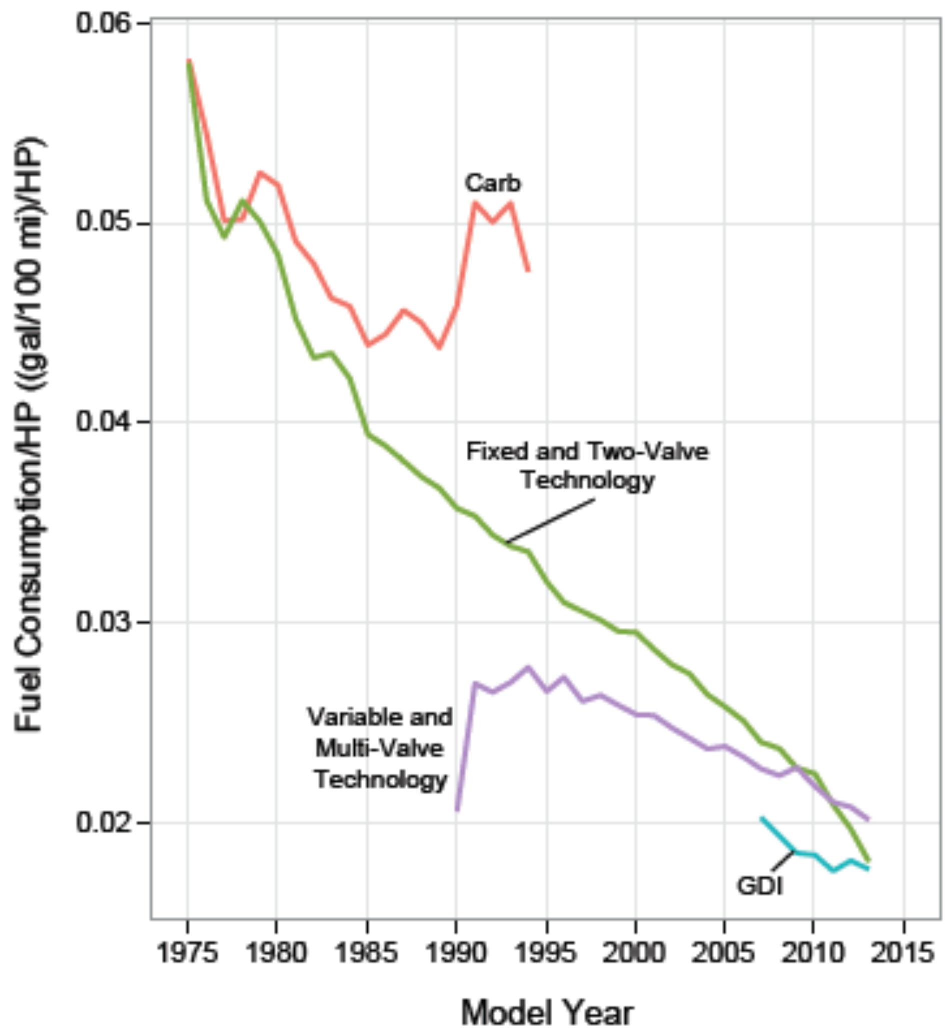
- IC engines used by road vehicle have improved greatly over the past decades

Fuel Delivery	**Valve Timing**	**Number of Valves**	**Key**
Carbureted	Fixed	Two-Valve	1
	Variable	Multi-Valve	2
Throttle Body Injection	Fixed	Two-Valve	3
	Fixed	Multi-Valve	4
Port Fuel Injection	Fixed	Two-Valve	5
		Multi-Valve	6
	Variable	Two-Valve	7
		Multi-Valve	8
Gasoline Direct Injection (GDI)	Fixed	Multi-Valve	9
	Variable	Multi-Valve	10
Diesel	—	—	11

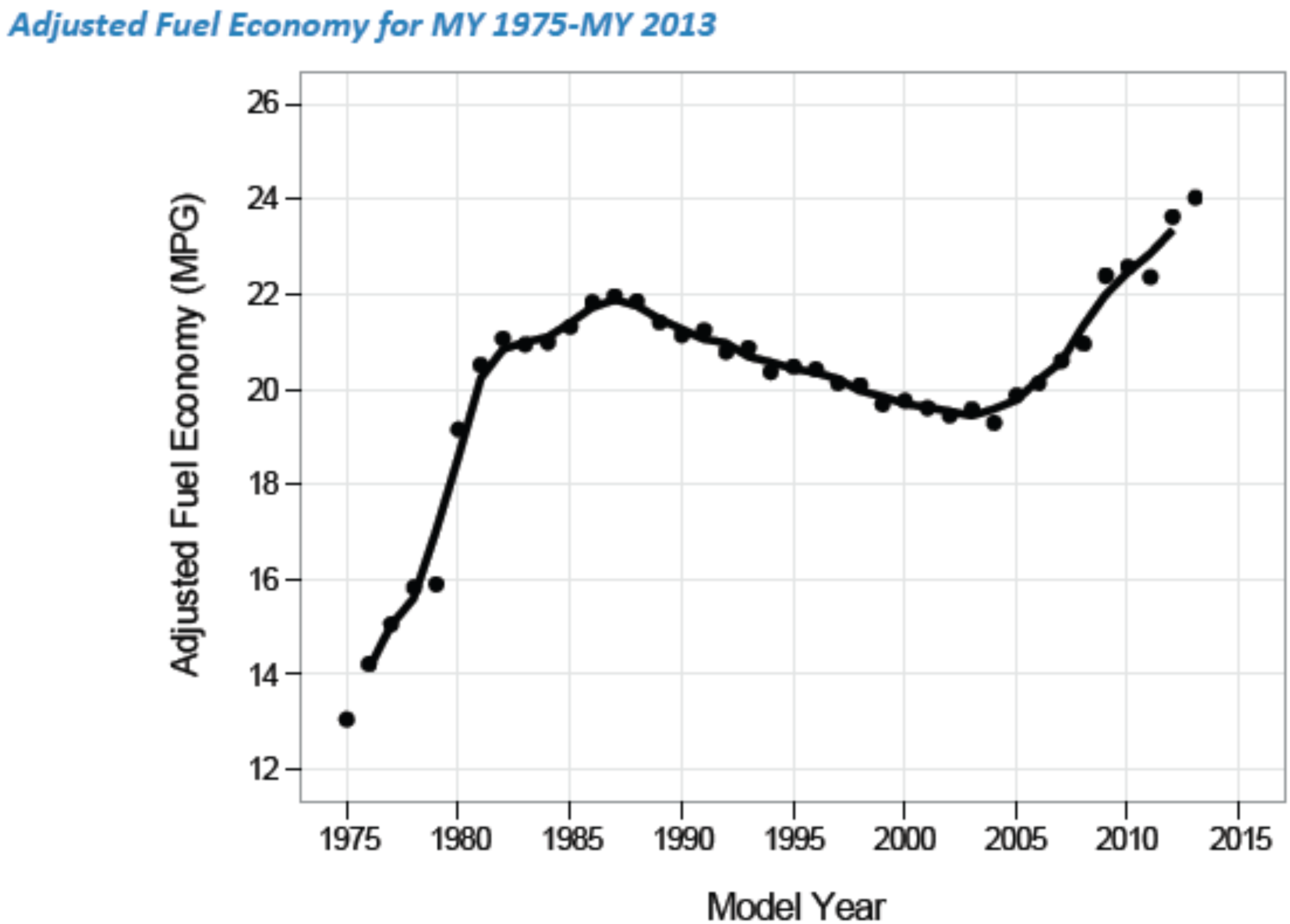


Production Share
100%
75%
50%
25%
0%
Car
Truck
1
2
3
4
5
6
7
8
9
10
11
1975
1980
1985
1990
1995
2000
2005
2010
2015
Model Year

