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REPORT IN BRIEF

# Cost, Effectiveness and Deployment of Fuel Economy Technologies for Light-Duty Vehicles

Board on Energy and Environmental Systems · Division on Engineering & Physical Sciences · June 2015

**Over the next several decades, increasingly stringent fuel economy and greenhouse gas emission standards will come into force, as set out by the National Highway Traffic Safety Administration (NHTSA) and the Environmental Protection Agency (EPA). In response, the light-duty vehicle fleet can be expected to undergo substantial technological changes as automakers incorporate new powertrain designs, alternative fuels, and advanced materials. Cost, Effectiveness and Deployment of Fuel Economy Technologies for Light-Duty Vehicles, a study carried out for NHTSA by the National Research Council (NRC), evaluates the costs, benefits, and implementation of new light-duty vehicle technologies under NHTSA and EPA standards. The report estimates manufacturing costs and fuel consumption reductions for individual technologies, and also discusses safety, manufacturing impacts, consumer acceptance and the NHTSA standard setting methodology.**

**The report finds that by the end of the next decade, new light-duty vehicles will be more fuel efficient, lighter, emit less air pollution, safer and more expensive to purchase relative to current vehicles. Improvements in gasoline-powered engines will account for the largest reductions in fuel consumption through 2025, though alternative powertrains are being implemented in an increasing number of models. Evidence suggests that standards based on vehicle footprint (wheelbase times track width) will lead the nation's light-duty vehicle fleet to become lighter but not less safe. The NRC judged the NHTSA and EPA analysis in setting the 2017-2025 MY CAFE/GHG standards to be thorough and of high-caliber overall, however the NRC recommends a number of areas the agencies should re-examine during the upcoming mid-term review.**

## Background

NHTSA, together with the EPA, has been progressively tightening Corporate Average Fuel Economy (CAFE) and greenhouse gas (GHG) emission standards. The new CAFE/GHG standards cover model years (MY) 2017-2025 and call for an average light-duty vehicle fleet fuel economy of 40.3-41.0 miles per gallon (mpg) by 2021 and 48.7-49.7 mpg by 2025. Combined with provisions for reducing air conditioning emissions and other sources of greenhouse gas emissions, light-duty vehicles in the U.S. fleet will emit no more than 163 grams of carbon dioxide (CO2) per mile on average by 2025, which is equivalent to 54.5 mpg.

Recognizing the uncertainties and legal constraints in setting standards out to 2025, NHTSA is committed to an interim review to judge progress. By April 2018, NHSTA and EPA will complete a mid-term review of the MY 2022-2025 standards. To inform this review, NHTSA requested that the National Research Council convene a committee of experts to assess the CAFE standards program, the Agencies' analysis underlying the standards, and the costs and fuel consumption improvements of a variety of light-duty vehicle technologies. Using the committee's own expertise along with input received from NHTSA, EPA, other federal agencies, automakers, suppliers, and researchers, the NRC developed this independent evaluation.

## Estimated Fuel Consumption Reductions and Cost

The report finds the analyses conducted by NHTSA and EPA in their development of the 2017-2025 standards to be thorough and of high caliber. Full vehicle simulation modeling in combination with increased vehicle testing has improved the Agencies' estimates of fuel economy impacts, while teardown studies have helped provide more accurate cost estimates.

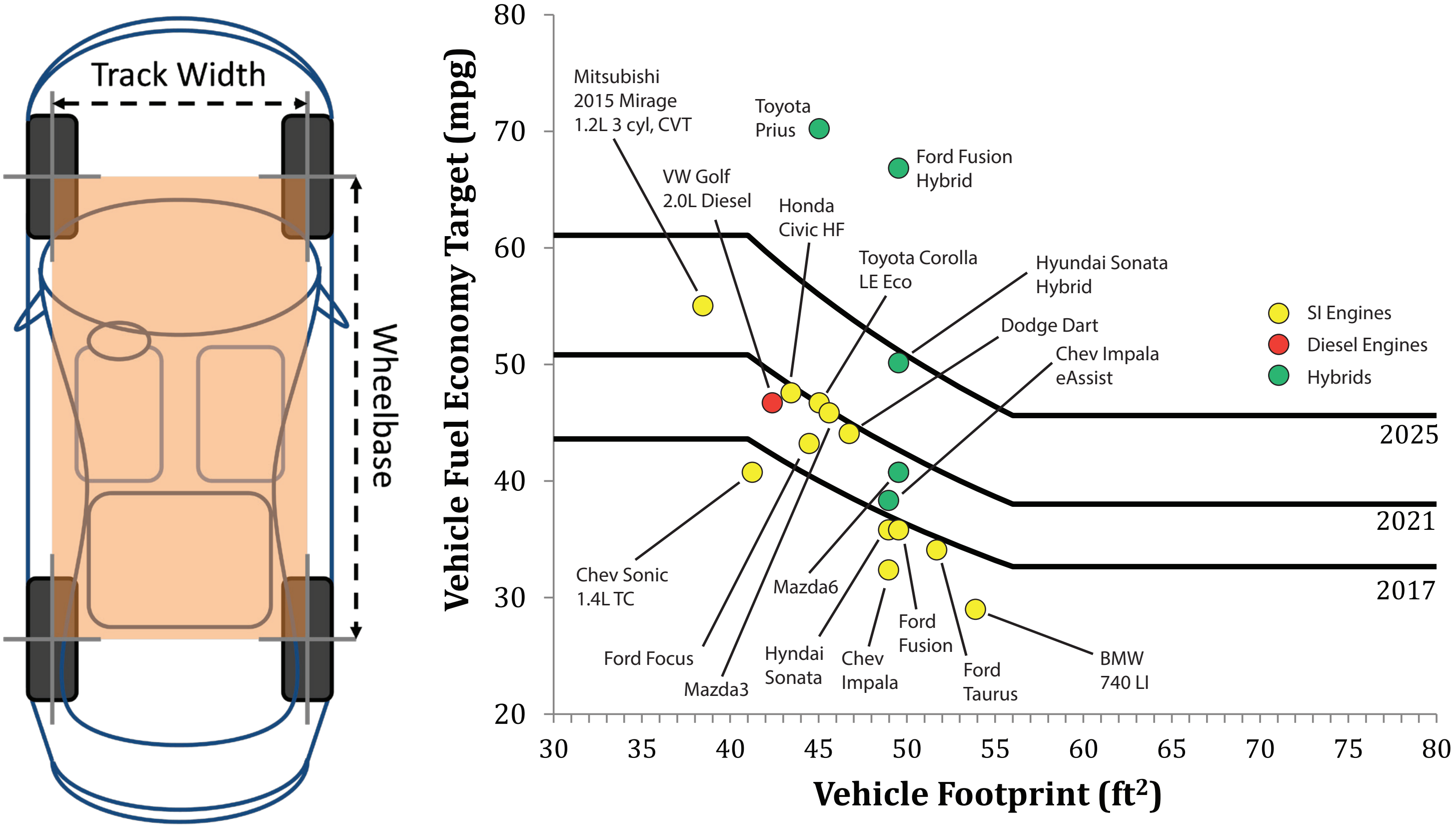
The report committee independently developed estimates of the cost and potential fuel consumption reductions for new light-duty vehicle technologies that might be employed from 2020 to 2030. The enclosed tables show estimates of the most likely fuel consumption benefits and direct manufacturing costs for each considered technology for year 2025. These values are not meant to represent the full range of possible values for cost and effectiveness, but rather the most likely values predicted by committee experts for the 2017-2025 time period. For some technologies, committee members held different views on the best estimate of cost and effectiveness; these viewpoints are represented by a range of values in the tables. Certain technologies are in need of further analysis, including the cost and effectiveness of turbocharged, downsized engines and the cost and implementation of mass reduction.

