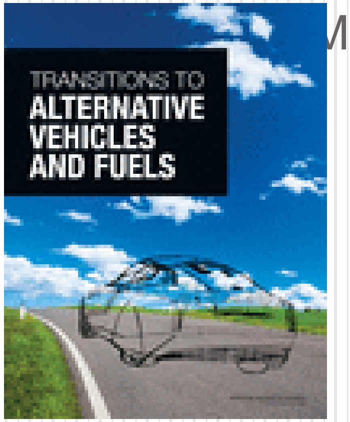
http://www.nap.edu/catalog.php?record_id=18264#toc

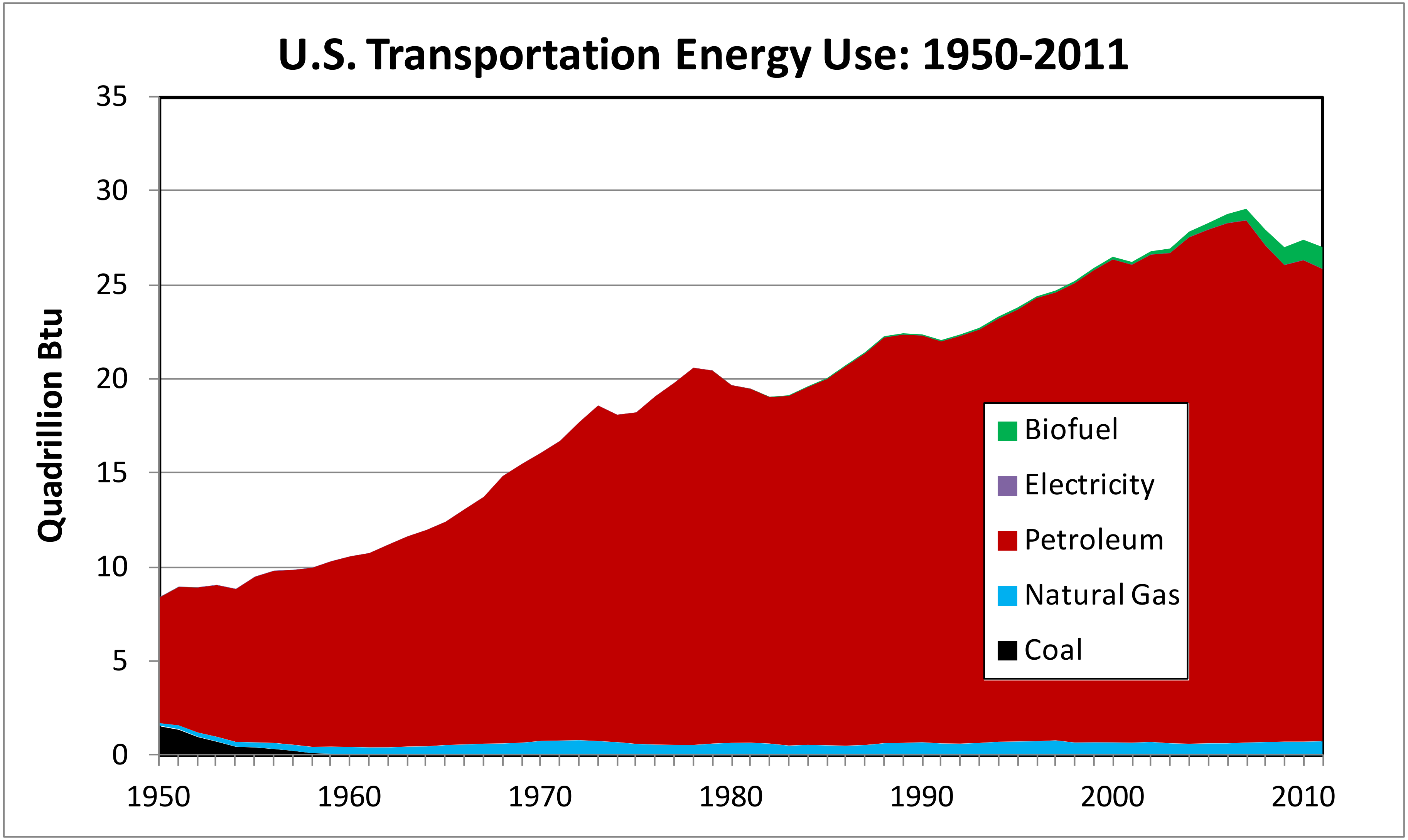
# Transitions to Alternative Vehicles and Fuels
# Report of the NRC Committee



**David L. Greene**
Member, Committee on Transitions to Alternative Vehicles and Fuels
Corporate Fellow, Oak Ridge National Laboratory
Senior Fellow, Howard H. Baker, Jr. Center for Public Policy
The University of Tennessee

**Hydrogen and Fuel Cell Technical Advisory Committee**
**Washington, DC**
**April 23, 2013**

# If it were easy…



Energy Information Administration, Annual Energy Review 2011, table 2.1e.

# There’s too much to cover.

- Overview of task and findings
- Progress of key technologies to 2050
- Key results for fuel cell vehicles

# Statement of Task

- Relative to 2005, how can on-road LDV fleet reduce
  - Petroleum use by 50 percent by 2030 and by 80 percent by 2050?
  - GHG emissions by 80 percent by 2050?
- Assess cost and performance of vehicle and fuel technology options that contribute to meeting the goals and barriers that hinder their adoption.
- Suggest policies to achieve the goals.
- Comment on Federal R&D programs.

# A key premise of the study is that society wants to do this.

- Committee identified promising combinations of fuel and vehicle pathways.
- These combinations were quantified and analyzed to assess their capacity to meet goals and determine required policies associated with each.
- Strong, sustained policy support is essential.
  - Continued tightening of fuel economy/emissions standards.
  - Broad-based GHG policies to insure low W-T-W GHG in energy supply.
  - Transition policies to overcome “technology lock-in”
- All successful pathways combine continued improvement in vehicle fuel economy plus at least one other pathway.

# Potential Pathways

- Four pathways contribute to both goals
  - Highly efficient internal combustion vehicles
  - Vehicles operating on biofuels
  - Vehicles operating on electricity
  - Vehicles operating on hydrogen
- Natural gas vehicles reduce petroleum consumption but have minor impact on GHG emissions

Note: The GHG benefits of biofuels, electricity and hydrogen depend on their being produced without large GHG emissions. This expands the need for controlling emissions beyond the transportation sector.

# Six vehicle technologies were included in the scenarios analyzed.

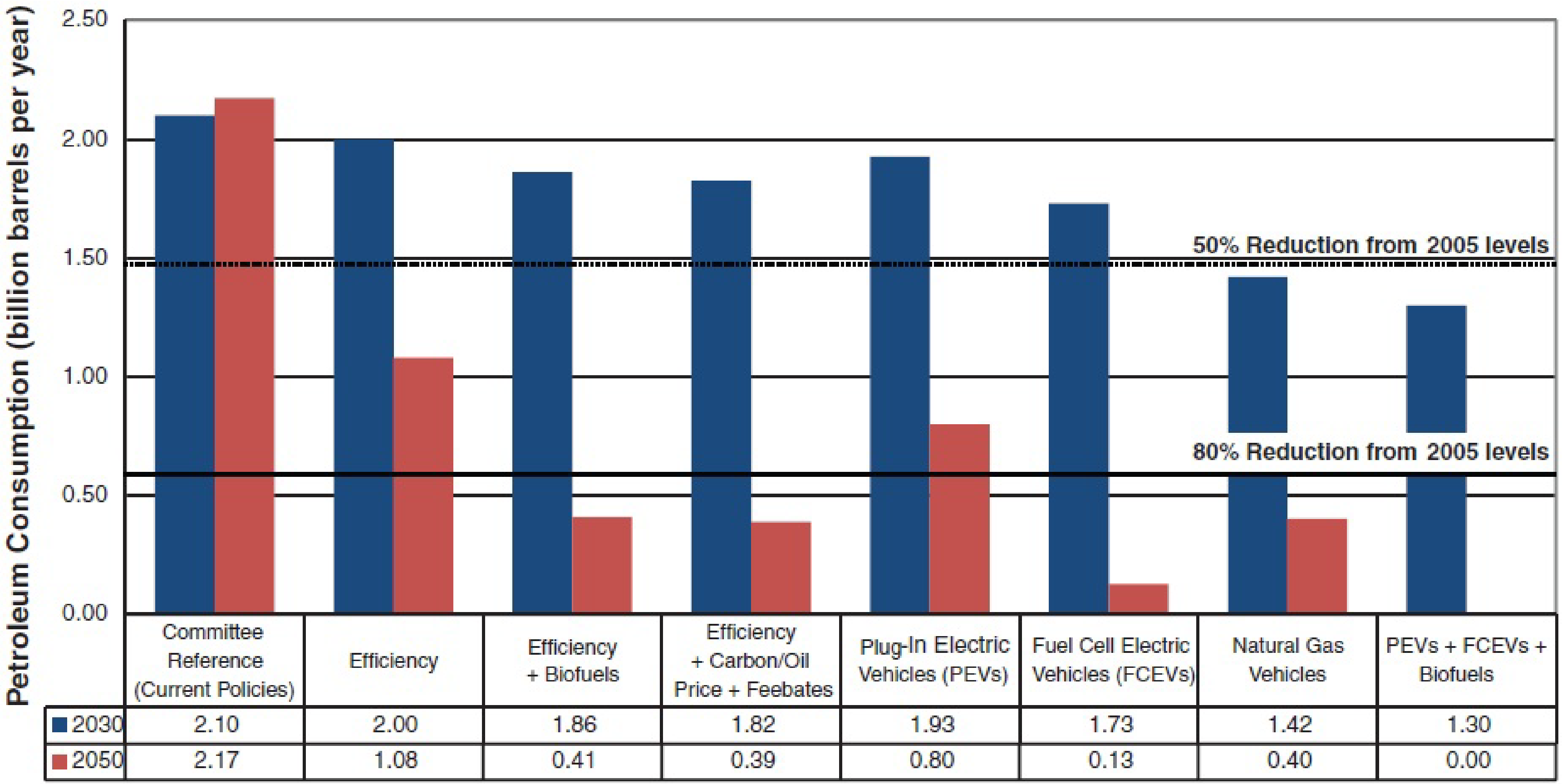
- Highly efficient Internal Combustion Engine Vehicles (ICEVs)
- Hybrid Electric Vehicles (HEVs)
- Plug-in Vehicles (PEVs)
  - Plug-in Hybrid Vehicles (PHEVs)
  - Battery electric Vehicles (BEVs)
- Fuel Cell Electric Vehicles (FCEVs)
- Natural Gas Vehicles (NGVs)