Fuel consumption per horsepower



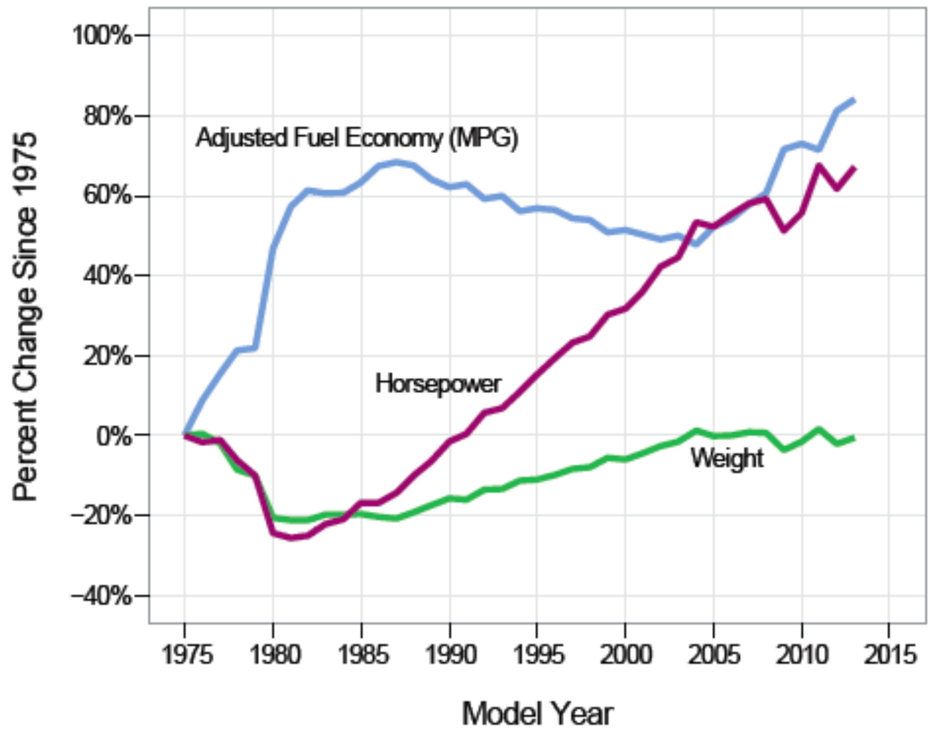
However, in spite of this, between the late 1980s and about 2005, average new vehicle adjusted fuel economy actually <u>fell</u>



Source: Trends—2013, p.6

What explains this pattern?

Adjusted Fuel Economy, Weight, and Horsepower for MY 1975-2013



Policy challenge: assuring that much higher share of future technology improvements used to reduce fuel consumption and GHG emissions

Emerging technologies – gasoline direct injection

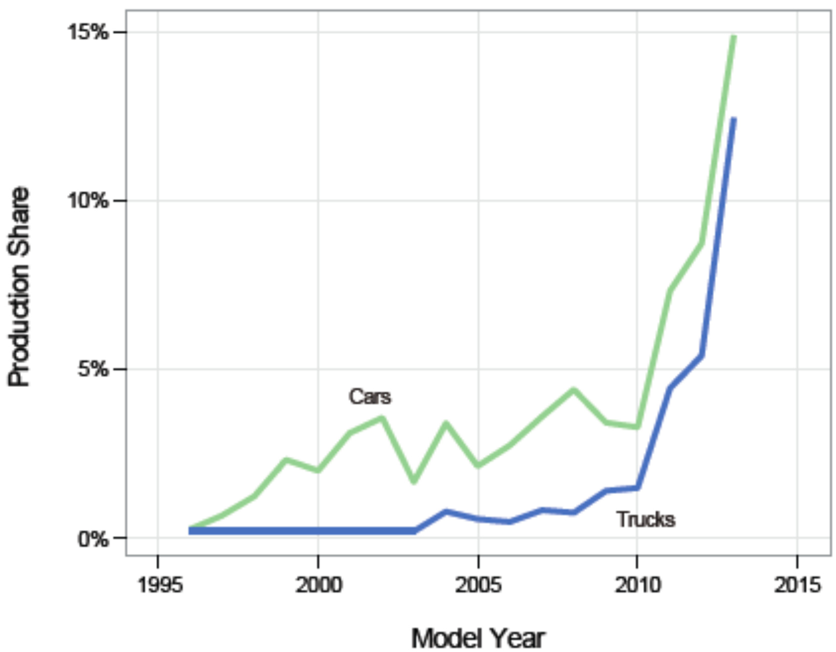
- Much more precise injection of fuel
  - More efficient combustion
    - Reduced use of fuel
    - Reduced conventional and CO_2 emissions
- GDI use is expanding rapidly
  - First appeared in MY2008 – 2.3% of new LDVs
  - In MY2013, used in 30.8% of new LDVs

Emerging technologies – cylinder deactivation

- First appeared in early 1980s in notorious GM “4-6-8” engine
  - Was a V-8 engine that could deactivate 2 or 4 cylinders
  - Electromechanical technology not up to the job; technology soon disappeared
- Reappeared in much more sophisticated form in MY2006
  - Achieved nearly 10% new LDV penetration by MY2010
- Not clear how widely used it will become

Emerging technologies: Turbo-downsizing

- Use smaller displacement engine with a turbocharger in place of a larger naturally-aspirated engine
  - Smaller engine (generally, but not always, using GDI) permits increased fuel economy for most vehicle operation while retaining the ability to obtain increased power from turbocharger when needed



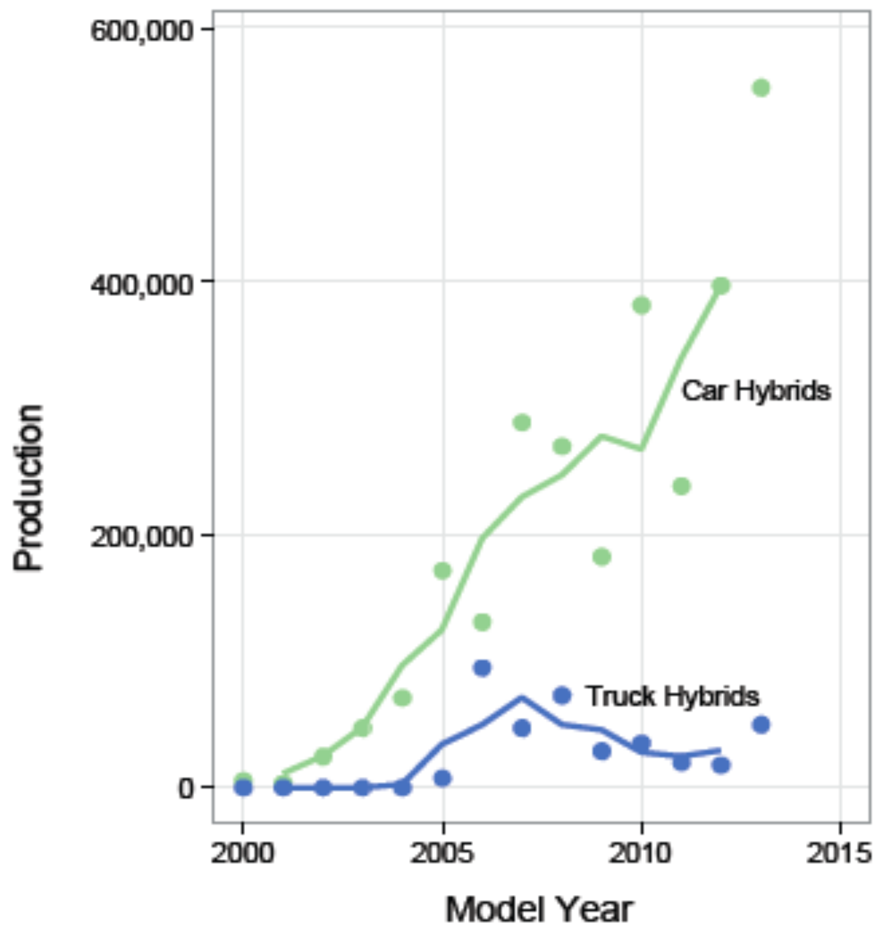
Distribution of MY 2013 Turbocharged Engines (Excludes Diesel)