**Recommendation: While the committee concurred with the Agencies' costs and effectiveness values for a wide array of technologies, in some cases the committee developed estimates that significantly differed from the Agencies' values, so the committee recommends that the Agencies pay particular attention to the reanalysis of these technologies in the mid-term review. Further, the committee notes that the use of full vehicle simulation modeling in combination with lumped parameter modeling and teardown studies contributed substantially to the value of the Agencies' estimates of fuel consumption and costs, and it recommends they continue to increase the use of these methods to improve their analysis.**

## Spark-Ignition Engines

The spark-ignition (SI) engine fueled with gasoline is by far the primary powertrain configuration in the United States for light-duty vehicles and will likely continue this dominance through the 2025 timeframe and beyond. The Agencies consider substituting turbocharged, downsized engines for larger displacement, naturally aspirated engines as a major option for reducing fuel consumption to meet the standards. The combined SI engine improvements should provide overall fuel consumption reductions close to that estimated by NHTSA but with as much as 15 percent higher direct manufacturing costs for several of the technologies.

**Recommendation: Since spark-ignition engines are expected to be dominant beyond 2025, updated effectiveness and cost estimates of the most effective spark-ignition engine technologies should be developed for the mid-term review of the CAFE standards. Updated effectiveness estimates should be derived from full system simulations using engine maps based on measured data or generated engine model maps derived from validated baselines and include models**



(Left) Vehicle footprint is determined by the track length times the wheelbase. (Right) The official EPA certification fuel economy values for select passenger vehicles incorporating some of the technologies identified by NHTSA compared to CAFE targets for 2017, 2021, and 2025 (solid lines). The vehicles represent a range of powertrains and vehicle footprints, including many high volume models.

**for fuel octane requirements and drivability. Updated cost estimates using teardown cost studies of recently introduced spark-ignition engine technologies, including all vehicle integration costs, should be developed to support the mid-term review.**

## Compression-Ignition Engines

While the NRC agrees with the Agencies' fuel consumption reduction estimates for compression-ignition (CI) engines fueled by diesel, it finds that the current EPA fuel economy certification data do not show such large reductions.

**Recommendation: EPA and NHTSA should expand their full system simulations supported by mapping the latest diesel engines that incorporates as many of the latest technologies as possible, as discussed in this chapter. EPA and NHTSA should conduct a teardown cost study of a modern diesel engine with the latest technologies to provide an up-to-date estimate of diesel engine costs.**

## Hybrid and Electrified Powertrains

Electrification of the powertrain is a powerful method to reduce fuel consumption and GHG emissions. The NRC generally agrees with the Agencies' estimates of fuel consumption benefits for hybrid electric vehicles (HEVs), and battery cost estimates of plug-in electric vehicles (PEVs) but has concerns about the regulatory treatment of the GHG emissions from the generation of electricity. The penetration of HEVs, battery electric vehicles (BEVs), and plug-in hybrid electric vehicles (PHEVs) by MY 2025 will likely be larger than the respective 5%, 0% and 2% that the Agencies included in their compliance demonstration path. The NRC also finds that the Agencies made critical assumptions that need to be revised about the implementation of the P2 HEV design, usable battery capacity for some hybrid technologies and non-battery costs for PEVs.

**Recommendation: For their mid-term review, the Agencies should examine auto manufacturer's experiences of battery life to determine the appropriate state of charge swing for PHEVs and BEVs so that they can assign costs appropriately. Further, at the time of the mid-term review, there will be several vehicles with electrified powertrains in the market. The Agencies should commission teardown studies of the most successful examples of (1) stop-start, (2) strong hybrids (PS, P2, and two motor architectures), (3) PHEV20 and PHEV40, and (4) BEV100. At that time there will be better estimates of volumes for each type in the 2020 to 2025 time frame so that a better estimate of cost can be calculated.**

## Transmissions

The most popular transmission design is the planetary automatic transmission (AT), and it is expected to remain the dominant architecture in the US in the 2025 timeframe. However, continuously variable transmissions (CVTs), which provide continuously variable gear ratios to improve efficiency, will likely experience higher market penetration than assumed in the Agencies' compliance demonstration path and should be examined in the midterm review.

