

Impact of Electric Drive Vehicle Technologies on Fuel Efficiency to Support 2017-2025 CAFE Regulations

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ABSTRACT

Manufacturers have been considering various technology options to improve vehicle fuel economy. Some of the most promising technologies are related to vehicle electrification. To evaluate the benefits of vehicle electrification to support the 2017-2025 CAFE regulations, a study was conducted to simulate many of the most common electric drive powertrains currently available on the market: 12V Micro Hybrid Vehicle (start/stop systems), Belt-integrated starter generator (BISG), Crank-integrated starter generator (CISG), Full Hybrid Electric Vehicle (HEV), PHEV with 20-mile all-electric range (AER) (PHEV20), PHEV with 40-mile AER (PHEV40), Fuel-cell HEV and Battery Electric vehicle with 100-mile AER (EV100). Different vehicle classes were also analyzed in the study process: Compact, Midsize, Small SUV, Midsize SUV and Pickup. This paper will show the fuel displacement benefit of each powertrain across vehicle classes.

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INTRODUCTION

The U.S. Department of Transportation's (DOT) National Highway Traffic Safety Administration (NHTSA), in coordination with the U.S. Environmental Protection Agency (EPA), recently issued a joint final rulemaking to establish Corporate Average Fuel Economy (CAFE) and Greenhouse Gas (GHG) emission standards for model year (MY) 2017-2021 passenger cars and light trucks. DOT/NHTSA's CAFE standards were established pursuant to the amendments made by the Energy Independence and Security Act (EISA) of 2007 to the Energy Policy and Conservation Act (EPCA).

In developing the standards, DOT/NHTSA made use of the CAFE Compliance and Effects Modeling System (the "Volpe model"), which was developed by DOT's Volpe National Transportation Systems Center for the 2005-2007 CAFE rulemaking and continuously updated since. The model is the primary tool used by the agency to evaluate potential CAFE stringency levels by applying technologies incrementally to each manufacturer's fleet until the requirements under consideration are met. The Volpe model relies on numerous technology-related and economic inputs such as a market forecasts, technology cost, and effectiveness estimates; these inputs are categorized by vehicle classification, technology synergies, phase-in rates, cost learning curve adjustments, and technology "decision trees."

Part of the model's function is to estimate CAFE improvements that a given manufacturer could achieve by applying additional technology to specific vehicles in its product line. To inform

decisions regarding the design of specific vehicles, manufacturers may apply techniques such as vehicle and component testing, combustion simulation, powertrain simulation, computational fluid dynamics (CFD) simulation, and full vehicle simulation. Because CAFE standards apply to the average fuel economy across manufacturers' entire fleets of new passenger cars and light trucks, the model, when simulating manufacturers' potential application of technology, considers the entire range of each manufacturer's product line. This typically involves accounting for more than 1,000 distinct vehicle models and variants, many more than can be practically examined using full vehicle simulation (or the other techniques mentioned above). Instead, the model uses estimates of the effectiveness of specific technologies, and arranges technologies in decision trees defining logical progressions from lower to higher levels of cost, complexity, development requirements, and/or implementation challenges.

DOT/NHTSA has made use of vehicle simulation results to update technology effectiveness estimates used by the model. In recent rulemakings, the decision trees have been expanded so that DOT/NHTSA is better able to track the incremental and net/cumulative cost and effectiveness associated with each technology, which substantially improves the "accounting" of costs and effectiveness for CAFE rulemakings. A detailed description of the Volpe model can be found in NHTSA's Final Regulatory Impact Analysis (FRIA) supporting the 2012 rule establishing CAFE standards applicable beginning MY 2017.

The FRIA and all other rulemaking documents, the model, source code, model documentation, and all model inputs and outputs are available at <http://www.nhtsa.gov/fuel-economy> [2].

HYBRID TECHNOLOGY DECISION TREE

Manufacturers have been considering various technology options for improving vehicle fuel economy; DOT/NHTSA has typically categorized these technology options into several groups, including engine technologies, transmission technologies, hybrid and electrification technologies, and what the agency calls “vehicle” technologies (e.g., weight reduction, aerodynamic drag improvement). In particular, the number of electric drive vehicle technologies offered by manufacturers has been increasing in recent years.