Category	Turbo Share
Car	
4 cylinder Car	60.1%
6 cylinder Car	3.4%
8 cylinder Car	3.4%
Other Car	1.4%
Truck	
4 cylinder Truck	15.2%
6 cylinder Truck	14.7%
8 cylinder Truck	1.8%

Emerging technologies -- hybrids

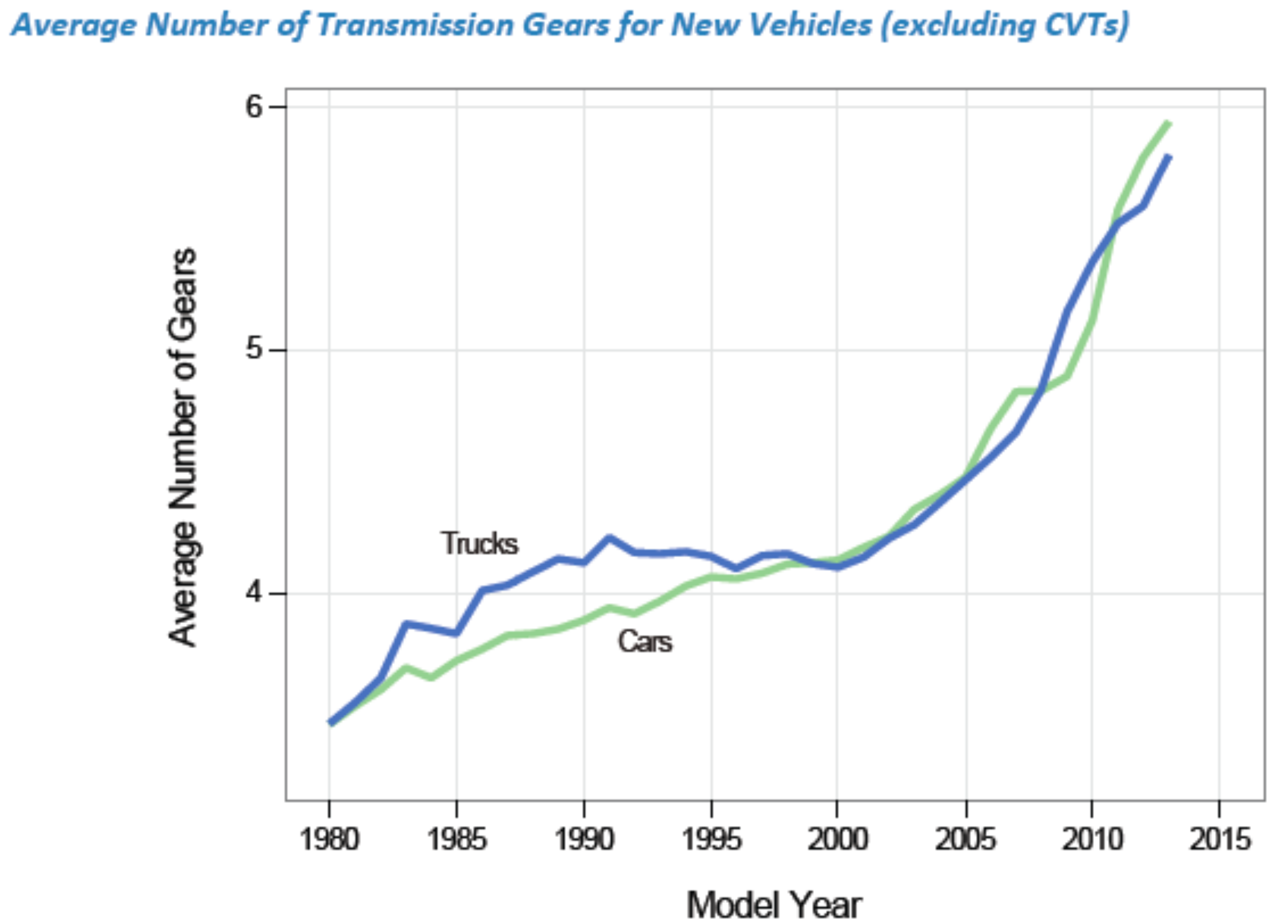
- “Hybrid” combines two types of powerplants
  - Internal combustion engine
  - Electric motor
- Several types of “hybrid”
  - “mini” hybrid (stop-start)
    - Electric motor is starter motor, source of electric power is larger version of standard vehicle battery; Series hybrid, parallel hybrid, combined hybrid
  - Different ways of combining IC engine power and electric motor power
    - Much larger batteries than “mini”-hybrid; sometimes designed to power vehicle alone for relatively short distances
    - Main impact is to allow more efficient use of IC engine
      - More nearly constant speed
      - Different combustion cycles

Car hybrids (excluding mini-hybrids) growing rapidly in last few years – primarily Toyota Prius



EPA projects that “conventional” hybrids reached 4.2% of new vehicle production in MY 2013; “mini-hybrids” reached an additional 2.1%

Emerging technologies – transmissions with more gears or with no gears (CVT)



CVT use was 11.83% in MY2012, expected to have reached 14.3% in MY2013

Emerging electric drive technologies – all-electric vehicles and plug-in hybrids

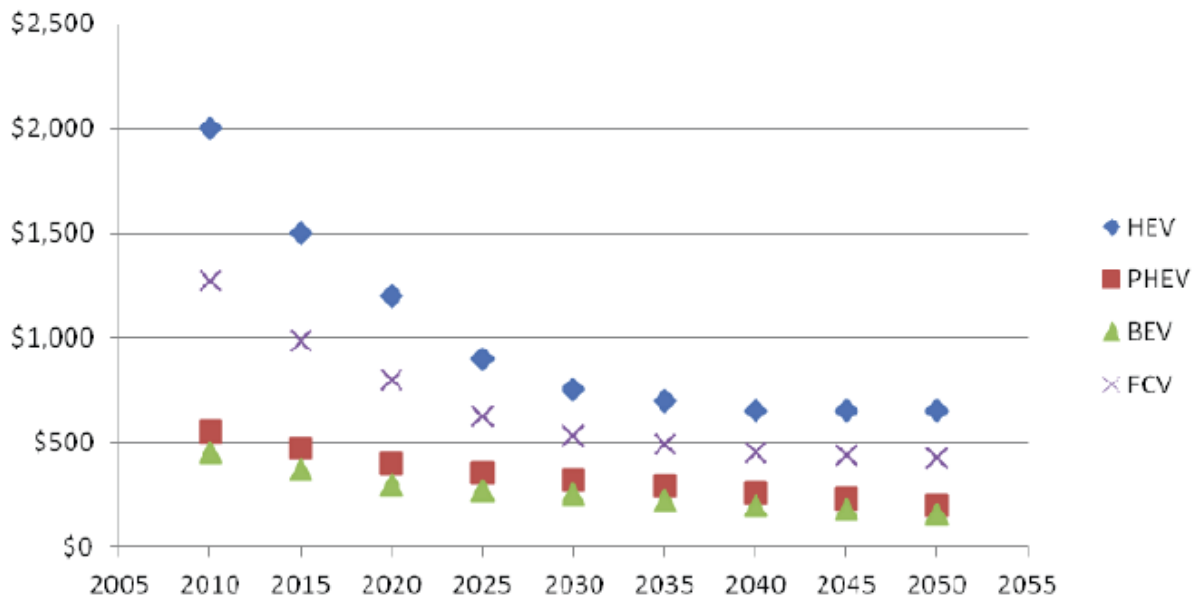
- All-electric vehicles
  - Powered entirely by electric power using batteries that are charged from the electric grid
  - Batteries have evolved from lead-acid to nickel metal hydride to lithium-ion
  - Challenges relating to battery pack costs, vehicle range, and charging time remain
- Plug-in hybrids
  - Rely more on battery power obtained from electric grid than “conventional” hybrids, which rely on electricity generated by the vehicle’s IC engine
  - Chevrolet Volt uses only electric power until limit of battery is reached at approximately 50 miles; then IC engine begins to operate
  - Intended to eliminate “range anxiety” felt with all-electric vehicles
  - Except for “range anxiety,” challenges similar to all-electric vehicles