**Recommendation: NHTSA and EPA should add the CVT to the list of technologies applicable for the 2017-2025 CAFE standards. NHTSA and EPA should update the analyses of technology penetration rates for the midterm review to reflect the anticipated low DCT penetration rate in the U.S. market.**

## Non-Powertrain Technologies

There are many opportunities outside of the vehicle's powertrain to adopt fuel-saving technologies, including mass reduction, aerodynamics, tires, vehicle accessories, and the rapidly developing area of vehicle automation systems. The mass reductions identified in the EPA/NHTSA compliance demonstration path are overly conservative for midsize and large cars. Mass reductions across all vehicle sizes will likely be greater than what the Agencies estimated with proportionately more mass removed from heavier vehicles.

**Recommendation: The committee recommends that the Agencies augment their current work with a materials-based approach that looks across the fleet to better define opportunities and costs for implementing lightweighting techniques, especially in the area of decompounding. A characterization of current vehicles in terms of materials content is a prerequisite for such a materials-based approach and for quantifying the opportunities to incorporate different lightweighting materials in the fleet.**

## Cost and Manufacturing Considerations

In theory, the report agrees with the Indirect Cost Multiplier method used by the Agencies. However, attribution for these indirect costs can be ambiguous, especially for future costs, and it was not possible to validate the Agencies' Indirect Cost Multipliers. Product development for new vehicles is accelerating in order to better comply with regulations and respond to consumer demands. However, the rapid deployment of new technologies also increases stranded capital and incurs higher product deployment costs.

**Recommendation: The Agencies should continue research on indirect cost multipliers with the goal of developing a sound empirical basis for their estimation. It also recommends the Agencies continue to conduct and review empirical evidence for the cost reductions that occur in the automobile industry with volume, especially for large volume technologies that will be relied on to meet the CAFE/GHG standards.**

## Consumer Impacts and Acceptance Issues

Consumer response to more fuel efficient vehicles is a critical element of success for the CAFE/GHG standards. Consumers are purchasing fuel-efficient vehicles that meet their other wants and needs. There is evidence that most consumers will not widely adopt technologies that interfere with driver experience, comfort or perceived utility even for large improvements in fuel economy.

**Recommendation: The committee recommends that the Agencies do more research on the existence and extent of the energy paradox in fuel economy, the reasons for consumers' undervaluation of fuel economy relative to its discounted expected present value, and differences in consumers' perceptions across the population. The Agencies should study the value of vehicle attributes to consumers, consumer willingness to trade off other attributes for fuel economy, and the likelihood of consumer adoption of new, unfamiliar technologies in the vehicle market. The Agencies should conduct more research on the existence and extent of supply-side barriers to long-term investments in fuel economy technologies.**

## Assessment of CAFE Program Methodology and Design

The combined CAFE/GHG standards adopted for the MY 2017-2021 and proposed through 2025 build on earlier standards in important ways, including the development of combined fuel economy and greenhouse gas emission standards, the use of a footprint-based standard and added flexibility for manufacturer compliance through credit markets.

**Recommendation: The Agencies should monitor the effects of the CAFE/GHG standards by collecting data on fuel efficiency, vehicle footprint, fleet size mix, and price of new vehicles to understand the impact of the rules on consumers' choices and manufacturers' products offered. The Agencies, perhaps in collaboration with other federal agencies, should conduct an on-going, scientifically-designed survey of the real-world fuel economy of light-duty vehicles. This information will be useful in determining the adequacy of the current test cycle and could inform the establishment of improved, future (post 2025) test cycles, if necessary. Permanent regulatory treatment of alternate-fuel vehicles (AFVs) should be commensurate with the well-to-wheels GHG and petroleum reduction benefits.**

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**Committee on the Assessment of Technologies for Improving Fuel Economy of Light-Duty Vehicles, Phase 2: Jared Cohon**, NAE, Carnegie Mellon University, *Chair*; **Khalil Amine**, Argonne National Laboratory; **Chris Baillie**, AxleTech International; **Jay Baron**, Center for Automotive Research; **R. Stephen Berry**, NAS, University of Chicago; **L. Catherine Brinson**, Northwestern University; **Matt Fronk**, Matt Fronk & Associates, LLC; **David Greene**, University of Tennessee-Knoxville; **Roland Hwang**, Natural Resources Defense Council; **Linos Jacovides**, NAE, Michigan State University; **Therese Langer**, American Council for Energy Efficient Economy; **Rebecca Lindland**, King Abdullah Petroleum Studies and Research Center; **Virginia McConnell**, Resources for the Future; **David Merrion**, Merrion Expert Consulting, LLC; **Clemens Schmitz-Justen**, CSJ Schmitz-Justen & Company; **Anna Stefanopoulou**, University of Michigan Automotive Research Center; **Wallace Wade**, NAE, Ford Motor Company (retired); **William Walsh**, Automotive Safety Consultant

**Staff: K. John Holmes**, Study Director; **Elizabeth Zeitler**, Associate Program Officer; **E. Jonathan Yanger**, Research Associate; **Elizabeth Euller**, Program Assistant; **Michelle Schwalbe**, Program Officer; **Linda Casola**, Senior Program Assistant; **James J. Zucchetto**, Director; **LaNita Jones**, Administrative Coordinator; **Dana Caines**, Financial Manager; **Steven Godwin**, Transportation Research Board

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**Copies of this report are available free of charge from http://www.nap.edu.**