Figure 1 and Figure 2 show two original decision trees provided by DOT/NHTSA for electric drive vehicles. These original trees, for a midsize conventional vehicle, were used in the initial Notice of Proposed Rulemaking (NPRM) analysis. Step-by-step improvements are presented, from conventional vehicle to micro hybrid electric vehicle (MHEV), full HEV, plug-in HEV (PHEV), and battery electric vehicle (BEV). The incremental effectiveness estimates represent the actual fuel efficiency improvement value of moving from one step to another, whereas the absolute value signifies the overall improvement starting from the reference baseline vehicle. The initial fuel consumption improvements for the electric drive technologies estimate 90.4% fuel-consumption reduction, starting from a baseline conventional vehicle with a fixed valve, naturally aspirated and multi-point fuel injected gasoline engine mated to a 5-speed automatic transmission with no electrification (e.g. electric power steering, stop-start, etc.) or vehicle (e.g. mass reduction, low rolling resistance tires, etc.) technologies applied. It should be noted that in the original decision trees that all strong hybrids (P2) and PHEVs assume the use of a 6-speed DCT and for the second generation of strong hybrids (SHEV2) and PHEVs an advanced high Brake Mean Effective Pressure (BMEP) turbocharged and downsized engine was assumed. The majority of effectiveness estimates shown below in Figure 1 and Figure 2 were based upon simulation results generated by Ricardo and then incorporated into EPA's lumped parameter model (LPM). A detailed description of the Ricardo simulation work and how it was incorporated into the LPM can be found in the Joint Technical Support Document (TSD) found at <http://www.nhtsa.gov/fuel-economy>.

However, DOT/NHTSA based the effectiveness estimations for PHEVs and EVs on experimental data. When evaluating the effectiveness of PHEVs and EVs for reducing fuel consumption, DOT/NHTSA referenced the FTP and HFET fuel economy data of 3 pairs of vehicles for which DOT/NHTSA had fuel economy data in the CAFE database:

- The MiniE electric vehicle and the gasoline-powered Mini with automatic transmission,

- The Tesla Roadster electric vehicle and the gasoline-powered rear-wheel-drive Lotus Elise Sedan with a 6-speed manual transmission, and
- The MY 2012 Nissan Leaf electric vehicle and the gasoline-powered Nissan Sentra with automatic transmission.

A full description of how HEV, PHEV and EV effectiveness estimates were determined for the NPRM can be found in the Regulatory Impact Analysis found at <http://www.nhtsa.gov/fuel-economy>.

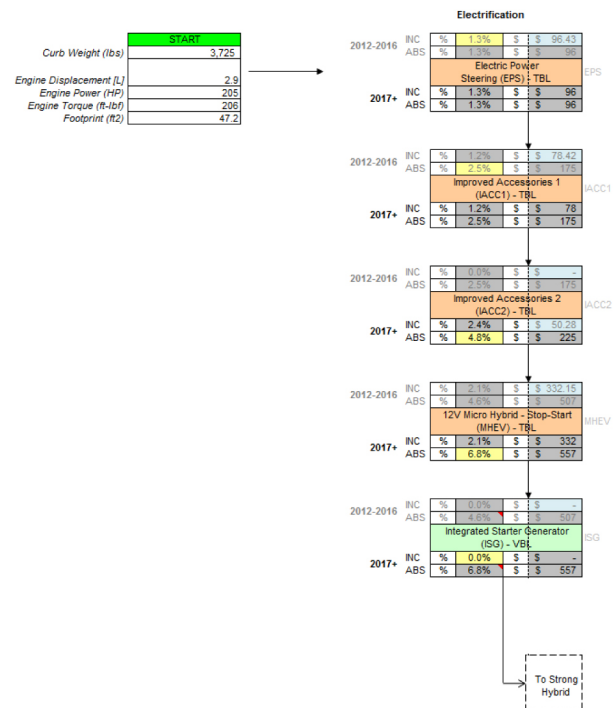


Figure 1. Original DOT/NHTSA Hybrid Decision Tree - Part 1

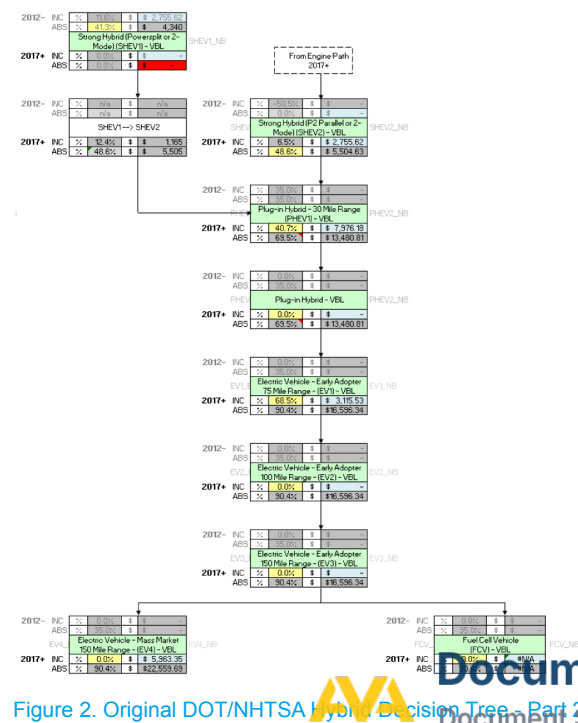


Figure 2. Original DOT/NHTSA Hybrid Decision Tree - Part 2

The objectives of the present study were to:

- Update the current decision tree structure based on the latest electric drive powertrain technologies, and
- Quantify the impact of each technology option as both an incremental improvement from the previous technology and absolute improvement over the baseline.

Argonne National Laboratory used its vehicle simulation tool, Autonomie, to provide DOT/NHTSA with fuel-efficiency improvement results for different technologies within the decision trees. The technologies considered included the following:

- 12-V MHEV (start/stop)
- Belt-integrated starter generator (BISG)
- Crank-integrated starter generator (CISG)
- Full HEV
- PHEV with 20-mile all-electric range (AER) (PHEV20)
- PHEV with 40-mile AER (PHEV40)
- Fuel-cell HEV
- Battery Electric vehicle with 100-mile AER (EV100)

NHTSA used these updated decision trees and effectiveness estimates for the Final Rulemaking (FRM) analysis for the 2017-2021 CAFE regulations.

AUTONOMIE

Autonomie [3, 4] is a MATLAB®-based software environment and framework for automotive control-system design, simulation, and analysis. Autonomie is used in this study to assess the fuel consumption of advanced powertrain technologies. Autonomie has been validated for several powertrain configurations and vehicle classes using vehicle test data from Argonne's Advanced Powertrain Research Facility (APRF) [5, 6, 7, and 8].

Autonomie allows to evaluate the impact of component sizing on fuel consumption for different powertrain technologies [9, 10], as well as to define the component requirements (e.g., power, energy) to maximize fuel displacement for a specific application [11, 12]. This is important for the current study because the use of validated plant models, vehicle controls, and complete vehicle models is critical to properly evaluating the benefit of any specific technology. The vehicle-level control algorithms (e.g., engine ON/OFF logic, component operating conditions algorithm) are critical to properly evaluating any powertrain configuration or component-sizing impact, especially for electric drives. Argonne has extensive experience in developing shifting algorithms for conventional vehicles based on the different component characteristics (e.g., engine fuel rate, gear ratios).

The ability to simulate a large number of powertrain configurations, component technologies, and vehicle-level controls over numerous drive cycles has been used to support a large number of studies, focusing on fuel efficiency [13, 14, 15, 16], cost-benefit analysis, or greenhouse gases [17, 18].

ASSUMPTIONS

The main objective of vehicle electrification is to provide drivers with better fuel consumption while maintaining or exceeding the performance and drive quality of conventional vehicles. The selection of hybridization degree and powertrain configuration is complex, since numerous options exist. On the basis of current production vehicles as well as future trends, the following powertrain configurations were selected for the modeling analysis to match NHTSA requests:

- 12-V MHEV (start/stop)
- BISG
- CISG
- Full HEV: single-mode power split configuration with fixed ratio for compact and midsize cars and two-mode power split with four fixed gears for small-SUV, midsize-SUV and pickup classes.
- PHEV20: single-mode power split configuration with fixed ratio.
- PHEV40: Voltec configuration with 40-mile AER on the FTP drive cycle
- Fuel-cell HEV: series configuration with 320 miles range on the FTP drive cycle
- BEV with 100-mile AER on the FTP drive cycle.

Note that the AER values are based on unadjusted electrical consumptions. In addition, the belt losses were included for both the MHEV and BISG cases. The pre-transmission parallel configuration was not selected for HEVs and PHEVs because the single mode power split configuration is expected to represent the highest volume of vehicles in the timeframe considered and provide a lower fuel consumption. The two-mode power split was used for SUVs and pickup truck to avoid oversizing the electric machine of a single mode power split or adding a third electric machine in the rear. This option also allows a cost reduction due to lower component peak power requirements. The initial decision tree was modified to represent these selections, as shown in Figure 3.

The Midsize vehicle class only will be detailed in the following section, though the other vehicle classes were studied using a similar process. For full specifications on all vehicle classes, refer to the simulation report released with the final rulemaking at [25].