Emerging electric drive technologies – fuel cells

- Vehicles employ fuel cell which produces electricity from on-board fuel (hydrogen), stores electricity in battery, and draws electricity from battery to power electric propulsion motors
- Interest grew during early 2000's, but latter part of decade saw research funding cut and resources shifted to all-electric vehicles
- Problems were fuel cell cost, durability, cold start performance; hydrogen storage capability and cost; and hydrogen availability
- Committee members most familiar with fuel cells believe that most problems (other than hydrogen availability) have been largely solved, though costs remain high
- First commercially-available fuel cell vehicles being introduced in MY2015

Battery pack costs an important issue for all electric-drive vehicles, but especially for PHEV's and BEV's

- Our NRC committee estimated battery pack costs per kilowatt-hour for each type of electric drive vehicle through 2050



PHEVs require battery pack providing 4-20 kwh that can be charged from the grid. (Depends on battery-only range.) BEVs require 20-100 kwh.

Non-drivetrain Options for Reducing Vehicle Fuel Consumption

Light weighting	Structural materials Component materials Smart design
Rolling resistance	Tire materials and design Tire pressure maintenance Low-drag brakes
Aerodynamics	C_d (drag coefficient) reduction Frontal area reduction
Accessory efficiency	Air conditioning Efficient alternator Efficient lighting Electric power steering Intelligent cooling system

Lightweighting

- Steel accounts for approximately half the weight of material used in the typical LDV. This has been true for decades.
- Much recent talk about substantially increasing use of aluminum
  - Toyota will be using aluminum hood for Camry in 2018
  - Jaguar XE claims that it will be the "highest volume aluminum body car on the market" when it arrives in the US in 2016
    - 75% of car's components will be aluminum, including hood and fenders
  - Ford's 2015 F150 pickup will use aluminum body and cargo box
    - Ford aiming to reduce vehicle weight by between 625 and 732 pounds, with 450 pounds being saved by the use of aluminum body construction. The remainder comes from smaller engine (turbocharged V6 rather than V8), use of "stop-start," active grill shutters, better aerodynamics, and other engineering changes (including an all-new and lighter steel ladder frame). Target is to produce the first full-sized pickup to achieve 30mpg (base 2WD) without compromising utility or payload

Ford’s lightweighting effort on the F150 is risky

- F150 is one of Ford’s largest-selling vehicles – projected to be 700,000+ units per year when at full production (25% of Ford’s North American sales; also one of the most profitable per unit.
- Challenge is much greater than simple material substitution
  - Stamping is different
    - “Aluminum is less formable than steel. You can’t bend it as much…. Aluminum can splinter when stamped….Spot welding is very robust and can work on ‘dirty steel that has oil on it,’ but with aluminum, ‘cleanliness is much more important. They really have to get all the dust off these blanks.’”*
  - Assembly is different; use rivets and adhesives instead of spot welding
    - “Nobody’s riveted and glued at this speed yet….I wouldn’t be surprised if there’s 10 to 15 diffferent kinds of rivets….I estimate crudely that the cost of joining materials are roughly double the cost of joining a spot-welded vehicle.”*
  - Body repair is different
    - Dealers will have to invest in new (and separate) repair facilities

*Jay Baron, president of Center for Automotive Research, Ann Arbor, MI, in *Automotive News*, September 8, 2014, p. 41.

Other automakers are more cautious

- "…for most vehicles, automakers are going to make an incremental switch to aluminum – one component at a time."
- Report by Drucker Worldwide, a suburban consulting firm, predicts that by 2025, the average vehicle will have 547 pounds of aluminum*, including:
  - 85% of hoods
  - 46% of doors
  - 33% of truck lids and liftgates
  - 30% of roofs
  - 27% of fenders
- Moreover, some steelmakers now claiming: "We can do what aluminum can."

*Average amount of aluminum in MY2012 vehicles = 344 pounds.

What about carbon fiber?

Committee's Estimate of Weight Reduction Potential and Cost Relative to Base Year 2010

	Cars and Unibody Light Trucks			Body-on Frame Light Trucks		
Year	Weight Reduction	Cost ($/lb)	Reduction with Weight Growth	Weight Reduction	Cost ($/lb)	Reduction with Weight Growth
2050	40%	$1.73	Midrange 30%	32%	$1.38	Midrange 22%
			Optimistic 40%			Optimistic 32%
2050 (carbon fiber)	50%	$6.00	Optimistic 50%	40%	$6.00	Optimistic 40%

Source: NRC 2013, p. 20, Table 2.2

Committee's estimate of potential improvements in rolling resistance and aerodynamic drag

	Rolling Resistance		Aerodynamic Drag	
	Cars	Trucks	Cars	Trucks
2030 Midrange	26%	15%	18%	15%
2030 Optimistic	40%	30%	31%	29%
2050 Midrange	33%	23%	26%	24%
2050 Optimistic	46%	37%	39%	37%

NRC2013, p. 37, Table 2.11

Committee's "mid-range and "optimistic" fuel consumption and fuel economy projections to 2050 for ICEs employing internal combustion and hybrid technologies