## **TABLE S.1** NRC Committee's Estimated Fuel Consumption Reduction Effectiveness of Technologies

### Percent Incremental Fuel Consumption Reductions
### NRC Estimates

| Technologies | | Midsize Car I4 DOHC | Large Car V6 DOHC | Large Light Truck V8 OHV | Relative To |
|---|---|---|---|---|---|
| **Spark Ignition Engine Technologies** | Abbreviation | Most Likely | Most Likely | Most Likely | |
| NHTSA Technologies | | | | | |
| Low Friction Lubricants - Level 1 | LUB1 | 0.7 | 0.8 | 0.7 | Baseline |
| Engine Friction Reduction - Level 1 | EFR1 | 2.6 | 2.7 | 2.4 | Baseline |
| Low Friction Lubricants and Engine Friction Reduction - Level 2 | LUB2_EFR2 | 1.3 | 1.4 | 1.2 | Previous Tech |
| VVT- Intake Cam Phasing (CCP - Coupled Cam Phasing - OHV) | ICP | 2.6 | 2.7 | 2.5 | Baseline for DOHC |
| VVT- Dual Cam Phasing | DCP | 2.5 | 2.7 | 2.4 | Previous Tech |
| Discrete Variable Valve Lift | DVVL | 3.6 | 3.9 | 3.4 | Previous Tech |
| Continuously Variable Valve Lift | CVVL | 1.0 | 1.0 | 0.9 | Previous Tech |
| Cylinder Deactivation | DEACD | N/A | 0.7 | 5.5 | Previous Tech |
| Variable Valve Actuation (CCP + DVVL) | VVA | N/A | N/A | 3.2 | Baseline for OHV |
| Stoichiometric Gasoline Direct Injection | SGDI | 1.5 | 1.5 | 1.5 | Previous Tech |
| Turbocharging and Downsizing Level 1 - 18 bar BMEP 33%DS | TRBDS1 | 7.7 - 8.3 | 7.3 - 7.8 | 6.8 - 7.3 | Previous Tech |
| Turbocharging and Downsizing Level 2 - 24 bar BMEP 50%DS | TRBDS2 | 3.2 - 3.5 | 3.3 - 3.7 | 3.1 - 3.4 | Previous Tech |
| Cooled EGR Level 1 - 24 bar BMEP, 50% DS | CEGR1 | 3.0 - 3.5 | 3.1 - 3.5 | 3.1 - 3.6 | Previous Tech |
| Cooled EGR Level 2 - 27 bar BMEP, 56% DS | CEGR2 | 1.4 | 1.4 | 1.2 | Previous Tech |
| Other Technologies | | | | | |
| By 2025: | | | | | |
| Compression Ratio Increase (with regular fuel) | CRI-REG | 3.0 | 3.0 | 3.0 | Baseline |
| Compression Ratio Increase (with higher octane regular fuel) | CRI-HO | 5.0 | 5.0 | 5.0 | Baseline |
| Compression Ratio Increase (CR~13:1, exh. scavenging, DI (aka Skyactiv)) | CRI-EXS | 10.0 | 10.0 | 10.0 | Baseline |
| Electrically Assisted Variable Speed Supercharger 1/ | EAVS-SC | 26.0 | 26.0 | 26.0 | Baseline |
| Lean Burn (with low sulfur fuel) | LBRN | 5.0 | 5.0 | 5.0 | Baseline |
| After 2025: | | | | | |
| Variable Compression Ratio | VCR | Up to 5.0 | Up to 5.0 | Up to 5.0 | Baseline |
| D-EGR | DEGR | 10.0 | 10.0 | 10.0 | TRBDS1 |
| Homogeneous Charge Compression Ignition (HCCI) + Spark Assisted CI 2/ | SA-HCCI | Up to 5.0 | Up to 5.0 | Up to 5.0 | TRBDS1 |
| Gasoline Direct Injection Compression Ignition (GDCI) | GDCI | Up to 5.0 | Up to 5.0 | Up to 5.0 | TRBDS1 |
| Waste Heat Recovery | WHR | Up to 3.0 | Up to 3.0 | Up to 3.0 | Baseline |
| Alternative Fuels*: | | | | | |
| CNG-Gasoline Bi-Fuel Vehicle (default UF = 0.5) | BCNG | Up to 5 Incr [42] | Up to 5 Incr [42] | Up to 5 Incr [42] | Baseline |
| Flexible Fuel Vehicle (UF dependent, UF = 0.5 thru 2019) | FFV | 0 [40 thru 2019, then UF TBD] | 0 [40 thru 2019, then UF TBD] | 0 [40 thru 2019, then UF TBD] | Baseline |
| Ethanol Boosted Direct Injection (CR = 14:1, 43% downsizing) (UF~0.05) | EBDI | 20 [24] | 20 [24] | 20 [24] | Baseline |

* Fuel consumption reduction in gge (gasoline gallons equivalent) [CAFE fuel consumption reduction]
1/ Comparable to TRBDS1, TRBDS2, SS, MHEV, IACC1, IACC2
2/ With TWC aftertreatment. Costs will increase with lean NOx aftertreatment.

| **Diesel Engine Technologies** | | | | | |
|---|---|---|---|---|---|
| NHTSA Technologies | | | | | |
| Advanced Diesel | ADSL | 29.4 | 30.5 | 29.0 | Baseline |
| Other Technologies | | | | | |
| Low Pressure EGR | LPEGR | 3.5 | 3.5 | 3.5 | ADSL |
| Closed Loop Combustion Control | CLCC | 2.5 | 2.5 | 2.5 | ADSL |
| Injection Pressures Increased to 2,500 to 3,000 bar | INJ | 2.5 | 2.5 | 2.5 | ADSL |
| Downspeeding with Increased Boost Pressure | DS | 2.5 | 2.5 | 2.5 | ADSL |
| Friction Reduction | FR | 2.5 | 2.5 | 2.5 | ADSL |
| Waste Heat Recovery | WHR | 2.5 | 2.5 | 2.5 | ADSL |