# Non-Petroleum-Based Fuel Technologies

- Hydrogen
- Electricity
- Biofuels – “Drop-in” synthetic gasoline via pyrolysis + refining
- Natural Gas
- Gas- and Coal-to-Liquids

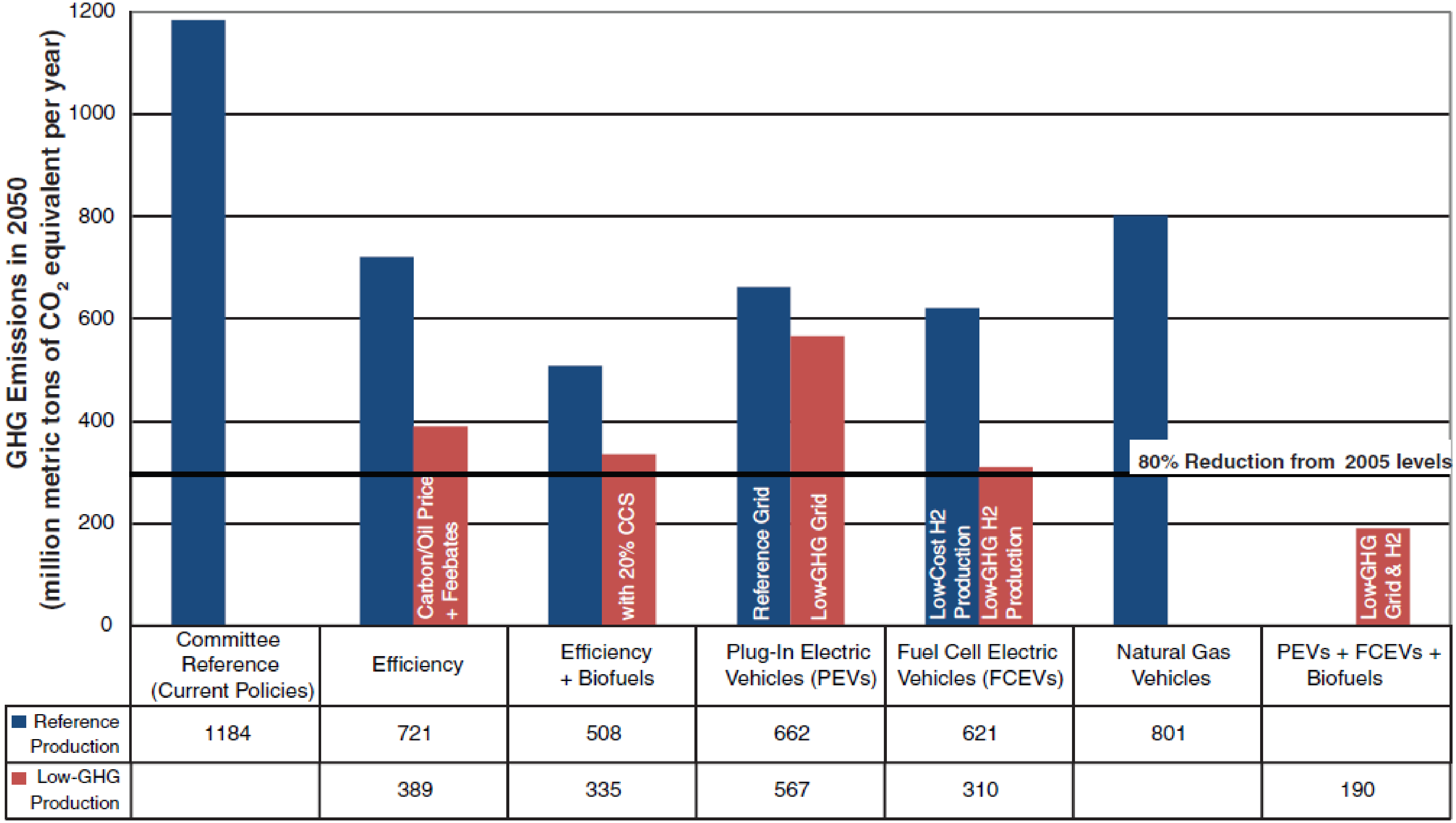
Note: hydrogen, electricity and biofuels must be produced without large GHG emissions to meet the GHG goal of the study. Otherwise these fuels plus natural gas and GTL/CTL contribute to the petroleum goals but little or not at all to the GHG goal.

# The petroleum reduction goal for 2030 was at least as difficult as the 2050 goal.



| | Committee Reference (Current Policies) | Efficiency | Efficiency + Biofuels | Efficiency + Carbon/Oil Price + Feebates | Plug-In Electric Vehicles (PEVs) | Fuel Cell Electric Vehicles (FCEVs) | Natural Gas Vehicles | PEVs + FCEVs + Biofuels |
|---|---|---|---|---|---|---|---|---|
| 🟦 2030 | 2.10 | 2.00 | 1.86 | 1.82 | 1.93 | 1.73 | 1.42 | 1.30 |
| 🟥 2050 | 2.17 | 1.08 | 0.41 | 0.39 | 0.80 | 0.13 | 0.40 | 0.00 |

