Program Record (EERE Offices of Fuel Cell, Vehicle, and Bioenergy Technologies)	
Record #: 17008	**Date:** March 12, 2018
Title: Levelized Cost of Driving for Future ICEV as Transportation Metric	
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Items:

To improve transportation energy affordability, strengthen national security, support energy dominance and enable future economic growth, DOE performs early-stage research on several advanced transportation technology options in the Vehicle Technologies Office, the Bioenergy Technologies Office and the Fuel Cell Technologies Office within the Office of Energy Efficiency and Renewable Energy. Common metrics have been applied across all three programs to evaluate advanced options compared to the lifecycle costs and total energy use of conventional technologies. This record documents recent data inputs and the peer-reviewed methodology provided in the 2016 Cradle to Grave (C2G) report from Argonne National Lab (ANL) and the U.S. DRIVE partnership [1] and the lifecycle total energy consumption from the most recent GREET® model by ANL [2] for a projected average midsize gasoline internal combustion engine vehicle (ICEV) in 2030 that meets Vehicle Technologies Office technical targets. The levelized cost of driving (LCD) which includes the vehicle and fuel (90% gasoline and 10% corn ethanol) of a modeled 2030 ICEV is projected to be 27 cents per mile. The lifecycle total energy use (includes fossil fuel energy use [petroleum, coal, natural gas] and non-fossil fuel energy use [solar, wind hydroelectric, nuclear]) of a modeled 2030 ICEV is approximately 4,700 Btu/mile (4.9 MJ/mile, 3 MJ/km).

Methodology:

This section describes the methods and updates to the LCD and energy use per mile calculations for the modeled 2030 ICEV with Vehicle Technologies Office technical targets.

Levelized cost of driving

The methodology for developing the LCD is based on the ANL and U.S. DRIVE 2016 "Cradle-to-Grave Lifecycle Analysis of U.S. Light-Duty Vehicle-Fuel Pathways" [1]; the cost per mile uses the methodology from the 2016 C2G analysis with updated data inputs from the 2017 Energy Information Administration's Annual Energy Outlook and a forthcoming ANL vehicle simulation modeling (Autonomie) report [2]. The cost per mile is based on a 15-year vehicle or 178,200 mile lifetime over 15 years [3]; see Table 1 for assumptions used to calculate the LCD.

Table 1. Assumptions Used to Calculate 2030 ICEV Levelized Cost of Driving

	2030 Autonomie Modeled Midsize Gasoline ICEV
Vehicle Lifetime	178,200 miles over 15 years [3]
MPG (on-road)	35 [1]
Vehicle Cost	$24,800 [2]
Fuel (gasoline), untaxed	$2.50/gallon [4]
Model Year	2030 (2025 lab technology)
Discount Rate	5%

The LCD is defined as the sum of the amortized net vehicle cost per mile and the levelized fuel cost and has units of dollars per mile driven. The LCD calculation does not include insurance and maintenance costs due to lack of reliable data maintaining consistency across vehicle type. Costs in this analysis are estimated in real 2017 dollars (2017$). Fuel costs are assumed constant in 2017$ from the time of the vehicle purchase through the end of vehicle's lifetime.

A discount rate is applied to equate capital cash flows that occur at different points in time, i.e., the initial vehicle purchase price, fuel costs, and the residual value after *t* years.[1] In this analysis, a discount rate of 5% is assumed. This discount rate, applied to consumer cash flow, is in real terms and excludes inflation (as noted above, all inflation has been factored out of the analysis).

Updated data inputs for LCD

Vehicle fuel consumption, fuel cost and vehicle cost are critical inputs to estimate the LCD for each vehicle-fuel combination. The fuel consumption and vehicle cost are calculated using an automotive control-system design and simulation tool (Autonomie). Autonomie is a MATLAB©-based software environment and framework for automotive control-system design, simulation, and analysis. Autonomie, developed by Argonne (in collaboration with industry), is designed for rapid and easy integration of models with varying levels of detail (low to high fidelity) and abstraction (from subsystems to systems and entire architectures), as well as processes (e.g., calibration, validation). Several Autonomie powertrain simulations for various vehicle classes have been validated using Argonne's Advanced Powertrain Research Facility vehicle test data [5-9].