**TABLE S.1** (Continued) NRC Committee’s Estimated Fuel Consumption Reduction Effectiveness of Technologies

| Technologies | | Midsize Car I4 DOHC | Large Car V6 DOHC | Large Light Truck V8 OHV | Relative |
|---|---|---|---|---|---|
| Transmission Technologies | Abbreviation | Most Likely | Most Likely | Most Likely | To |
| NHTSA Technologies | | | | | |
| Improved Auto. Trans. Controls/Externals (ASL-1 & Early TC Lockup) | IATC | 2.5 - 3.0 | 2.5 - 3.0 | 2.5 - 3.0 | 4 sp AT |
| 6-speed AT with Improved Internals - Lepelletier (Rel to 4 sp AT) | NUATO-L | 2.0 - 2.5 | 2.0 - 2.5 | 2.0 - 2.5 | IATC |
| 6-speed AT with Improved Internals - Non-Lepelletier (Rel to 4 sp AT) | NUATO-NL | 2.0 - 2.5 | 2.0 - 2.5 | 2.0 - 2.5 | IATC |
| 6-speed Dry DCT (Rel to 6 sp AT - Lepelletier) | 6DCT-D | 3.5 - 4.5 | 3.5 - 4.5 | N/A | 6 sp AT |
| 6-speed Wet DCT (Rel to 6 sp AT - Lepelletier) (0.5% less than Dry Clutch) | 6DCT-W | 3.0 - 4.0 | 3.0 - 4.0 | 3.0 - 4.0 | 6 sp AT |
| 8-speed AT (Rel to 6 sp AT - Lepelletier) | 8AT | 1.5 - 2.0 | 1.5 - 2.0 | 1.5 - 2.0 | Previous Tech |
| 8-speed DCT (Rel to 6 sp DCT) | 8DCT | 1.5 - 2.0 | 1.5 - 2.0 | 1.5 - 2.0 | Previous Tech |
| High Efficiency Gearbox Level 1 (Auto) (HETRANS) | HEG1 | 2.3 - 2.7 | 2.3 - 2.7 | 2.3 - 2.7 | Previous Tech |
| High Efficiency Gearbox Level 2 (Auto, 2017 and Beyond) | HEG2 | 2.6 - 2.7 | 2.6 - 2.7 | 2.6 - 2.7 | Previous Tech |
| Shift Optimizer (ASL-2) | SHFTOPT | 0.5 - 1.0 | 0.5 - 1.0 | 0.5 - 1.0 | Previous Tech |
| Secondary Axle Disconnect | SAX | 1.4 - 3.0 | 1.4 - 3.0 | 1.4 - 3.0 | Baseline |
| Other Technologies | | | | | |
| Continuously Variable Transmission with Improved internals (Rel to 6 sp AT) | CVT | 3.5 - 4.5 | 3.5 - 4.5 | N/A | Previous Tech |
| High Efficiency Gearbox (CVT) | CVT-HEG | 3.0 | 3.0 | N/A | Previous Tech |
| High Efficiency Gearbox (DCT) | DCT-HEG | 2.0 | 2.0 | 2.0 | Previous Tech |
| High Efficiency Gearbox Level 3 (Auto, 2020 and beyond) | HEG3 | 1.6 | 1.6 | 1.6 | Previous Tech |
| 9-10 speed Transmission (Auto, Rel to 8 sp AT) | 10SPD | 0.3 | 0.3 | 0.3 | Previous Tech |
| | | | | | |
| Electrified Accessories Technologies | | | | | |
| NHTSA Technologies | | | | | |
| Electric Power Steering | EPS | 1.3 | 1.1 | 0.8 | Baseline |
| Improved Accessories - Level 1 (70% Eff Alt, Elec. Water Pump and Fan) | IACC1 | 1.2 | 1.0 | 1.6 | Baseline |
| Improved Accessories - Level 2 (Mild regen alt strategy, Intelligent cooling) | IACC2 | 2.4 | 2.6 | 2.2 | Previous Tech |
| | | | | | |
| Hybrid Technologies | | | | | |
| NHTSA Technologies | | | | | |
| Stop-Start (12V Micro-Hybrid) (Retain NHTSA Estimates) | SS | 2.1 | 2.2 | 2.1 | Baseline |
| Integrated Starter Generator | MHEV | 6.5 | 6.4 | 3.0 | Previous Tech |
| Strong Hybrid - P2 - Level 2 (Parallel 2 Clutch System) | SHEV2-P2 | 28.9 - 33.6 | 29.4 - 34.5 | 26.9 - 30.1 | Baseline |
| Strong Hybrid - PS - Level 2 (Power Split System) | SHEV2-PS | 33.0 - 33.5 | 32.0 - 34.1 | N/A | Baseline |
| Plug-in Hybrid - 40 mile range | PHEV40 | N/A | N/A | N/A | Baseline |
| Electric Vehicle - 75 mile | EV75 | N/A | N/A | N/A | Baseline |
| Electric Vehicle - 100 mile | EV100 | N/A | N/A | N/a | Baseline |
| Electric Vehicle - 150 mile | EV150 | N/A | N/A | N/A | Baseline |
| Other Technologies | | | | | |
| Fuel Cell Electric Vehicle | FCEV | N/A | N/A | N/A | Baseline |