# Even getting close to 80% GHG reduction requires W-T-W low-C energy.



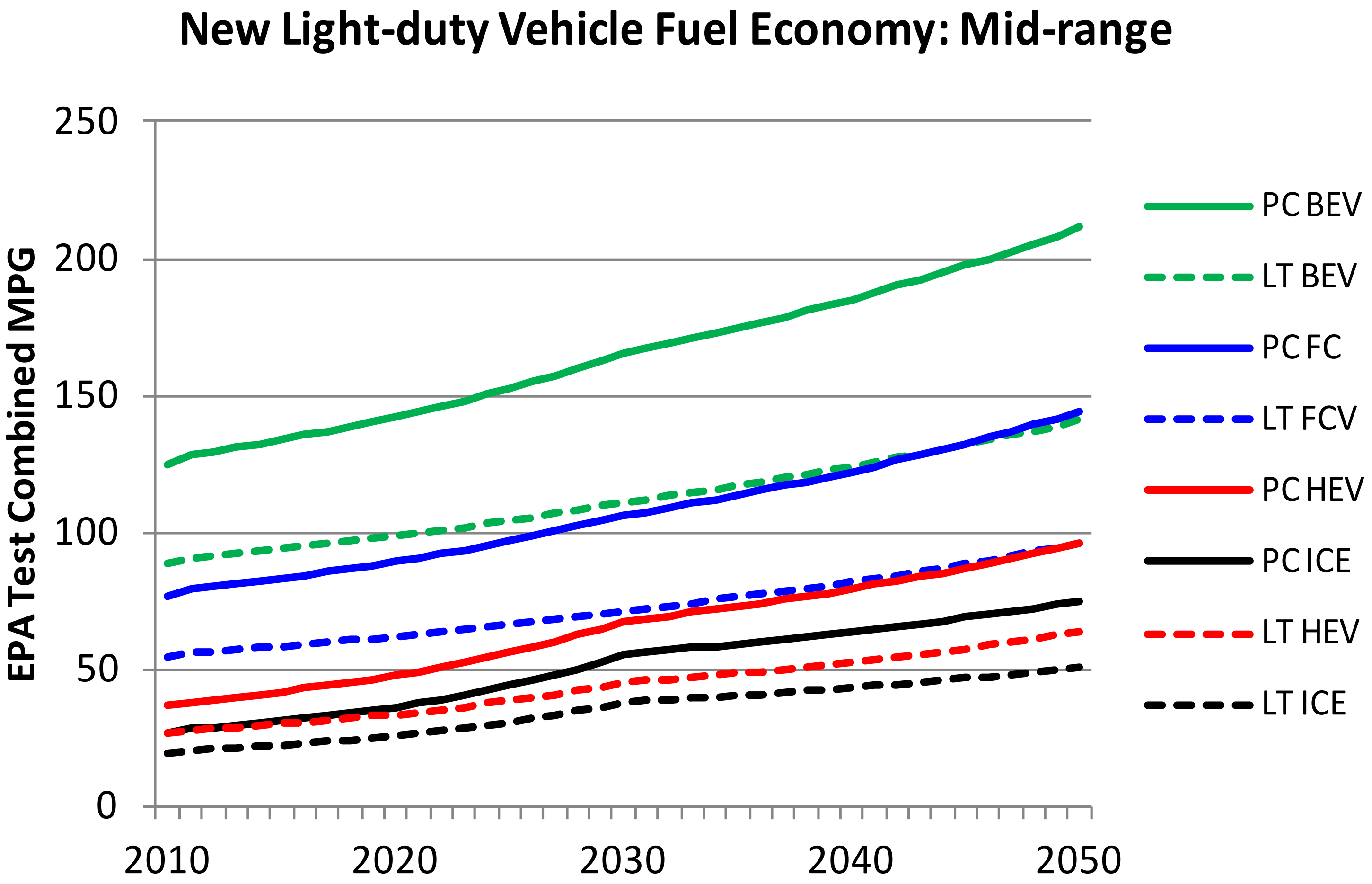
| | Committee Reference (Current Policies) | Efficiency | Efficiency + Biofuels | Plug-In Electric Vehicles (PEVs) | Fuel Cell Electric Vehicles (FCEVs) | Natural Gas Vehicles | PEVs + FCEVs + Biofuels |
|---|---|---|---|---|---|---|---|
| 🟦 Reference Production | 1184 | 721 | 508 | 662 | 621 | 801 | |
| 🟥 Low-GHG Production | | 389 | 335 | 567 | 310 | | 190 |

# Progress of key technologies to 2050.

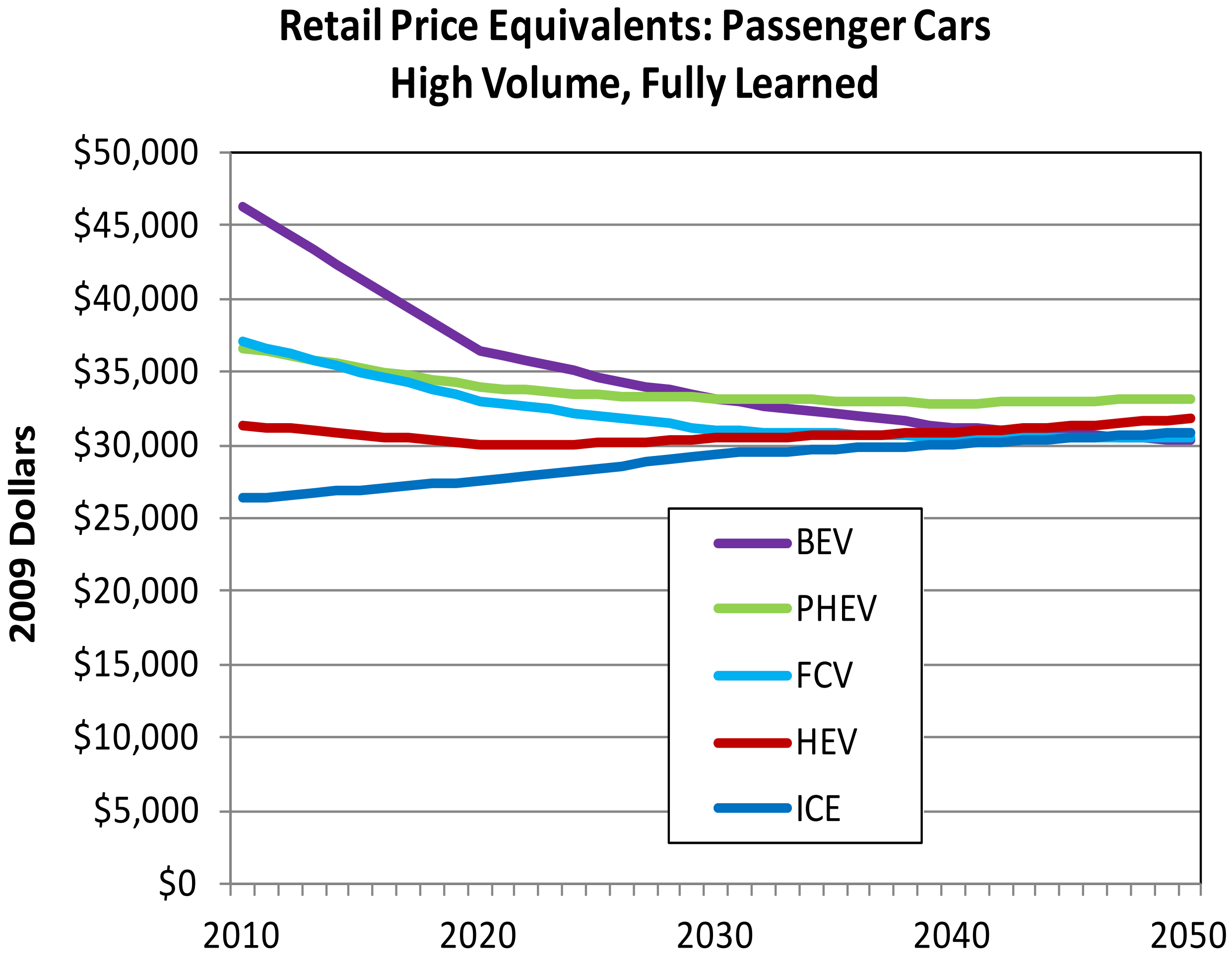
# Internal Combustion Engine vehicles can achieve 75 MPG without reducing size or performance.

- Large fuel economy gains beyond 2025 standards are feasible.
- Gains come from improved engine and drive-train efficiency and load reduction, e.g., reduced weight and rolling resistance.
- **Load reduction favors FCVs and BEVs in the long run.**
- Passenger car weight reduction:
  - 2030 = -20%
  - 2050 = -30%
- Light truck (body on frame) weight reduction:
  - 2030 = -15%
  - 2050 = -22%
- More could be done using C-fiber (50%/40%).