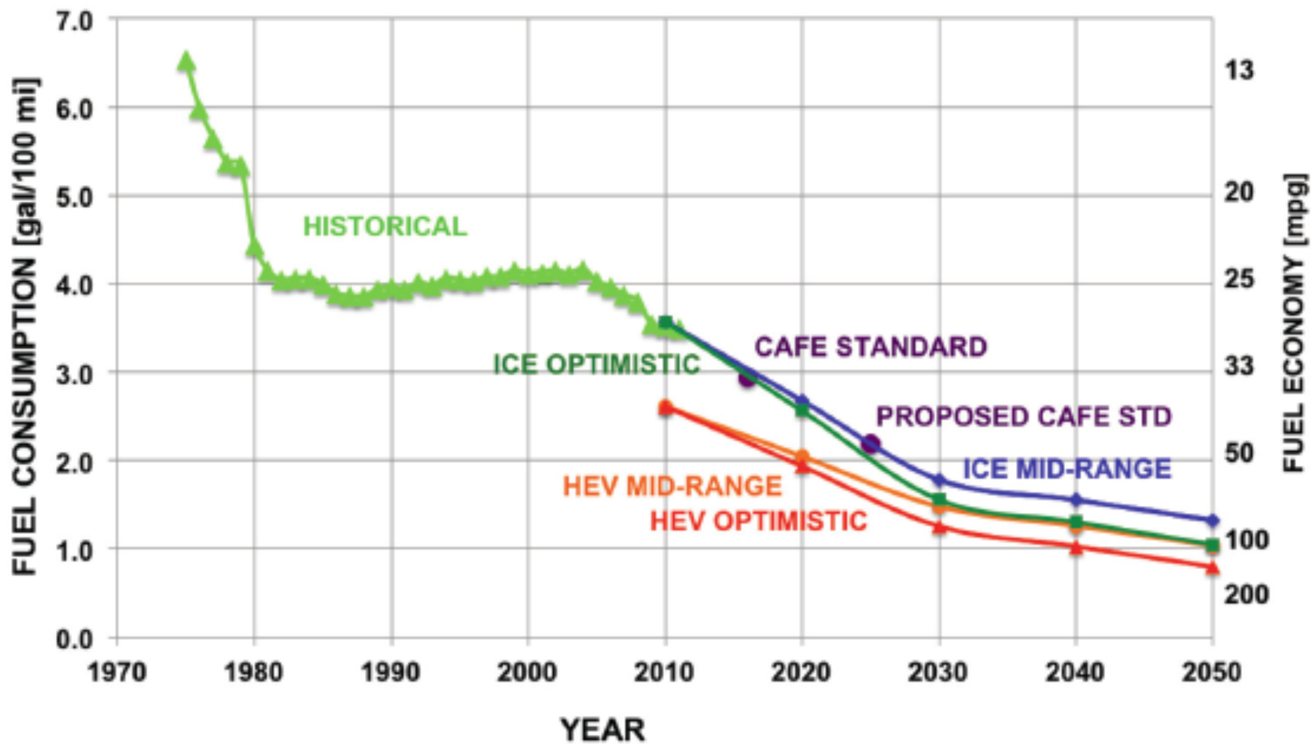


FIGURE 2.1 Historical and projected light-duty vehicle fuel economy.
NOTE: All data is new fleet only using unadjusted test values, not in-use fuel consumption.

This table shows the Committee's projections for battery-electric and fuel cell vehicles

NRC Committee's projections for fuel economy and fuel consumption of battery electric and fuel cell electric vehicle (in mpgge)								
	BEV				FCEV			
	Cars		Light Trucks		Cars		Light Trucks	
Year	mpg	mpgge/100mi	mpg	mpgge/100mi	mpg	mpgge/100mi	mpg	mpgge/100mi
2010 Baseline	144	0.69	106	0.94	89	1.12	65	1.54
2030 Midrange	190	0.53	133	0.75	122	0.82	86	1.16
2030 Optimistic	243	0.41	169	0.59	166	0.60	115	0.87
2050 Midrange	219	0.46	154	0.65	145	0.69	102	0.98
2050 Optimistic	296	0.34	205	0.49	206	0.49	143	0.70

Note: All data is new fleet only using unadjusted test values, not in-use fuel economy or fuel consumption

Source: NRC2013, p. 37, Table 2.12, with additional calculations by the speaker

Blue arrow at bottom left of chart shows approximate range of BEV and FCEV 2050 results

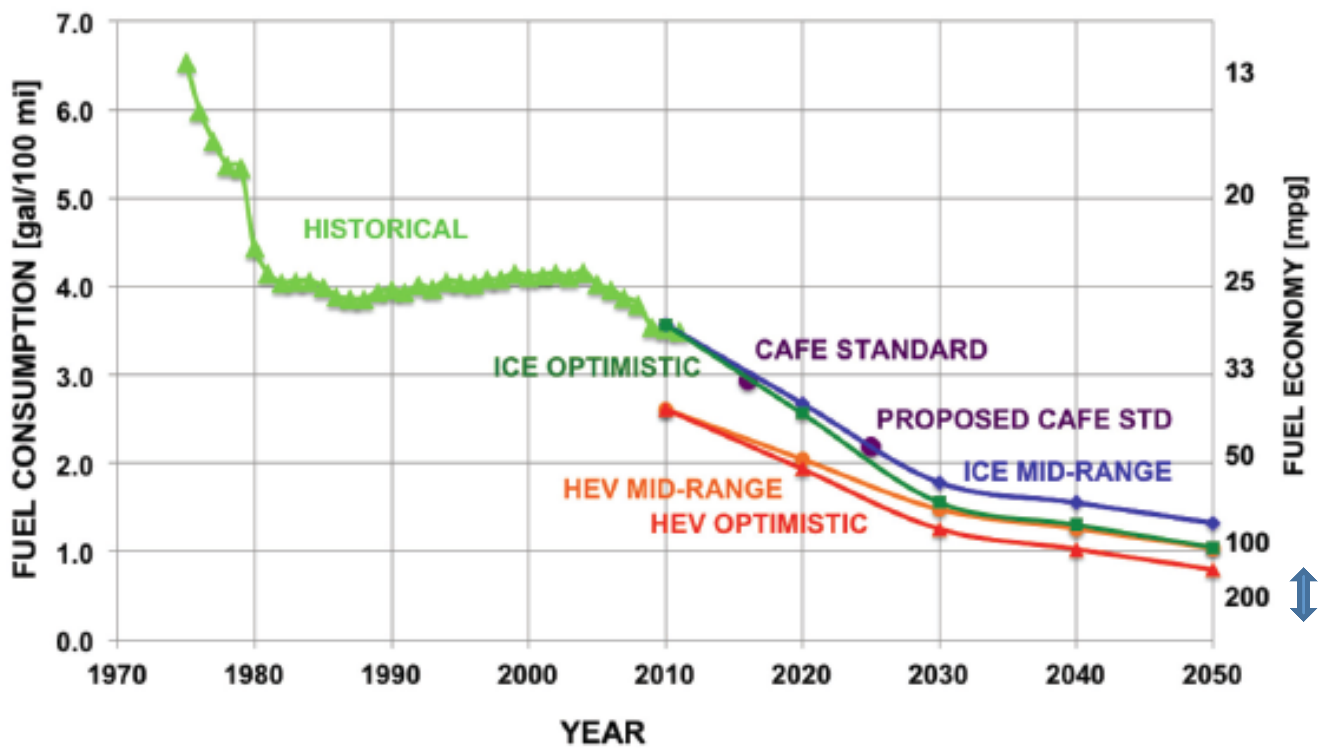


FIGURE 2.1 Historical and projected light-duty vehicle fuel economy.
NOTE: All data is new fleet only using unadjusted test values, not in-use fuel consumption.