**TABLE S.1** (Continued) NRC Committee's Estimated Fuel Consumption Reduction Effectiveness of Technologies

| Technologies<br>Vehicle Technologies | Abbreviation | Midsize Car I4 DOHC<br>Most Likely | Large Car V6 DOHC<br>Most Likely | Large Light Truck V8 OHV<br>Most Likely | Relative<br>To |
|---|---|---|---|---|---|
| NHTSA Technologies | | | | | |
| Without Engine Downsizing 3/ | | | | | |
| 0 - 2.5% Mass Reduction (Design Optimization) | MR2.5 | 0.80 | 0.80 | 0.85 | Baseline |
| 2.5 - 5% Mass Reduction | | 0.81 | 0.81 | 0.85 | Previous MR |
| 0 - 5% Mass Reduction (Material Substitution) | MR5 | 1.60 | 1.60 | 1.69 | Baseline |
| With Engine Downsizing (Same Architecture) 3/ | | | | | |
| 5 - 10% Mass Reduction | | 4.57 | 4.57 | 2.85 | Previous MR |
| 0 - 10% Mass Reduction (HSLA Steel and Aluminum Closures) | MR10 | 6.10 | 6.10 | 4.49 | Baseline |
| 10 - 15% Mass Reduction (Aluminum Body) | | 3.25 | 3.25 | 2.35 | Previous MR |
| 0 - 15% Mass Reduction (Aluminum Body) | MR15 | 9.15 | 9.15 | 6.73 | Baseline |
| 15 - 20% Mass Reduction | | 3.37 | 3.37 | 2.41 | Previous MR |
| 0 - 20% Mass Reduction (Aluminum Body, Magnesium, Composites) | MR20 | 12.21 | 12.21 | 8.98 | Baseline |
| 20 - 25% Mass Reduction | | 3.47 | 3.47 | 2.46 | Previous MR |
| 0 - 25% Mass Reduction (Carbon Fiber Composite Body) | MR25 | 15.26 | 15.26 | 11.22 | Baseline |
| Summary - Mass Reduction Relative to Baseline | | | | | |
| 0 - 2.5% Mass Reduction | MR2.5 | 0.80 | 0.80 | 0.85 | Baseline |
| 0 - 5% Mass Reduction | MR5 | 1.60 | 1.60 | 1.69 | Baseline |
| 0 - 10% Mass Reduction | MR10 | 6.10 | 6.10 | 4.49 | Baseline |
| 0 - 15% Mass Reduction | MR15 | 9.15 | 9.15 | 6.73 | Baseline |
| 0 - 20% Mass Reduction | MR20 | 12.21 | 12.21 | 8.98 | Baseline |
| 0 - 25% Mass Reduction | MR25 | 15.26 | 15.26 | 11.22 | Baseline |
| Low Rolling Resistance Tires - Level 1 (10% Reduction) | ROLL1 | 1.9 | 1.9 | 1.9 | Baseline |
| Low Rolling Resistance Tires - Level 2 (20% Reduction) | ROLL2 | 2.0 | 2.0 | 2.0 | Previous Tech |
| Low Drag Brakes | LDB | 0.8 | 0.8 | 0.8 | Baseline |
| Aerodynamic Drag Reduction - Level 1 (10% Reduction) | AERO1 | 2.3 | 2.3 | 2.3 | Baseline |
| Aerodynamic Drag Reduction - Level 2 (20% Reduction) | AERO2 | 2.5 | 2.5 | 2.5 | Previous Tech |

3/ FC Reductions - Ricardo 2007
Car:
Without engine downsizing: +3.3% mpg/10% MR = -3.2% FC/10% MR
With engine downsizing (for MR > 10%): +6.5% mpg/10%MR = -6.1% FC/10% MR
Truck
Without engine downsizing: +3.5% mpg/10% MR = -3.4% FC/10% MR
With engine downsizing (for MR > 10%): +4.7% mpg/10%MR = 4.5% FC/10% MR

Midsize Car: 3500 lbs
Large Car: 4500 lbs
Large Light Truck: 5500 lbs

**TABLE S.2** NRC Committee's Estimated 2025 MY Direct Manufacturing Costs of Technologies

2025 MY Incremental Direct Manufacturing Costs (2010$)
NRC Estimates

| Technologies | | Midsize Car I4 DOHC | Large Car V6 DOHC | Large Light Truck V8 OHV | Relative |
|---|---|---|---|---|---|
| Spark Ignition Engine Technologies | Abbreviation | Most Likely | Most Likely | Most Likely | To |
| NHTSA Technologies | | | | | |
| Low Friction Lubricants - Level 1 | LUB1 | 3 | 3 | 3 | Baseline |
| Engine Friction Reduction - Level 1 | EFR1 | 48 | 71 | 95 | Baseline |
| Low Friction Lubricants and Engine Friction Reduction - Level 2 | LUB2_EFR2 | 51 | 75 | 99 | Previous Tech |
| VVT- Intake Cam Phasing (CCP - Coupled Cam Phasing - OHV) | ICP | 31 - 36 | 63 - 73 | 31 - 36 | Baseline for DOHC |
| VVT- Dual Cam Phasing | DCP | 27 - 31 | 61 - 69 | 31 - 36 | Previous Tech |
| Discrete Variable Valve Lift | DVVL | 99 - 114 | 143 - 164 | N/A | Previous Tech |
| Continuously Variable Valve Lift | CVVL | 49 - 56 | 128 - 147 | N/A | Previous Tech |
| Cylinder Deactivation | DEACD | N/A | 118 | 133 | Previous Tech |
| Variable Valve Actuation (CCP + DVVL) | VVA | N/A | N/A | 235 - 271 | Baseline for OHV |
| Stoichiometric Gasoline Direct Injection | SGDI | 164 | 246 | 296 | Previous Tech |
| Turbocharging and Downsizing Level 1 - 18 bar BMEP 33%DS | TRBDS1 | 245 - 282 | -110 to -73 | 788 - 862 | Previous Tech |
| V6 to I4 and V8 to V6 | | | -396* to -316* | 700* - 800* | |
| Turbocharging and Downsizing Level 2 - 24 bar BMEP 50%DS | TRBDS2 | 155 | 155 | 261 | Previous Tech |
| I4 to I3 | | -82* to -86* | | | |
| Cooled EGR Level 1 - 24 bar BMEP, 50% DS | CEGR1 | 180 | 180 | 180 | Previous Tech |
| Cooled EGR Level 2 - 27 bar BMEP, 56% DS | CEGR2 | 310 | 310 | 523 | Previous Tech |
| V6 to I4 | | | | -453* to -469* | |
| Other Technologies | | | | | |
| By 2025: | | | | | |
| Compression Ratio Increase (with regular fuel) | CRI-REG | 50 | 75 | 100 | Baseline |
| Compression Ratio Increase (with higher octane regular fuel) | CRI-HO | 75 | 113 | 150 | Baseline |
| Compression Ratio Increase (CR~13:1, exh. scavenging, DI (aka Skyactiv)) | CRI-EXS | 250 | 375 | 500 | Baseline |
| Electrically Assisted Variable Speed Supercharger | EAVS-SC | 1,302 | 998 | N/A | Baseline |
| Lean Burn (with low sulfur fuel) | LBRN | 800 | 920 | 1,040 | Baseline |
| After 2025: | | | | | |
| Variable Compression Ratio | VCR | 597 | 687 | 896 | Baseline |
| D-EGR | DEGR | 667 | 667 | 667 | TRBDS1 |
| Homogeneous Charge Compression Ignition (HCCI) + Spark Assisted CI 1/ | SA-HCCI | 450 | 500 | 550 | TRBDS1 |
| Gasoline Direct Injection Compression Ignition | GDCI | 2,500 | 2,875 | 3,750 | Baseline |
| Waste Heat Recovery | WHR | 700 | 805 | 1,050 | Baseline |
| Alternative Fuels: | | | | | |
| CNG-Gasoline Bi-Fuel Vehicle | BCNG | 6,000 | 6,900 | 7,800 | Baseline |
| Flexible Fuel Vehicle | FFV | 75 | 100 | 125 | Baseline |
| Ethanol Boosted Direct Injection (incr CR to 14:1, 43% downsizing) | EBDI | 740 | 870 | 1,000 | Baseline |