# Rates of new vehicle energy efficiency improve in line with 2025 standards to 2030, then slow.

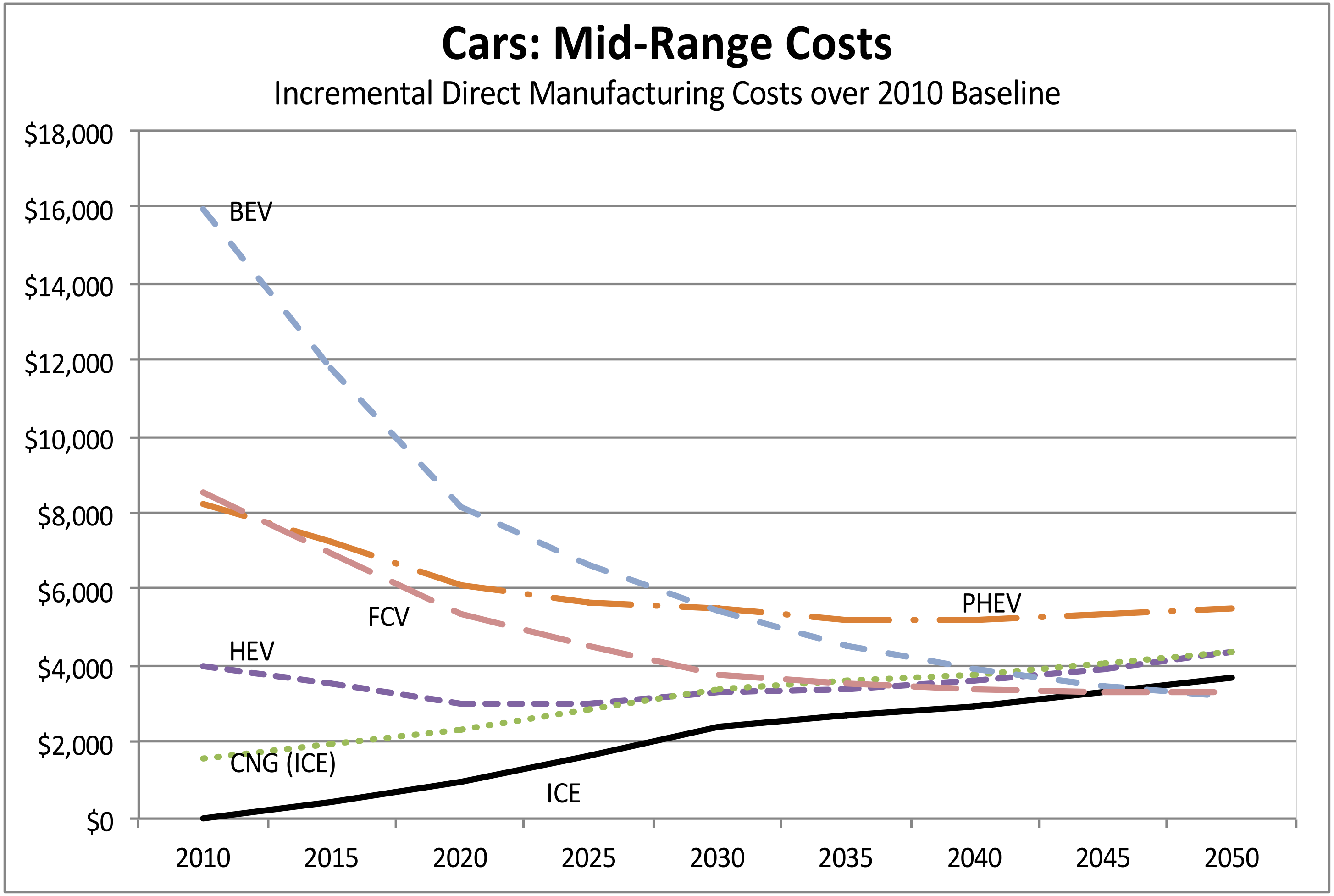


# "Mid-range technology": By 2050, passenger cars cost about $5,000 more than in 2010 and FCVs and BEVs could be cheaper than ICEs.

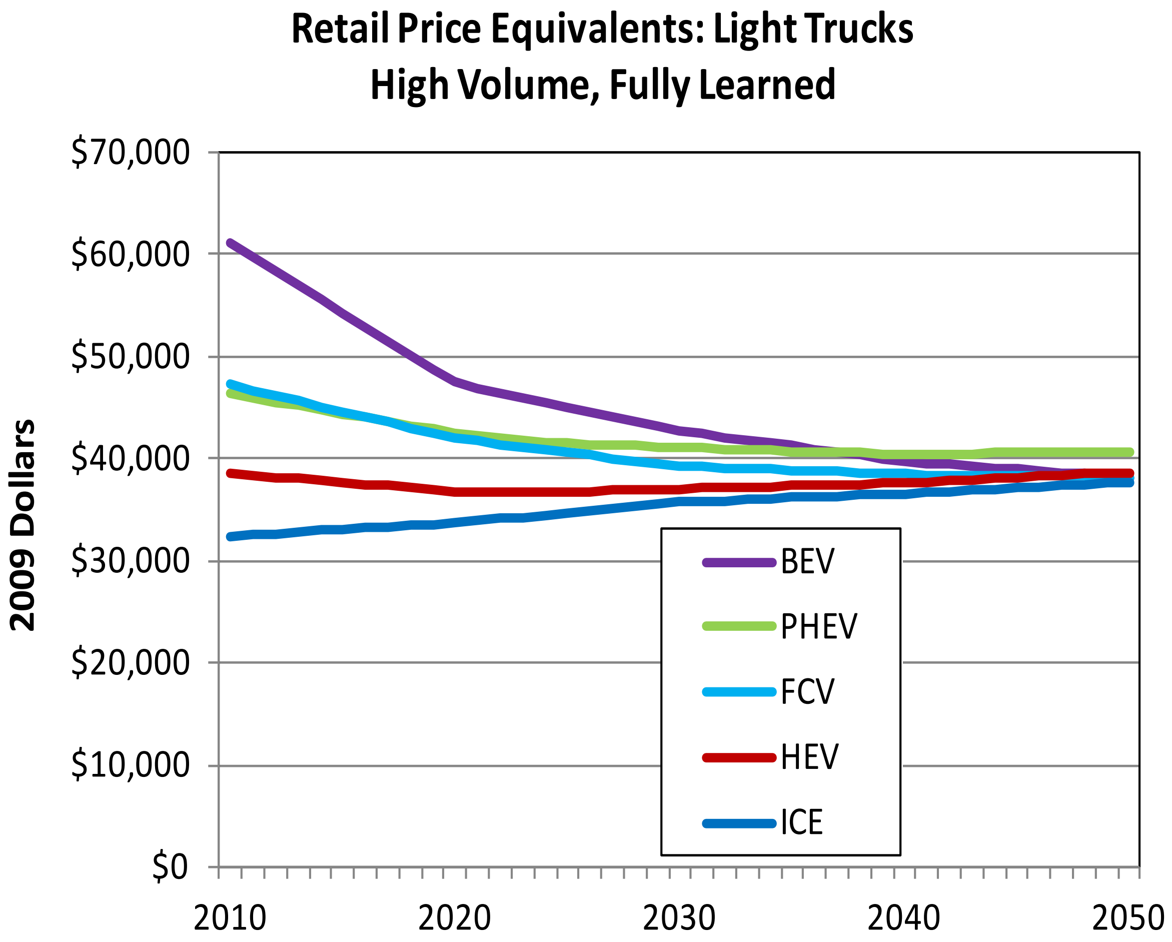


Retail Price Equivalents: Passenger Cars
High Volume, Fully Learned

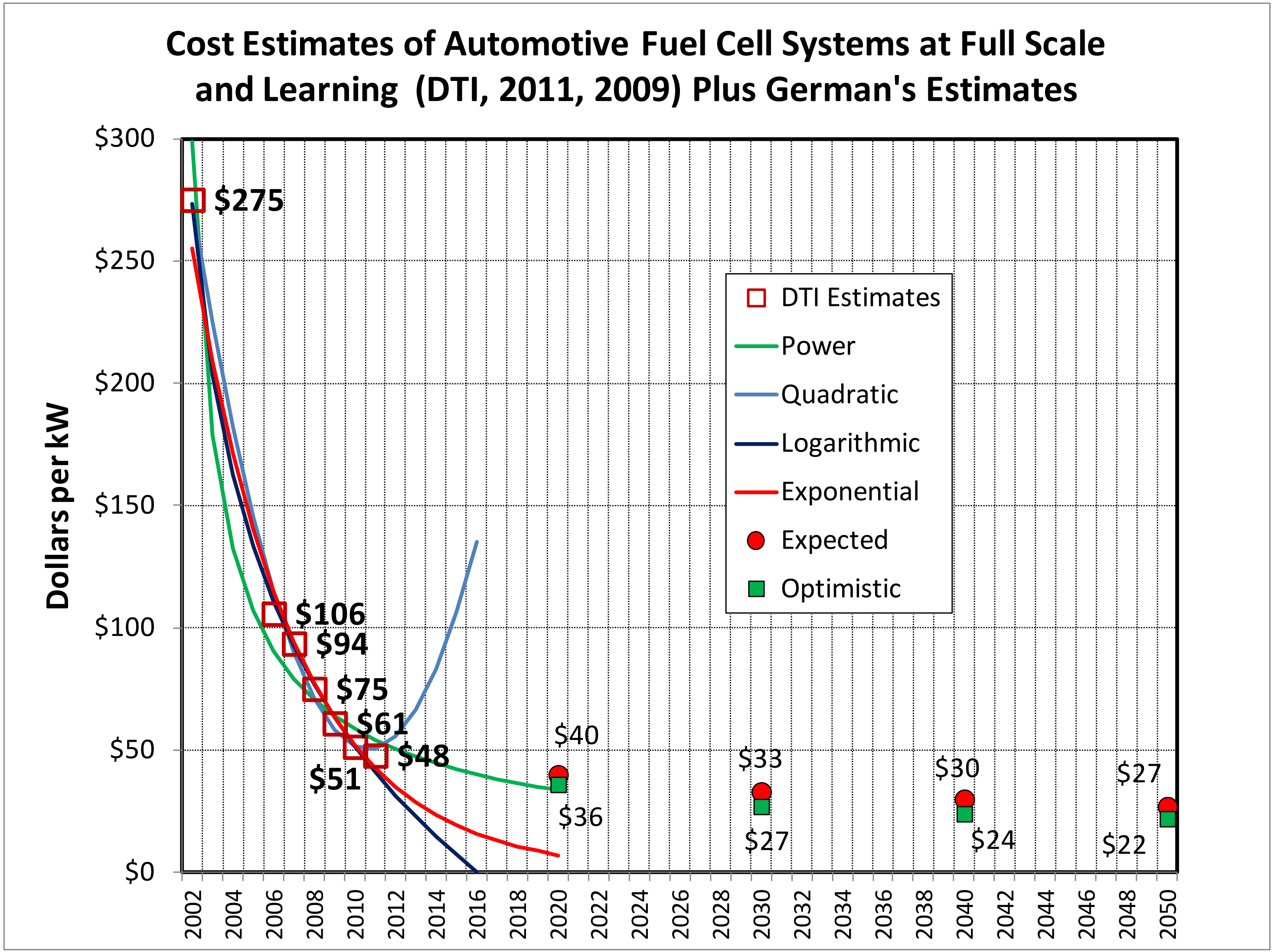
# This graph shows high-volume, fully-learned incremental manufacturing costs.