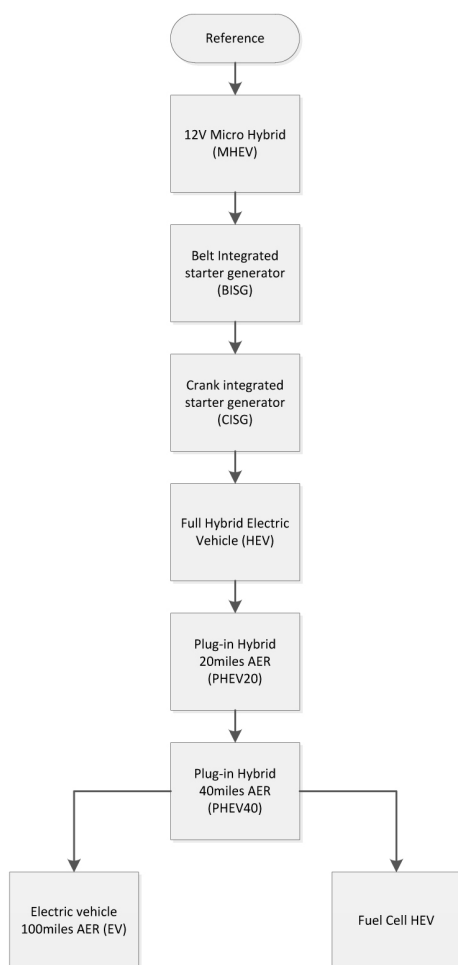


Figure 3. Modified Hybrid Technology Decision Tree

Reference Vehicles Assumptions

Five different vehicle classes were simulated in this study: compact car, midsize car, small SUV, midsize SUV, and pickup truck. The reference vehicles used as a starting point are based on conventional powertrains with the midsize vehicle specifications summarized below and in Table 1.

- Transmission: 5-speed gearbox with ratios of [0, 2.563, 1.552, 1.022, 0.727, 0.52]
- Final drive ratio: 4.43

Table 1. Baseline Vehicle Main Specifications

Baseline Vehicle Specification	Midsize
Engine power (kW)	130
Vehicle test weight (kg)	1580
Drag coefficient	0.3
Frontal area (m ²)	2.244
Rolling resistance coefficient 1	0.008
Rolling resistance coefficient 2	0.00012

For each vehicle class considered in this study, all the vehicles have been sized to meet the same requirements:

- Initial vehicle movement (IVM) to 60 mph in 9 sec ± 0.1 sec
- Maximum grade (grade ability) of 6% at 65 mph at gross vehicle weight (GVW)
- Maximum vehicle speed >100 mph

These requirements are a good representation of the current American automotive market as well as American drivers' expectations. A relationship between curb weight and GVW was developed on the basis of current technologies to estimate the GVW of future technologies.

Engine Assumptions

The engine is one of the main components affecting the fuel consumption performance of conventional and electric drive vehicles. The engine assumptions selected for this analysis represent state-of-the-art engine technologies. A port-injected engine with a peak efficiency of 35% was used for the conventional, MHEV and starter-alternator configurations. An Atkinson engine (Figure 4) was used for the other applications.

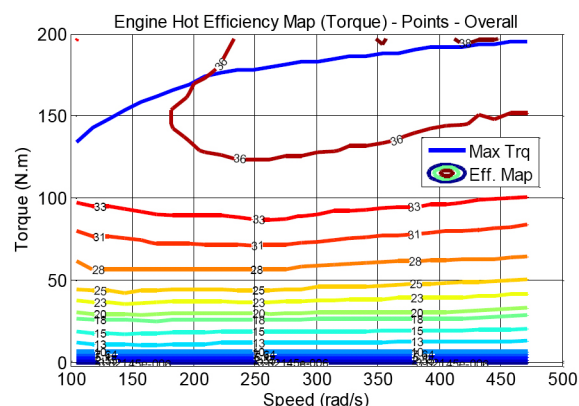


Figure 4. Atkinson Engine Map (Argonne data)

All the mechanical losses of the components required to run the engine on the dynamometer are included in the engine maps.

Electric Machine Assumptions

The electric machine performance data (Figure 5 and Figure 6) were provided by Oak Ridge National Laboratory and represent a synchronous permanent-magnet technology. Figure 5 represents the electric machine efficiency map use for the micro HEV, BISG and CISG. Figure 6 represents the efficiency map of the electric machine used for the HEV and PHEVs. In both cases, the electric machine power was adjusted by scaling the torque values. The efficiency maps have been developed assuming component normal temperature operating conditions. The electric machine inverter losses are included in the map.