* Costs with reduced number of cylinders, adjusted for previously added technologies. See Appendix T for the derivation of turbocharged, downsized engine costs.
1/ With TWC aftertreatment. Costs will increase with lean NOx aftertreatment.

| Diesel Engine Technologies | | | | | |
|---|---|---|---|---|---|
| NHTSA Technologies | | | | | |
| Advanced Diesel | ADSL | 2,572 | 3,034 | 3,228 | Baseline |
| Other Technologies | | | | | |
| Low Pressure EGR | LPEGR | 113 | 141 | 141 | ADSL |
| Closed Loop Combustion Control | CLCC | 58 | 87 | 87 | ADSL |
| Injection Pressures Increased to 2,500 to 3,000 bar | INJ | 20 | 22 | 22 | ADSL |
| Downspeeding with Increased Boost Pressure | DS | 24 | 24 | 24 | ADSL |
| Friction Reduction | FR | 54 | 82 | 82 | ADSL |
| Waste Heat Recovery | WHR | 700 | 805 | 1,050 | ADSL |

**TABLE S.2** (Continued) NRC Committee's Estimated 2025 Direct Manufacturing Costs of Technologies

| Technologies | | Midsize Car I4 DOHC | Large Car V6 DOHC | Large Light Truck V8 OHV | Relative |
|---|---|---|---|---|---|
| Transmission Technologies | Abbreviation | Most Likely | Most Likely | Most Likely | To |
| NHTSA Technologies | | | | | |
| Improved Auto. Trans. Controls/Externals (ASL-1 & Early TC Lockup) | IATC | 42 | 42 | 42 | Baseline 4 sp AT |
| 6-speed AT with Improved Internals - Lepelletier (Rel to 4 sp AT) | NUATO-L | -11 | -11 | -11 | IATC |
| 6-speed AT with Improved Internals - Non-Lepelletier (Rel to 4 sp AT) | NUATO-NL | 165 | 165 | 165 | IATC |
| 6-speed Dry DCT (Rel to 6 sp AT - Lepelletier) | 6DCT-D | -127 to 26 | -127 to 26 | N/A | 6 sp AT |
| 6-speed Wet DCT (Rel to 6 sp AT - Lepelletier) | 6DCT-W | -75 to 75 | -75 to 75 | -75 to 75 | 6 sp AT |
| 8-speed AT (Rel to 6 sp AT - Lepelletier) | 8AT | 47 - 115 | 47 - 115 | 47 - 115 | Previous Tech |
| 8-speed DCT (Rel to 6 sp DCT) | 8DCT | 152 | 152 | 152 | Previous Tech |
| High Efficiency Gearbox Level 1 (Auto) (HETRANS) | HEG1 | 102 | 102 | 102 | Previous Tech |
| High Efficiency Gearbox Level 2 (Auto, 2017 and Beyond) | HEG2 | 165 | 165 | 165 | Previous Tech |
| Shift Optimizer (ASL-2) | SHFTOPT | 22 | 22 | 22 | Previous Tech |
| Secondary Axle Disconnect | SAX | 86 | 86 | 86 | Baseline |
| Other Technologies | | | | | |
| Continuously Variable Transmission with Improved internals (Rel to 6 sp AT) | CVT | 154 | 154 | NA | Baseline |
| High Efficiency Gearbox (CVT) | CVT-HEG | 107 | 107 | NA | Baseline |
| High Efficiency Gearbox (DCT) | DCT-HEG | 127 | 127 | 127 | Baseline |
| High Efficiency Gearbox Level 3 (Auto, 2020 and beyond) | HEG3 | 128 | 128 | 128 | Baseline |
| 9-10 speed Transmission (Auto, Rel to 8 sp AT) | 10SPD | 65 | 65 | 65 | Baseline |
| | | | | | |
| Electrified Accessories Technologies | | | | | |
| NHTSA Technologies | | | | | |
| Electric Power Steering | EPS | 74 | 74 | 74 | Baseline |
| Improved Accessories - Level 1 (70% Eff Alt, Elec. Water Pump and Fan) | IACC1 | 60 | 60 | 60 | Baseline |
| Improved Accessories - Level 2 (Mild regen alt strategy, Intelligent cooling) | IACC2 | 37 | 37 | 37 | Previous Tech |
| | | | | | |
| Hybrid Technologies | | | | | |
| NHTSA Technologies | | | | | |
| Stop-Start (12V Micro-Hybrid) | SS | 225 - 275 | 255 - 305 | 279 - 329 | Baseline |
| Integrated Starter Generator | MHEV | 888 - 1,018 | 888 - 1,115 | 888 - 1,164 | Previous Tech |
| Strong Hybrid - P2 - Level 2 (Parallel 2 Clutch System) | SHEV2-P2 | 2,041 - 2,588 | 2,410 - 3,086 | 2,438 - 3,111 | Baseline |
| Strong Hybrid - PS - Level 2 (Power Split System) | SHEV2-PS | 2,671 | 2,889 | N/A | Baseline |
| Plug-in Hybrid - 40 mile range | PHEV40 | 8,236 - 9,672 | 11,083 - 13,135 | N/A | Baseline |
| Electric Vehicle - 75 mile | EV75 | 8,451 - 8,963 | 11,025 - 11,929 | N/A | Baseline |
| Electric Vehicle - 100 mile | EV100 | 9,486 | 11,971 | N/A | Baseline |
| Electric Vehicle - 150 mile | EV150 | 12,264 | 14,567 | N/A | Baseline |
| Other Technologies | | | | | |
| Fuel Cell Electric Vehicle | FCEV | N/A | N/A | N/A | |