# The retail price projections for light trucks are similar but ICEs remain the least expensive.



# The historical progress of batteries and fuel cells is relatively clear. Future progress could be much slower and goals would still be met.

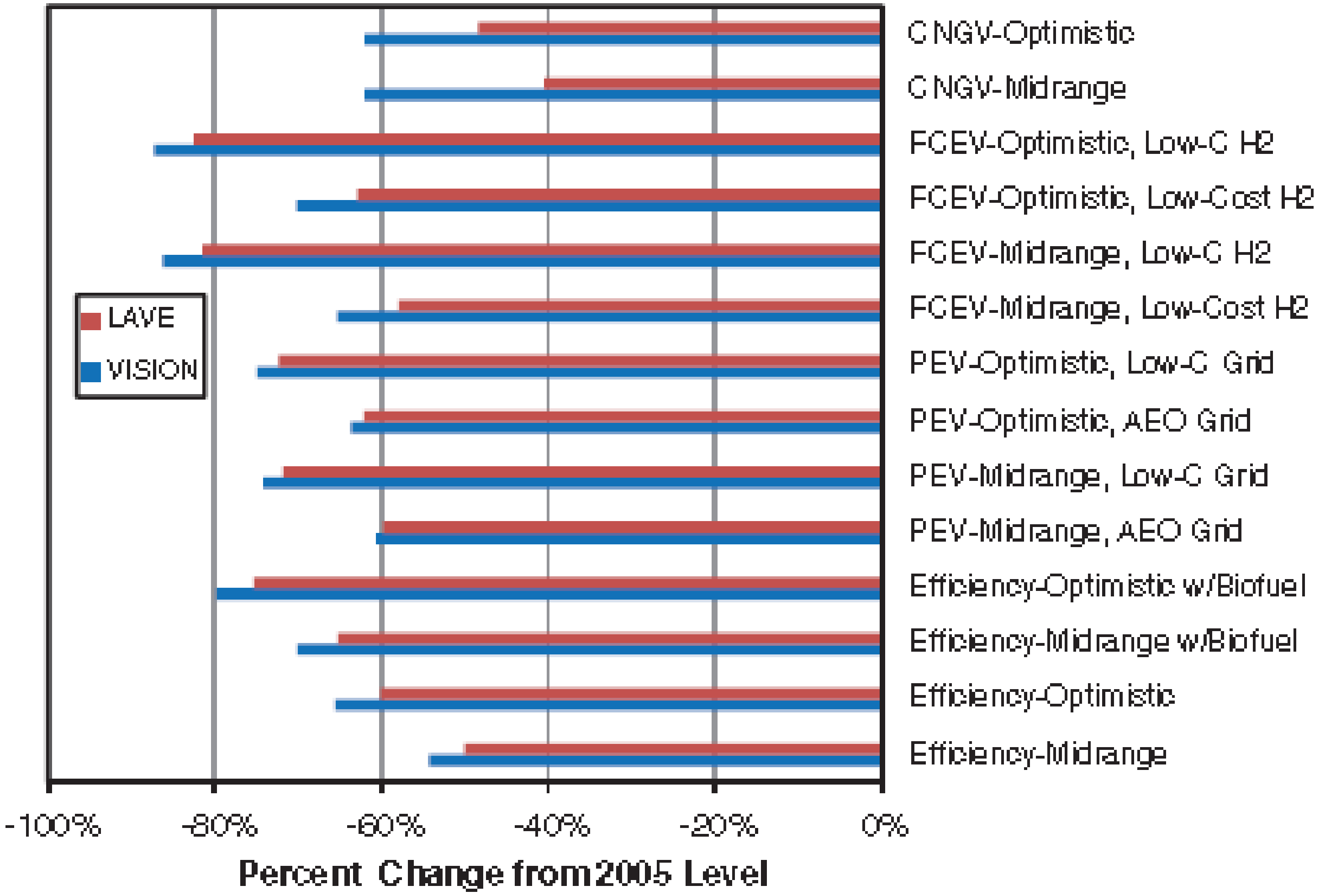


Cost Estimates of Automotive Fuel Cell Systems at Full Scale and Learning (DTI, 2011, 2009) Plus German's Estimates

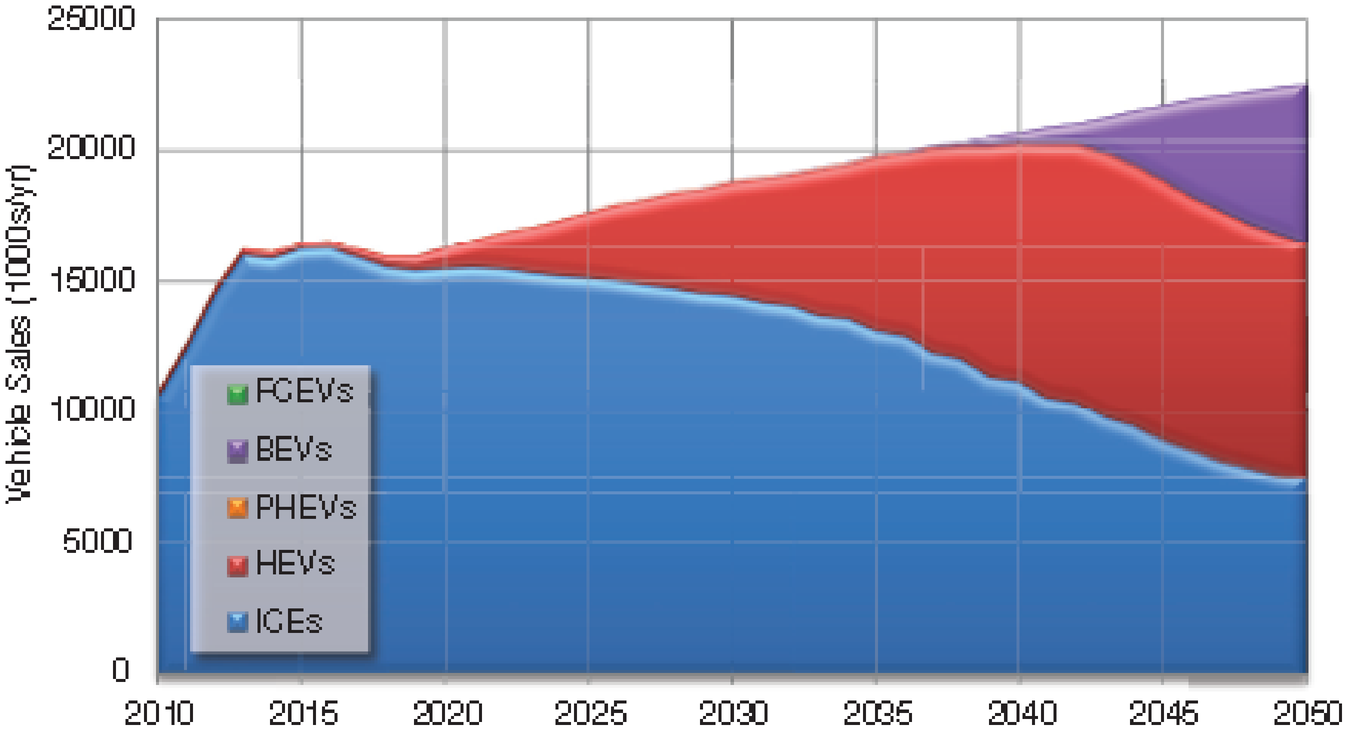
# A significant amount of drop-in bio-fuel is in every scenario.