Second factor: Vehicle miles traveled

LDV travel and fuel use trends 1970-2005			
	1970	2005	% change
Gallons of fuel used/100 miles	7.7	5.0	-36%
Vehicle miles traveled (billion)	1,040.0	2,749.5	164%
Fuel used (million gallons)	80,133.0	136,287.0	70%
Source: Calculated by speaker from TEDB 33, Tables 4.1 and 4.2			

Impact of VMT assumptions

- In NRC committee's analysis, assumed that LDV VMT in 2050 would be 5.1 trillion, an average annual rate of growth of 1.9%.
  - This was consistent with growth rate projections being employed by DOE at the time (e.g., AEO2007)
- This VMT growth assumption had a major impact in our conclusion that improvements in conventional ICE-powered and hybrid vehicles alone could not meet 2050 targets
- Committee was aware that VMT had fallen after 2006 peak due to recession, but in previous recessions, VMT had recovered and resumed growth soon after recession ended.
- However, since 2008 recession, VMT has not recovered as previously, and growth rate has declined drastically

How economic indicators of travel have become "disconnected" and impact on future LDV VMT

Figure IF4-1. Economic indicators of travel, 1975-2012 (index, 1995 = 1.0)

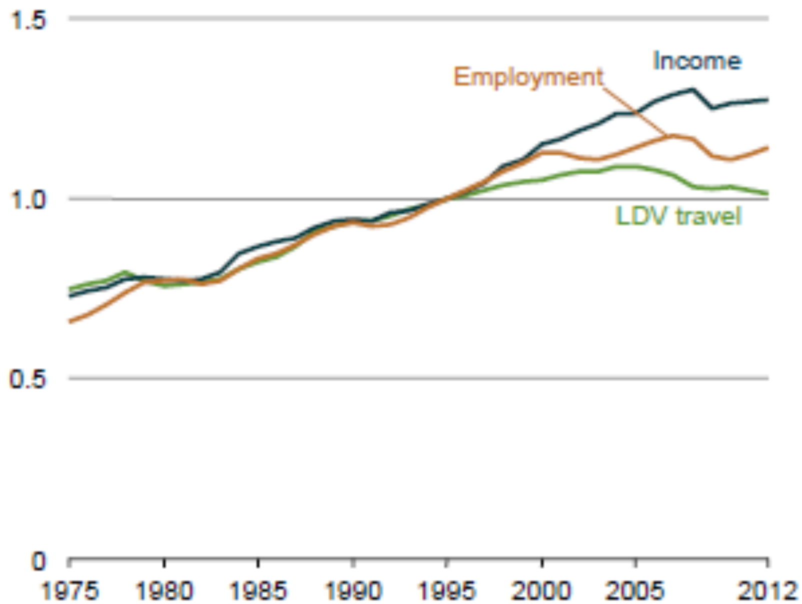
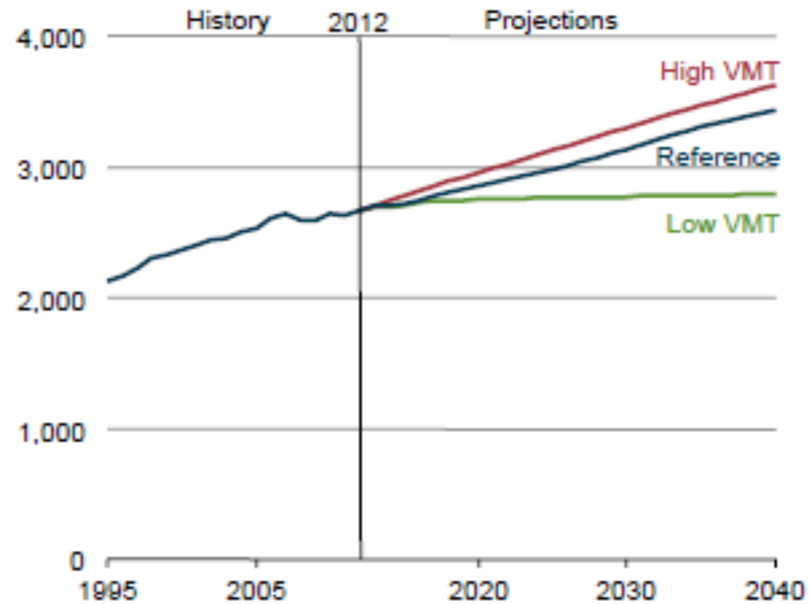


Figure IF4-2. Total light-duty vehicle miles traveled in three cases, 1995-2040 (billion miles)



AEO2014, p. IF-22.

Implications of slower VMT growth

- NRC committee stated that to reach 2050 goals, at least one new electric vehicle technology (BEV or FCEV) would have to be introduced in significant volume by about 2025.
- Based on current information, wasn't clear which one made the most sense.
- A great deal depends on whether electric utility sector can be "decarbonized."
- Could nation afford to introduce *both* FCEVs and BEVs?
- With substantially slower VMT growth, perhaps can rely on improved "conventional" IC-powered vehicles plus improved hybrids for a longer time.

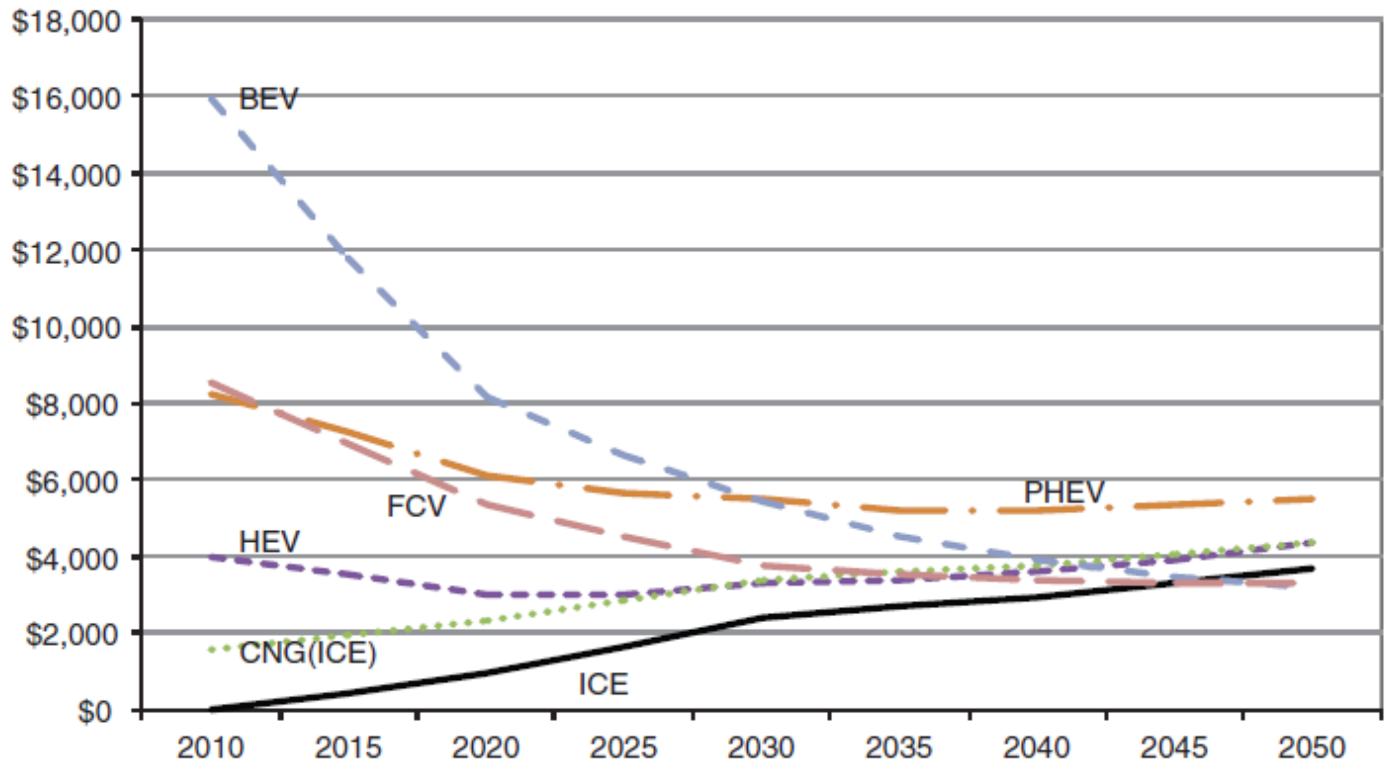
Third factor: Emissions per unit of fuel used

- Until recently, this factor has been relatively unimportant, since nearly all transportation vehicles have used petroleum-based liquid fuels – mainly gasoline. GHG emissions for each fuel is approximately the same.
- Introduction of PHEV, BEV, and FCEV vehicles changes this
  - In case of PHEV and BEV, critical issue is how the electricity is generated
    - If by coal, GHG emissions from these vehicles aren't much different from conventional IC and conventional hybrid vehicles
    - If by "zero GHG emissions" techniques of generation, emissions are somewhat better
  - In the case of FCEV vehicles, hydrogen must be produced and a hydrogen refueling network must be created

Questions?