**TABLE S.2** (Continued) NRC Committee's Estimated 2025 Direct Manufacturing Costs of Technologies

| Technologies | | Midsize Car I4 DOHC | Large Car V6 DOHC | Large Light Truck V8 OHV | Relative |
|---|---|---|---|---|---|
| Vehicle Technologies | Abbreviation | Most Likely | Most Likely | Most Likely | To |
| NHTSA Technologies | | | | | |
| Without Engine Downsizing | | | | | |
| 0 - 2.5% Mass Reduction (Design Optimization) | MR2.5 | 0 - 22 | 0 - 28 | 0 - 39 | Baseline |
| 2.5 - 5% Mass Reduction | | 0 - 66 | 0 - 85 | 0 - 112 | Previous MR |
| 0 - 5% Mass Reduction (Material Substitution) | MR5 | 0 - 88 | 0 - 113 | 0 - 151 | Baseline |
| With Engine Downsizing (Same Architecture) 3/ | | | | | |
| 5 - 10% Mass Reduction | | 151 - 315 | 194 - 405 | 264 - 558 | Previous MR |
| 0 - 10% Mass Reduction (HSLA Steel and Aluminum Closures) | MR10 | 151 - 403 | 194 - 518 | 264 - 710 | Baseline |
| | | | | | |
| 10 - 15% Mass Reduction (Aluminum Body) | | 431 - 730 | 554 - 938 | 751 - 1,279 | Baseline |
| 0 - 15% Mass Reduction (Aluminum Body) | MR15 | 431 - 730 | 554 - 938 | 751 - 1,279 | Baseline |
| 15 - 20% Mass Reduction | | 486 - 600 | 626 - 772 | 866 - 1,064 | Previous MR |
| 0 - 20% Mass Reduction (Aluminum Body, Magnesium, Composites) | MR20 | 917 - 1,330 | 1,179 - 1,710 | 1,617 - 2,343 | Baseline |
| 20 - 25% Mass Reduction | | 1,026 - 1,260 | 1,319 - 1,620 | 1,807 - 1,947 | Previous MR |
| 0 - 25% Mass Reduction (Carbon Fiber Composite Body) | MR25 | 1,943 - 2,590 | 2,498 - 3,330 | 3,424 - 4,290 | Baseline |
| | | | | | |
| Mass Reduction Cost ($ per lb.) | | | | | |
| 0 - 2.5% Mass Reduction | MR2.5 | 0.00 - 0 .25 | 0.00 - 0 .25 | 0.00 - 0.28 | Baseline |
| 0 - 5% Mass Reduction | MR5 | 0.00 - 0.49 | 0.00 - 0.49 | 0.00 - 0.55 | Baseline |
| 0 - 10% Mass Reduction | MR10 | 0.43 - 1.15 | 0.43 - 1.15 | 0.48 - 1.29 | Baseline |
| 0 - 15% Mass Reduction | MR15 | 0.82 - 1.39 | 0.82 - 1.39 | 0.91 - 1.55 | Baseline |
| 0 - 20% Mass Reduction | MR20 | 1.31 - 1.90 | 1.31 - 1.90 | 1.47 - 2.13 | Baseline |
| 0 - 25% Mass Reduction | MR25 | 2.22 - 2.96 | 2.22 - 2.96 | 2.49 - 3.12 | Baseline |
| | | | | | |
| Low Rolling Resistance Tires - Level 1 (10% reduction in rolling resistance) | ROLL1 | 5 | 5 | 5 | Baseline |
| Low Rolling Resistance Tires - Level 2 (20% reduction in rolling resistance) | ROLL2 | 31 | 31 | 31 | Previous Tech |
| Low Drag Brakes | LDB | 59 | 59 | 59 | Baseline |
| Aerodynamic Drag Reduction - Level 1 | AERO1 | 33 | 33 | 33 | Baseline |
| Aerodynamic Drag Reduction - Level 2 | AERO2 | 100 | 100 | 100 | Previous Tech |

3/ Includes mass decompounding: 40% for cars, 25% for trucks

Midsize Car: 3500 lbs
Large Car: 4500 lbs
Large Light Truck: 5500 lbs