- Drop-in Biofuels (direct replacement for gasoline) can be produced from cellulosic biomass and introduced without major changes in delivery infrastructure or vehicles
- Achievable production levels at acceptable cost are uncertain, but the potential is large.
  - Maximum 2050 production:
    - 45 BGGE/700 Mt biomass/58M acres
  - Reference Assumption:
    - 13.5 BGGE/210Mt biomass/17M acres
- Drop-in Biofuels coupled with high efficiency ICEVs and HEVs could be a major contributor to reducing petroleum use and GHG emissions.

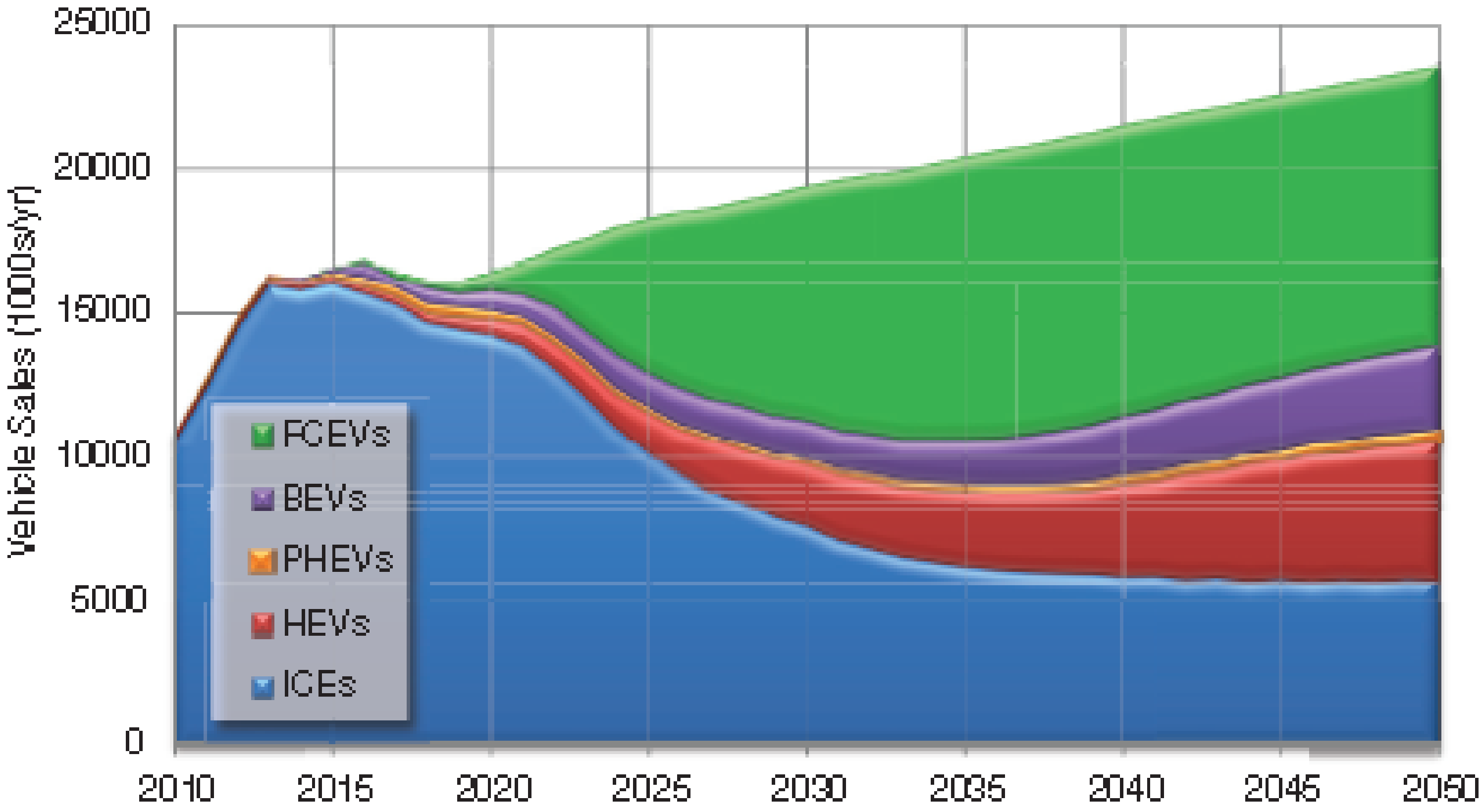
# Impacts on oil use and GHG emissions were estimated using two models: a simple spreadsheet calculator (VISION) and a model including market behavior (LAVE).



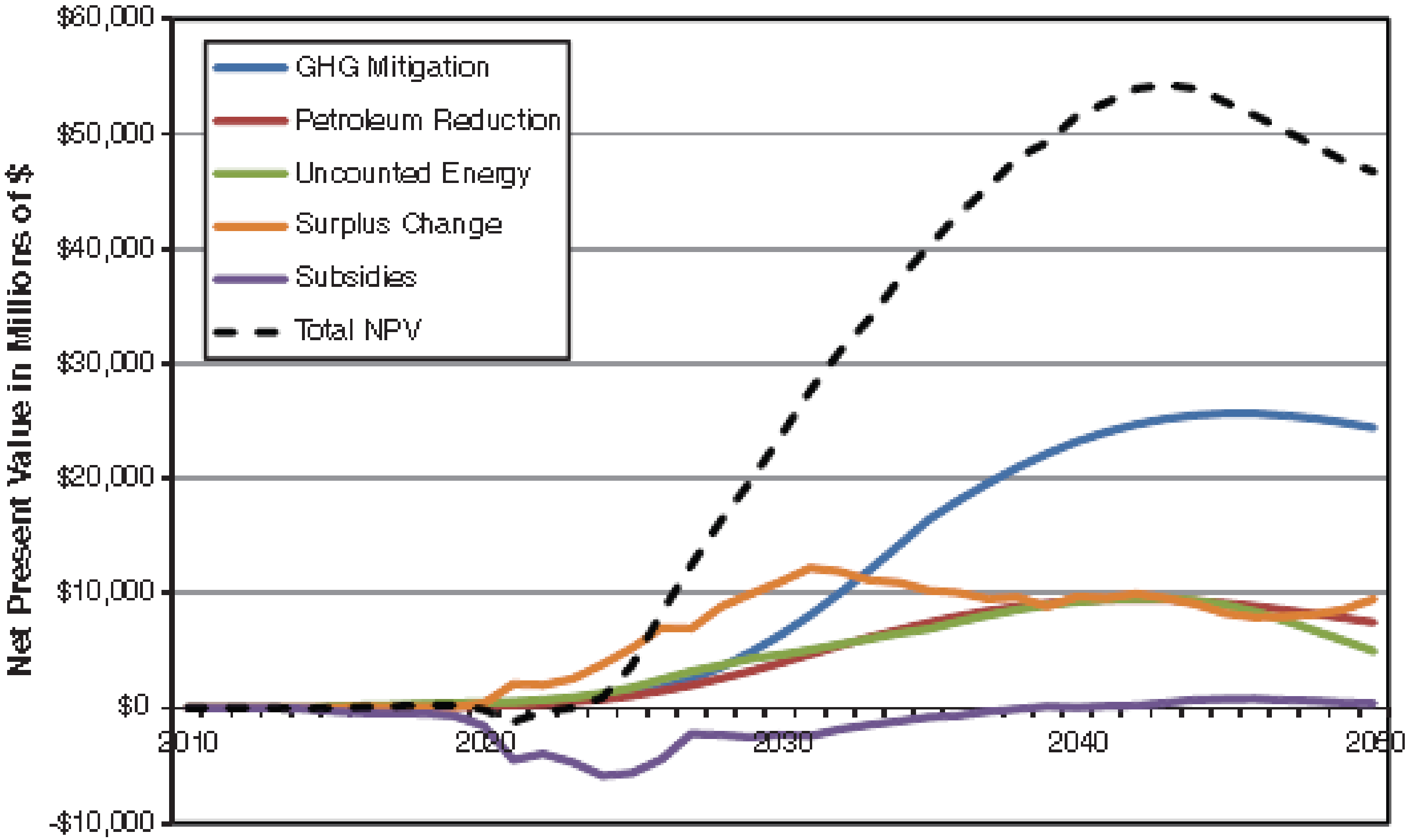
In the market model (LAVE) fuel economy & emissions standards plus technological progress and a highway tax indexed to MPG produced a 52% reduction in GHG emissions and a 64% reduction in petroleum use. No vehicle subsidies, no subsidized hydrogen infrastructure.



# A strategy promoting both FCVs and PEVs led to an 88% reduction in GHG emissions and a 100% reduction in petroleum use by 2050.



# Earlier market success of plug-in vehicles or transition to hydrogen fuel cell vehicles required subsidies for a decade or so. Yet total benefits exceeded costs by roughly an order of magnitude.