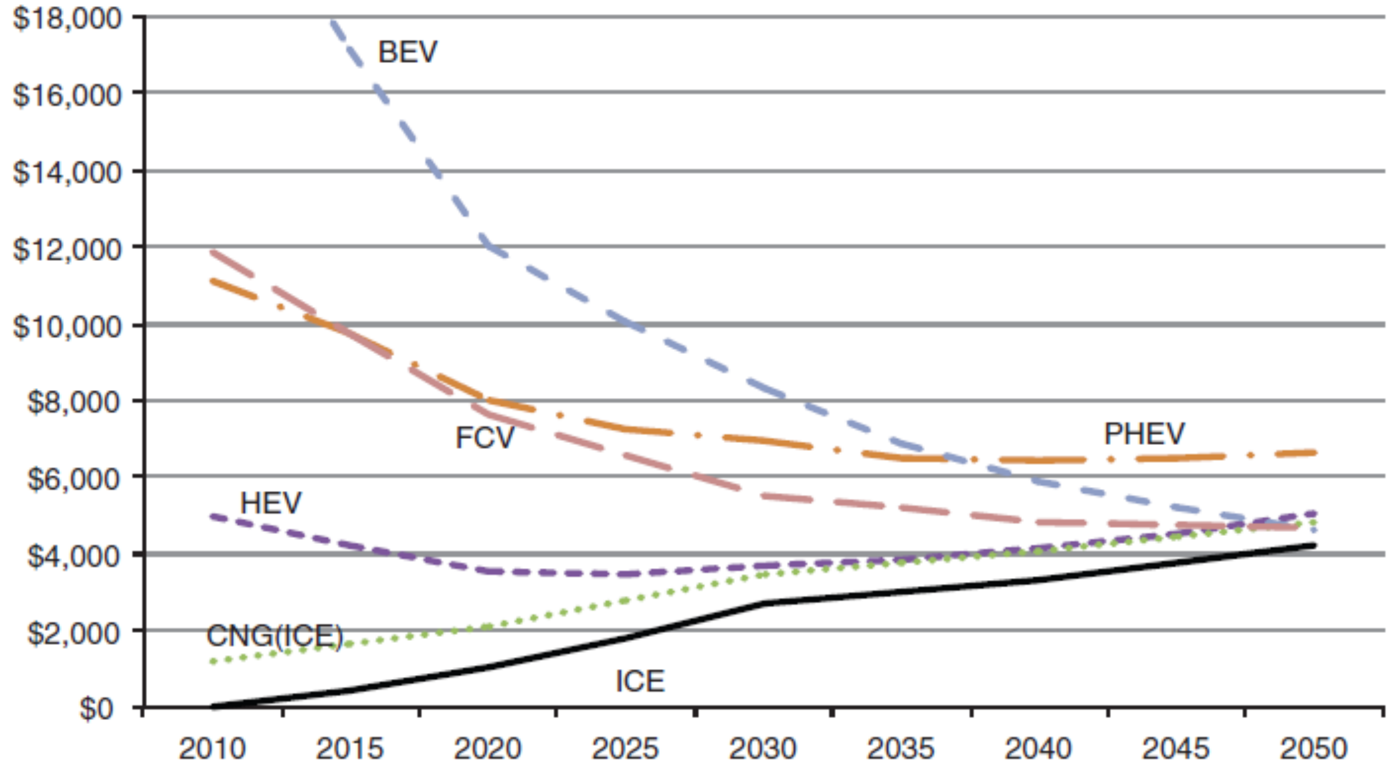
Backup

Car incremental costs versus 2010 baseline – midrange case



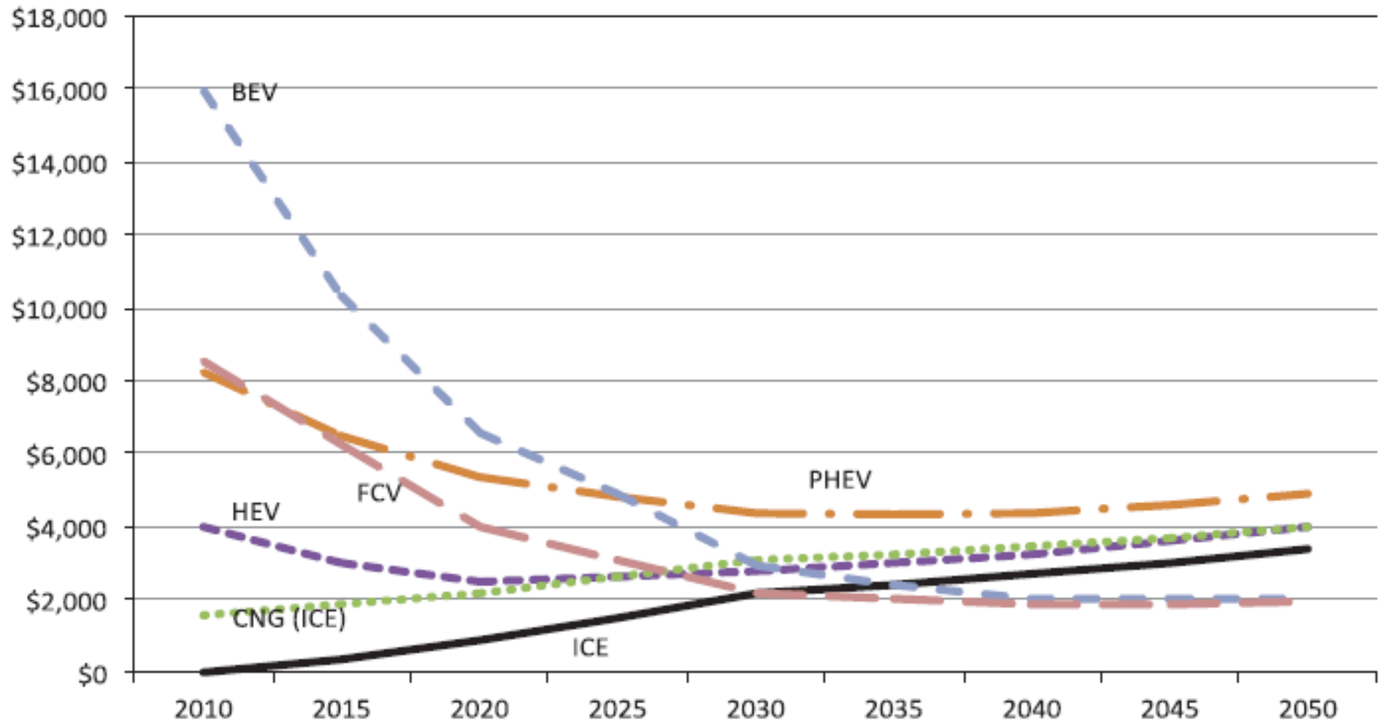
Car incremental cost versus 2010 baseline ($26,341 retail price)—Midrange case.