To evaluate the fuel consumption and cost of a given vehicle architecture, a vehicle model is built from the ground up based on performance and cost data for each component in the main Autonomie database. The vehicle components are sized by internal algorithms to meet the desired vehicle performance specification. Then, the vehicle component sizes are used to estimate the vehicle cost by summing the cost of all individual components and adding the manufacturing costs for a given vehicle manufacturing volume. Autonomie provides estimates of total vehicle manufacturing costs at high volumes based on a summation of component costs plus the assembly costs [10]. Vehicles are modeled using a set of performance parameters (e.g., acceleration time, top speed, gradeability, etc.). All costs are multiplied by a factor of 1.5 to

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[1] Note for this analysis, the residual value is zero because the analysis window is the lifetime of the vehicle (15 years).

estimate the retail price equivalent (RPE) of each vehicle. Finally, the fuel consumption (e.g., in MJ/mile) is simulated on the Urban Dynamometer Driving Schedule (UDDS) and Highway Federal Emissions Test (HWFET) cycles. The fuel consumption from these test driving cycles are then adjusted to reflect actual on-road fuel consumption (or fuel economy) using standard formulae developed by the Environmental Protection Agency (EPA).

Energy per mile

The ANL's GREET® [11] model was used to calculate the lifecycle total energy consumption by gasoline ICEV. The calculation includes the energy use in the recovery of the primary feedstock; transportation of the feedstock; production of the fuel from the feedstock; and transportation, distribution, storage; use of the fuel consumption during vehicle operation and the energy use associated with the production and processing of vehicle materials, the manufacturing and assembly of the vehicle, and the end of life (EOL) decommissioning and recycling of vehicle components.

Updated inputs for energy per mile

The GREET® model is widely-used, open source lifecycle model created and updated by ANL on an annual basis to ensure the most up-to-date research and input data are incorporated. The methodology described in the C2G report was used to estimate the lifecycle total energy use per mile. There was no significant change to the 2030 ICEV total energy use per mile results compared to the C2G peer-reviewed results. The lifecycle total energy use per mile is calculated at 4,700 Btu/mile (4.9 MJ/mile, 3 MJ/km). Please refer to Table 1 above for additional details on the fuel economy assumption used as input to the GREET® model.

References:

[1] Elgowainy et al., 2016. *Cradle-to-Grave Lifecycle Analysis of U.S. Light Duty Vehicle-Fuel Pathways.* Argonne National Lab. https://greet.es.anl.gov/publication-c2g-2016-report

[2] Islam et al., forthcoming. *An Extensive Study on Sizing, Energy Consumption, and Cost of Advanced Vehicle Technologies*. Argonne National Lab.

[3] NHTSA (National Highway Traffic Safety Administration), National Center for Statistics and Analysis, 2006. *Vehicle Survivability and Travel Mileage Schedules*. http://www-nrd.nhtsa.dot.gov/Pubs/809952.pdf (Note: The vehicle lifetime of 178,200 miles is still valid today.)

[4] EIA (Energy Information Agency), 2017. *Annual Energy Outlook 2017 with projections to 2040.*

[5] Cao et al., 2007. "PHEV Hymotion Prius Model Validation and Control Improvements," In: *23rd International Electric Vehicle Symposium (EVS23)*. Anaheim, CA.

[6] Kim et al., 2009. *Tahoe HEV Model Development in PSAT*, SAE Technical Paper 2009-01-1307, Warrendale, PA.

[7] Pasquier et al., 2001. “Validating Simulation Tools for Vehicle System Studies Using Advanced Control and Testing Procedure.” In: *The 18th International Electric Vehicle Symposium (EVS18)*. Berlin, Germany.

[8] Rousseau, A., 2000. “Simulation and Validation of Hybrid Electric Vehicles Using AUTONOMIE.” In: *The 3rd Global Powertrain Congress*, Detroit, MI.

[9] Rousseau et al., 2006. *Integrating Data, Performing Quality Assurance, and Validating the Vehicle Model for the 2004 Prius Using PSAT.* SAE Technical Paper 2006-01-0667, Warrendale, PA.

[10] Moawad et al., 2016. *Assessment of Vehicle Sizing, Energy Consumption and Cost through Large Scale Simulation of Advanced Vehicle Technologies.* Report ANL/ESD-15/28. Argonne National Laboratory, Argonne, IL. http://www.autonomie.net/publications/fuel_economy_report.html

[11] Wang et al., 2018. GREET® 2017 model. Available at: https://greet.es.anl.gov/index.php