# Key Findings

- No pathway is adequate by itself; at least two and maybe more will be needed.
- Improved efficiency is essential to the success of the other pathways.
- New  non-petroleum fuel infrastructures must be developed as well as new vehicles capturing the required market share.
- Reducing GHG emissions for all fuels will depend on their production and use without large emissions of carbon dioxide.
- If fossil resources are to be sources of non-carbon transportation fuels—i.e., electricity and hydrogen—carbon capture and storage will be essential.
- Making the necessary changes in the non-petroleum fuel infrastructure will be costly; however, our analyses show the societal benefits are many times larger than the projected costs.
- Federal policy is required to drive these changes.

# Policy Suggestions

- Robust and adaptive policies are required to achieve success with any scenario.
- Continued, government-supported R&D is strongly endorsed.
- Policies included in scenarios:
  - Fuel economy/emissions standards and vehicle pricing induced by standards reflecting social costs of oil and GHGs.
  - Highway user fee on energy indexed to average energy efficiency of all vehicles in use.
  - Additional, temporary vehicle and fuel subsidies to overcome transition barriers.
  - Taxes on fuels reflecting social costs.
- Not included but suggested: A floor on the price of petroleum

# THANK YOU.

# Electric Vehicles

- All forms of electric vehicles are critically dependent on battery performance and costs.
- Battery costs are projected to drop steeply and battery vehicles could become less expensive than ICEVs of 2050.

| | | | | |
|---|---|---|---|---|
| BEV battery | $/kWh | $450 | $250/$200 | $160/$150 |
| PHEV battery | $/kWh | $550 | $320/$260 | $200/$190 |
| HEV battery | $/kWh | $2,000 | $750/$650 | $650/$650 |
| FC system | $/kW | $50 | $33/$27 | $27/$22 |

- However, limited range and long charging times remain barriers to consumer acceptance.

# The cost of producing bio-fuel via pyrolysis and refining is expected to decrease over time but remain sensitive to the cost of feedstock.

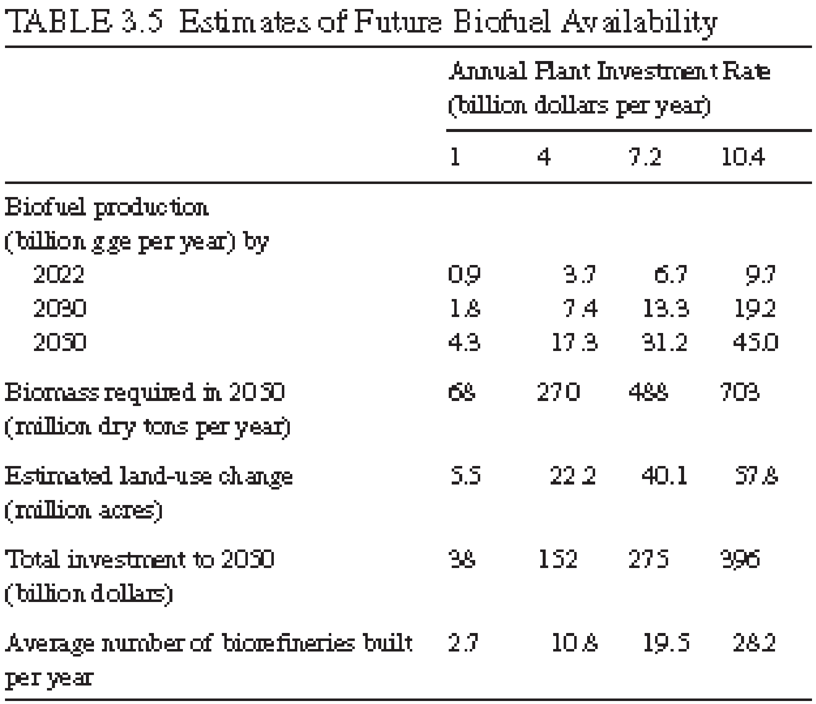


TABLE 3.5 Estimates of Future Biofuel Availability

| | Annual Plant Investment Rate (billion dollars per year) | | | |
|---|---|---|---|---|
| | 1 | 4 | 7.2 | 10.4 |
| Biofuel production (billion gge per year) by | | | | |
| 2022 | 0.9 | 3.7 | 6.7 | 9.7 |
| 2030 | 1.8 | 7.4 | 13.3 | 19.2 |
| 2050 | 4.3 | 17.3 | 31.2 | 45.0 |
| Biomass required in 2050 (million dry tons per year) | 68 | 270 | 488 | 703 |
| Estimated land-use change (million acres) | 5.5 | 22.2 | 40.1 | 57.8 |
| Total investment to 2050 (billion dollars) | 38 | 152 | 275 | 396 |
| Average number of biorefineries built per year | 2.7 | 10.8 | 19.5 | 28.2 |

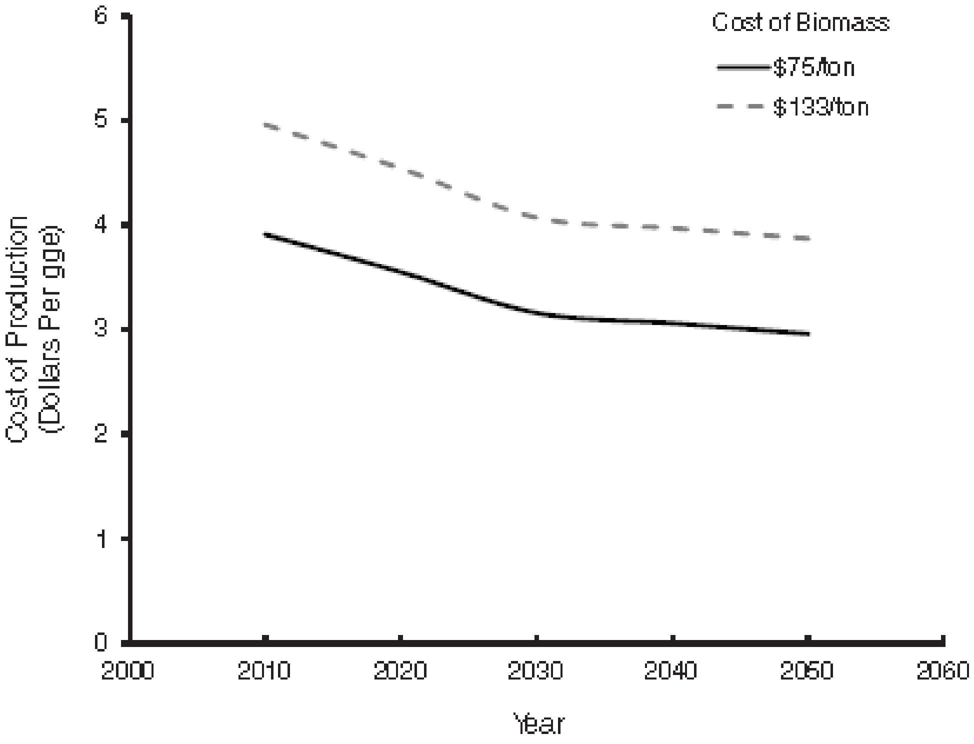


FIGURE 3.2 Sensitivity of biofuel cost to biomass cost.

# COMMITTTEE ON TRANSITIONS TO ALTERNATIVE VEHICLES AND FUELS

- DOUGLAS M. CHAPIN, *Chair, NAE,1 MPR Associates, Inc., Alexandria, Virginia*
- RALPH BRODD, Broddarp of Nevada, Henderson
- GARY COWGER, GLC Ventures, LLC, Bloomfield Hills, Michigan
- JOHN M. DECICCO, University of Michigan, Ann Arbor
- GEORGE C. EADS, Charles River Associates (retired), Washington, District of Columbia
- RAMON ESPINO, University of Virginia, Charlottesville
- JOHN M. GERMAN, International Council for Clean Transportation, Ann Arbor, Michigan
- DAVID L. GREENE, Oak Ridge National Laboratory, Knoxville, Tennessee
- JUDITH GREENWALD, Center for Climate and Energy Solutions, Arlington, Virginia
- L. LOUIS HEGEDUS, NAE, Arkema, Inc. (retired), Bryn Mawr, Pennsylvania
- JOHN HEYWOOD, NAE, Massachusetts Institute of Technology, Cambridge
- VIRGINIA McCONNELL, Resources for the Future, Washington, District of Columbia
- STEPHEN J. McGOVERN, PetroTech Consultants LLC, Voorhees, New Jersey
- GENE NEMANICH, ChevronTexaco Corporation (retired), Scottsdale, Arizona
- JOHN O'DELL, Edmunds, Inc., Orange, California
- ROBERT F. SAWYER, NAE, University of California, Berkeley
- CHRISTINE S. SLOANE, Sloane Solutions, LLC, Kewadin, Michigan
- WILLIAM H. WALSH, JR., Consultant, McLean, Virginia
- MICHAEL E. WEBBER, University of Texas at Austin