Light-truck incremental cost versus 2010 baseline – midrange case



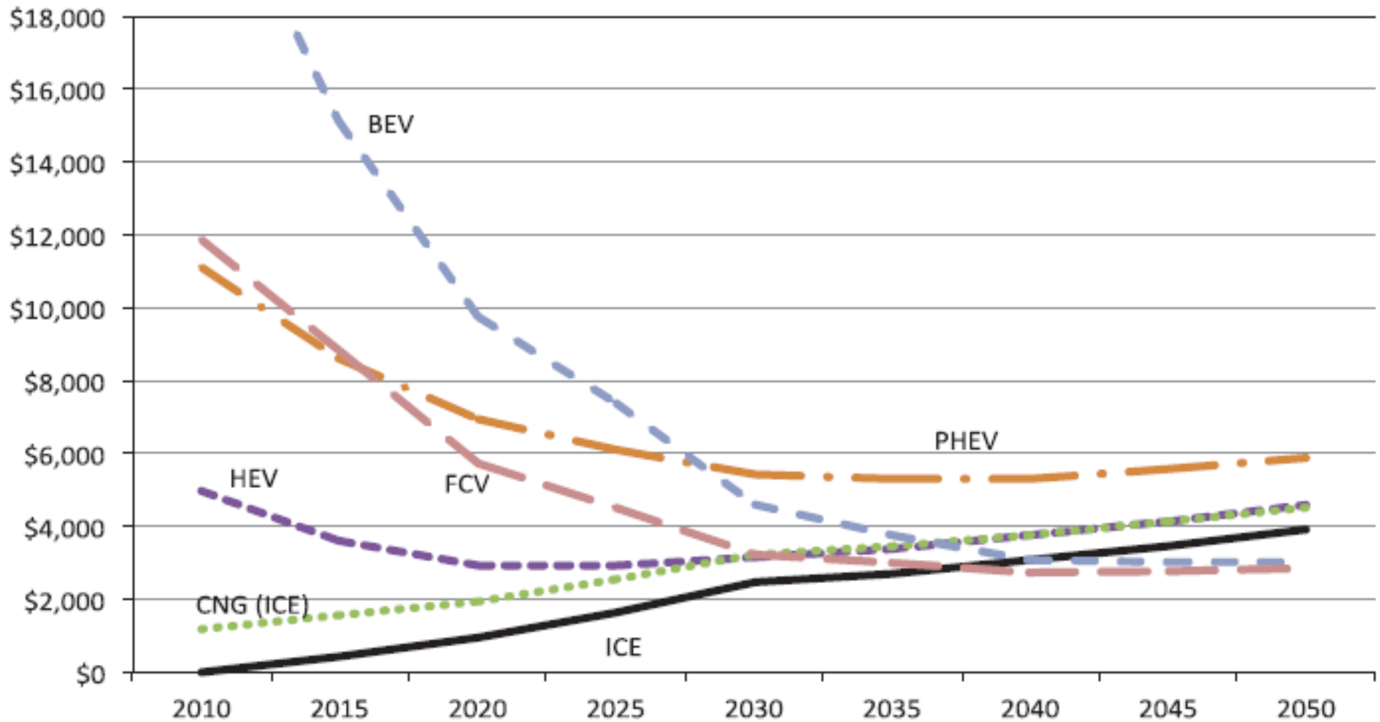
Light truck incremental cost versus 2010 baseline ($32,413 retail price)—Midrange case.

Car incremental cost versus 2010 baseline – optimistic case



Car Incremental cost versus 2010 baseline ($26,341 retail price)—Optimistic case.

Light truck incremental cost versus 2010 baseline – optimistic case



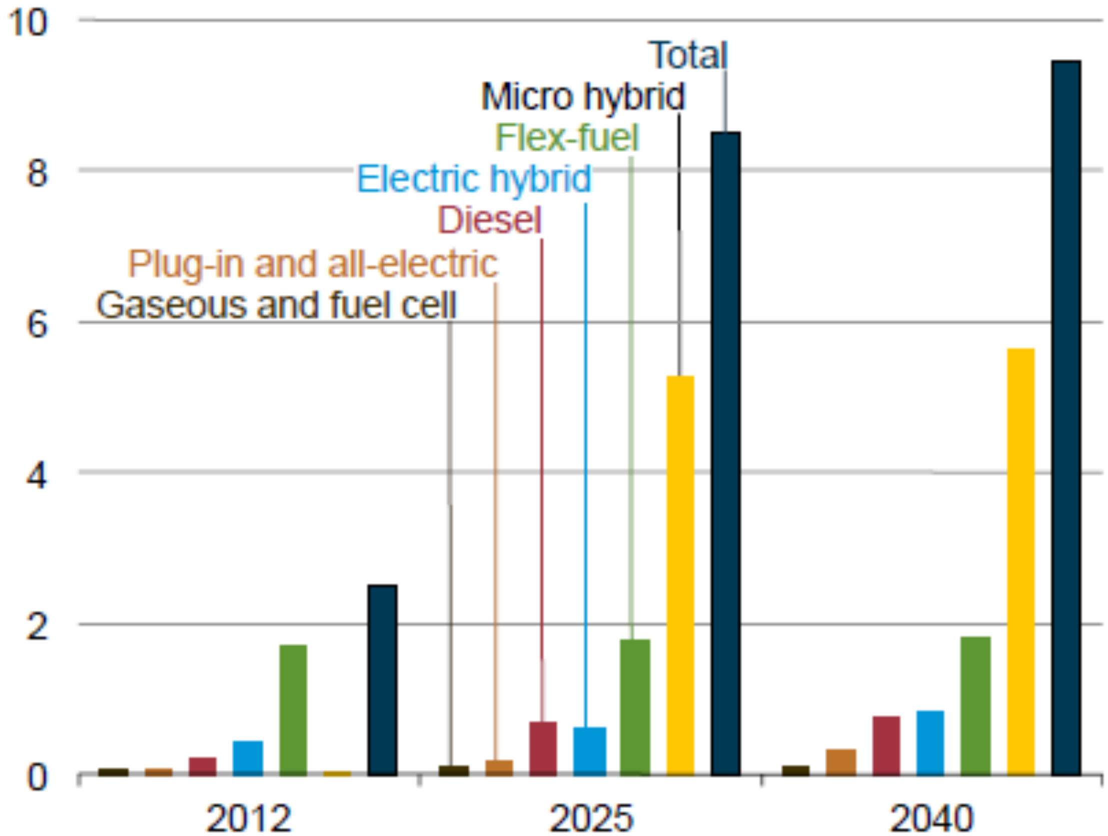
Light truck incremental cost versus 2010 baseline ($32,413 retail price)—Optimistic case.

Steel accounts for about half of average material consumption for a domestic LDV in both MY1995 and MY2012

Material use in LDVs, MY1995 and 2012

	MY1995		MY2012	
Material	Pounds	%	Pounds	%
Regular steel	1630	44.1%	1542	38.2%
Medium- and high-strength steel	324	8.8%	559	13.8%
Stainless steel	51	1.4%	73	1.8%
Other steels	46	1.2%	33	0.8%
All steels	2051	55.5%	2207	54.6%
Iron castings	466	12.6%	237	5.9%
Aluminum	231	6.3%	344	8.5%
Plastics and plastic composites	240	6.5%	378	9.4%
Other materials	706	19.1%	874	21.6%
Total	3694	100.0%	4040	100.0%

AEO 2014 projection of sales of light-duty vehicles using nongasoline technologies by type in their reference case, 2012, 2025, 2040 (million vehicles sold)



Share of total LDV sales: 2012 = 18%; 2040 = 55%

AEO2014, p. MT-15, Figure MT-27.