# Study Committee Charge

- The NRC will appoint an ad hoc study committee to conduct a comprehensive analysis of energy use within the light-duty vehicle transportation sector, and use the analyses to conduct an integrated study of the technology and fuel options (including electricity) that could reduce petroleum consumption and greenhouse gas emissions. As was accomplished with the NRC *Transitions to Alternative Transportation Technologies: A Focus on Hydrogen* study, the study will address the following issues over the time frame out to 2050:
- Assess the current status of light-duty vehicle technologies and their potential for future improvements in terms of fuel economy and costs including:
  - Advanced conventional ICE and hybrid-electric vehicles, including improved combustion and rolling resistance, and weight reduction (safety implications of lighter weight vehicles will be considered);
  - All-electric and plug-in hybrid electric vehicles;
  - Hydrogen fueled ICE and fuel cell vehicles;
  - Biofueled vehicles; and
  - Natural gas vehicles.
- Assess the status and prospects for current and future fuels and electric power that would be needed to power the vehicles. A variety of alternative fuels will be considered such as hydrogen, fuels derived from fossil feedstocks, and different biofuels derived from biomass feedstocks.
- Develop scenarios or estimates of the rate at which each of the vehicle technologies considered might be able to penetrate the market and what would be the associated costs, greenhouse gas emissions and petroleum consumption impacts out to 2050. This would also include the infrastructure needs either for production of the vehicles or supplying the energy requirements for the vehicles. Costs would be put on a consistent basis to serve as a better index of comparing options. 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 also be considered.
- Identify the barriers that might exist in transitioning to these vehicle and fuel technologies.
- Consider and compare, as appropriate, the results to those obtained in recent National Academies studies as well as in other outside analyses and make comparisons based on similar assumptions and cost and benefit calculations.
- Recommend improvements in, and priorities for, the federal R&D program activities to accelerate the development of the most promising technologies.
- Suggest policies and strategies for achieving up to 80 percent reduction in petroleum consumption and carbon dioxide emissions by 2050 through commercial deployment of the light-duty vehicle technologies analyzed in the study.
- Write a report documenting the analyses, conclusions, and recommendations.
- To the extent possible the committee will consider issues relating to vehicle duty cycles, regional distinctions, and technology development timelines and will build on the recent work of the National Academies reports as well as other recent studies that have been conducted.

# How are these fuel economies achieved? Reduced load + improved efficiency.

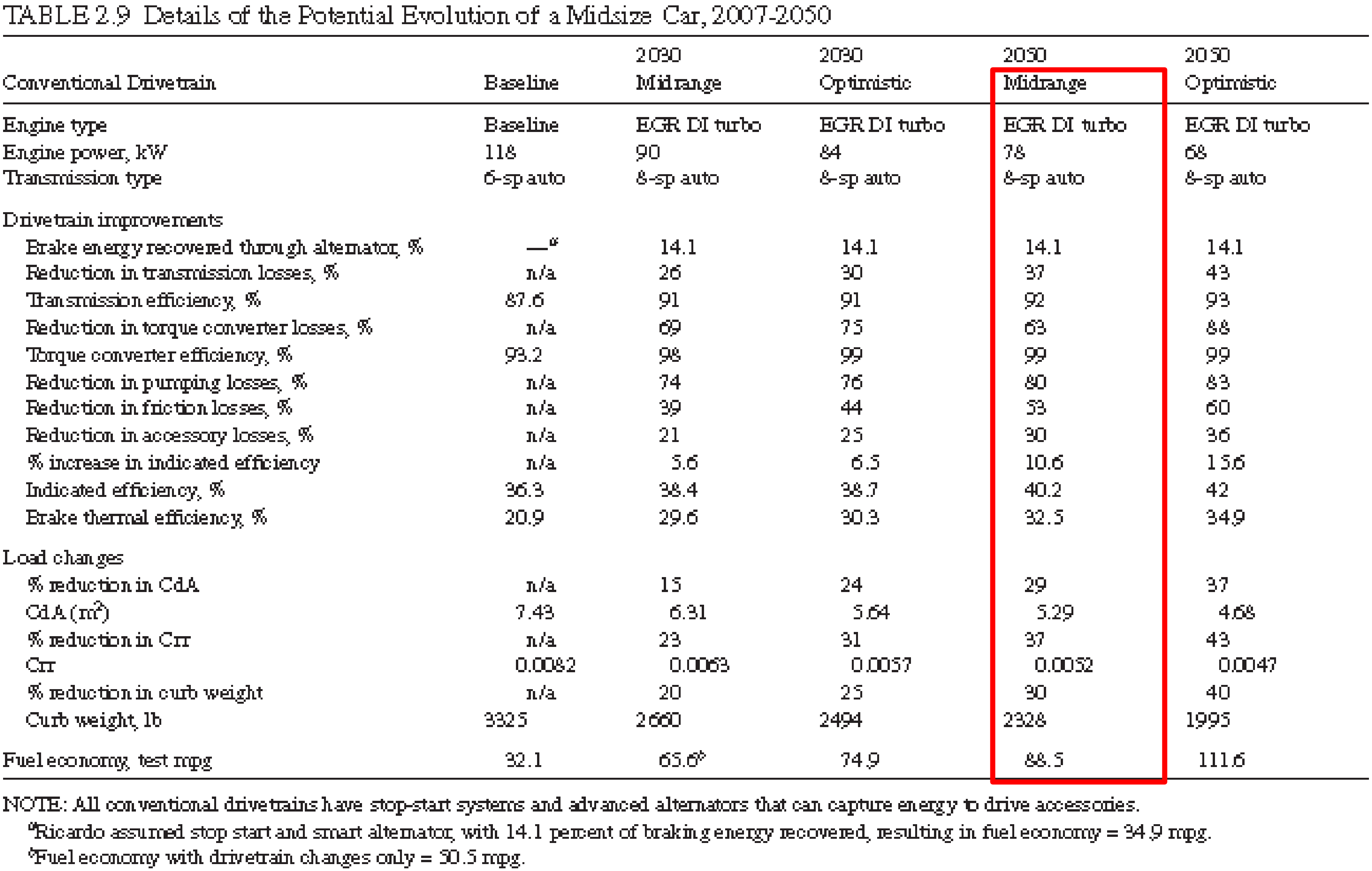


TABLE 2.9 Details of the Potential Evolution of a Midsize Car, 2007-2050

| Conventional Drivetrain | Baseline | 2030 Midrange | 2030 Optimistic | 2050 Midrange | 2050 Optimistic |
|---|---|---|---|---|---|
| Engine type | Baseline | EGR DI turbo | EGR DI turbo | EGR DI turbo | EGR DI turbo |
| Engine power, kW | 118 | 90 | 84 | 78 | 68 |
| Transmission type | 6-sp auto | 8-sp auto | 8-sp auto | 8-sp auto | 8-sp auto |
| Drivetrain improvements | | | | | |
| Brake energy recovered through alternator, % | —[a] | 14.1 | 14.1 | 14.1 | 14.1 |
| Reduction in transmission losses, % | n/a | 26 | 30 | 37 | 43 |
| Transmission efficiency, % | 87.6 | 91 | 91 | 92 | 93 |
| Reduction in torque converter losses, % | n/a | 69 | 75 | 63 | 88 |
| Torque converter efficiency, % | 93.2 | 98 | 99 | 99 | 99 |
| Reduction in pumping losses, % | n/a | 74 | 76 | 80 | 83 |
| Reduction in friction losses, % | n/a | 39 | 44 | 53 | 60 |
| Reduction in accessory losses, % | n/a | 21 | 25 | 30 | 36 |
| % increase in indicated efficiency | n/a | 5.6 | 6.5 | 10.6 | 15.6 |
| Indicated efficiency, % | 36.3 | 38.4 | 38.7 | 40.2 | 42 |
| Brake thermal efficiency, % | 20.9 | 29.6 | 30.3 | 32.5 | 34.9 |
| Load changes | | | | | |
| % reduction in CdA | n/a | 15 | 24 | 29 | 37 |
| CdA ($m^2$) | 7.43 | 6.31 | 5.64 | 5.29 | 4.68 |
| % reduction in Crr | n/a | 23 | 31 | 37 | 43 |
| Crr | 0.0082 | 0.0063 | 0.0057 | 0.0052 | 0.0047 |
| % reduction in curb weight | n/a | 20 | 25 | 30 | 40 |
| Curb weight, lb | 3325 | 2660 | 2494 | 2328 | 1995 |
| Fuel economy, test mpg | 32.1 | 65.6[b] | 74.9 | 88.5 | 111.6 |

NOTE: All conventional drivetrains have stop-start systems and advanced alternators that can capture energy to drive accessories.

[a] Ricardo assumed stop start and smart alternator, with 14.1 percent of braking energy recovered, resulting in fuel economy = 34.9 mpg.

[b] Fuel economy with drivetrain changes only = 50.5 mpg.